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DIGITAL POWER COMPENDIUM

3E
Enhanced Performance
Energy Management
End-user Value

30 YEARS OF INDUSTRY FIRST SAVING ENERGY

1983

PKA
DC/DC
power module
(Ceramic Carrier)
Efficiency >82%

1996

PKG
Schottky Rectifier
(Chip-on-board)
Efficiency >85%

1996

PKN
Low Profile
Synchronous
Rectification
Efficiency >90%

2003

PKM-C
High Power
Density
Low loss
MosFET
Efficiency >93%

2000

PKD
Lead free
Low Profile
DC/DC
Efficiency >92%

1998

PKJ
High Power
Synchronous
Rectification
Efficiency >91%

2008

BMR453
High Power
Flat High
Efficiency
Digital Power
Efficiency >95%

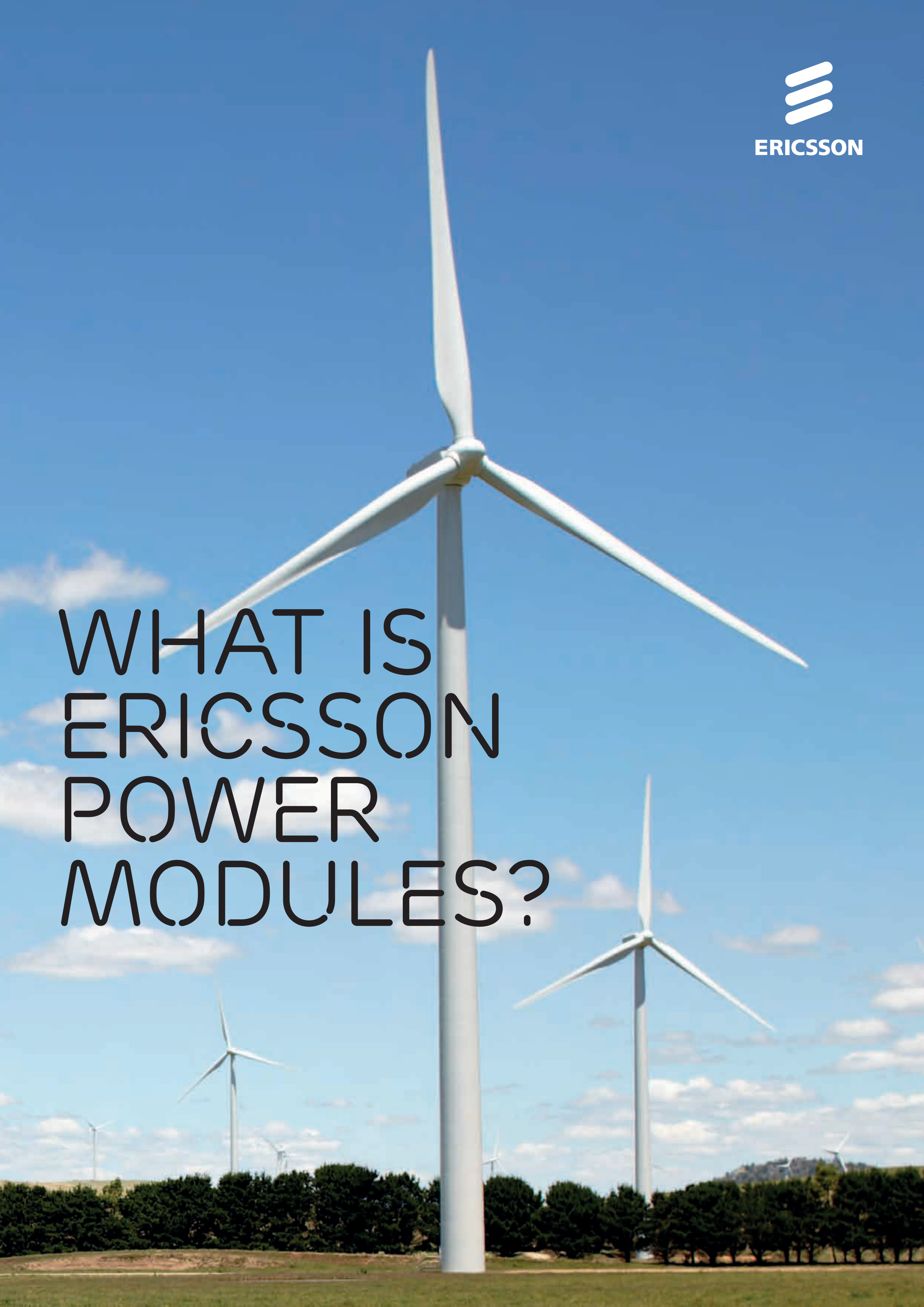
2011

BMR 46X
PMBus Advanced
Point-Of-Load
Digital Power

2012

Launch of the
FRIDA II digital
platform designed
for high-efficiency,
fast response
time and tightly
regulated output
voltage.
Efficiency >96%

CONTENTS



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WHAT IS ERICSSON POWER MODULES?

ERICSSON POWER MODULES

Ericsson Power Modules primarily designs and manufactures isolated DC-DC converters and non-isolated voltage regulators such as point-of-load (POL) units for use in information and communication technology (ICT) applications in distributed power architectures.

Our products are aimed at – but not limited to – the new generation of ICT equipment designed for optimized control and reduced power consumption. The most important application areas are wireless and fixed networks – but our products are also suitable for a broad range of other industrial applications.

Industry first
Formed in the late seventies, Ericsson Power Modules is the source of many industry first innovations. In 1983, we introduced the first high-frequency switching DC-DC power module, and in 1993 the first miniaturized DC-DC converter.

In 2001, we launched the first DC-DC converter intended for lead-free soldering. Later, in 2008, we introduced the first fully digitally controlled and programmable quarter brick DC-DC converter (BMR 453), as well as digitally controlled POL regulators (BMR 450 and BMR 451). These were followed in 2009 by an eighth-brick (BMR454) and in 2011 we introduced the second generation of digital POL, the BMR462, BMR463 and BMR464 offering an unprecedented level of flexibilities to systems architects when optimizing energy distribution while reducing energy consumption.

Design for environment
We apply a design for environment (DfE) policy in all our product development projects. This includes the removal of hazardous substances according to the RoHS directive, and the continuous development of designs and solutions for lower power consumption and the lowest possible total cost of ownership for the end user.

Our operations and portfolio
We have our key design centers in Stockholm and Kalmar in Sweden, and Shanghai, China, whilst manufacturing is carried out in our factory in Shanghai and by qualified partners. Our emphasis is on quality and highly automated production, which has made us one of the largest volume manufacturers in the power-modules industry.

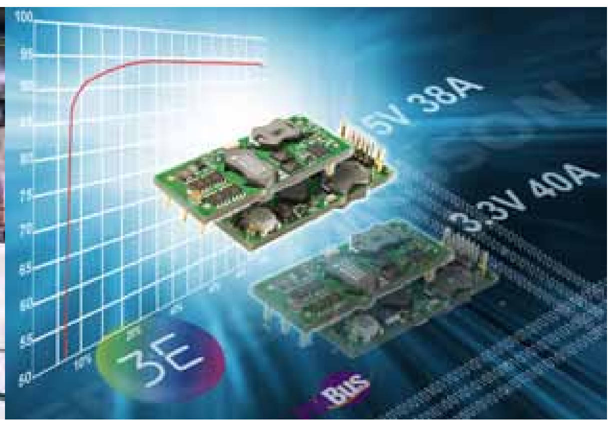
In order to support a global market, we have three hubs, located in North America, China and Europe, as well as an extensive network of sales partners offering local support and easy access to our products.

To date, we offer more than 500 board-mounted products for a wide variety of applications and have supplied over 80 million units.

These can be divided into:
• DC/DC converters
• intermediate bus converters (IBC)
• point-of-load regulators
• board power management.

Every product design is the result of extensive research and development in power technology, a broad application and system knowledge with a focus on design for environment and design for manufacturing, as well as efficient logistics and global support.

The result is:
• low failure rate and long lifetime
• excellent dynamic load performance
• high efficiency over a wide load range
• efficient thermal management.



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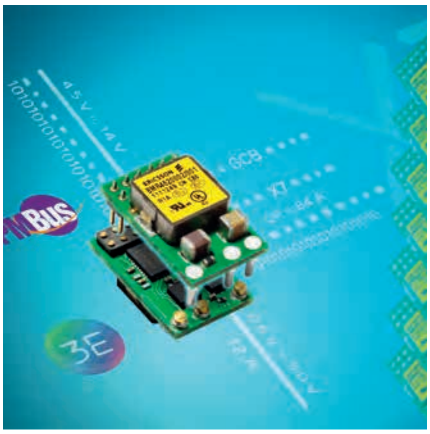
TELECOM POWER DRIVES INNOVATION

TELECOM POWER DRIVES INNOVATION

From the start, the telecommunications industry has pioneered the field of powering systems. It has been the source of important innovations such as distributed power architecture, high efficiency/high power density bricks, digital power control, and new ways to power sites so as to reduce CO_2 emissions. Worldwide, power supply innovations contribute to a better environment and to local development, and help to make life better for future generations.

Managing energy for sustainability
Since the early days of DC/DC power conversion, the issue of increasing energy efficiency has been a key concern for power and components designers. This development has been triggered by requirements for reduced space, lower power dissipation and longer system lifetime.

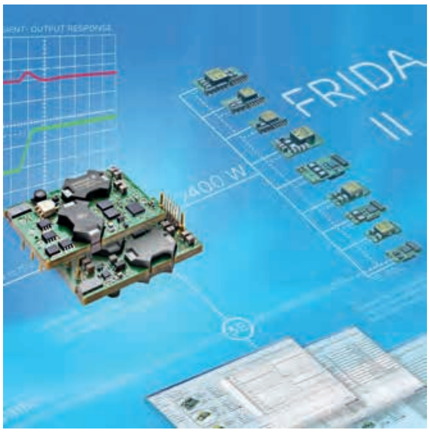
One of the first really challenging projects for power supply designers was the Apollo Spacecraft project in the US, in the late 1960s. In those days, most of the DC/DC converters were designed for military applications and had an energy efficiency of about 40 percent, which resulted in very high power dissipation. The Apollo Spacecraft, and especially the Lunar Excursion Module (LEM), required a new way to distribute energy throughout the vehicle while preserving the precious energy delivered by the fragile batteries. Part of this project was the investigation of a new concept for “integrated DC/DC converters”, which 10 years later became known as “bricks”. The real challenge however, was to improve the efficiency of a system limited by the components and topologies available at the time.



When in July 20, 1969, the LEM landed on the Moon, DC/DC converters were in their infancy. But from that date on they have continuously been improved and, step-by-step, replaced by new topologies.
In the late 1970s, the telecoms industry adopted the bricks concept and Ericsson was the first company in the industry to offer a board-mounted power module that boasted energy efficiency in excess of 60 percent – the benchmark at that time. Due to improvements in components and topologies, energy efficiency increased to over 93 percent in the year 2000. But around 2006, the efficiency gains started to flatten out, requiring engineers to break new ground and move from “passive” to “active” efficiency.

Moving toward active efficiency
To reach even higher levels of energy efficiency at a reasonable cost, power engineers combined analogue technologies with an emerging new technology; digital power control and management.

DC/DC power converters are designed to deliver optimal performance in certain conditions that – when in operation – are not always present. The introduction of digital power control and management – which permanently monitors load and input voltage



conditions so that power supply parameters can be dynamically adjusted to the real conditions – has reduced power losses to a very low level. Additionally, the ability to adjust the bus voltage to suit load conditions has resulted in even greater energy savings without any extra cost.

Combining digitally controlled DC/DC converters and systems energy management has allowed board-mounted power solutions to make the leap from passive efficiency to active efficiency, closing the gap between product and systems optimization.

We at Ericsson Power Modules are very enthusiastic about the possibilities of further reducing energy consumption and improving systems’ performances through new technologies. With this first release of our digital power compendium, we welcome you to learn more about these technologies and our portfolio of digital board-mounted power module solutions.

ERICSSON WHITE PAPER

284 23-3095 Uen Rev C | September 2010

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POWER SUPPLIES GO DIGITAL

Power supplies go digital

Digital control inside an on-board power supply facilitates improved efficiency, reduced total cost and advanced system power management.

DIGITAL TECHNIQUES IN POWER CONVERSION

The concept of “digital power” has received significant attention and promotion in the past few years, from both semiconductor suppliers and power supply manufacturers. There is a need to explain the concepts of digital power; explore the advantages and tradeoffs of digital techniques compared to analog approaches; discuss some of the standardization directions; and explore the possibilities for digital power.

Digital power is defined and implemented differently by various suppliers; moreover, there is not yet an appreciable field history of successful large-scale designs using digital approaches. The result is an atmosphere of uncertainty and some confusion about digital power. Is it cost effective? How does its performance compare to conventional analog approaches? Is it reliable? Does it affect the complexity of the design and development process? Are developers with specialized skills needed? How “standardized” is it and will it affect second sourcing?

A more proactive stance is needed in defining the process to enable the implementation of power supplies and systems using digital power. Most importantly, the above questions must be answered so that the end user – a system integrator or original equipment manufacturer (OEM) – can work confidently with digital power.

Why is power conversion still mostly in the analog domain? The main reason is that efficiency is vital for most power system applications. No matter how many “bells and whistles” going digital might add, if it detracts from efficiency it will have limited appeal. The added power dissipation “overhead” in the form of additional circuitry for digital controls made this approach quite unattractive until very recently. Cost and packaging density are also issues. Happily, the advent of a mature complementary metal oxide semiconductor (CMOS) digital technology has solved these issues by providing digital processing with high density, negligible power dissipation at low cost.

DIGITAL CONTROL AND MANAGEMENT

"Digital power" is a broad term that encompasses several concepts and subdisciplines, and the end user can benefit from digital power on several different levels. One of the major features of digital power is that for any given system application, the end user will typically select only a subset of the available digital power solutions. This decision will be based on factors such as cost, complexity and system availability and maintenance requirements.

One key concept is the distinction between power control and power management. The term "power control" is used to address the internal control functions in a power supply, especially the cycle-by-cycle management of the energy flow. Note that a power supply using digital power control techniques will appear identical to the end user as a power supply using analog power control techniques.

The term "power management" is used to address communication and/or control outside one or more power supplies. This includes functions such as power system configuration, control and monitoring and fault detection. Presently, these functions tend to be a combination of analog and digital. Digital power management implies that all of these functions are implemented with digital techniques and some type of data communications bus structure.

POWER SUPPLY CONTROL

A classic analog power supply control loop is shown in Figure 1. A pulse width modulator (PWM) integrated circuit (IC) is used as the primary control element. The power supply output voltage is sampled by means of a resistive voltage divider and compared with a DC reference voltage by an error amplifier.

The error amplifier output signal is used by the PWM to control the "on time" of the power switch.

For loop compensation, which is needed to ensure the proper balance of dynamic response and stability, a fixed resistor and capacitor network is typically used external to the PWM IC.

Two other major sections of the power supply are the input and output filter networks. These sections, composed of inductors, capacitors and resistors, provide several functions. The input filter helps protect the power supply from transients in the supply voltage, provides some energy storage for power supply operation during dynamic load changes, and includes filter networks to allow the power supply to meet its input conducted emissions specifications.

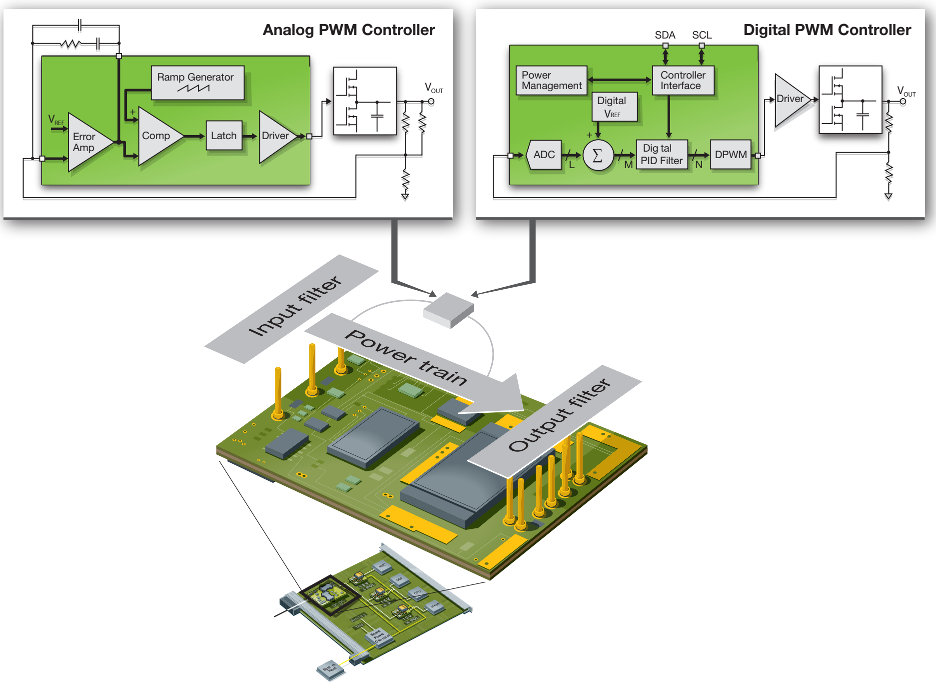


Figure 1: Block diagrams of analog and digital control systems depicted together with some parts of the power train.

The output filter provides smoothing of the output voltage to ensure that the ripple and noise specifications are achieved and also contains energy storage for servicing dynamic current requirements of the load circuits. It is important to note that the input and output filters and the power devices remain essentially the same with either an analog or a digital control structure.

Figure 1 depicts the structure of a typical digital power supply control system. The sensing of the output voltage is similar to that in an analog design. Rather than an error amplifier, however, the sensed analog voltage is converted to a binary digital number with an analog to digital converter (ADC). The digital outputs from the analog to digital coverter (ADC) are fed to a microcontroller (µC) that provides the processing. On board read-only memory (ROM) program memory is used to store the control algorithms for the µC. These algorithms allow the µC to perform a series of calculations on the digital outputs from the analog to digital converter (ADC). The results of these calculations are such parameters as the error signal, the desired pulse widths for the drivers, optimized values for delay in the various drive outputs, and also the loop compensation parameters. The external loop compensation components used with the analog system are no longer needed.

All values of parameters such as output voltage, output current and temperature are stored in electrically erasable programmable read-only memory (EEPROM) at manufacturing or via transfer with a communications bus. The EEPROM content is downloaded to the random access memory (RAM) during power-up, and the µC then uses this part of the memory for read and write operations.

Digital control is considerably more flexible than analog control in its ability to adapt to changes in line and load conditions. It has the ability to change the control parameters as a function of the power supply operating conditions. This is illustrated by the following examples.

In a synchronous buck power supply, the top and bottom metal oxide semiconductor field-effect transistors (MOSFETs) are operated so that both never conduct simultaneously. This is guaranteed by defining a "dead time" period after one of them is turned off and before the other is turned on. With digital control the dead time does not need to be fixed, but can be varied via a digital control loop as a function of operating conditions to optimize the power supply efficiency. This technique is especially valuable at low load as shown in the comparison in Figure 2.

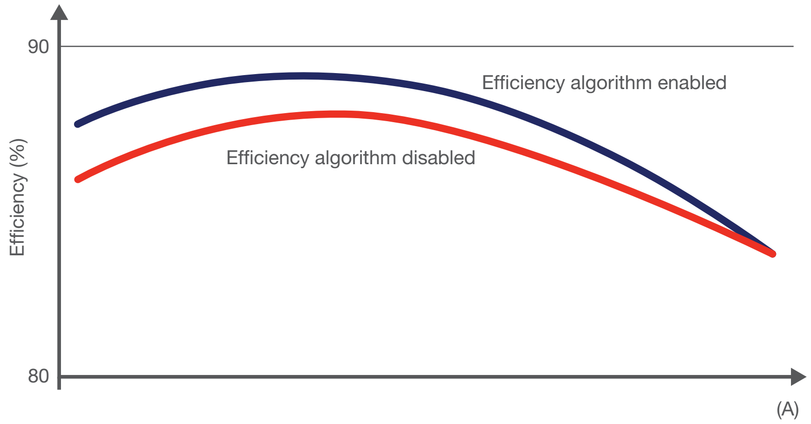


Figure 2: A parameter such as "dead time" in a synchronous buck power supply may be optimized over line and load conditions to improve efficiency.

In analog control designs, the feedback loop compensation is a compromise between stability and dynamic response performance.

Using digital control techniques, it is possible to construct non-linear, or adaptive, control loops that change the compensation as a function of operating conditions. That is, the power supply displays fast response when it needs to and slower response in other situations.

Figure 3 shows examples of this adaptive behavior. In addition to the enhanced dynamic response, this approach has other benefits to the power system. Fewer output decoupling capacitors are required to ensure a given voltage tolerance, with resulting savings in cost and component space. Nonlinear control can also be used to allow power supply operation in discontinuous mode without the usual disadvantage of poor dynamic performance.

Because of advantages such as those described above, digital control is now the preferred approach and will gradually be used more and more for new power supply designs. The fact that some of the embedded digital control circuitry in the power supplies can be used for system power management purposes is an added bonus. Therefore, much of the hardware for the power management capability that will be described in the next section comes "for free" as far as the system designer is concerned.

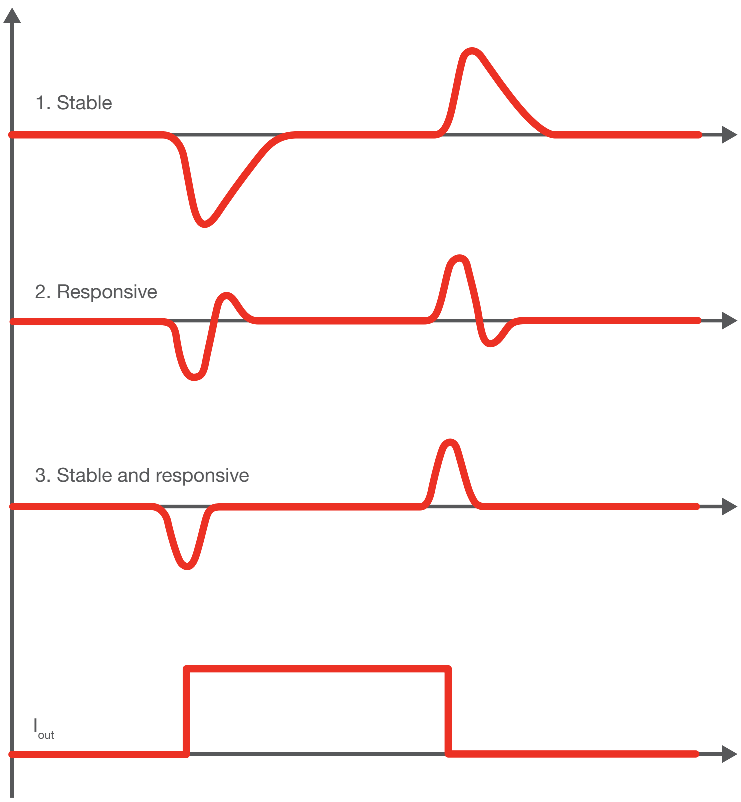


Figure 3: Non-linear, or adaptive, control loops can combine the benefits of stability and responsiveness.

POWER SYSTEM MANAGEMENT

Digital power management offers several benefits and opportunities and can be used at several different stages of the power supply and power system life cycle. Flexibility is the key; the power system designer may pick and choose only those features and capabilities that are important to a specific application:

- During manufacturing of the power supply, automated test equipment (ATE) control can be used to configure parameters such as output, voltage trimming, protection trip points and loading of date codes and serial numbers.
- During optimization of the power system design, the digital interface can be utilized to measure temperature, voltage and output currents and to set the trip points for fault protection circuits.
- During assembly and testing of the board and system, the digital power management interface can be used by an ATE.
- With a power system host control, start-up and shut-down sequencing can be provided. Operating temperatures can be monitored to regulate the cooling fans and fault detection, and management routines can be developed that take into account conditions elsewhere in the system.

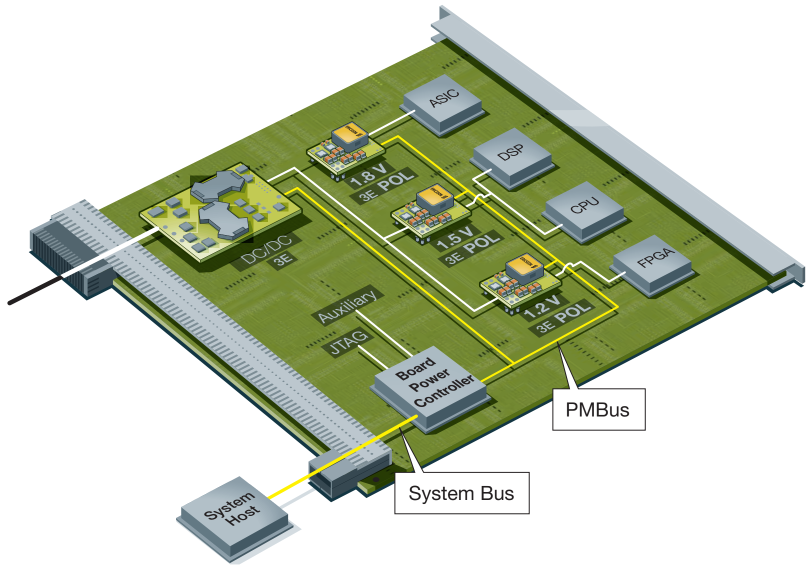


Figure 4: A digital power management system consisting of power supplies (slaves) connected to a controller (master) via a communications bus depicted by the yellow lines.

The digital power management system has a basic architecture consisting of power supplies that communicate with a centralized power system host control via a digital communications bus as described in figure 4.

The power supplies are DC/DC converters or point of load (POL) regulators. The control device can take many forms, including:

- An IC dedicated to power system control
- A general purpose microcontroller
- A laptop computer with a graphical user interface (GUI)
- ATE during the power supply or system testing process.

The host device has a control domain consisting of a single system board, and for some larger scale systems, this host will in turn interact with higher system level controllers.

System power control is becoming more complex as the number of voltage levels on a typical board increase. This greatly increases the complexity of the voltage sequencing.

Sequencing order, ramp times and delays need to be controlled for both normal start-up and shut-down operation as well as for some fault conditions. All this is straightforward with digital management – without resorting to installing analog control and timing components or even using a soldering iron.

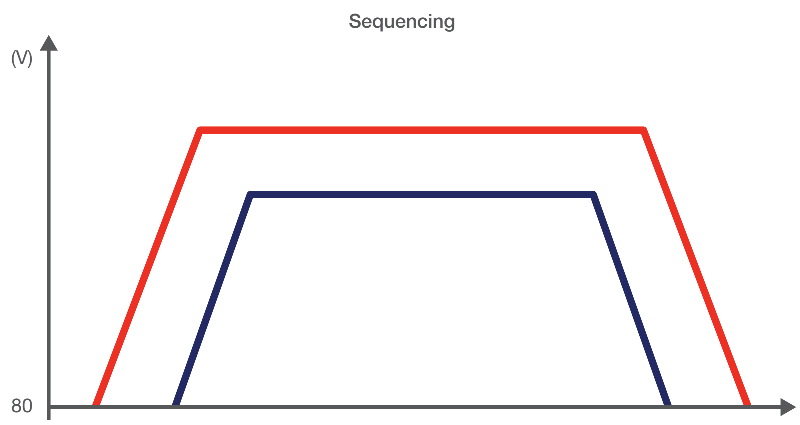


Figure 5: The sequencing order for start-up and shut-down of multiple power supplies can be controlled using digital power management.

Voltage margining is another example of using digital management for power supply control. This is used during the final stages of production to verify the robustness of the unit. Voltages are varied by perhaps +/-5 percent in different combinations. Using the digital communications bus, this can be accomplished in less than a second without any additional hardware or interconnections.

A common requirement that falls into the configuration category is programming thresholds for fault detectors. Using a digital bus results in extreme flexibility:

- Temperature protection can be set, and operation can be configured digitally for either latching or automatic restart.

- Over current protection can be set, and latching or automatic recovery modes can be programmed.
- An over voltage protection trip point for a specific output voltage trimming and latching is easily programmed, as are automatic recovery modes.

Monitoring consists of measurement of such parameters as input and output voltages and currents, operating frequency, and temperatures interior to the power supplies. Most OEMs will find this capability to be of the greatest use during the design and evaluation phases of a new system.

Digital monitoring allows for all of these measurements to be made via a laptop computer and GUI rather than with thermocouples, soldering irons and component replacements. Gaining parametric information at this stage allows for optimization of the power system and for the selection of the most cost-effective power supplies.

Designers of high-end and high-availability systems may want to incorporate these kinds of capabilities in the final product, so that parametric data can be collected in the system operating environment. Examples of capabilities with this approach are:

- Efficiency may be monitored and degradation noted prior to actual failure so that part replacements can be made without affecting system availability.
- System fan speed can be controlled as a function of actual temperatures inside power supplies.
- A complete field population of systems can be queried to find the locations of power supplies with a particular serial number, in order to replace a suspect batch of power supplies before the advent of field failures.

Most users will not need to use this degree of sophistication in their designs. An intermediate approach is to use an interrupt-driven design.

Here, the host controller does not do routine monitoring of parametric data, but is only notified by a power supply when it is experiencing a problem. The host can then take the required action as a function of the power supply fault mode.

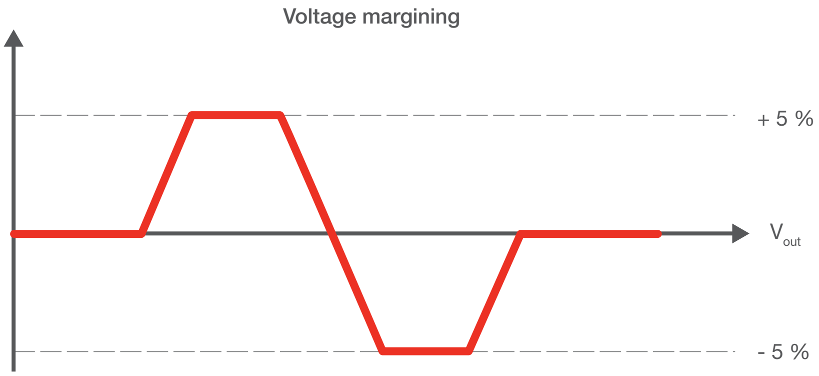


Figure 6: Digital power management can be used for voltage margining of the output from the power supply (corner testing).

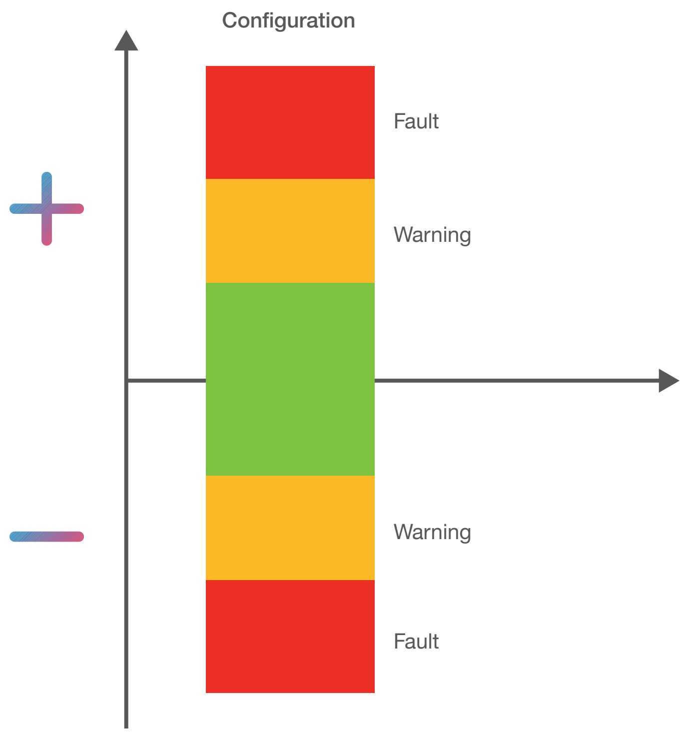


Figure 7: Limits for both warning and fault conditions can be programmed for parameters such as temperature, output voltage and output current.

PMBUS

The Power Management Bus (PMBus) is an existing protocol that has been adopted and supported by several power supply manufacturers. The protocol is owned by the System Management Interface Forum (SMIF).

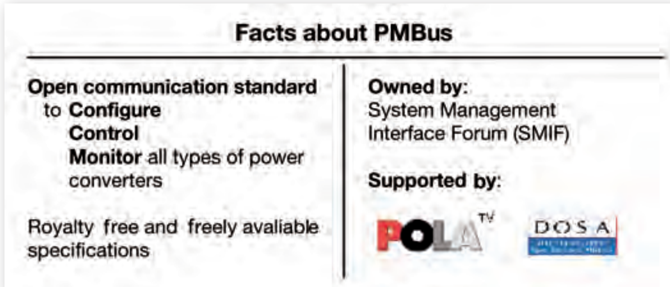
Membership of SMIF is open to all interested parties, and the PMBus specification is freely distributed and is available for use on a royalty-free basis.

The PMBus is a broad, generic and flexible interface that can be applied to a wide range of devices, and it works well with all kinds of power supplies.

The PMBus addresses the host to the controlled device communication architecture described earlier and does not include provision for direct device to device communication. PMBus provides a dependable and widely used and understood digital power control and management interface without limiting innovation with other advanced techniques.

In its most basic form, the PMBus is a two wire serial bus that is based on the System Management Bus (SMBus), which is a derivative of the popular Inter-IC (I2C bus), but enhanced to provide greater functionality for power control applications.

The physical implementation is not defined by the PMBus. Power supply manufacturers and industry organizations, such as the Distributed-power Open Standard Alliance (DOSA) and Point of Load Alliance (POLA), are therefore cooperating to establish standard configurations for form factors, pin outs and mechanical interfaces for the connections and programming pins.



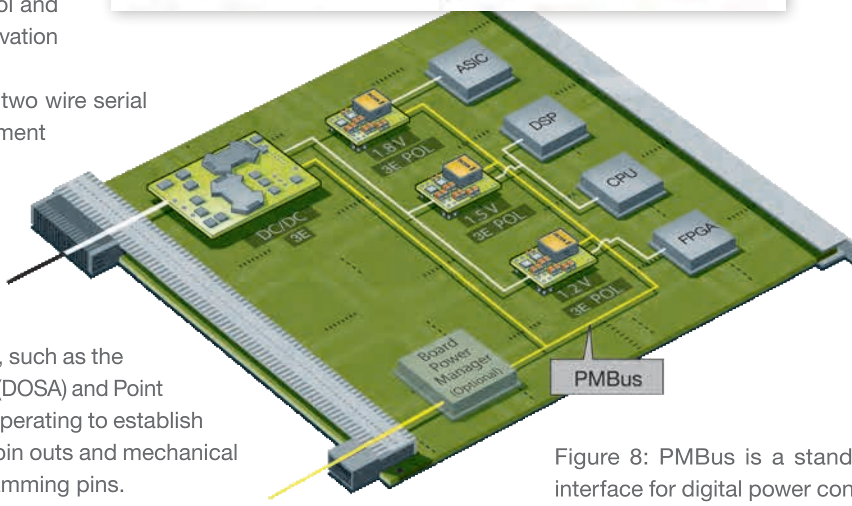


Figure 8: PMBus is a standard interface for digital power control and management.

CONCLUSION

Digital power techniques have been proposed for some years now, but have not been able to successfully compete with analog solutions. Thanks to an increase in IC density, hard work on the part of semiconductor suppliers and a mature and reliable CMOS technology, digital processing for power conversion applications is now very attractive. Most importantly, the use of digital techniques results in capabilities and performance levels at both the power supply and system levels that are not possible with analog techniques.

While much of the publicity and controversy about digital power techniques is focused on power system management issues, the most important issue, and the ultimate driver for its acceptance, will be the benefits that it brings to the power supply itself. These benefits are real, measurable and available with today's technology:

- Improved efficiency
- Improved reliability due to higher integration of digital control circuitry
- Reduced system cost because of fewer decoupling capacitors due to enhanced load transient response of adaptive digital control
- Increased power supply power density due to smaller digital control circuitry
- Tighter output voltage tolerances due to enhanced initial set point trimming
- Lower overall cost of ownership due to the above improvements.

Due to the cost parity between digital and analog control implementations using today's technology, these benefits are "free" to the end user and represent real customer value.

There are sound advantages in utilizing the digital interface to power supplies during the system design, development and evaluation periods. The communications bus allows for complete user customization, and the net result is a reduction in design time, facilitated power management and a resulting reduction in time to market for the end product.

The user customization also allows a single power supply part number to serve several purposes, thereby reducing the inventory, the number of part numbers being managed, and the time required for sourcing power supplies.

GLOSSARY

ADC	analog to digital converter
ASIC	application-specific integrated circuit
ATE	automated test equipment
CMOS	complementary metal oxide semiconductor
Comp	comparator
CPU	central processing unit
DOSA	Distributed-power Open Standards Alliance
DPWM	digital pulse width modulator
DSP	digital signal processing
EEPROM	electrically erasable programmable read-only memory
Error Amp	error amplifier
FPGA	field-programmable gate array
GUI	graphical user interface
IC	integrated circuit
I2C	Inter-IC
JTAG	Joint Test Action Group, which developed the JTAG standard (later named IEEE 1149.1) for boundary-scan technology to assist in the testing, maintenance and support of assembled printed circuit boards.
MOSFET	metal oxide semiconductor field-effect transistor
OEM	original equipment manufacturer
PID	proportional integral derivative
POL	point of load
POLA	Point of Load Alliance
PMBus	Power Management Bus
PWM	pulse width modulator or pulse width modulation
RAM	random access memory
ROM	read-only memory
SCL	Serial Clock Line
SDA	Serial Data Line
SMBus	System Management Bus
SMIF	System Management Interface Forum
µC	microcontroller

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IS DIGITAL POWER MOVING FORWARD?

It is now several years since commercial products with 'added digital performance' aiming to revolutionize the power industry have been around in the marketplace. However, a certain market perception gives the feeling that behind the noise generated by the media, digital power seems not to have moved as fast as expected. Wrong perception or reality?

CONTENTS

ABOUT THIS PAPER

The material contained in this paper was presented on March 18 at PCIM China 2008.

1. WHEN DID DIGITAL POWER GET STARTED?

1.1 THE PIONEERS

Before reviewing today's situation, it is important to remember the origins of digital power, and how from early research work conducted in the mid seventies by Trey Burns, N.R. Miller, and others, digital power gradually took its place in the power industry to reach a level of maturity that makes sense for a designer to consider such technology.

In the seventies, at time the power industry was slowly considering the migration from linear-power to switching-power, Trey Burns researched and explored the use of the State-Trajectory Control Law in Step-up DC/DC converters and he compared two methods of realization, one employing a digital processor and the other using analogue computational circuits [1] [2] [3].

The results of this research were presented at various conferences but PESC 1977 is considered as the origin of a wave of research in digital methods to drive, monitor and control DC/DC converters (e.g. Bell Labs engineers, Norman Richards Miller presented an innovative approach to digitally control a switching regulator [4], and Victor B. Boros presented a novel serial digital implementation of feedback control circuits for power conditioning equipments [5]).

At that point of time it is anecdotic but interesting to note that an experimental product built by Trey Burs was a boost converter operating at a switching frequency of 100Hz, given sounds slow - but it had to be slow because it took up to 450µsec to execute the digital program per sample.

The digital controller was a PDP 11/45 mini-computer *(figure 1)*, and the boost converter was built, using a 10mH cut-C core inductor (very big and heavy) and approximately 13,000 µF of capacitance. The research team rolled the circuit up to the computer on a cart.

Figure 1 - PDP 11/45 computer

Considering PESC 1977, it is interesting to remember few words from the introduction of the paper Victor Boros presented:

"TODAY, DIGITAL CONTROLLERS ARE ECONOMICALLY AND TECHNICALLY FEASIBLE. THE CONTROL FUNCTION IS NOT MORE COMPLICATED THAT CIRCUITS FOUND IN HAND CALCULATORS AND COSTS ARE COMPARABLE FOR LSI CIRCUIT REDUCTION."

1.2 TECHNOLOGY IMPULSE

If today, digital technologies are nothing new, we should remember Trey Burns using a PDP-11/45 to control and simulate his model, and that the most advanced micro-processors available in those days were 8 bits (e.g. Intel 8080 - *Figure 2*).

There is no doubt that the rapid development of the micro-processor industry boosted research in digital power management and control.

From PESC 1977 onwards, year-after-year, papers presented at various conferences confirmed the growing interest from the research community for digital techniques applicable to power systems.

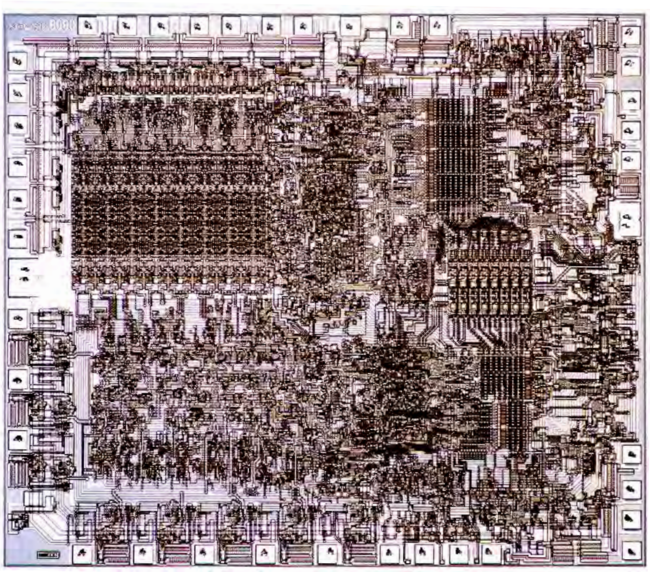

Figure 2 - Intel 8080

Researched progressed very fast though it was only in the mid eighties that we could consider that from the huge amount of research conducted for more than twenty years, that possible commercial applications would emerge.

As we consider PESC 1977 to be the ignition-point for research into digital-power, the years 1984 and 1985 are the second cornerstone in the evolution of digital power technology.

One example is when Chris Henze was working on his Ph. D at the University of Minnesota under the direction of Ned Mohan. Chris published some interesting parts of his work at PESC in Toulouse in 1985. In this work Chris was using a micro-processor and was switching at a reasonable frequency for a non-isolated dc-dc converter of that era. In his paper he identified issues like quantization issues and the need to dither to get adequate PWM resolution. [6]

The application presented by Chris Henze is one among many that are representative of the evolution; from pure research to possible commercial applications based on micro-processors.

1.3 THE FIRST WAVE OF APPLICATIONS

Since the original results of research presented in 1977, throughout the years the number of papers and patents relating to digital power management and control has increased impressively, confirming the growing interest for such technology.

In the late 1990's based on the digital signal processor C2000, TI contributed to develop the first fully digital controlled UPS.

Using a DSP to digitally control the switching and power management of a UPS system was the first practical application for digital power. This real-life application was the first in a long series of experiments aiming to optimise digital control in power supplies, expanding the scope of opportunities for the DSP.

At the same time, based on the communication Bus I2C developed by Philips, Telecom Power Manufacturers (e.g. Ericsson Energy Systems) introduced communication features that made it possible for operators to monitor and manage energy at site level.

2. THE MILLENIUM TURNS DIGITAL POWER ON

2.1 MILLENNIUM MILESTONE

Since PESC 1977, twentyfour years have passed, and, with the millennium, digital power reached a new cornerstone.

Fundamental and important research conducted by those pioneers, and the rapid development of new components based on micro-processor technologies (e.g. Digital Signal Processor DSP) have made it possible for power supply designers to access suitable controllers and topologies that simplify the migration from analogue to digital.

The list of initiatives would be too long to cover under this paper, though from 2000 to 2004, we could consider some of the more important steps that contributed to the digital power migration from research to real life applications.

October 2001
Within the scope to co-develop digital power management solutions for high-end desktop PCs, servers and notebook PCs, Intersil and Primarion formed the Digital Power Management Alliance (DPMA).

December 2002
Texas Instruments introduced the industry's first digital signal processing (DSP) Development Kit (MDS3P701235DPS) dedicated to Power Supplies.

March 2004
With the introduction of the Z-One™ Digital IBA architecture, Power-One announced the integration of power conversion, control, and communications in point-of-load power units.

September 2004
Market Analyst Darnell established the first forum dedicated to digital technologies applicable to power systems and solutions: Digital Power Forum (DPF).

2.2 MILLENNIUM FORWARD

From the millennium, the number of papers presented at various conferences demonstrating the benefits of digital control and energy management increased tremendously.

The semiconductor industry started to announce products expected to make the development of digital control and digital power management as simple as it was for analogue, and some end-user-ready products started to appear on the market.

Unfortunately, the lack of standardisation, and the multiplication of different communication protocols added a level of complexity when designers considered using this technology.

2.3 DO YOU SPEAK EASYBUS?

As for other industries, the development of a new technology always generates new demands, requiring new ways of working and standardisation.

For example, among new technologies introduced over the last decade, there is the short-range radio Bluetooth, which is an illustration of a new technology that in 10 years has moved from laboratory research to commercial success.

Everything started in 1994 when Ericsson initiated a study to investigate the feasibility of a low-power low-cost radio interface between mobile phones and their accessories. In February 1998, five companies, Ericsson, Nokia, IBM, Toshiba and Intel formed a Special Interest Group (SIG). 10 years later, 1.5 billion Bluetooth devices are in operation worldwide. [7]

Bluetooth is an illustration of a new technology born from the willingness of Industry leaders to share knowledge, working together to develop new solutions that make life easier, and more efficient.

Bluetooth could seem to be an odd example though it proves the efficiency of a new way-of-working when companies are collaborating to develop new technologies, making it possible to develop interoperable units by creating a standard.

The new possibilities and simplicity offered by the addition of digital control into power supplies revealed the lack of efficient communication protocols dedicated to this new domain of applications emerging in the power industry.

Introduced by Philips in the early eighties, the Inter-IC-BUS (I2C) cohabited with RS-232, RS-485, SMBus, SPI Bus, CAN Bus, and many proprietary protocols and formats.

In this jungle, components manufacturers, power industry leaders, and end-users began considering how to develop and standardise a common vehicle and a package of instructions to support this new technology.

In the same spirit as Bluetooth, in May 2004, Artesyn Technologies, Astec Power, and a group of semiconductor suppliers (Texas In-struments, Volterra Semiconductors, Microchip Technology, Summit Microelectronics, and Zilker Labs) formed a coalition to develop an open standard for a communication vehicle and protocol dedicated to power systems. A standard named PMBus™ was born *(Figure 3)*.

Figure 3

At the end of 2007, the PMBus™ Implementers Forum (PMBus-IF), comprised about 30+ adopters with the objective to provide support to, and facilitate adoption amongst users.

3. DIGITAL FORWARD

From 2004, in parallel to the development of PMBus™, step by step companies started to introduce new products and solutions to facilitate the evolution from analogue to digital.

As in the previous example, the following events listed in this paper are for information, provided as an illustration. Many more could be added.

July 2005
Atmel, C&D Technologies, and Power-One, announce the launch of z-alliance.org. Roal announced a digitally controlled 2KW power supply, the PS194

September 2005
Artesyn announced its first digital POL, the DPL20C series

Astec is the first to use bi-directional PMBus™ into a dc/dc converter, the DTX series

March 2006
Linear Technology introduced a digital dc/dc controller IC with PMBus™ interface

July 2006
Zilker Labs launched a 3A controller IC that in-tegrates digital power management and PMBus™

Maxim to release digital power supply controller that uses PMBus™

March 2007
Intersil announced PWM controller PMBus™ enabled, the ISL8601

April 2007
With the UCD9240 Texas Instruments introduced the First 'Digital Power System Controller'

Primarion launched Industry's First Dual Output Digital Synchronous DC/DC Controller (dual-phase PX7522)

May 2007
TI released a new concept, "PowerTrain" combining UCD9240 and termination module PTD08A010W. This combination of control IC and semi-finish products modules is a unique approach, which some consider as a midway solution between pure discrete solution and modules.

August 2007
Power-One launched a digital POL providing 60A (ZY8160)

September 2007
Primarion announced a reference design for its PMBus™ compliant PX7522

October / November 2007
Different forums (USA and Europe) confirm the positive trend in digital power, supporting the idea that, as for other industries, standardisation will be a strategic decision factor for end-customers when migrating from analogue to digital.

This short overview should comfort the opinion that digital power has moved forward though, despite signs of evidences that technology is now ready and mature, supporters from both camps, "Analogue Forever" and "Digital For Future" are still debating.

4. REVOLUTION OR EVOLUTION?

Novelties, new ideas and concepts are always a source of debate, bringing pros and cons arguments to defenders and challengers.

The number of papers, articles, technical summits, products and solutions released from the Millennium should be enough to demonstrate the benefits of implementing digital technology into an industry that has for some time been considered as a commodity, and slow moving in terms of innovation when compared to others.

However, fuelled by the force of marketing led arguments about the inevitable replacement of analogue by digital, digital aficionados predict that as it has been for other market segments, the power industry will not be able to avoid the inevitable digital revolution, comparing it to other industries such as the music industry and the death of vinyl, replaced by the CD [9].

Looking at the other side of the argument, analogue aficionados claim that digital power is nothing new, and that adding digital functionalities to a power supply is as old as the launch by Philips of the world famous Inter-IC Bus (I2C) introduced in early eighties [10], and that nothing will drastically change just because digital marketing is in the air.

Taking into consideration the arguments from both camps, the power industry generally behaves similar to others, following the same rules in terms of technical evolution, technology transition, and marketing.

The transition from vinyl to recordable CD has always been highlighted as a reference, but that is without considering other products and standards, where despite technical benefits and leading edge technology haven't encountered expected market recognition.

As the data-storage industry presently battles with the standardization of the next generation of high density DVD format (Blue-Ray versus HD-DVD), we should remember that a few years ago Betamax lost the battle against VHS - despite Betamax's better performance.

As it was for the adoption of a video standard, even at it's relatively modest level, digital power conversion is following the same rules and the principle of 'R.G. Cooper's Law' [11]; "for every four products that enter development, only one becomes a commercial success."

5. CONCLUSION

Driven by growing concerns about energy preservation and reduction of CO2 emissions by the Information Communication Technology (ICT) industry, power supply manufacturers have taken seriously the measure of the situation and initiated a number of projects that contribute to reduce the environmental impact.

The development of efficient power conversion systems associated with active energy management, made possible by digital technologies, is the most evident way to go, contributing to the rapid development of commercial "digital power solutions."

Despite the belief in some that one technology will prevail over another, it will not be a war between analogue and digital, but more a cohabitation between both, and a smooth transition when equipment manufacturers consider new systems or major updates.

We should remember that volume applications such as radio base stations or datacentres have longer lifecycles than most consumer products, and that the interoperability requirement increases the design time of such products as well.

Whatsoever, and to conclude, as it has been for other industries (remember how Bluetooth turned into success), the migration to digital power will require the power industry to consider new ways of working and efforts to standardize the basic principle.

That is the only way to go to guarantee market adoption by designers and end-users of digital power technology; nothing will happen by magic.

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All referenced papers and data sheets can be found at Ericsson Power Modules’ web site: http://www.ericsson.com/powermodules

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ERICSSON

GET AHEAD WITH 3E DIGITAL DC/DC CONVERTERS AND POL REGULATORS

3E – Enhanced performance, Energy management and increased End-user value

CONTENTS

1. INTRODUCTION

Ericsson Power Modules has recently introduced a comprehensive set of products that establish an innovative approach to the goals of end-user value, flexibility, and system performance. These new products contain several unique concepts spanning multiple disciplines in circuit and system design, all focused on optimizing performance, flexibility, and value for the end-user. Ericsson Power Modules refers to the high-level end-user benefits of this approach as "3E", the 3 Es being:

- Enhanced Performance
- Energy Management
- End-user Value

This technical paper describes the initial set of isolated-output DC/DC intermediate-bus converters (IBCs) and non-isolated point-of-load (POL) regulators in the new product family, which we refer to generically as "3E DC/DC converters" and "3E POL regulators". *Figure 1* introduces these components and highlights their major specifications.

The sections that follow describe some of the key concepts, definitions, and terminology that apply when working with 3E family products and the power system architectures that they enable.

A description of the 3E DC/DC converters and 3E POL regulators follows, together with more information regarding the benefits to the end-user with particular respect to hardware features, electrical performance, and mechanical details.

The last part of this technical paper expands the discussion of the 3E concept as it applies to active power management methodologies and outlines example application scenarios that end-users may wish to explore as well as expand upon.

BMR 450

Key Features
- Small package 25.65 x 12.9 x 8.2 mm
- 20 A output current
- 4.5 V-14 V input voltage range
- 0.6 V-5.5 V output voltage range
- High efficiency, typ. 96.8% at half load, 5 V in, 3.3 V out
- 5 million hours MTBF
- Through hole and surface mount versions
- PMBus compliant

Power Management
- Digital soft start/stop
- Precision delay and ramp-up
- Voltage sequencing and margining
- Voltage/current/temperature monitoring
- Transistor dead-time optimization for improved efficiency
- Configurable output voltage
- Configurable loop compensation

BMR 451

Key Features
- Small package 30.85 x 20 x 8.2 mm
- 40 A output current
- 4.5 V–14 V input voltage range
- 0.6 V–3.6 V output voltage range
- High efficiency, typ. 96.4% at half load, 5 V in, 3.3 V out
- 2.6 million hours MTBF
- Through hole and surface mount versions
- PMBus compliant

Power Management
- Digital soft start/stop
- Precision delay and ramp-up
- Voltage sequencing and margining
- Voltage/current/temperature monitoring
- Transistor dead-time optimization for improved efficiency
- Configurable output voltage
- Configurable loop compensation

BMR 453

Key Features
- Industry standard Quarter-brick
- Input 36-75 V
- Output up to 33 A / 396 W
- High efficiency, typ. 96% at half load, 12 V out
- +/- 2% output voltage tolerance band
- 1500 Vdc input to output isolation
- 1.1 million hours MTBF
- Optional baseplate
- ISO9001/14001 certified supplier
- PMBus compliant

Power Management
- Programmable built-in active current share up to 792 W in parallel configuration
- Configurable soft start/stop
- Precision delay and ramp-up
- Voltage sequencing and margining
- Voltage/current/temperature monitoring
- Configurable output voltage
- Power good
- Synchronization
- Voltage track

BMR 454

Key Features
- Industry standard Eighth-brick
- Input 36-75 V
- Output up to 20 A / 240 W
- High efficiency, typ. 95.5% at half load, 12 V out
- +/- 2% output voltage tolerance band
- 1500 Vdc input to output isolation
- 1.13 million hours MTBF
- Optional baseplate
- ISO9001/14001 certified supplier
- PMBus compliant

Power Management
- Configurable soft start/stop
- Precision delay and ramp-up
- Voltage sequencing and margining
- Voltage/current/temperature monitoring
- Configurable output voltage
- Synchronization
- Voltage track

Figure 1 – 3E family POL regulators and DC/DC converters.

2. CONCEPTS, TERMINOLOGY & DEFINITIONS

Because the internal design of the 3E DC/DC converters and 3E POL regulators uses digital power control techniques, end-user applications can benefit from system-level approaches to digital power and energy management. While it is perfectly possible to apply these products using the same techniques as for conventional analog power converters, considering the digital approach makes it possible to select between conventional and digital techniques to make the best choice for a particular system. This section describes the distinctions between digital power control and digital power and energy management, and makes comparisons with conventional analog systems. Further information is available in the reference material that is available from Ericsson's website.

This discussion assumes the use of a fairly conventional intermediate bus architecture (IBA) such as *Figure 2* shows, with a board-level intermediate bus converter (IBC) feeding multiple POL regulators that are located close to the load circuitry and supply the final operating voltages. The IBC output voltage, and POL input voltages, will typically be between 3.3 and 12 VDC. In the discussion that follows, the term "board-mounted power supply" is generic and applies to both IBCs and POLs. The figure also shows an optional board power manager and its digital power management bus (PMBus™).

Conventional analog DC/DC converters and POLs use a pulse-width-modulation (PWM) control IC together with a multitude of external resistors, capacitors, inductors, and active discrete semiconductor devices to achieve the feedback and control functions that the board-mounted power supply (BMPS) requires. For instance, linear analog component networks set the time constants that balance the power converter's response and its stability, and sensors and comparators establish and perform internal fault-detection duties. As a result, user configurability is typically quite limited, with resistive trim for output voltage programming being the commonest facility.

Ericsson Power Modules uses the term "digital power control" to describe a power converter in which digital circuitry replaces much of the analog control functionality. Typically, the digital content includes the feedback loops, MOSFET gate-drive generation, and fault detection. The MOSFET switches and the main output LC filter are often very similar to those in an analog converter. Importantly, digital power control can be completely transparent to the end-user: two BMPS devices, one implemented digitally and one with analog circuitry, can be plug-compatible and may be indistinguishable to the end-user. However, using digital techniques within a DC/DC converter or POL offers significant density and performance advantages, as well as dramatically increasing the power converter's flexibility and configurability.

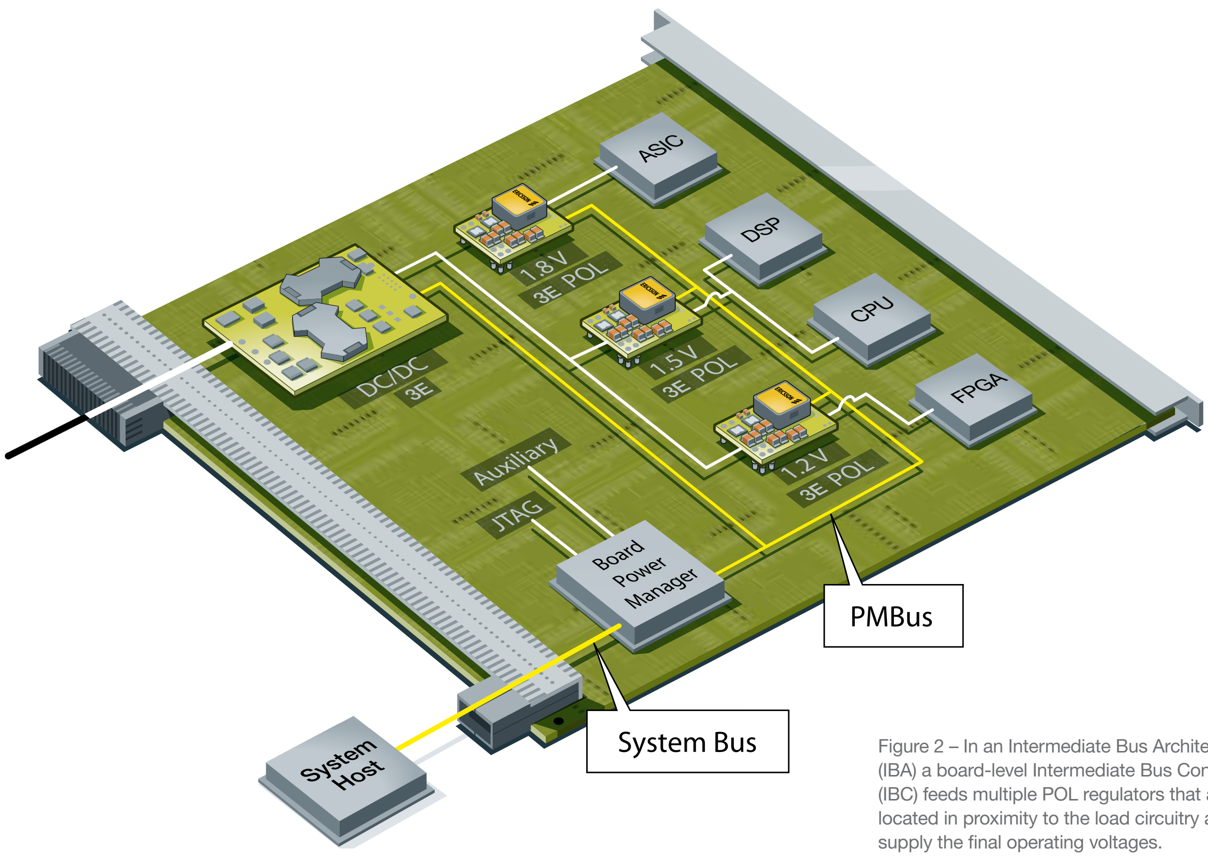


Figure 2 – In an Intermediate Bus Architecture (IBA) a board-level Intermediate Bus Converter (IBC) feeds multiple POL regulators that are located in proximity to the load circuitry and supply the final operating voltages.

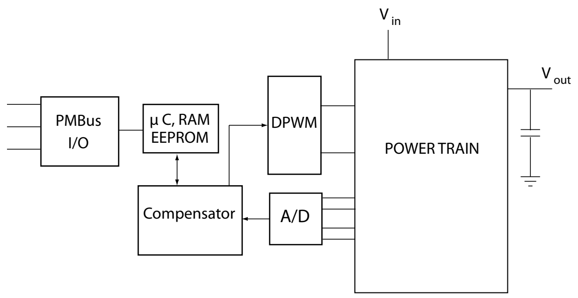
While digital power control only applies to the circuitry within a power supply and is designed and controlled by the BMPS manufacturer, digital power management and energy management extends beyond the physical boundaries of a DC/DC converter or POL regulator and into the end-user's system. This extension significantly increases the capabilities of the end-user's system, but also requires the power system designer to help implement the digital communications structure. Ericsson Power Modules uses the term "digital power management" to describe a system in which DC/DC converters and/or POL regulators communicate digitally with other system elements in order to monitor and control the behavior of the power supplies. This digital communication is typically used for power control, fault handling, configuration changes, and efficiency optimization. Communication is conventionally facilitated via a digital interface known as the power management bus (PMBus™) that the yellow line in *Figure 2* represents.

One of the major advantages of using digital control within a DC/DC converter or POL regulator is the ability to integrate the control and monitoring functions and the communications interface alongside the core logic. By comparison, analog systems optionally implement these facilities externally, consuming more space and power with inferior coupling between the core control logic and peripheral elements. While the digital power control core must operate on a cycle-by-cycle basis at the power supply's operating frequency to control the energy flow, the digital power management subsystem usually operates on a considerably slower time scale that reacts to changes within the system.

The efficiency of DC/DC converters and POL regulators has always been a key performance criterion. It is receiving ever more attention due to the increasing emphasis on energy consumption and the environmental impact of large-scale data processing and telecom installations. Digital power control allows for "on-the-fly" reconfiguration of operating parameters within a power supply as a function of system operating conditions, while the synergy between digital power control and digital power management results in further efficiency improvements that also lower energy consumption. In a conventional DC/DC converter or POL regulator many operating parameters are fixed, resulting in an efficiency level that is a compromise based on the expected range of system operating conditions.

By contrast, if a digitally-controlled POL regulator or DC/DC converter operates within a system that implements digital power management, the system status can be used to dynamically program the power supply's operating parameters. For example, a regulator's PWM dead-time can be varied as a function of its input voltage, temperature, and output current to optimize conversion efficiency over a wide variety of operating conditions.

Similarly, dynamically varying an IBC's output voltage can optimize the power supply's overall conversion efficiency as a function of system operating conditions. "Digital energy management" is the term that Ericsson Power Modules uses for this strategy, which can also compensate for the effects of component variations due to factors such as temperature changes and ageing. In effect, digital energy management replaces compromise with optimization to deliver impressive energy savings.



The block diagram depicts the control system structure of 3E products. The sensing of the output voltage is similar to that of an analog system. Rather than an error amplifier, however, the sensed analog voltage is converted to a digital value by an analog-to-digital converter.

In addition to output voltage, it is useful to know the value of other analog parameters such as output current, temperatures in the converter, etc. These digital outputs are fed to a microcontroller (μC) that provides processing for the system. On-board ROM program memory is used to store the control algorithms for the μC. These algorithms allow the μC to perform a series of calculations on the digital outputs from the A/D converter. The results of these calculations are parameters like the error signal, the desired pulse widths for the drivers, optimized values for delay in the various drive outputs, and the loop compensation parameters. All desired parameter values such as output voltage, over-current, and over-temperature protection limits are stored in EEPROM at manufacturing or via PMBus transfers. The EEPROM content is downloaded to the RAM during power-up and the μC uses this part of the memory for read and write operations.

3. 3E DC/DC CONVERTERS

The BMR453 and BMR454 are the first members of the 3E DC/DC converter family, respectively available in quarter-brick and eighth-brick footprints to deliver up to 396 W or 240 W. Both converters employ a digitally-controlled, isolated full-bridge topology to provide outstanding levels of efficiency, power density, flexibility, and performance. In addition, each 3E DC/DC converter integrates a full PMBus system that furnishes extensive power-management capabilities that complement the 3E POL regulators. Detailed electrical specifications for each of these products appear within the technical specifications that are available from Ericsson's website.

- PMBus interface
- Configurable output voltage
- Configurable OVP, OTP, OCP
- Remote sense
- Switching frequency synchronization
- Power good
- Voltage tracking
- Extensive power management programmability
- Optional baseplate
- High reliability
- Start-up into pre-biased output

While product-specific details such as power handling differ between the BMR453 and BMR454, the digital control architecture that these DC/DC converters share confers numerous common features that allow them to out-perform the best previous-generation analog converters.

Figure 3 shows the fully-regulated, isolated-output digital architecture that powers these 3E DC/DC converters. The topology relocates the output voltage control circuitry from a conventional intermediate bus converter's primary-side to the secondary side. This seemingly simple change requires exceptionally careful design to achieve accurate control loop operation, but it enables the 3E DC/DC converters to provide tight voltage regulation while improving upon the power handling ability of previous-generation analog DC/DC converters that either provided tight voltage regulation at relatively low power levels or sacrificed regulation accuracy for high output power.

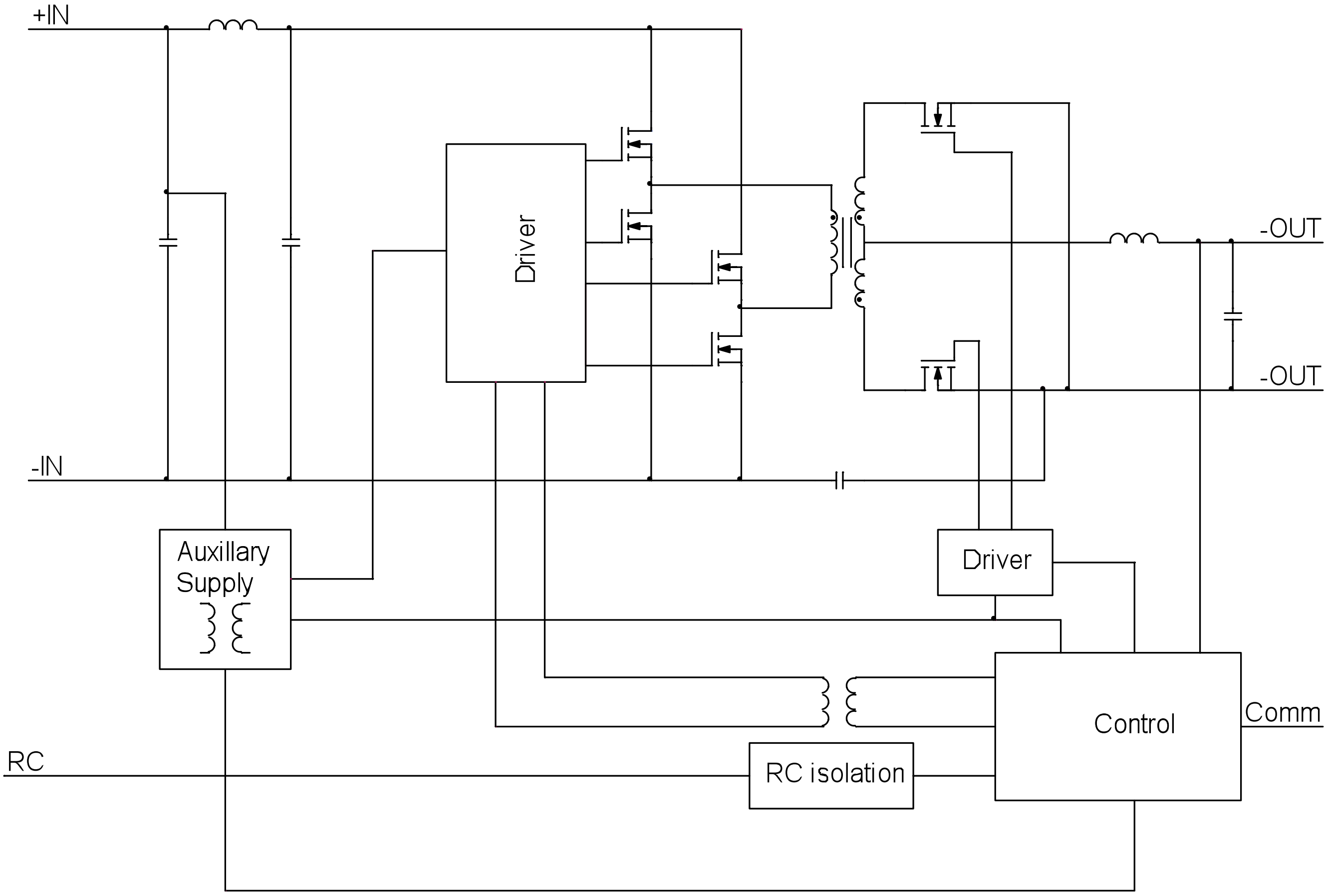
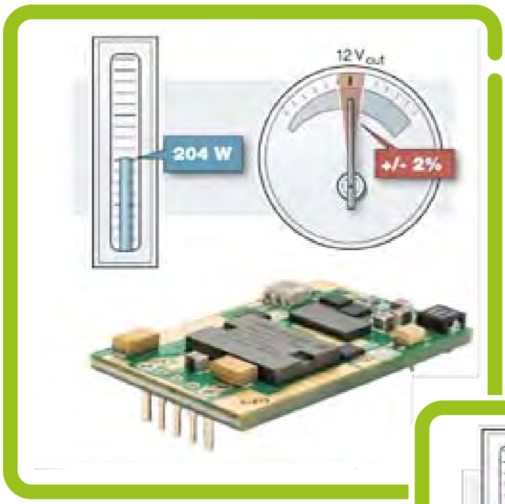
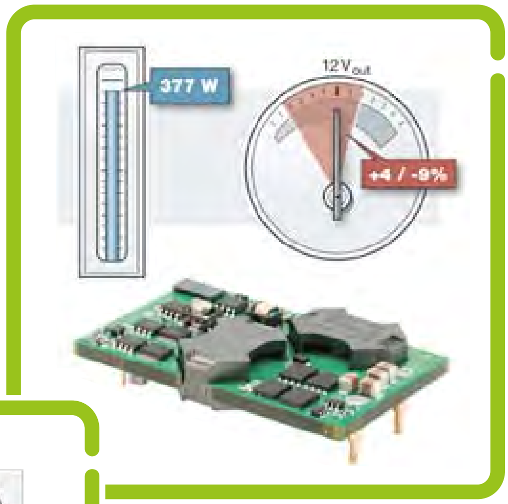


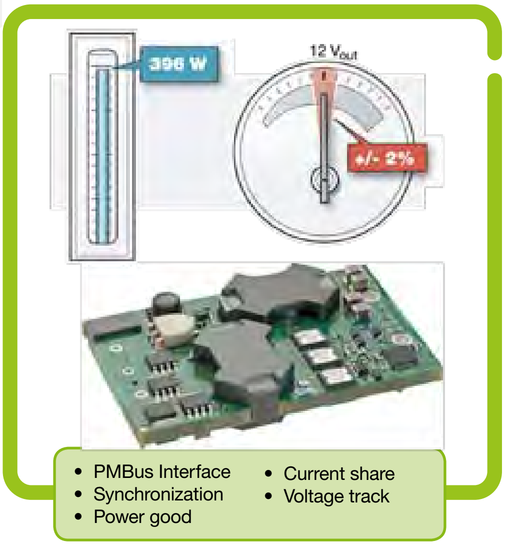
Figure 3 – 3E DC/DC converters: fully-regulated isolated-output digital architecture.



Fully regulated PKM 4213C



Intermediate Bus Converter PKM 4304B



Digitally controlled BMR453

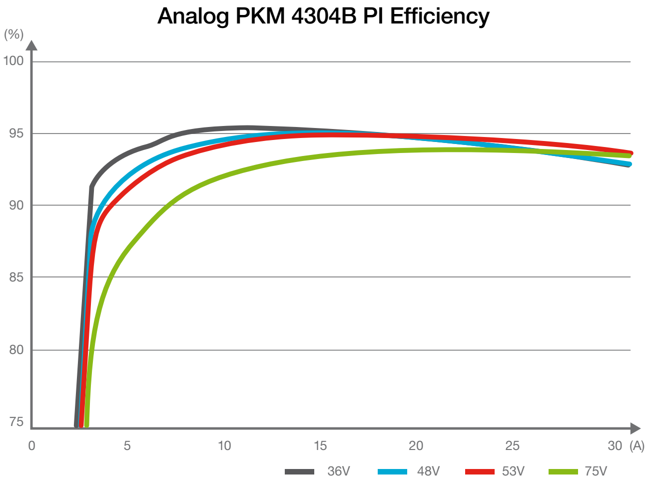
Figure 4 – The 3E DC/DC converter architecture combines the tight output tolerance of the traditional DC/DC converter and the high power and efficiency of the IBC together with the benefits of digital power control and digital power management.

For instance, the BMR453 manages up to 33 A at 12 VDC (396 W) with ±2% regulation while the PKM4304BPI intermediate bus converter is rated at 377 W with +4%, -9% regulation accuracy. Alternatively, the fully-regulated PKM4213CPI offers ±2% regulation accuracy but only manages 204 W. The 3E architecture enables an approximately 5% increase in power-handling capacity relative to the previous-generation intermediate bus converter together with an improvement in regulation accuracy that makes it possible to directly supply voltage-sensitive devices – such as hard disk drives – without further regulation and the additional component footprint and efficiency losses that would otherwise occur. While all three converters accommodate the 36 – 75 VDC input range that 48 VDC and 60 VDC systems require, the comparisons in *figure 4* were made at an input voltage level of 48 VDC and an output level of 12 VDC.

Efficiency improves too, with the BMR453 managing slightly over 96% at half-load compared with 96% for the PKM4304BPI and 94% for the PKM4213CPI. Perhaps more significantly, the digital architecture within the BMR453 and BMR454 extends the range over which these converters operate at high efficiency with the result that their efficiency curves are almost flat from as little as 10% of output load right up to full load. While passive components fix the behavior of conventional analog converters that are necessarily a compromise for the expected range of operating conditions, the 3E digital DC/DC converters adapt to changes of input line and output load levels in real time by adjusting digital control-loop constants on-the-fly.

Figure 5 shows a comparison between the already highly efficient analog PKM4304BPI and the digital BMR453 for a range of input voltage conditions, and without applying any system-level optimizations to the digital converter. Note the characteristic shape of the digital converter's efficiency curve, which is almost identical for the BMR454.

12 V/33 A TYPICAL CHARACTERISTICS



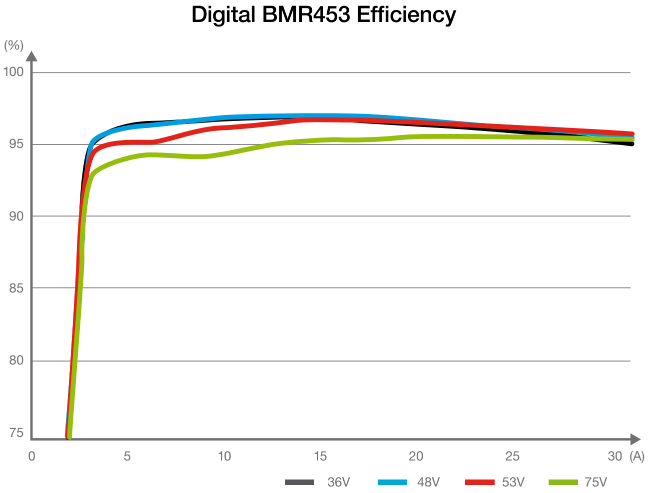


Figure 5 – The 3E digital architecture improves conversion efficiency together with the range of efficient operation, even without any system-level optimizations that we discuss later in this technical paper.

The close relationship between these two converters is apparent from their physical appearance, with the BMR454 clearly resembling a smaller version of the BMR453. Both devices are available with an optional baseplate that aids power dissipation, as *figure 6* shows:

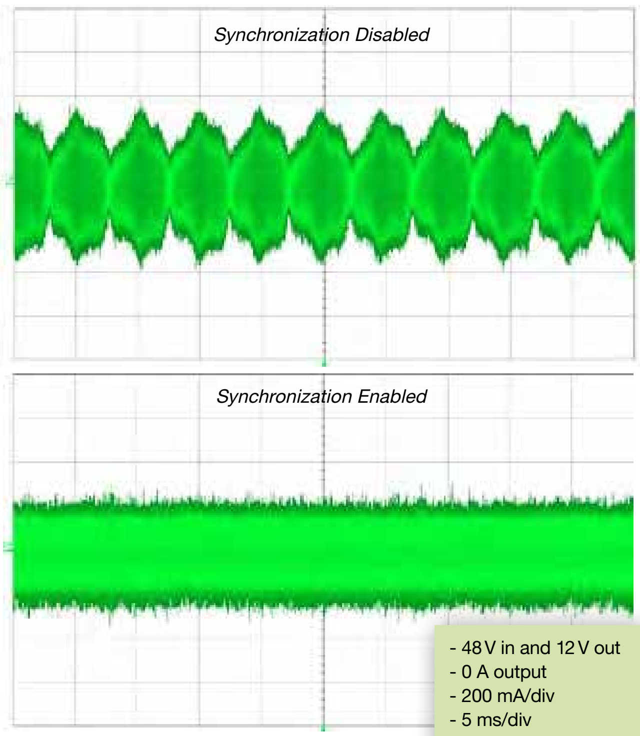
BMR454 without optional baseplate

BMR453 with optional baseplate

Figure 6 – The BMR454 eighth-brick and BMR453 quarter-brick DC/DC converters are available in open-frame or baseplate-equipped versions. Both products can be used with or without the communications interface connector.

Both converters can share a common footprint, making it easy to change between models as system power demands evolve. Either converter can be used with or without the communications connector, whose principal purpose is to provide PMBus connectivity. Other connector functions include a direct converter-to-converter link that allows synchronization to a common clock frequency, making it possible to interleave converters to minimize reflected input ripple currents that can be challenging to quash in high-power DC/DC converter applications. No intervention from the PMBus is necessary.

The synchronization scheme uses a “master-slave” configuration, where the slave converter assumes the same operating frequency as the master but with a 90 degree phase shift between them. This phase shift is critical in minimizing the input ripple current of the combined converters in an interleaved full-bridge topology. As *figure 7* shows for a pair of BMR453s, the effect of this approach on the input ripple current is dramatic. Because the maximum ripple current – and the most stringent EMI criteria – for this topology occurs at light load, testing was performed with no load on the converters’ outputs. The top trace displays the input current with the synchronization feature disabled while the bottom trace shows the result of enabling the synchronization feature. The significant reduction in ripple current in the bottom trace demonstrates the effectiveness of this solution and allows for a very compact implementation of the conducted EMI filter.



- 48 V in and 12 V out
- 0 A output
- 200 mA/div
- 5 ms/div
- 150 kHz
- 90° interleaving
- No filter on input

Figure 7 – Enabling the synchronization and interleaving feature helps quash input ripple currents, greatly easing EMC filter design.

AC INPUT RIPPLE CURRENT

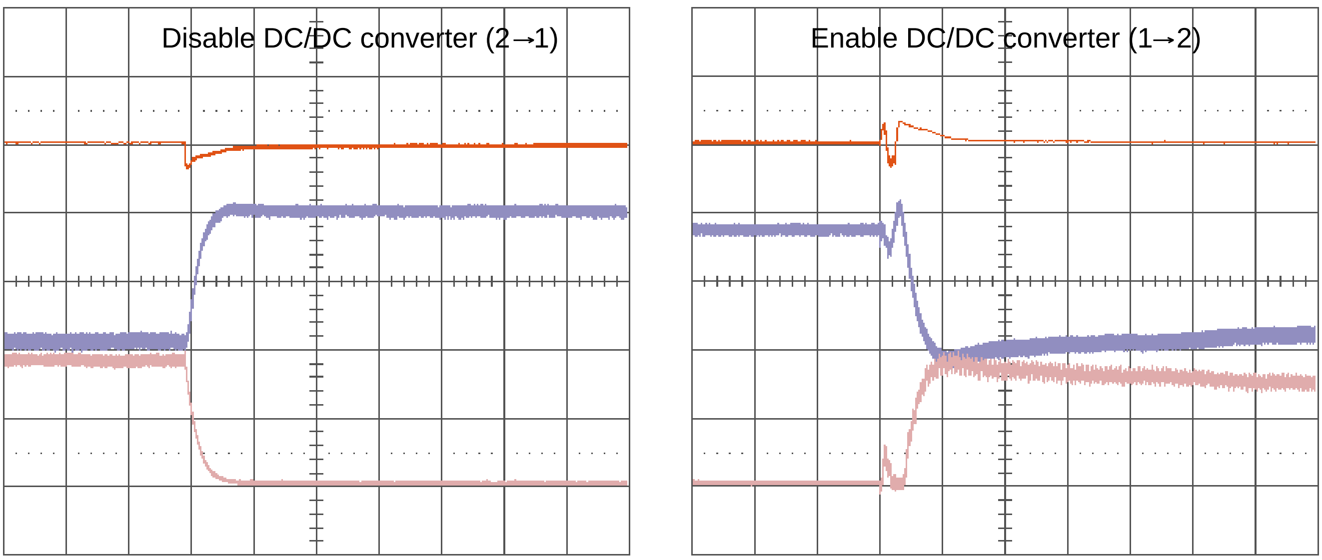
For some applications, it is also possible to parallel a pair of converters without needing any OR-ing diodes or MOSFETs. This approach not only saves external components and board area, but slashes wasteful power dissipation.

Furthermore, the sophisticated design of the output stage control system that the 3E DC/DC converters use allows them to start up into pre-biased loads without any danger of sinking uncontrolled currents, again dispensing with the need for external OR-ing components. This ability can be especially useful when paralleling a pair of converters for increased output current. Ericsson's applications engineers will be pleased to advise customers wishing to take advantage of this possibility.

Figure 8 shows the output voltage waveforms when switching off one of a pair of BMR453s to conserve energy under light load conditions and then turning the second converter on again. This second state is especially demanding as the second converter is now starting into a heavily pre-biased load and – without the intelligent control that the 3E digital architecture provides – its output-stage synchronous-rectification MOSFETs could conduct large reverse currents.

Importantly for legacy applications, it is perfectly possible to treat these digital converters just like their analog predecessors, trimming for example output voltage with a single resistor. While this approach excludes the possibilities that digital power management offers, users will still benefit from the fundamental improvements in performance that the 3E digital architecture delivers.

PMBus connectivity and the potential that active power management make possible are features that are common to all 3E products, and are essential for maximizing performance in today's power-conscious systems. We will present just some of the benefits that applying 3E DC/DC converters and POL regulators can deliver in the System Power and Energy Management section of this technical paper that follows an overview of the 3E POL regulator products.



CURRENT SHARE AND PRE-BIASED OPERATION

- Top trace: Output voltage (500 mV/div)
- Bottom traces: Output current (5 A/div)
- 48 V in and 12 V out
- 1 x 20 A or 2 x 10 A output
- Time scale: (1 ms/div)
- 2.2 mF output capacitance
- No ORing on output

Figure 8 – Enabling and disabling a second DC/DC converter during current share operation puts tough requirements on dynamic load performance and the ability to start against a pre-biased load.

4. 3E POINT-OF-LOAD REGULATORS

This section introduces the first two members of a family of 3E digitally-controlled POL regulators. These initial products provide tightly regulated, nonisolated output voltages at up to 20 A and 40 A. Later introductions will expand this output current range.

Each of these 3E POL regulators is extremely flexible, with the capability of efficiently spanning an input voltage range of 4.5 to 14 V and an output voltage range of 0.6 to 3.6 and 5.5 V. Each 3E POL regulator includes a connector that interfaces to the PMBus and is available in SMT (surface-mount technology) or PTH (plated-through-hole) packages with a common interconnection footprint that allows easy system scalability. *Figure 9* shows the initial 3E POL regulators – the BMR451 and BMR450 that respectively source up to 40 A and 20 A.

The broad input voltage range (4.5 V to 14 V) of the 3E POL regulators allows them to operate with the most commonly-used intermediate bus voltages of 5, 9, and 12 V. Their output voltage range extends from 0.6 to 3.6 V (BMR451) or 5.5 V (BMR450), with settings configurable via the PMBus or a single resistor.

Figure 9 – 40 A and 20 A 3E POL regulators.

The architecture of these nonisolated-output POL regulators resembles that of a conventional buck converter, but with digital techniques replacing analog pulse-width modulation control. As *figure 10* shows, the 3E POL regulators retain normal analog POL features such as remote sensing, but add full PMBus connectivity alongside a proprietary connection that supports functions such as resistive output-voltage trimming and POL-to-POL synchronization. In addition, the 3E POL regulators are able to start up into pre-biased loads without requiring any external OR-ing diodes to prevent reverse currents flowing into their output stages.

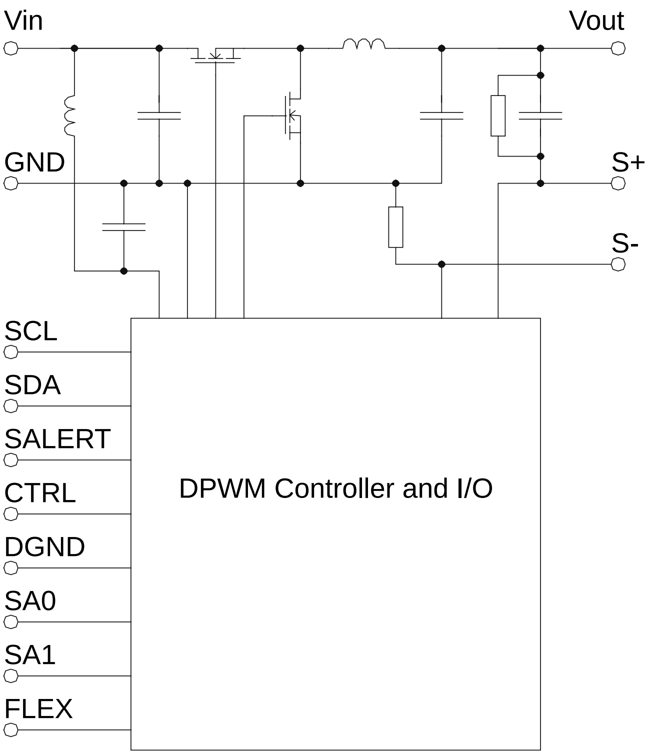


Figure 10 – The 3E POL regulators resemble a digitally-controlled buck converter with normal analog facilities but also add PMBus functionality.

The efficiency of the 3E POL regulators is in line with the best currently-available solutions, and it can be improved even further by applying some of the digital control and power management techniques that the next section of this technical paper describes. Similarly, the default dynamic response characteristics of the 3E POL regulators can be further optimized to suit individual systems' needs by adjustment to system-level requirements. *Figure 11* shows the normal, non-optimized performance for the BMR450 (top graph) and the BMR451 for a 3.3 V output voltage and various input levels. Notice the characteristic shape of these response curves, which – due to the underlying digital architecture – are virtually indistinguishable between the 20 A and 40 A parts.

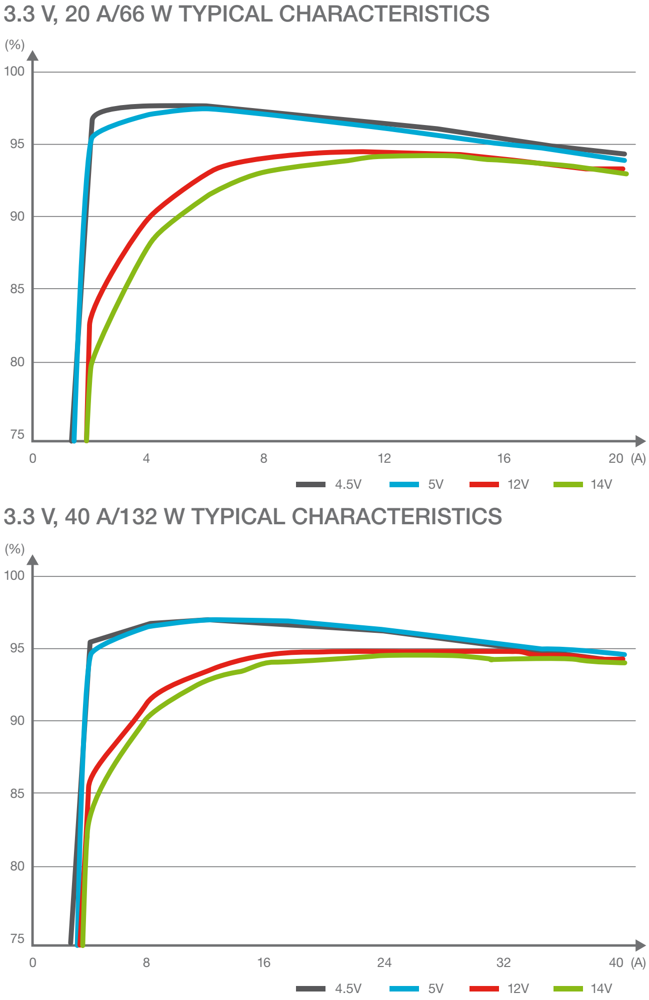


Figure 11 – The digital architecture within the 3E POL regulators results in consistently high efficiency even without system-level optimization.

Perhaps the most obvious improvement in electrical performance appears in terms of physical size and power density. This is primarily due to the lower parts count within a 3E digitally-controlled POL regulator. The *table* below summarizes the power and current densities of the initial 3E POL regulators compared with a traditional 18 A analog POL regulator. These data assume an output voltage setting of 3.3 V at maximum rated current and an input voltage of 12 V. Keep in mind that these improvements were made despite including the new interface for digital power management.

DEVICE	POWER DENSITY W/cm³	CURRENT DENSITY A/cm³
18 A ANALOG POL	7.4	2.1
20 A 3E POL	24.3	6.0
40 A 3E POL	26.1	6.5

Figure 12 shows these products alongside one another to provide a real sense of the dramatic step-change improvement in current density that the 3E POL regulators introduce. The considerable reduction in component count also contributes towards higher reliability, helping to lower operating costs and increase customer satisfaction.

Each 3E POL regulator includes a raft of default protection features for conditions such as overcurrent, overvoltage, and overtemperature, as well as a soft-start function that reduces inrush currents and protects sensitive loads. Like a conventional analog POL, it is possible to set the output voltage using a single resistor, and the normal remote-sense connections that maintain accurate voltages at the load are provided. As a result, it is perfectly possible to use these parts in a standalone mode to replace analog POLs and in effect to ignore the digital communications functions.

Taking advantage of the PMBus connectivity that the 3E POL regulators offer vastly increases flexibility compared with any conventional analog POL. For instance, it then becomes possible to program the output voltage, set turn-on and -off delays and slew rates to implement voltage sequencing for multi-rail loads such as FPGAs, and program custom warning and fault thresholds for the integral protection hardware. It is even possible to adjust the response of the converter's digital control loop to optimize its response within a given application. Any or all of these features are accessible when the end equipment is manufactured using ATE or similar programming methods (so-called "set-&-forget" operation) or in realtime as the system runs – which together with the range of measurements that the 3E POLs return while running offers the possibility of dynamic system optimization that the next section of this technical paper explores.

While the digital power management connector was added primarily to support the PMBus interface, it includes pins that may be used to implement additional functions. These include the remote sense connections together with several other features, some of which are programmable via the PMBus. For instance, the BMR450 and BMR451's FLEX pin can be used as either an analog voltage adjustment input or as a clock synchronization input that also allows multiple 3E POL regulators to operate in interleaved mode. This feature can be very useful to ease input filter design by reducing the peak ripple current on the supply bus, and can also reduce the amount of bulk capacitance that the supply bus requires.

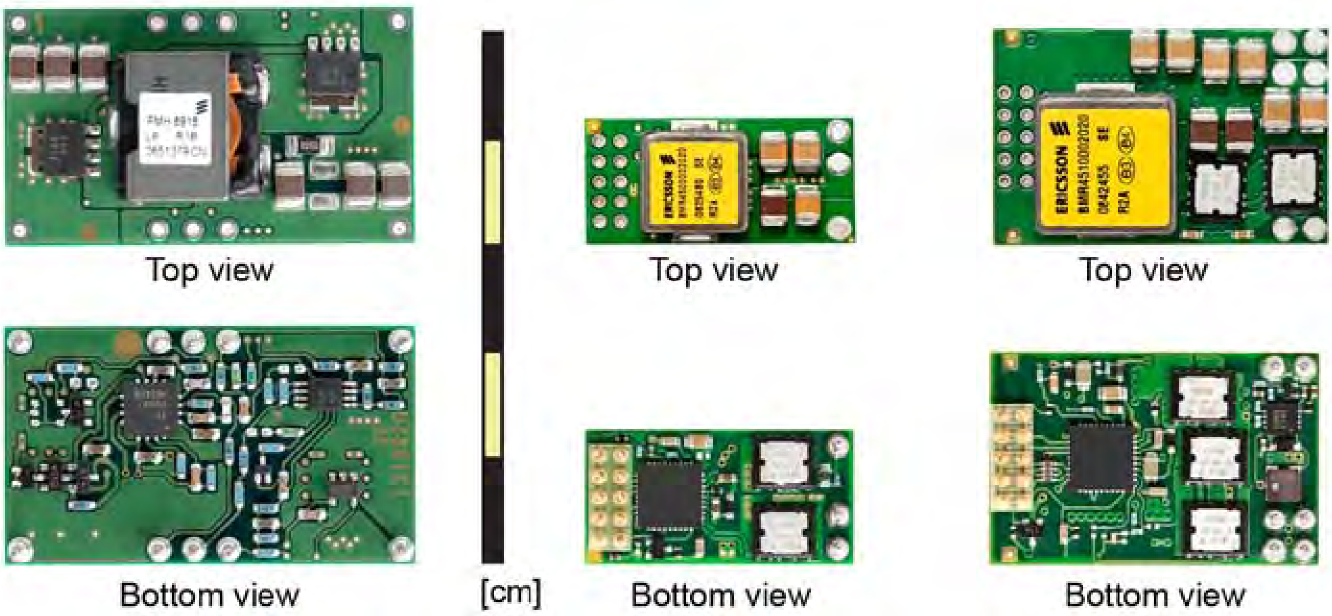


Figure 12 – From left to right: the relative size difference of a traditional 18 A analog POL regulator compared with the 20 A and 40 A 3E POL regulators.

The requirement to include the PMBus interface demanded a new packaging and interconnection concept that has several end-user benefits. Compared with previous-generation analog POLs, the combination of 3E digital control techniques and the new package design increases current density (A/cm²) by up to 300% with a corresponding increase in power density. The physical dimensions of the new 3E POL regulators are:

CURRENT RATING	OVERALL L x W x H (mm)
20 A	25.7 x 12.9 x 8.2
40 A	30.9 x 20.0 x 8.2

A metric-standard 2.00 mm pitch dual-row header is used for the PMBus communications interface, while thick pins handle high-current paths. Because the footprint layouts of the 3E POL regulators are scalable, the power system designer can create a single circuit board layout that will accommodate any of these products. This ability can be especially valuable in terms of minimizing costly and time-consuming layout changes during the product development cycle, when the exact current requirements are not well defined. *Figure 13* illustrates this concept.

As the figure shows, the digital power management interface pins on the right-hand side remain the same for for each of the regulator families. The larger input and output power pins to the left can be bussed together on the user's circuit board to connect to any 3E POL regulator. This pin layout has an added advantage during the end-product's manufacturing process. The pins are arranged into three groups – the power management connector on the right, and the upper and lower group of high current pins on the left. This grouping forms a "three-legged stool" structure that minimizes the coplanarity problems during soldering processes that can plague sizeable components
with pins in each corner.

All 3E POL regulators feature an output inductor with a flat surface on the top of the package. This provides a convenient attachment point for vacuum nozzle pick-&-place equipment. Both tray and tape-&-reel device packaging is available to maximize compatibility with contemporary manufacturing processes.

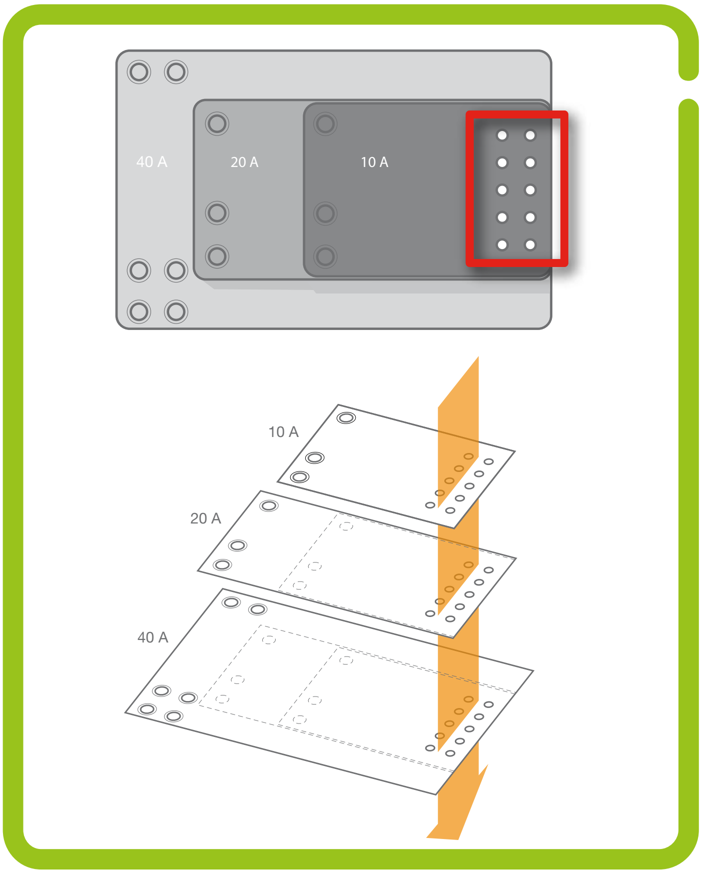


Figure 13 – The scalable footprints of the 3E POL regulators permit a single PCB layout to accommodate any of these products.

5. SYSTEM-LEVEL APPLICATIONS OF 3E DIGITAL POWER CONVERTERS

The 3E DC/DC converters and POL regulators are extremely flexible in terms of the available management methodologies that end-users can apply throughout the life-cycle of an application. For example:

A Each 3E family product can be treated the same as a conventional analog power converter. The digital communications connector can be ignored and the functional pin-out become the same as for an analog converter – input voltage, output voltage, remote sense, etc. For 3E family power converters, the output voltage would be pre-set during manufacture, either as delivered from Ericsson Power Modules or as part of the user's ATE processes. In addition, it is possible to use resistive programming for the 3E POL regulators. If using ATE programming, it is also possible to set a whole range of additional custom parameters, such as turn on and off delays, protection thresholds, etc.

This approach enables the 3E products to be used in systems that have no need for a more sophisticated control system, or that have an existing analog-based control implementation. In this scenario, many of the performance benefits of the 3E products -such as increased efficiency, regulation accuracy, and power density – are still realized.

B A dedicated converter-to-converter connection can be used independently of and/or without connecting the PMBus. This connection allows the converters to operate synchronously relative to a common clock frequency to eliminate the beat frequencies that complicate EMC filter designs and/or to enable interleaved operation to minimize input ripple currents.

C The PMBus can be used for digital communication between the 3E DC/DC converters and POL regulators and a board power manager. This board power manager provides the interface between the converters and an external system host controller that performs overall supervision and control duties. This is by far the most flexible option for obtaining maximum benefit from 3E family converters and the system-level optimization that digital power management makes possible.

Figure 14 shows some examples of these three levels of control.

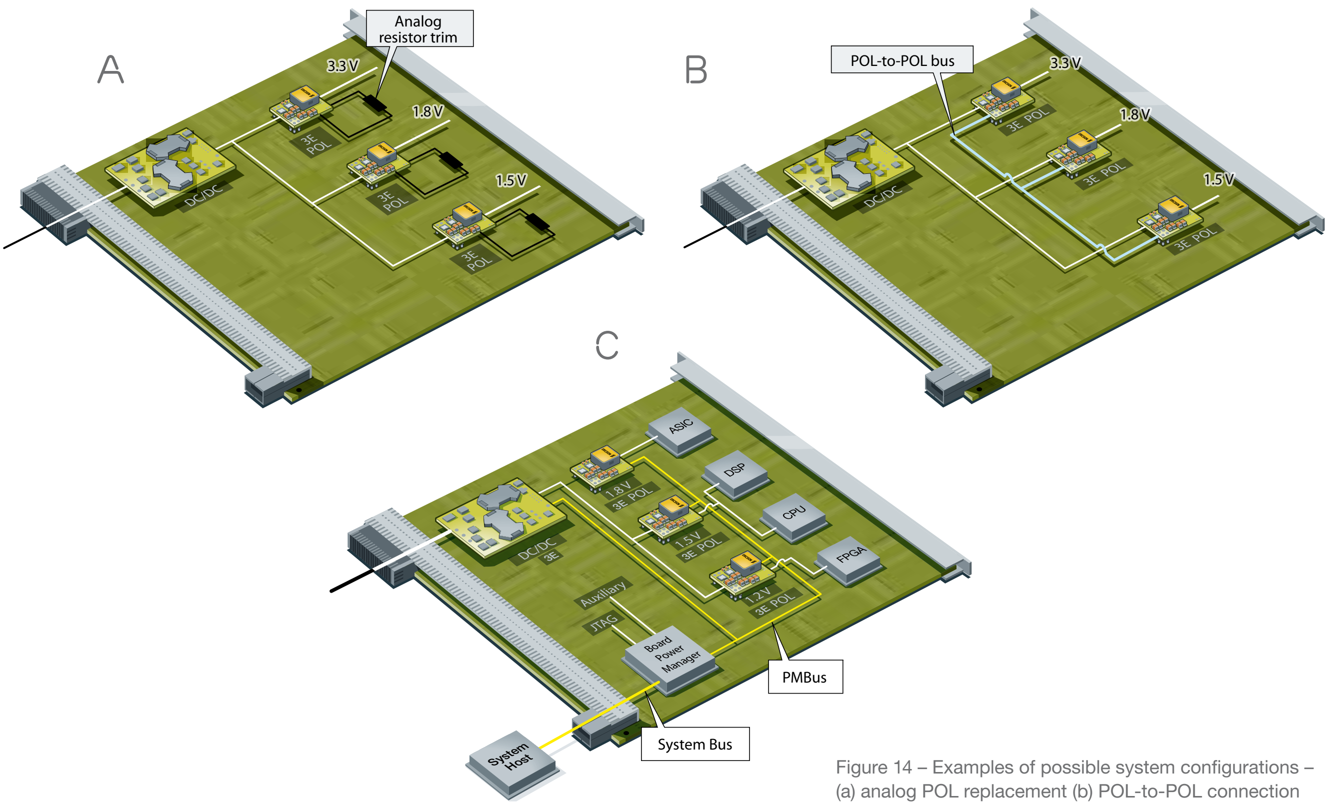


Figure 14 – Examples of possible system configurations – (a) analog POL replacement (b) POL-to-POL connection (c) full PMBus control.

THE PMBus

In a typical intermediate bus architecture system, there will be one system host controller that is responsible for overall system supervision and control duties. This system host may be a local PC that runs appropriate application software, or an embedded controller that might have links to remote systems via Internet or other local or wide-area networks, as the sophistication of the user's application determines.

Each board in the system is likely to include its own local controller that we refer to here as the board power manager – *see example C in figure 14*. Its primary role is to provide the communications bridge between the onboard power devices and the system host controller, which may or may not itself use PMBus protocols for its communications with the board power manager. While we make the distinction between the system host controller and board power manager to differentiate between overall and local levels of communication and/or control, the board power manager may be functionally invisible in some applications.

Again depending upon the sophistication of the user's application, the board power manager may optionally also implement varying degrees of board-level control according to its own pre-programmed intelligence. Because the board power manager communicates with the devices that it controls via the PMBus, it can be a simple device such as a microcontroller, or even be built from leftover gates in an FPGA:

The PMBus is a bidirectional multi-node digital interface that uses the two-wire SMBus™ (basically a more robust version of I^2C) for the underlying serial communications. Like I^2C and SMBus, practical implementation details limit PMBus to applications within a single board. PMBus adds two lines specifically for power control applications for a total of four conductors that have the following functions:

- Clock (SCL)
- Data (SDA)
- Control (CTRL)
- Alert (SMBALERT#)

The clock and data lines transfer bidirectional data between the board power manager and the 3E DC/DC converters and 3E POL regulators on the board, as well as any other PMBus devices within the network. The control line provides a signal for simultaneously commanding devices to turn on and off. The alert line is an interrupt signal that devices can use to gain the board power manager's attention.

Each converter in a PMBus network has a unique address that allows the board power manager to communicate with it individually. For the 3E family of DC/DC converters and POL regulators, these addresses are physically assigned by resistive programming. Two pins in the communications connector are available on each converter for this purpose, and chip resistors that connect from these pins to Gnd establish the programming. Eight pre-defined discrete values of resistance are available per pin to provide a total of 62 combinations, which number is more than enough addresses for most systems.

While using the PMBus is optional, doing so will greatly increase the flexibility of the end-user's power system. If 3E family or other products with PMBus connectivity are used, it really only requires the designer to bus the four PMBus conductors to the board power manager in order to take advantage of the benefits of digital power management.

A common misconception is that the board power manager must be resident in the end system. This is just one option. These three scenarios show how the PMBus might be used during a system's development, manufacture, and deployment phases:

1. The PMBus is used during product development and evaluation. The board power manager in this case could be an external PC connected to the prototype system or subsystem. This is an extremely fast and convenient way to experiment with parameters such as output voltage settings, power sequencing routines, voltage margining, fault handling, etc. without any need for hardware changes in the system. No board power manager hardware is required in the system itself. Ericsson Power Modules has a PC-compatible evaluation kit for the 3E products that includes a USB-to-PMBus adapter and dedicated software to ease control of all the connected 3E family converters, providing an excellent introduction to exploring such capabilities.

2. The PMBus is used during system manufacturing and test, and the board power manager could be part of the Automated Test Equipment (ATE). In this scenario the ATE could automatically configure the 3E family devices during the system's manufacturing process. Again, no board power manager is required in the system itself.

3. The scenario with the most capability and flexibility is to include the board power manager within each board's power system. This configuration permits the same board power manager to be used throughout a system's life cycle of development, manufacture, and deployment. Again, the board power manager very rarely needs to be powerful and expensive – its specifications are typically very modest, and in many systems it can be a general-purpose microcontroller or some spare gates of an FPGA.

We will now assume that the power system designer has decided to use the PMBus in one of the implementations that we have outlined, and will give some examples of how digital power management techniques can be applied to optimize a system. Because these are only a very few of the many possibilities, designers are very likely to find other ways to take advantage of these capabilities within their own systems.

To help designers explore the possibilities that the 3E digital converters and PMBus control offer, Ericsson Power Modules has developed an evaluation kit that contains a simple circuit board, samples of the 3E DC/DC converters and 3E POL regulators, software, cabling, and documentation – see *figure 15*. The board includes a USB-to-PMBus adapter that allows seamless connection to a PC. Designers only need to add a few pieces of conventional lab equipment – such as a power supply, a DMM, and test loads – to be up and running within minutes of opening the box. The software includes a graphical user interface (GUI) that greatly simplifies monitoring and programming 3E family devices. The software also makes it easy to save configuration data for development or for re-use in – for instance – programming devices during the manufacturing process.

Using PMBus connectivity together with a board power manager in the ATE during the manufacturing process can take advantage of the mandatory "set-&-forget" capability of PMBus-compatible devices. This facility makes it possible to set custom parameters during manufacture for the full range of programmable features that the respective 3E family devices provide. No board power manager is required in the end-user system, although if one is present, it is possible to program new values that override those set during board manufacture.

One application for this facility is to provide a fast and reliable method of setting power sequencing routines, and it represents a vast reduction in complexity relative to traditional systems that use analog-based power controllers for this purpose. All 3E family converters are programmable for turn-on and -off delay times as well as slew rates, making it possible to precisely set independent delay values and to constrain inrush currents.

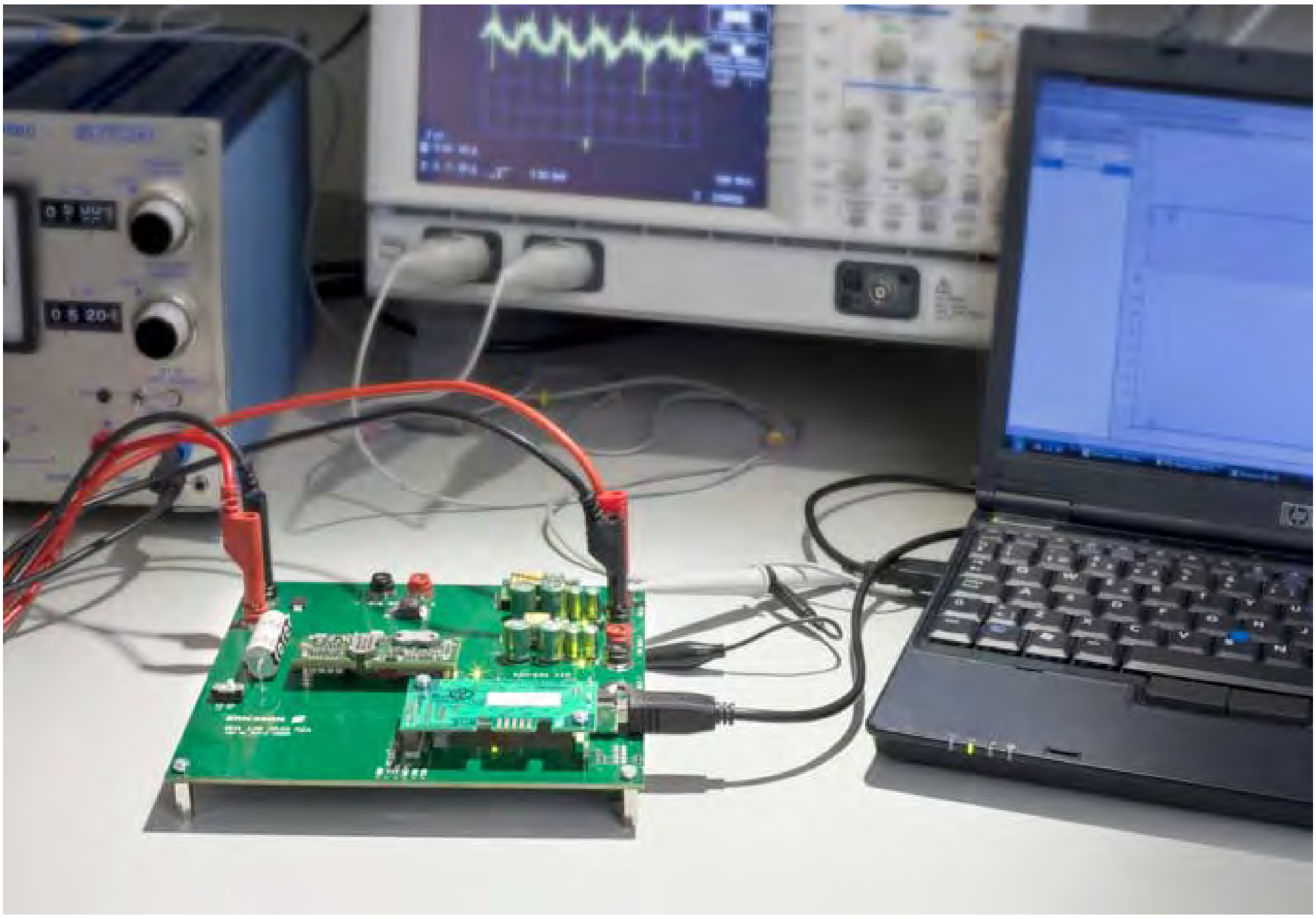


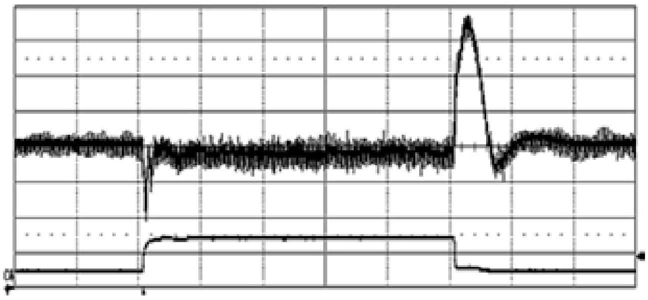
Figure 15 – The 3E evaluation kit helps designers explore the 3E family and the potential of PMBus connectivity.

In addition, the 3E DC/DC converters provide a "power-good" output signal that indicates when the converter is within its regulation band and operating normally. This facility greatly simplifies the end-user's circuitry in event-based sequencing applications. Alternatively, this output can be configured as an input to support a voltage tracking feature that creates custom output voltage ramp-up profiles in response to a control voltage ramp.

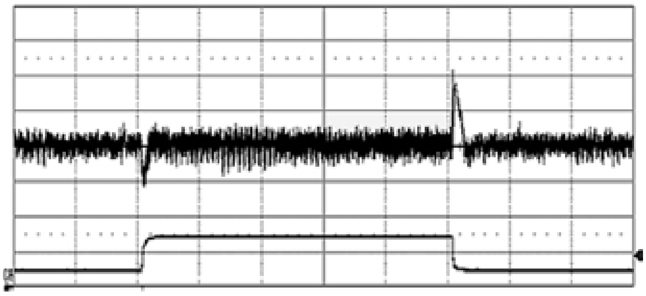
All 3E family converters make it easy to implement voltage margin testing during manufacturing to verify system operation over the extremes of the design's operational envelope. It is also possible to program custom output voltages, which can be useful in several ways. For instance, one type of 3E POL regulator can be configured for multiple output voltages, reducing inventory requirements. It is also possible to fine-tune the output voltage of the 3E POL regulators during functional testing to take into account the variable voltage drops and losses of sensitive load circuitry. This can be useful to guarantee the tight margins that today's sub-1V circuits require.

Unlike conventional analog converters, digital control makes it possible to re-program the internal control-loop dynamics of the 3E family devices to optimize their dynamic responses for a particular application and/or the amount of load capacitance present in the system. *Figure 16* shows an example of this technique being applied to a 3E POL regulator, where the optimal configuration clearly outperforms the robust factory-default setting.

DEFAULT ROBUST DYNAMIC CONFIGURATION



LOAD OPTIMAL DYNAMIC CONFIGURATION



Output voltage response to load current step change (5-15-5 A). Resistive load with slewrate > 7 A/µs at: T_{ref} = +25°C, V_I = 12 V, C_{out} = 470 µF.
Top trace: output voltage (50 mV/div.). Bottom trace: load current (10 A/div.). Time scale: (0.1 ms/div.).

Figure 16 – Optimizing dynamic response by reprogramming control-loop constants in a 3E POL regulator.

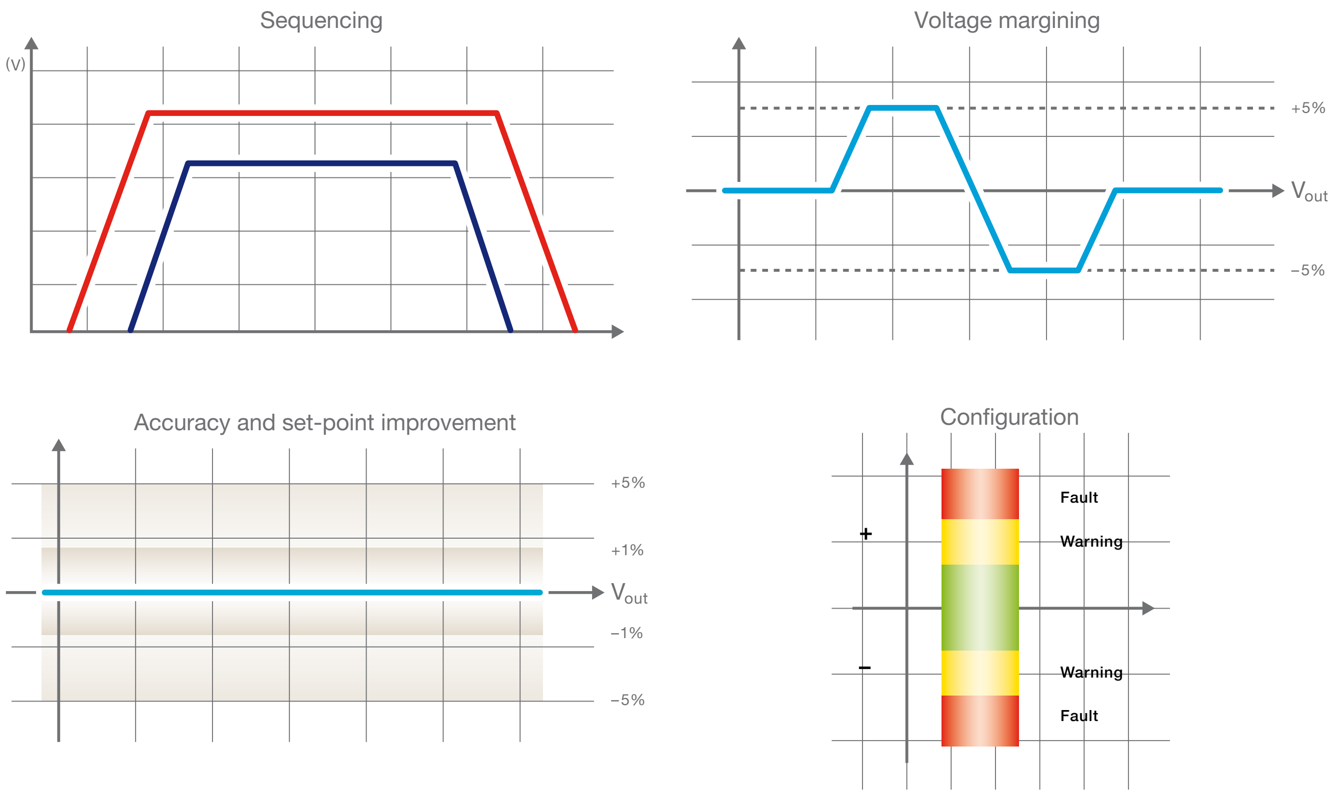


Figure 17 – Using the PMBus during board manufacture makes it easy to set precise voltage-sequencing delays, perform voltage margin testing, to set or trim output voltage levels, and to program warning and fault thresholds.

In the same way, it is easy to optimize how 3E family devices respond to fault conditions. Responses are selectable between latching mode – that is, the device turns off and remains off until restarted externally – and the default restart mode that will try to automatically restore normal operation. The board power manager can be programmed to set custom limits on each of the fault sensors (temperature, voltage, and current) within any 3E family device not only for absolute limits, but also for warning conditions. One important possibility that this opens up is the potential for application software to monitor each 3E device for persistent out-of-tolerance conditions that may signal an impending failure, which may in turn trigger a service alert to replace a suspect unit before a system failure occurs. Similarly, the availability of realtime measurements from each 3E family device can be helpful in general data-gathering applications. *Figure 17* shows examples of some of these concepts.

The 3E GUI Silver Edition software presents a simple and intuitive user interface that arranges all of these programmable facilities within a single Device Configuration page. The range of available features automatically reflects the 3E family device-under-test, with *figure 18* showing a typical screenshot and the focus of configuration set for a 3E POL regulator. Pressing the Save button at the bottom right-hand area of the screen writes new configuration data into the 3E device-under-test, when any changes will immediately take effect. It is also possible to load and save configuration data to disk using the respective buttons to the top-left area of the screen.

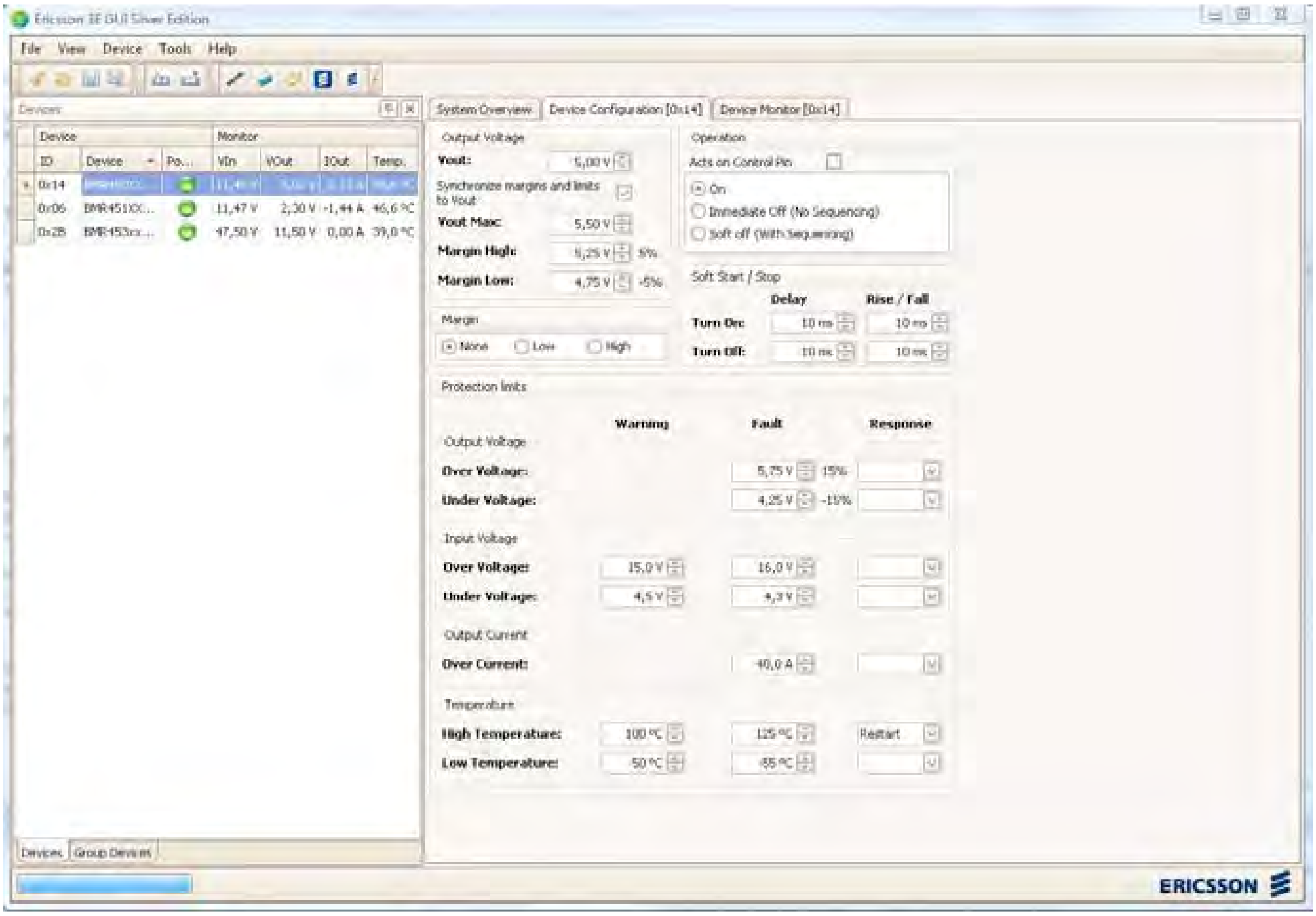


Figure 18 – The Device Configuration page within 3E GUI Silver Edition arranges key programmable features within a single screen.

These facilities make it easy to experiment with various set-ups for both the 3E DC/DC converters and the 3E POLs that they supply in order to optimize the target system's overall operational efficiency for a wide range of input voltage and output load conditions. Conventional analog DC/DC converters and POL regulators are designed for maximum efficiency under the most commonly expected system operating conditions. But each system application is unique, and individual systems will experience different operating conditions as a function of installed features and operating mode. Consequently, the output current of each DC/DC converter and POL regulator will vary with time, as will its efficiency.

The wide output voltage adjustment range of the 3E DC/DC converters makes it possible to optimize system efficiency by applying digital power management techniques. For instance, POL regulators are generally most efficient at lower values of input voltage when they are supplying light loads. The system would then be most efficient when using a low value of DC/DC converter output voltage – perhaps in the range of 9 to 10 V. But during high output current conditions, the system power demand may require a higher voltage to increase the DC/DC converter's available power output. In this scenario, the end-user's application software could automatically increase a 3E DC/DC converter's output voltage to 12 V or more by sensing the system current demand and re-programming the converter via the PMBus. Characterizing the system for its full range of operating conditions enables the application software to select the intermediate bus voltage that maximizes overall efficiency. This dynamic bus voltage adaptation technique can be very useful for system energy management, and can save significant amounts of energy to help minimize power utility costs and environmental impact.

Another possibility for energy saving exists within current-sharing applications. *Figure 19* plots the combined efficiency of two BMR453 DC/DC converters working in parallel against the efficiency curve of a single unit.

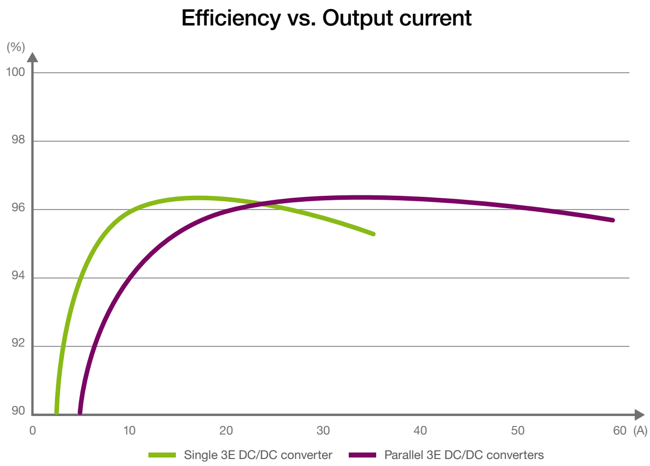


Figure 19 – Comparative efficiency curves for a single 3E DC/DC converter and a pair working in parallel.

The efficiency curve of the two units working in parallel is exceptionally broad, exceeding 96% from 25 to 55 A. But as the figure shows, one converter will be more efficient at output currents below about 25 A. For systems in which there is a very wide range of current demand, the application software can automatically switch between single-converter mode when system current requirements are low, and a dual-converter current-sharing mode when the load level increases. The underlying measurement and control would again be performed via the PMBus. To avoid overcurrent conditions, the switching point would need to contain a fair amount of hysteresis to ensure that a single converter would not risk operation close to its maximum current rating. But with an appropriate implementation, the performance that the BMR453 achieves is truly impressive – 96% efficiency from 10 to 55 A, and more than 90% even at loads as low as 2.5 A. This approach reduces power losses at light system loads.

The digital power management concept can be a powerful tool and it is important to emphasize that we have explored only a few of the possibilities that the 3E family and PMBus connectivity offers. While saving a few milliWatts in one small subassembly may not seem terribly important, the cumulative power savings in a system of even moderate size add up quickly, especially for systems that must operate for many hours per day. Lowering power consumption reduces heat dissipation, which can be significant in larger installations in terms of reducing the heat load that the building must manage and the air conditioning costs that result.

As digital power/energy management becomes more commonplace, it will become an enabling technology with ramifications beyond the specific system that implements it. It can easily become a powerful tool for data collection and analysis. The result will be increased knowledge of reliability and failure root-cause analysis that will be invaluable in the design of next-generation systems. *Figure 20* is a sample screenshot from 3E GUI Silver Edition that shows the software tracking the performance of a 3E POL regulator.

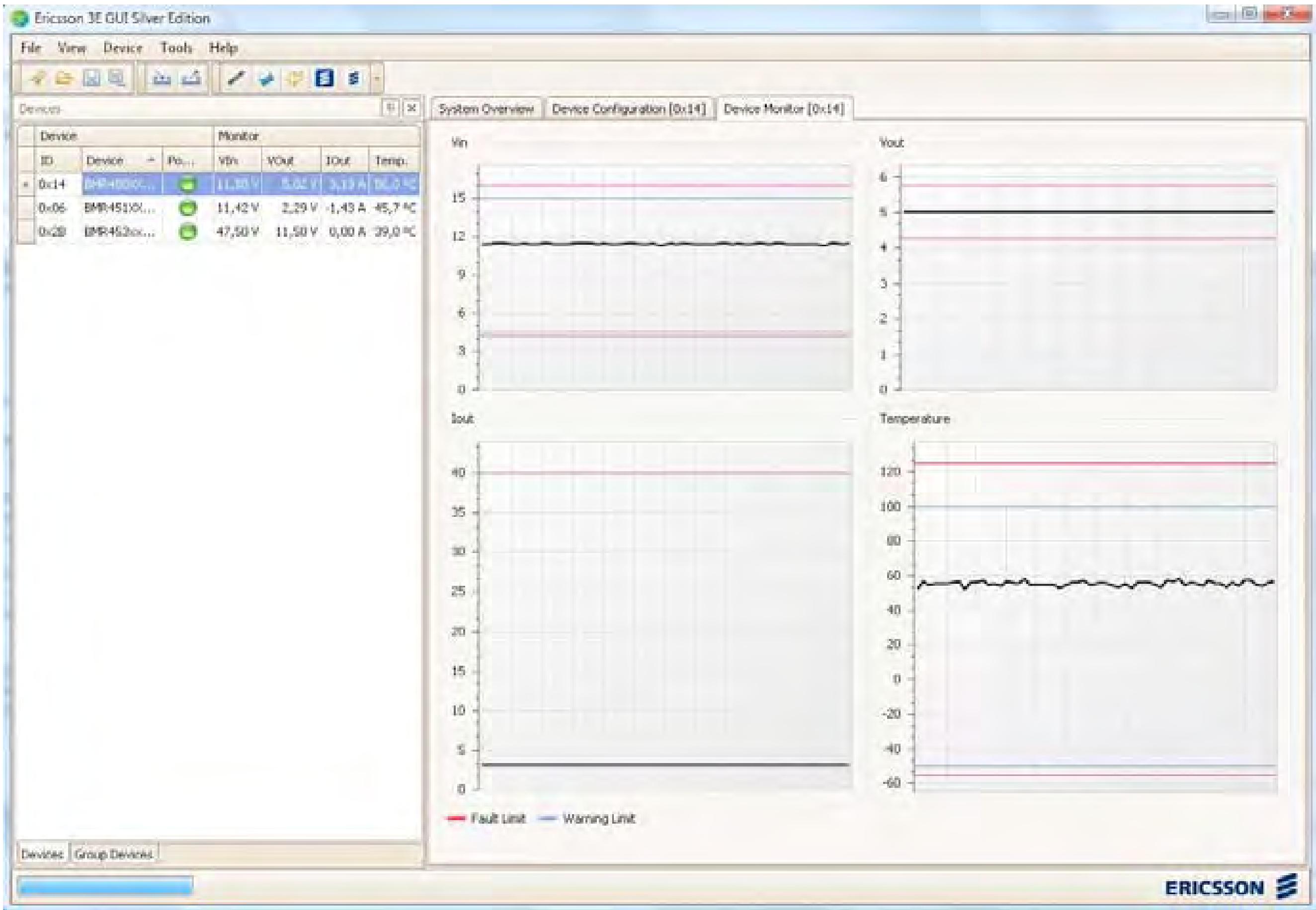


Figure 20 – Device monitoring may provide better knowledge of system operating conditions and enable failure root-cause analysis to help improve future-generation systems.

6. SUMMARY

This technical paper has presented several ways in which the new Ericsson Power Modules 3E DC/DC converters and 3E POL regulators can be used to add value to the end-user's systems while achieving state-of-the-art performance. Many of these advantages do not require using a digital power management bus in the end-user's system. For users who adopt this approach, applying the 3E family will be similar to using conventional analog components, and the design and testing processes will be very familiar.

Many users will take advantage of the increased functionality, flexibility, and opportunity for system optimization that the PMBus offers by using it as an interface during system development, manufacturing testing, and/or in the field environment. This approach embraces all of the benefits that the 3E concept delivers – many of them new or best-of-breed for the power conversion industry.

For some users, this will represent their first power system design using digital power management techniques. One of Ericsson Power Modules' goals is to make the transition from analog to digital power management systems as convenient as possible by supporting the new products with a wide variety of applications assistance. Possibly the fastest route to becoming familiar with the 3E family – and to explore some of the opportunities that PMBus connectivity and digital power management in general can offer – is to use the 3E evaluation kit that we described earlier in this technical paper. There is also a great deal more information regarding digital power management and the 3E family available from the company's website.

The new Ericsson Power Modules 3E family will eliminate many of the compromises that are inherent in current designs and create exciting opportunities for power system designers in terms of system performance, flexibility, configurability, optimization, and end-user value. Furthermore, system design using these products is fun and a rewarding experience!

Enhanced Performance

- Significantly higher power and current densities
- Industry-leading efficiency
- Scalable footprints
- Automatic synchronization for superior EMI performance
- Optimization of dynamic response
- Excellent feature set for stand-alone operation
- Flexible fault detection and error handling

Energy Management

- Simple low-cost PMBus
- Powerful system development tools
- Many levels of possible power management solutions
- Unparalleled flexibility during field deployment
- Adaptable systems possible
- Optimization of efficiency to end-user application
- Reduced energy consumption
- Reduced utility costs and environmental impact

End-User Value

- Reduced number of DC/DC converters and POLs to stock
- Enhanced reliability
- Improved system MTBF
- Increased customer satisfaction
- Backed by comprehensive pre-validation
- Reduced technical risk
- Reduced time-to-market
- Enabling technology for data collection and analysis

ERICSSON

SCALABLE FOOTPRINTS EXTEND DIGITAL POWER CONVERTERS' FLEXIBILITY

3E - Enhanced performance,
Energy management and
increased End-user value.

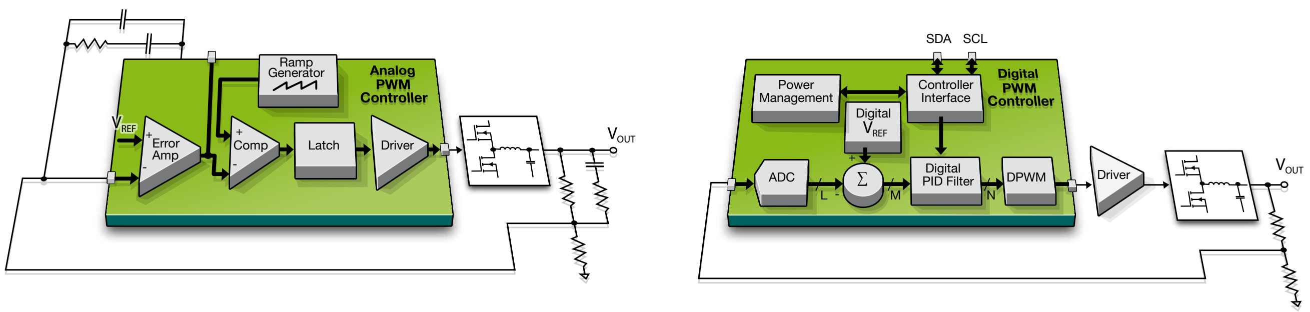
CONTENTS

SCALABLE FOOTPRINTS EXTEND DIGITAL POWER CONVERTERS' FLEXIBILITY

The advent of digitally-controlled power converter modules presents designers with a raft of new opportunities to explore in their continual quest for ever-greater system efficiency, flexibility, reliability, and overall cost-effectiveness. In developing the first commercially-available family of digital power converters — the 3E series — Ericsson proved the innate superiority of the digital control-loop architecture over its analog counterpart in terms of conversion efficiency improvements over a much wider range of output load conditions. This attribute alone can often justify upgrading an analog-based system with digital converters that offer drop-in replacement equivalency, especially for the increasing number of systems that experience significant variations in load demand. However, the transition from traditional analog-control based power converters to today's digital converters offers much more than improving the conversion efficiency and power density metrics that previously dominated system architects' thinking.

The core of any representative digital converter is a mixed-signal block that substitutes an analog-to-digital converter and digital signal processing techniques for the traditional error amplifier, ramp generator, and comparator that control the power switches via a pulse-width-modulator — see *figure 1*. It is the digital converter's ability to optimize its internal loop dynamics to line and load conditions in real time that explains its superior conversion efficiency relative to analog designs that are conventionally fixed by passive component networks. As a result, analog converters are typically set to operate best at around 50 – 70% of their full load capability, this being the area over which most users will apply them. While this profile suits systems that run continuously under similar load conditions, today's systems increasingly power down entire circuit blocks to save power whenever it is practical to do so, leading to far greater variations in load current demand that digital converters accommodate far better than analog-based designs.

At the same time, sizing a system's load-current demands is becoming another dynamic that designers must increasingly consider. Systems frequently evolve over several iterations that build upon a common platform, with inevitable changes in power needs that designers may be able to address by specifying power modules from a family that shares a scalable footprint. With some thought, this footprint can satisfy not only a range of power levels, but also serve a variety of applications that span analog-converter replacement to implementing sophisticated power-management schemes that can further reduce a system's power consumption. Because power modules are relatively bulky to solder and for pick-and-place equipment to handle, it is imperative that the packaging's mechanical design overcomes manufacturability issues. It is also helpful to be able to offer through-hole-mount packages and surface-mount versions that support identical functionality.



ANALOG PWM CONTROLLER DIGITAL PWM CONTROLLER

Figure 1. Digital converters embody mixed-signal technology that greatly extends their efficient operating range and packs power management functions on-chip.

EASING THE ANALOG TO DIGITAL TRANSITION

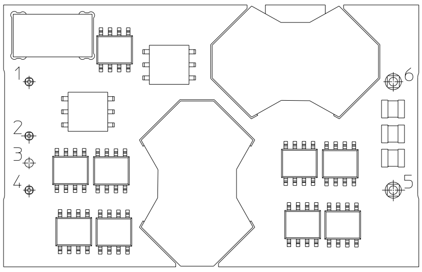
In designing its 3E series, Ericsson paid great attention to these everyday practical issues as part of the company's quest to deliver Enhanced performance, Energy management, and End-user value. A primary electromechanical consideration when making the transition from analog converters to any digital successor is the interconnection between the power module and its host board. Analog power modules almost invariably include dedicated pins for functions such as on/off control, output voltage adjustment, and remote voltage sensing. For a digital converter to be able to replace an analog one, it is essential to include these basic functions and to ensure that they can operate in a "stand-alone" mode — that is, independently of any overall supervisory control scheme that the digital converter may also implement.

Because the digital converter's core is a mixed-signal block, chip designers can pack supervisory measurement and control circuits alongside the basic dc/dc converter logic at negligible additional cost. This step offers previously unprecedented flexibility in implementing power-management schemes by integrating functions that previously required substantial external circuitry to realize. The module designer's challenge is now to design a footprint that accommodates the new digital connections alongside the traditional analog functions — and preferably in such a way as to ease life for system architects and board layout designers alike. The module designer's challenge is complicated by the fact that every new generation of digital control IC seems to add more functions that typically require extra pins to utilize, all of which requires a degree of forward planning that can only realistically be undertaken on a "best-effort" basis.

Ericsson's first 3E family member — the BMR453 advanced intermediate-bus converter that handles as much as 396 W from a standard quarter-brick footprint (*Figure 2*) – illustrates the result of a first-generation electromechanical design philosophy for digital converters that perfectly fits its intended purposes while allowing for future enhancements without requiring any substantial re-thinking on behalf of equipment designers.

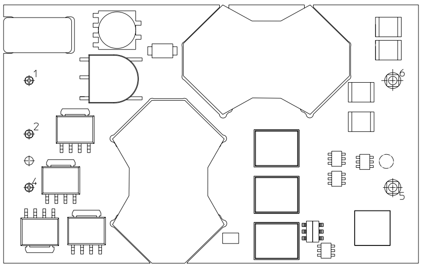
Figure 2. BMR453 – 396W fully-regulated, digitally-controlled quarter-brick advanced intermediate-bus converter with PMBus interface. From top to bottom: top view, bottom view of through-hole version, bottom view surface-mount.

As *figure 3* shows, comparing the company's previous-generation high-power quarter-brick intermediate-bus converter — the 377 W-rated PKM4304B PI — shows the minimal impact on footprint design that Ericsson's designers achieved in moving from a "dumb" voltage-in, voltage-out analog device to a fully-featured digital design that includes legacy analog functions such as remote control and voltage sensing as well as adding PMBus™ connectivity. Alternatively and to preserve total footprint compatibility, the BMR453 is available without the new communications connector to suit stand-alone applications that will still benefit from its superior performance.



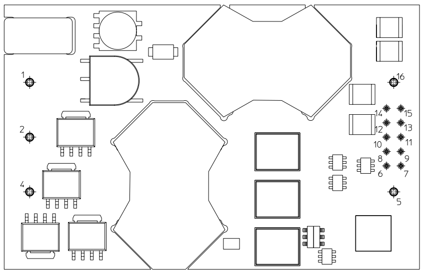
PKM 4304B PI – ANALOG (377W)

Pin	Designation	Function
1	+In	Positive input
2	RC	Remote control
3	Case	Case to GND (optional)
4	-In	Negative input
5	-Out	Negative output
6	+Out	Positive output



BMR453 – DIGITAL (396W)
WITHOUT PMBus CONNECTOR

Pin	Designation	Function
1	+In	Positive input
2	RC	Remote control
3	Case	Case to GND (optional)
4	-In	Negative input
5	-Out	Negative output
6	+Out	Positive output



BMR453 – DIGITAL (396W)
WITH PMBus CONNECTOR

Pin	Designation	Function
1	+In	Positive Input
2	RC	Remote Control
3	Case	Case to GND (optinal)
4	-In	Negative Input
5	-Out	Negative Output
6	S+	Positive Remote Sense
7	S-	Negative Remote Sense
8	SA0	Address pin 0
9	SA1	Address pin 1
10	SCL	PMBus Clock
11	SDA	PMBus Data
12	PG SYNC	Configurable I/O pin: Power Good output, SYNC-, tracking-, or ext ref-input
13	DGND	PMBus ground
14	SALERT	PMBus alert signal
15	CTRL CS	PMBus remote control or Current share
16	+Out	Positive Output

Figure 3. The transition from analog to fully-featured digital intermediate-bus converters shows the minimal additional impact that Ericsson's upgraded footprint creates. If PMBus connectivity and the additional features are not necessary, the BMR453 can use the same footprint as its analog predecessor.

Importantly, the BMR453's digital control system substantially increases the power density that a tightly-regulated power module can achieve. *Figure 4* compares the BMR453's performance alongside the previous-generation analog converters — the fully-regulated PKM4213C that achieves ±2% output regulation and 204 W of output power and the loosely-regulated PKM4304B PI that manages +4%, -9% output regulation and 380 W. The digital converter combines ±2% output regulation performance with 396 W of output power to provide a useful 5% improvement in raw power handling ability over the PKM4304B PI, and a >90% improvement for the equivalent regulation performance of the PKM4213C within a similar quarter-brick footprint. As the next section shows, the digital 3E point-of-load regulators also offer spectacular power-density improvements that shrink their footprint requirements.

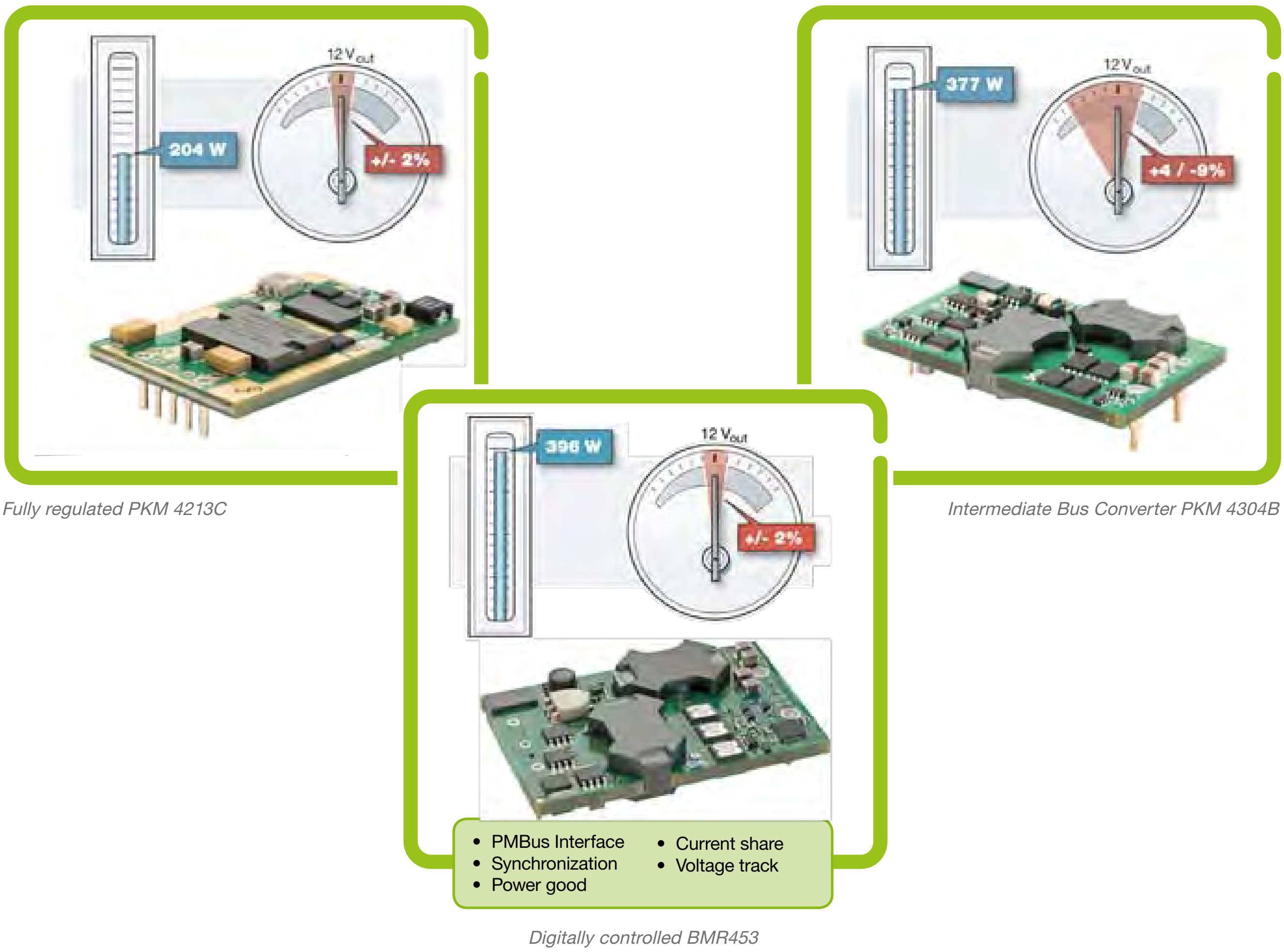


Figure 4. The 3E DC/DC converter's digital architecture achieves the tight output tolerance of a traditional fully-regulated DC/DC converter and the high power and efficiency of an intermediate bus converter while adding digital power control and management facilities.

NEW SIGNALS, NEW POSSIBILITIES

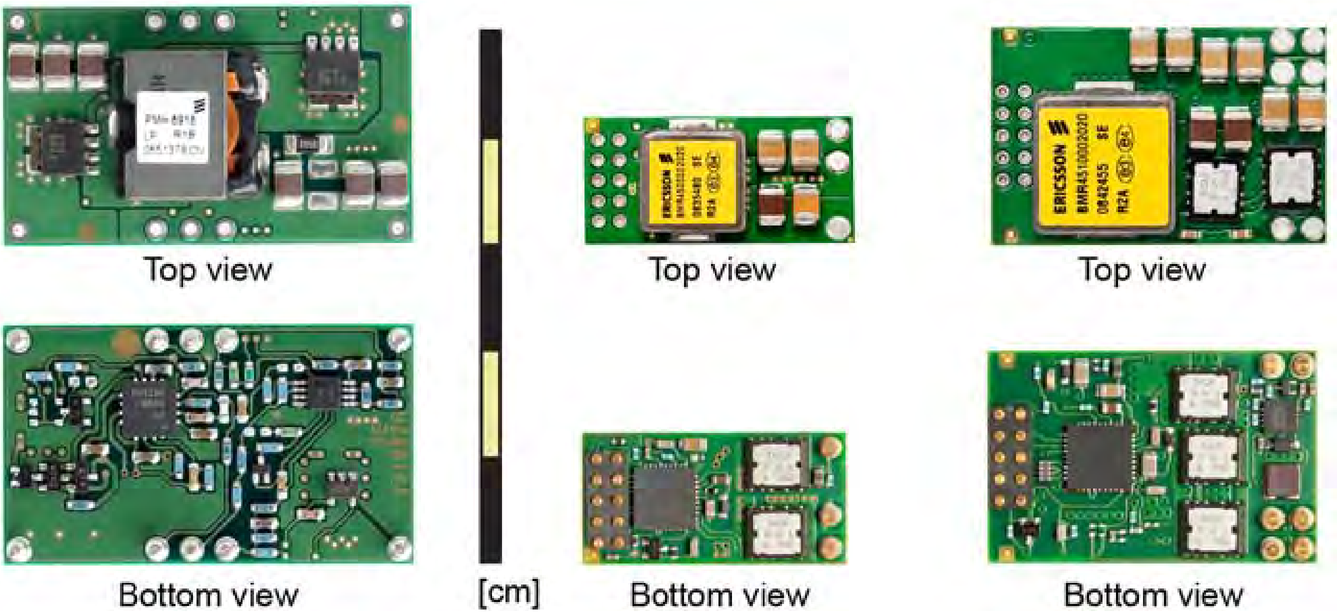
The signals that the BMR453's header carries include remote voltage sense; a configurable I/O pin that can function as a power-good output or as a clock synchronization, voltage tracking, or external reference input; a configurable remote PMBus on/off control or a dedicated module-to-module current-share input; and the PMBus connections that make it possible to configure and monitor the converter via a board-level serial bus.

With some functional variations to suit different target applications, other 3E family devices carry a similar set of signals that allows each device to operate stand-alone, or within a PMBus environment that offers designers hitherto unprecedented functionality and flexibility within device footprints that are similar to or smaller than their "dumb" analog predecessors.

For instance, *figure 5* compares the outline of a representative 18 A analog point-of-load regulator with the 20 A-rated BMR450 and its 40 A BMR451 companion part from the 3E product family. As for the BMR453, these digital point-of-load regulators offer greatly improved power density, superior electrical performance, and integrated PMBus functionality that further shrinks board area requirements.

The PMBus is a bidirectional multi-node digital interface that uses the two-wire SMBus™ standard (basically a more robust version of I2C) for serial communications. Like I2C and SMBus, implementation details typically limit PMBus to single-board applications. To support power control applications, PMBus adds two lines for a total of four conductors that comprise serial clock (SCL), serial data (SDA), control (CTRL), and SMBus alert (SMBALERT#). The serial clock and data lines transfer follow SMBus protocols to exchange bidirectional data between the board's power management logic and connected 3E family devices, as well as any other PMBus devices within the local network. The control line provides a signal for simultaneously turning devices on and off, while the alert line is an interrupt signal that devices can use to gain the board power manager's attention.

Each PMBus device must have a unique address that all 3E family products set using a space-saving pin-strap technique that minimizes the impact upon their respective footprints. Depending upon the specific 3E product, one or two resistors provide a sufficient number of individual addresses to suit any practical PMBus system. All 3E products embody a measurement and control subsystem that is fully configurable via the PMBus for a host of parameters, from output voltage setting to configuring warning and fault thresholds to fine-tuning a device's loop dynamics to optimize its transient response performance for a particular combination of load and bulk capacitance conditions. Each 3E product can also provide a wealth of information while it runs — such as the output current level and the converter's temperature — in response to standard PMBus commands.



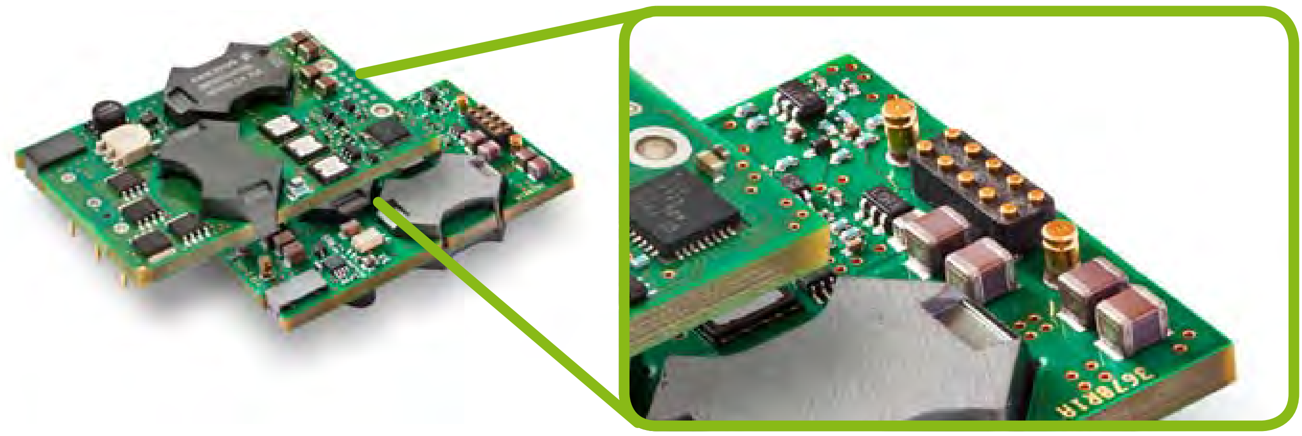
Device	Power density W/cm3	Area current density A/cm2
18 A analog POL – PMH8918LP	7.4	2.1
20 A 3E POL – BMR450	24.3	6.0
40 A 3E POL – BMR451	26.1	6.5

Figure 5. From left to right—the size of a traditional 18 A analog point-of-load regulator compared with the 3E family BMR450 (20 A) and BMR451 (40 A) devices.

PINS BETTER PADS FOR HIGH CURRENTS

Recognizing that many designers continue to prefer through-hole-mount technology for high-current devices, Ericsson offers the 3E family in through-hole as well as surface-mount versions. Like other currently-available 3E family members, the BMR453 uses robust pins to carry power into and out of the module while

Similarly, Ericsson chose its simple gold-flashed surface-mount pin design over techniques such as solderball-on-pin to maximize compatibility with established manufacturing processes. Another important feature of Ericsson's pinning layout is that it effectively forms a "three-legged stool" structure that minimizes co-planarity



BMR453 PI (top view)
BMR453 SI (bottom view)

BMR453 SI
signal input/output connector

Figure 6. Available in through-hole and surface-mount versions, the BMR453 advanced intermediate-bus converter benefits from a very well-developed interconnection system.

a metric-standard 2mm pitch pin-header provides the signal connections. *Figure 6* shows the through-hole-mounting version alongside the surface-mount derivative that uses a proprietary precision-fit pin design to guarantee co-planarity and easy solderability. Notice that this strategy permits one footprint to accommodate both through-hole and surface-mount outlines.

In favoring pins over alternative connection schemes such as land-grid-array style PCB pad lands that can suit simple low-current point-of-load regulators, Ericsson's designers recognized that pins provide superior performance for the applications that the currently-available members of the 3E family target. Through-hole-mount technology makes it easy to spread high currents through multilayer boards while using pins for surface-mount applications provides more thermal mass than pad lands, improving heat transfer between the converter and the board. Using pins can also significantly ease inspection tasks as it is then possible to use automated optical inspection equipment rather than the x-ray based techniques that pad lands require.

problems during soldering — as *figure 7* shows for the underside of a surface-mount BMR451 point-of-load regulator — while substantial flat surfaces on the module's top side make it easy for pick-and-place machines to handle using conventional vacuum nozzles. All 3E series modules share a similar coherent approach to their construction that simplifies board layout, minimizes manufacturability issues, and eases future compatibility concerns.

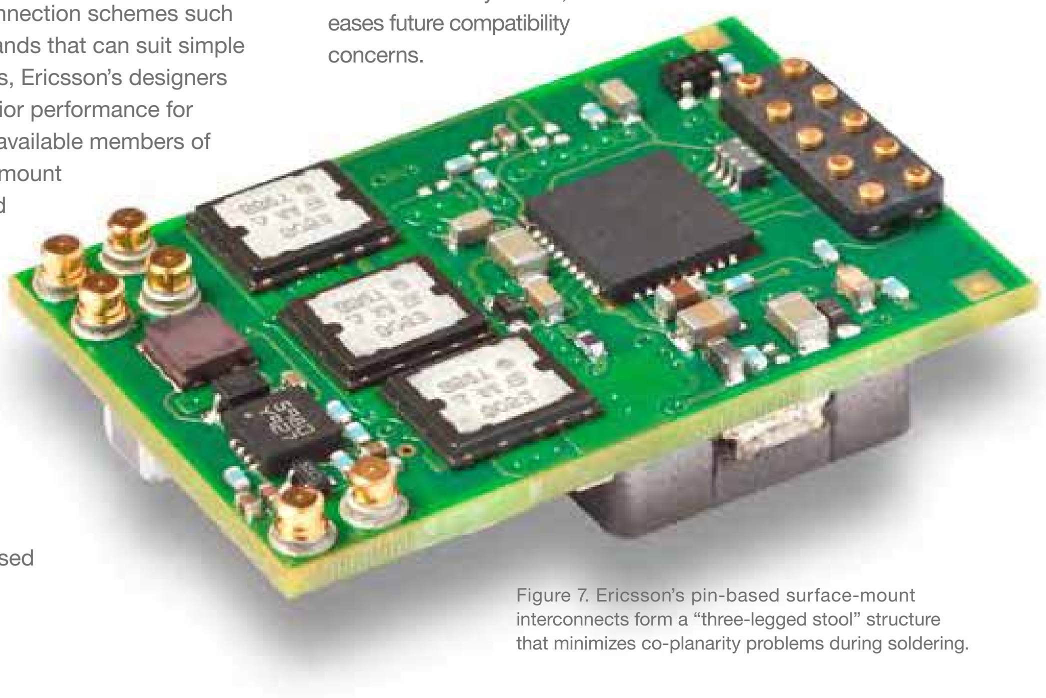


Figure 7. Ericsson's pin-based surface-mount interconnects form a "three-legged stool" structure that minimizes co-planarity problems during soldering.

SCALABLE, EXTENSIBLE FOOTPRINTS MADE REALITY

Ericsson's designers have been careful to preserve pinning arrangements that are as similar as possible between devices within the same category. This approach makes scalable footprints a reality for intermediate-bus converters such as the eight-brick BMR454 and the quarter-brick BMR453 — which share mechanically identical pin positions — as well as the BMR450 and BMR451 point-of-load converters that can again share a common outline. As a result, one footprint can accommodate up to 204 W or 396 W of intermediate bus power. Similarly, *figure 8* illustrates the harmonized footprint arrangement for the BMR450 and BMR451 that respectively source up to 20 A and 40 A:

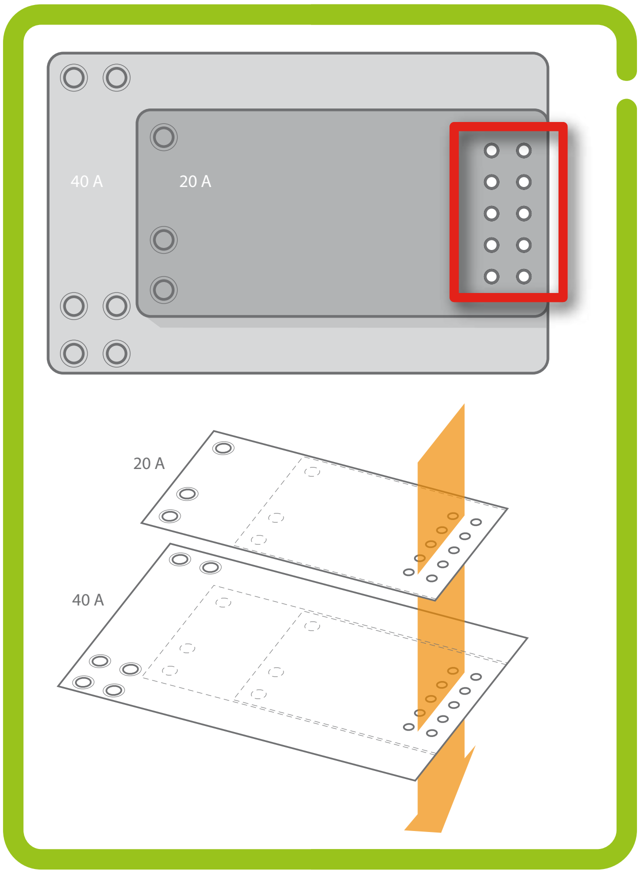
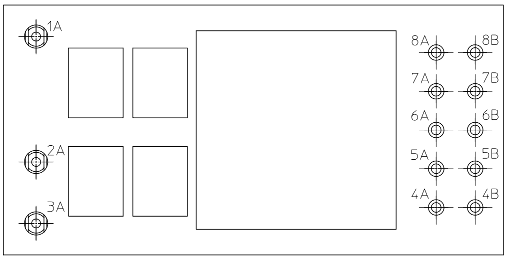
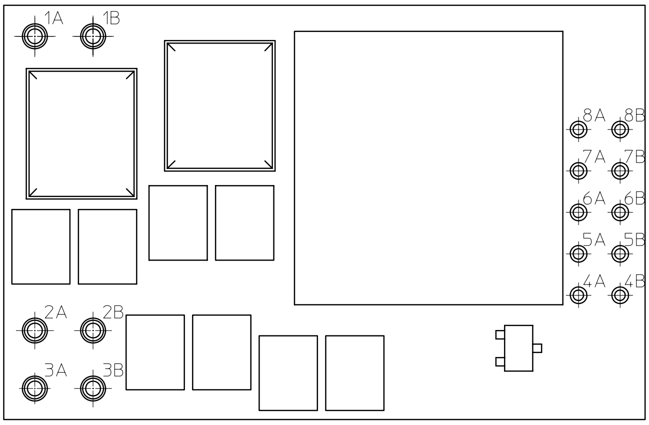


Figure 8. Like other 3E family devices within the same category, the BMR450 (20 A) and BMR451 (40 A) point-of-load regulators can share a common footprint.

The evolutionary challenge that a digital power module designer faces with regard to developing a generic footprint is easy to see by comparing the pinning arrangements of the original BMR450/BMR451 parts with the second-generation BMR46x devices that offer 12 A, 20 A, and 40 A load current ratings. The first-generation parts employ a 10-pin signal header whose pin-out appears in *figure 9*:





Pin	Designation	Function
1A	VIN	Input Voltage
2A	GND	Power Ground
3A	VOUT	Output Voltage
4A	+S	Positive sense
4B	–S	Negative sense
5A	SA0	Address pin 0
5B	SA1	Address pin 1
6A	SCL	PMBus Clock
6B	SDA	PMBus Data
7A	FLEX	Analog voltage adjust / Synchronization
7B	DGND	PMBus Ground
8A	SALERT	PMBus Alert
8B	CTRL	PMBus Control (Remote Control)

Pin	Designation	Function
1A, 1B	VIN	Input Voltage
2A, 2B	GND	Power Ground
3A, 3B	VOUT	Output Voltage
4A	+S	Positive sense
4B	–S	Negative sense
5A	SA0	Address pin 0
5B	SA1	Address pin 1
6A	SCL	PMBus Clock
6B	SDA	PMBus Data
7A	FLEX	Analog voltage adjust / Synchronization
7B	DGND	PMBus Ground
8A	SALERT	PMBus Alert
8B	CTRL	PMBus Control (Remote Control)

Figure 9. Connection arrangements for the first-generation BMR450 and BMR451 3E digital point-of-load regulator (top view).

Relative to the BMR450, the higher-current BMR451 doubles its input voltage, power ground, and output voltage connections (1A through 3B) to ensure loss-free power connections. This “right-sizing” scheme follows through in the BMR462/463/464 with similar pin placements that ease board power-layout considerations, while the 10-pin header that the first-generation parts employ has now expanded to occupy a 12- and 14-pin format that is necessary to accommodate additional features that the second-generation digital control chips offer — see *figure 10* and *figure 11*:

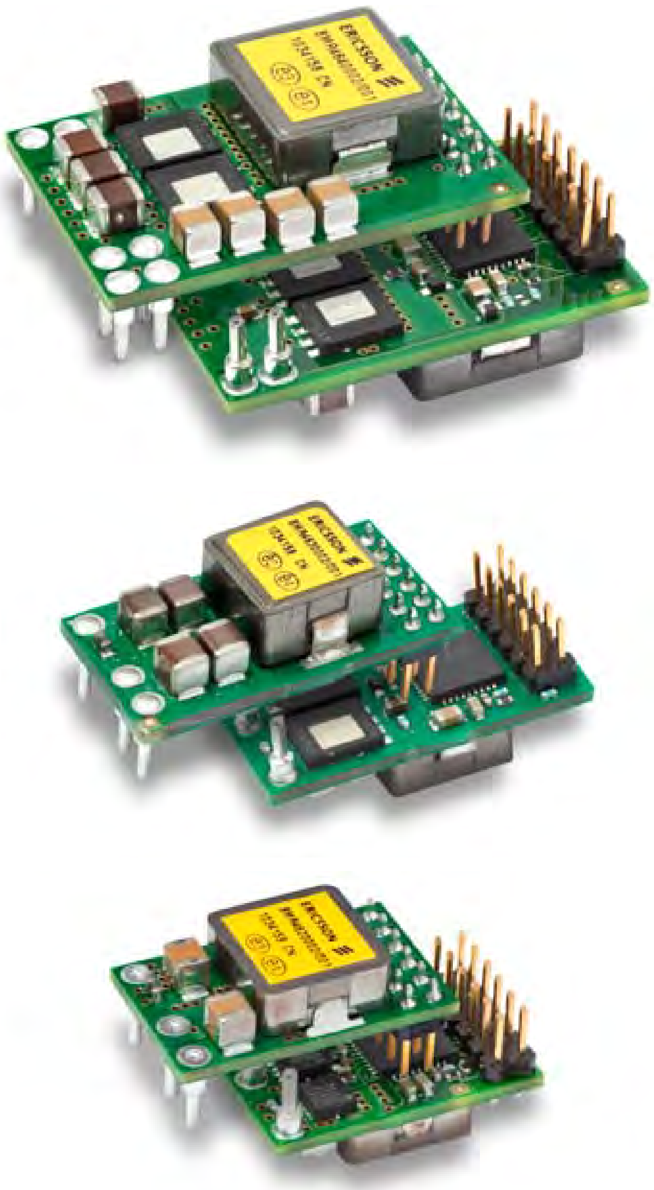
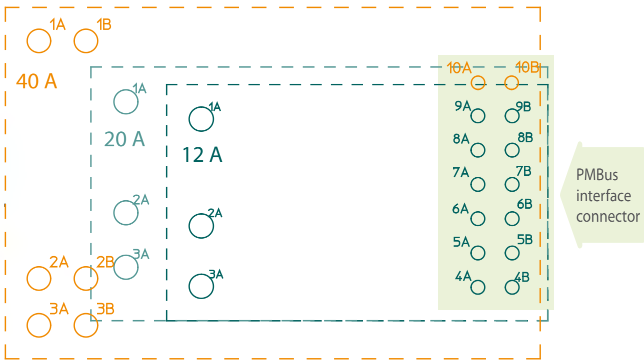


Figure 10. Second-generation of 3E digital point-of-load regulators, from top to bottom, BMR464 (40A) – BMR463 (20A) – BMR462 (12A)

FOOTPRINT BMR462/463/464



ELECTRICAL PINNING

Pin	Designation	Function
1A, B*	Vin	Input voltage
2A, B*	GND	Power ground
3A, B*	Vout	Output voltage
4A	Vtrk	Voltage tracking input
4B	SGND	Pin-strap ground reference
5A	+S	Positive sense
5B	–S	Negative sense
6A	SA0	PMBus address pin-strap
6B	GCB	Group communication bus
7A	SCL	PMBus clock
7B	SDA	PMBus data
8A	Vset	Output voltage pin-strap
8B	SYNC	Synchronization I/O
9A	SALERT	PMBus alert
9B	CTRL	PMBus control (Remote Control)
10A*	PG*	Power Good
10B*	SA1*	PMBus address pin-strap
*only on BMR464		

Figure 11. Despite new signal connections, the footprints for second-generation 3E digital point-of-load regulators remain scalable.

For instance, the new group communication bus (GCB) pin now allows multiple converters to communicate autonomously — that is, with no need for supervisory PMBus control — to support functions such as fault spreading and current sharing. In the event of a fault such as temporary overload, fault spreading allows regulators that are appropriately configured via PMBus commands to broadcast a fault event over the GCB that can initiate a controlled shutdown-and-restart sequence in a predetermined order. In this way, a system can automatically and safely remove and re-apply power to sensitive multi-rail devices, such as ASICs, FPGAs, and many microcontrollers. Again simplifying multi-rail applications, the analog voltage-tracking input complements the PMBus-programmable output voltage sequencing facility to make it possible for a regulator to track an external voltage and ramp up its output, either at the same rate as the reference voltage or as a configurable percentage of that rate.

The current sharing facility now includes the ability to add or shed phases in response to load conditions and offers several alternative approaches to implementing this feature. The analog output voltage pin-strap and clock synchronization I/O functions now have dedicated pins rather than the original multi-mode FLEX pin, improving application flexibility. It remains possible to synchronize each converter to a common clock frequency to eliminate beat frequencies and simplify EMC filter design, and the interleaving/phase-spreading capability that can drastically reduce peak currents on the input supply rail is still available. The 14-pin header that appears on the BMR464 (*Figure 12*) now provides an external power-good signal, which the converter asserts to signal that no fault condition is present and that the output voltage is within about -10/+15% of its target value. This tolerance is programmable for each BMR46x device, and each device's power-good status is readable from the PMBus.

Figure 12. 3E BMR464 (40 A) POL.

These points illustrate that more parameters are accessible and configurable via the PMBus to make the second-generation parts more capable and flexible than their forerunners, and this trend can confidently be expected to continue with future digital control ICs. Yet Ericsson's designers have retained the harmonized footprint philosophy that allows board designers to use a common footprint for all three new devices to accommodate systems whose power requirements are either not precisely known, or are likely to change over the lifetime of the equipment series. This strategy too will continue insofar as Ericsson's designers can possibly accommodate it, providing the company's customers with an ongoing assurance of continuity between succeeding generations of digital power converters.

DIGITAL CONNECTIVITY IS A KEY ENABLER

While any 3E series converter can operate stand-alone in analog-replacement mode, adopting the PMBus offers designers massive scope for innovation. Such benefits span the converter's entire lifecycle, from experimenting with different settings during initial development to programming custom parameters during manufacture to facilitating system-level power-management schemes that actively save energy in the end-user's equipment. To assist designers to become familiar with 3E family devices and PMBus protocols, Ericsson offers a 3E evaluation kit that allows users to configure, monitor, and control the power converters from a PC. Please visit the extensive resources at www.ericsson.com/powermodules for much more application information.

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DIGITAL DC/DC PMBUS CONNECT

Power modules
Digital DC/DC converter family
integrates PMBus connectivity

DIGITAL DC/DC CONVERTER FAMILY INTEGRATES PMBUS CONNECTIVITY

Able to work with any type of power converter, PMBus is a major success story. Its simple SMBus-based two-wire hardware interface is similar to and generally compatible with I2C, while the improved signaling protocols assure greater robustness. As a result, system designers can easily implement power management strategies that range from voltage sequencing or multi-voltage logic devices to monitoring and controlling entire systems using a uniform approach that has minimal impact upon resources.

Within the context of high-availability systems, PMBus makes it possible to integrate redundant power supply hardware while maximising the system's operating efficiency through intelligent power-management schemes.

This is especially significant for the distributed power architectures that industrial and telecom systems employ and that are becoming more widespread due to initiatives such as MicroTCA. Although the individual details vary, the general scheme comprises an AC/DC front-end that downconverts utility power to an intermediate level of typically 48VDC for distribution to all boards within a system.

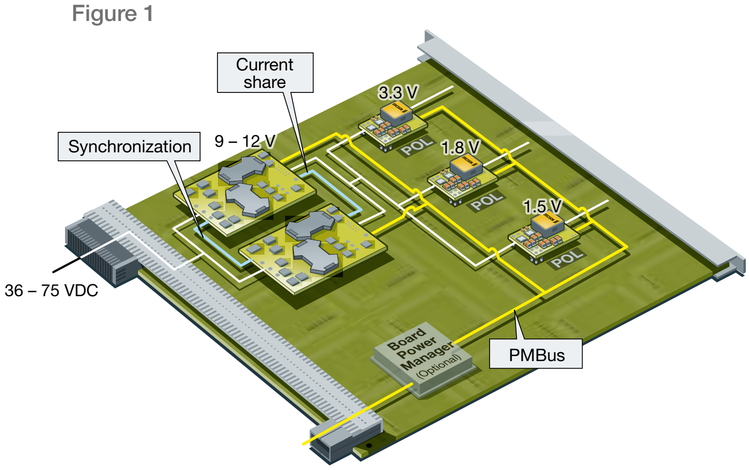
At board level, an intermediate bus converter (IBC) most often provides another level of isolation to satisfy safety standards, such as EN 60950. This IBC also downconverts to typically 9-12VDC to supply the non-isolated point of load DC/DC converters (POLs) that supply the voltages that logic and support circuits require. In a PMBus system, a local bus interconnects the board-level components and provides a uniform interface to the system host, which often also connects with the AC/DC front-end and peripherals, such as cooling fans - see *figure 1*.

ABOUT THIS PAPER

Material contained in this document has been presented
first in March 22, 2007 at PCIM China, session 3 – Future DC/DC Converter Concepts – Part I.

PCIM China is an independent event within Electronica & Productronica China, organized by Munich Exhibitions. Like PCIM Europe, which takes place annually in Nuremberg in Germany, the PCIM event in China is an international meeting ground for specialists in power electronics and its applications in drive technologies and power quality. The event offers a chance to see the latest developments in power electronics components and systems.

Figure 1



Importantly, PMBus devices must be capable of starting up safely without any host intervention. Also, the mandatory "set-&-forget" mode makes it possible to program a PMBus device once during manufacture, after which time the device can operate indefinitely without any bus communication.

PMBus includes several extensions to SMBus v1.1 as well as some features of SMBus v2.0. These include the group command protocol that sends one or more commands to multiple devices in a single, continuous transmission sequence. Because devices always execute the commands that they receive upon detecting the SMBus STOP condition, it is possible to update multiple devices at the same time. Another example is the extended command protocols that make available another 256 command codes for both byte and word formats. Any parameter that can be written must also be readable.

1. COMMAND LANGUAGE IS KEY

The power of PMBus is apparent in its command language, which comprises standard and device-specific commands. The basic single-byte format permits 256 commands, each of which may be followed by zero or more bytes of data. *Table 1* lists some of the standard commands that Ericsson's BMR450/451 digital DC/DC voltage regulators (DiPOLs) implement to enable the host to monitor key operating parameters.

TABLE 1
STANDARD PMBUS COMMANDS

STATUS COMMANDS	
CLEAR_FAULTS	03h
STATUS_BYTES	78h
STATUS_WORD	79h
STATUS_VOUT	7Ah
STATUS_IOUT	7Bh
STATUS_INPUT	7Ch
STATUS_TEMPERATURE	7Dh
MONITOR COMMANDS	
READ_VIN	88h
READ_VOUT	8Bh
READ_IOUT	8Ch
READ_TEMPERATUR_1	8Dh
READ_DUTY_CYCLE	94h

Operating from 4.5-14VDC, these converters use digital inner control loops to vary the pulsewidth modulation stream that switches the output MOSFETs in a synchronous buck-converter topology. An external resistor sets the output voltage over an exceptionally wide range—from 0.6 to 3.6VDC for the BMR451, or up to 5.5VDC for the BMR450. This approach allows the converter's firmware to optimize performance over a wider range of line and load conditions than is possible using a conventional analog control loop, typically achieving >96 percent efficiency at half load.

The firmware embodies functions such as precision delays and slew rate control at turn-on, while also supporting features such as undervoltage lockout, on/off control, remote sensing, and fault protection. Programmability during manufacture makes it possible for users to specify custom parameters that are then securely set in firmware for the product's lifetime. This implementation of the PMBus "set-&-forget" facility provides configuration flexibility that analogue converters typically cannot match—for instance, permitting adjustments to the inner control loop to optimize transient response—while making the component as easy to use as its analog counterparts. Aiding traceability, each DiPOL carries a unique serial number together with identification data that standard PMBus commands can access.

A key advantage of the DiPOL design is the integration of the PMBus interface and the monitoring and control hardware within the core of the digital controller. By comparison, an analog converter requires additional support circuitry that is less tightly coupled, occupies more space, and consumes

> "A KEY ADVANTAGE OF THE DIPOL DESIGN IS THE INTEGRATION OF THE PMBUS INTERFACE"

more power. For instance, an analog-to-digital converter IC that measures the intermediate bus voltage requires additional signal conditioning circuitry to provide filtering and scaling, consuming power and board space. Accordingly, the DiPOL design reduces component count, improving reliability and increasing power density. For example, the surface-mount version of the 40A-rated BMR451 packs 132W into a footprint that measures just 30.85x20.0x8.2mm, which equates to 7.90A/cm3 (129A/in3), while the companion BMR450 can supply

20A/100W from 25.65x12.9x8.2mm or 7.38A/cm3 (120A/in3). By comparison, similar analog DCDC converters manage only 2.37A/cm3 (43A/in3). The MTBF (meantime-between-failure) calculations for the BMR451 and 450 are 2.6 and 5 million hours, respectively.

2. DIGITAL CONVERTERS EASE SYSTEM INTEGRATION

The integrated read-back facility within Ericsson's DiPOL converters forms a fundamental building block in a higher-level power-management strategy.

At the subsystem level, monitoring load current and voltage fluctuations makes it possible to watch for conditions in the load circuitry that may signal that a change in intermediate-bus voltage is desirable, or that may signify abnormal conditions. The converter's temperature read-back facility might also provide an indication of irregular conditions, or be used to vary the speed of PMBus-compatible cooling fans. At system level, real-time measurements of key parameters permits supervisory software to adapt to changing line and load conditions, conserving power and minimizing heat generation.

3E Digital POL BMR450

A programmable IBC such as Ericsson's BMR453 is the hardware partner that enables such energy-saving schemes. This quarter-brick module isolates and down-converts a 36 – 75VDC power-distribution rail to levels that are programmable via PMBus commands within the range of 8.1 – 13.2VDC. Capable of supplying as much as 396W with ≥96 percent efficiency, this digital converter supplies some 5 percent more power than its analog predecessor, the PKM4304BPI. The BMR453 also maintains ±2 percent regulation accuracy—rather than the analogue converter's +4 percent and -10 percent —with approximately half the level of output noise and ripple, and a times-two improvement in transient response. Again, the BMR453 integrates the PMBus interface with all monitoring and control hardware and firmware elements within its core logic.

Taking advantage of the flexibility that PMBus standard and manufacturer-specific commands offer, the BMR453 implements an unprecedented level of in-system programmability. Divided into control, output, fault-limit, fault-response, time-setting, and supervisory categories, more than 50 standard PMBus commands are available to program the converter. These range from system level operations such as output-voltage and margin settings, turn on/off delays and slew-rate control, and setting fault limits, to device-specific functions such as altering the converter's switching frequency.

More than 20 standard read-only commands interrogate the converter to ascertain parameters such as its input and output

3E Digital POL BMR451

voltage levels, operating temperature, switching frequency and duty cycle. Thirty additional BMR453 specific commands configure features that range from the polarity of the power-good signal to the module's operating as a master or slave in a current-sharing configuration. One of the converter's more unusual design features is its ability to current-share with another BMR453 without needing any external support circuitry, such as OR-ing MOSFETs and diodes.

In conjunction with a development kit that supports the BMR453 and the BMR450/451 modules, Ericsson's 3E CMM software makes it easy for users to become familiar with the facilities that each component provides. Arranged as two channels that mirror one another, the 3E evaluation board accommodates up to three BMR450/451 modules and an optional BMR453 per channel.

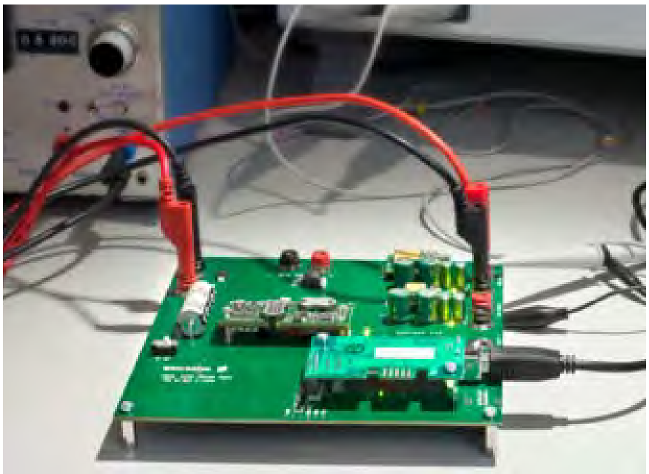


Figure 2

Users can easily connect sources and loads to evaluate the system's electrical performance in configurations that closely resemble their target applications - see *figure 2*.

Together with the evaluation board's USB-to-PMBus interface, the 3E CMM software makes it possible to access each module from a PC. During initialization, the software scans the PMBus to discover which modules are present and lists them in its uppermost pane, together with their addresses and major set-up parameters.

Highlighting a device causes the software to display four tabs—standard PMBus configuration, BMR45x-specific configuration, device monitoring, and file I/O— that access a series of command and view panes. For instance, the BMR453's standard configuration tab identifies the individual converter, allows users to program many of its standard PMBus commands, and reports each PMBus transaction as it executes - see *figure 3*. Similarly, the BMR45x specific configuration tab accesses less frequently altered device-specific parameters, while the device monitoring tab provides a real-time display of each converter's input voltage, output voltage and current, and its temperature together with a status pane that reflects fault and warning settings. The file I/O tab makes it easy to record, modify and restore a configuration file that contains all of the converter's operational settings in text-file format, which users can then use to program other converters and/or retain for documentation purposes.

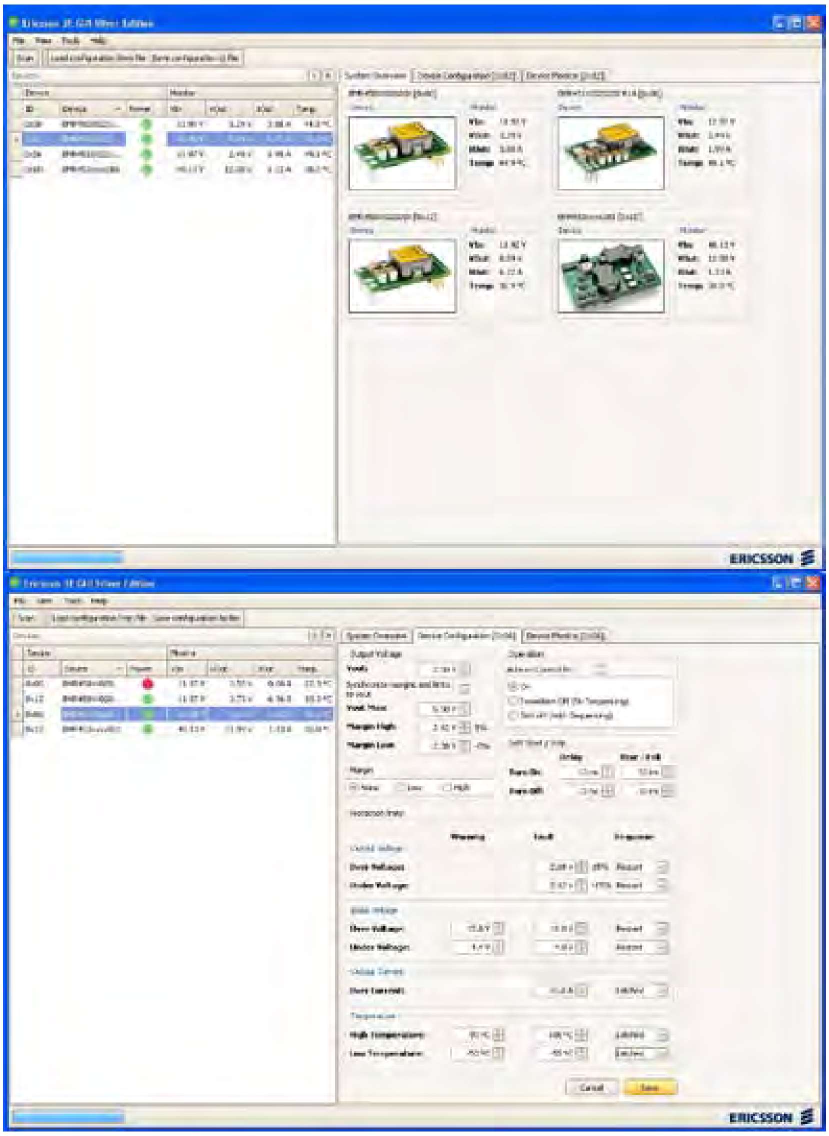


Figure 3

3. PMBUS INTEGRATION SAVES ENERGY

While integrating the PMBus interface and its measurement and control subsystems minimises component count and power consumption.The ability to adjust the IBC during normal operation makes it easy to implement schemes that deliver further system-level power savings.

Dynamic bus-voltage control is an established technique whereby supervisory software commands change in the IBC's output level to maximize efficiency over a range of line and load conditions. Some analog converters offer output-voltage control using potentiometers—offering the possibility of substituting digitally controlled potentiometers—or analog control voltage that a digital-to analog converter can satisfy. In either case, the adjustment range is relatively small, substantial support circuitry is necessary, and the dynamics of tuning the loop can be challenging.

The BMR453's digital design eases many of these concerns. Using the 3E evaluation board platform, tests at Ericsson demonstrate the effectiveness of dynamically altering the IBC's output in response to varying load conditions.

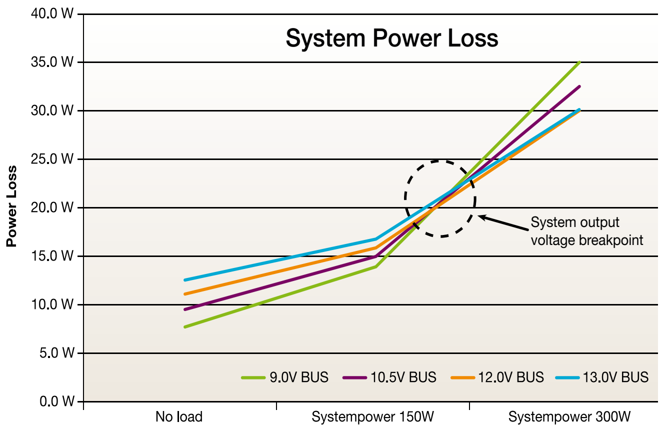


Figure 4

Figure 4 plots the power losses that result from varying the output voltage of a single BMR453 from 9 – 13V while supplying six DiPOL modules that source 0 – 300W. Neglecting external factors such as less energy for cooling, savings of up to 5W are clearly visible.

3E Digital DC/DC BMR453

When a pair of BMR453s supplies the DiPOLs in a current-sharing configuration, the ability to turn off one IBC during low-load conditions can save more than 2W of quiescent current. Furthermore, dispensing with the need for ORing diodes or MOSFETs saves yet more energy and space in the current-sharing and redundant-converter configurations that today's systems increasingly require.

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ERICSSON

DIGITAL POWER TECHNIQUES SET NEW STANDARDS FOR BOARD-MOUNTED POWER MODULES' FLEXIBILITY

Following a gestation period of several decades, digital power control techniques are rapidly gaining market share as designers increasingly appreciate the advantages that the technology offers.

CONTENTS

1. DIGITAL POWER TECHNIQUES SET NEW STANDARDS FOR FLEXIBILITY

Following a gestation period of several decades, digital power control techniques are rapidly gaining market share as designers increasingly appreciate the advantages that the technology offers over its analogue counterpart. Despite even more uncertain economic times than those of today, estimates made by power industry analysts in August 2009 awarded digital power an approximately 20% compound annual growth rate for the next five years, and the likelihood is that this figure was somewhat pessimistic—the same analysts thought 45% more appropriate just twelve months previously. Forecast accuracy apart, the key to any technology achieving rapid acceptance and sustainable growth lies with delivering tangible benefits at competitive cost.

As many designers have discovered, the combination of digital power control and digital power management exceeds routine evolutionary expectations to represent a real, cost-effective step change in overall capability. Here, digital power control refers to implementing the inner control loop of a power converter with digital circuitry rather than using familiar analogue schemes. For a simple buck converter, this means substituting an analogue-to-digital converter for the traditional error-signal feedback amplifier, and deriving correction for the pulse-width modulator that drives the power switches using digital signal processing techniques in place of a voltage reference, ramp generator, and comparator – **Figure 1**.

By contrast, digital power management denotes supervisory and control circuitry that communicates via a digital I/O scheme, which today almost invariably exploits the PMBus™ interface that has become the power-industry standard.

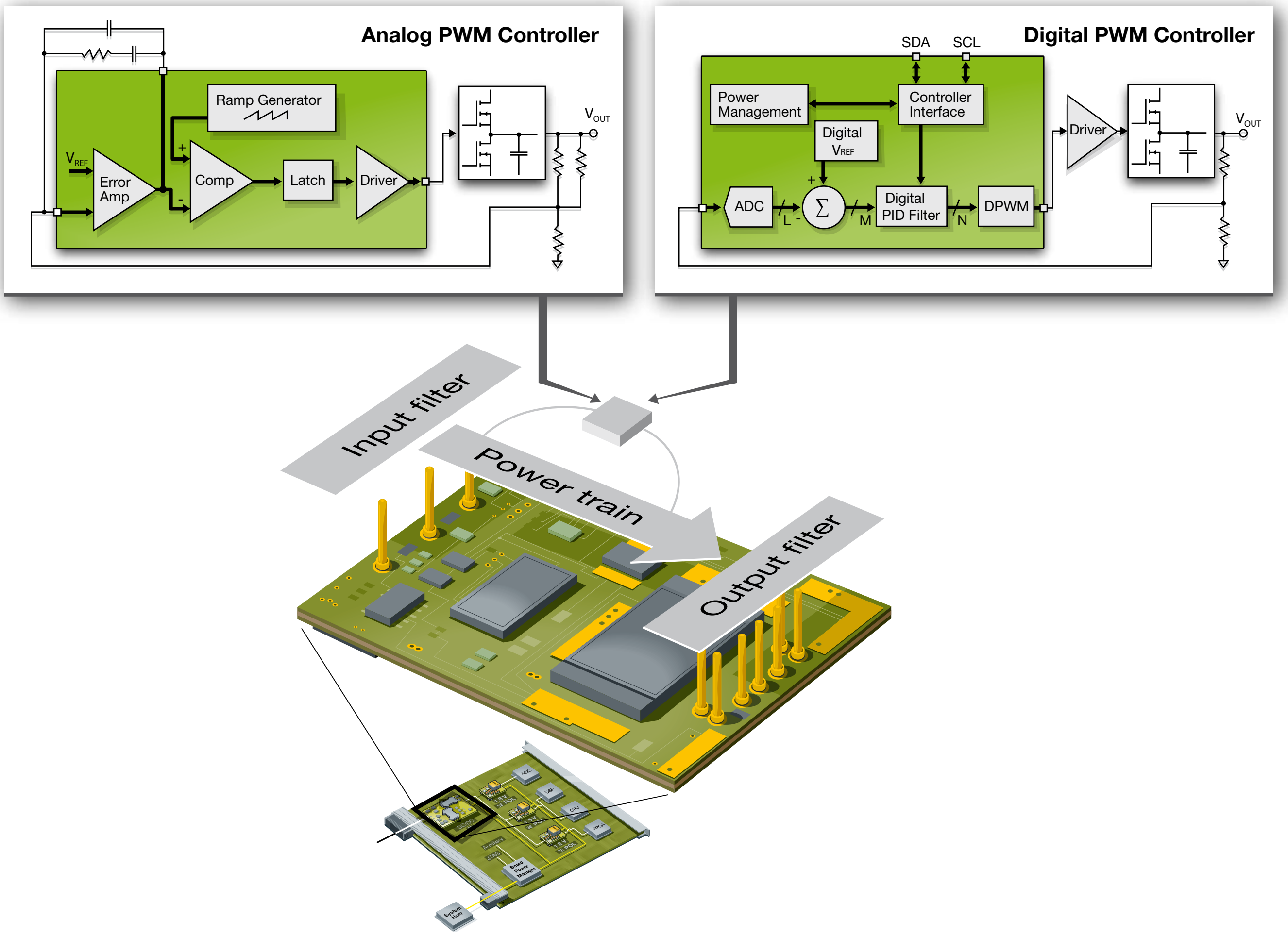


Figure 1 Block diagrams of analog and digital control systems depicted together with some parts of power train

Figure 2 Digitally controlled, PMBus-compliant Advanced Bus Converter BMR453

A converter that combines both of these digital power concepts can actively manage its conversion process to optimize efficiency for changing line and load conditions while including all of the power management system within the same package – **Figure 2**.

2. DIGITAL CONFIGURABILITY DELIVERS LIFE-CYCLE BENEFITS

But digital power has much more to offer than bettering the electrical performance and power-density requirements that previously dominated the mindset of power supply designers. Essentially, such performance improvements are due to the ability of a digital control loop to adapt its dynamics to optimally suit line and load conditions in real time; by contrast, passive components set an analogue converter's responses, which are inevitably a compromise between stability and dynamic response for the expected operating conditions. But in developing its 3E concept that embraces enhanced performance, energy management, and end-user value, Ericsson recognised that digital power could offer benefits that apply throughout a product's lifecycle.

As the digital converter's core is a mixed-signal IC it's possible to pack the supervisory measurement and control hardware together with its PMBus interface onto the same slice of silicon at negligible additional cost. This approach optimizes the electrical coupling between the converter's core and its control system, minimises power consumption, and slashes the amount of PCB real estate that's necessary to accommodate equivalent functionality using analogue-based solutions – **Figure 3**.

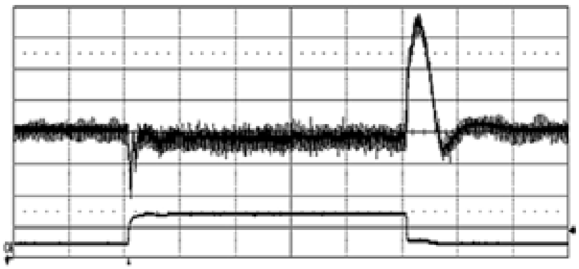
Crucially, it's now possible to configure the digital converter when it is initially made, during the development phase of the power-system designer's application, at the distributor's depot, when the equipment is manufactured, and/or when it is operating within the end-user's equipment.

Figure 3 Highly integrated functionalities reduce board-space, increase efficiency and reliability

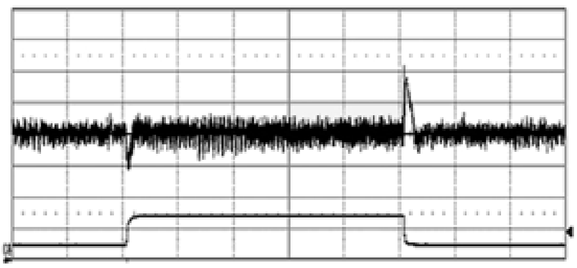
This unparalleled degree of flexibility extends the programmable logic model to the power conversion industry for the first time.

Each 3E family power converter offers an array of programmable parameters that includes output voltage selection, turn-on/off delay times to implement power sequencing for multi-rail loads, slew rate control that provides inrush current protection, voltage margining for system testing, and multiple thresholds for warning and fault conditions for overcurrent, overtemperature, and under- and overvoltage. It's even possible to adjust the response of a digital converter's control loop to optimize its performance for a particular set of load and bulk output capacitance conditions. **Figure 4** shows the result of fine-tuning the constants that set the responses of a 3E point-of-load regulator's control loop to optimize its transient response for a given environment. This is the digital equivalent of moving the poles-and-zeroes in an analogue converter by continuously adjusting the values of resistors and capacitors within its feedback loop, which is practically inconceivable.

Default robust dynamic configuration



Load optimal dynamic configuration



Output voltage response to load current stepchange (5-15-5 A). Resistive load with slewrate > 7A/µs at: $T_{ref} = +25°C$, $V_I = 12V$, $C_{out} = 470\mu F$.

Top trace: output voltage (50 mV/dev.). Bottom trace: load current (10 A/div.). Time scale: (0.1 ms/div.).

Figure 4 Reprogramming the control-loop constants in a digital power converter can optimize its dynamic performance for a given operating environment

3. PMBUS™ IS A KEY ENABLER

The PMBus can be invaluable during product evaluation and development. Here, the board power manager that controls PMBus-compatible devices might be a PC connected to a prototype board via a suitable adapter. Because the physical layer of PMBus relies upon SMBus—which is a development of I2C—PMBus is generally limited to the board domain, leaving designers free to implement their choice of backplane connectivity. **Figure 5** shows the general scheme.

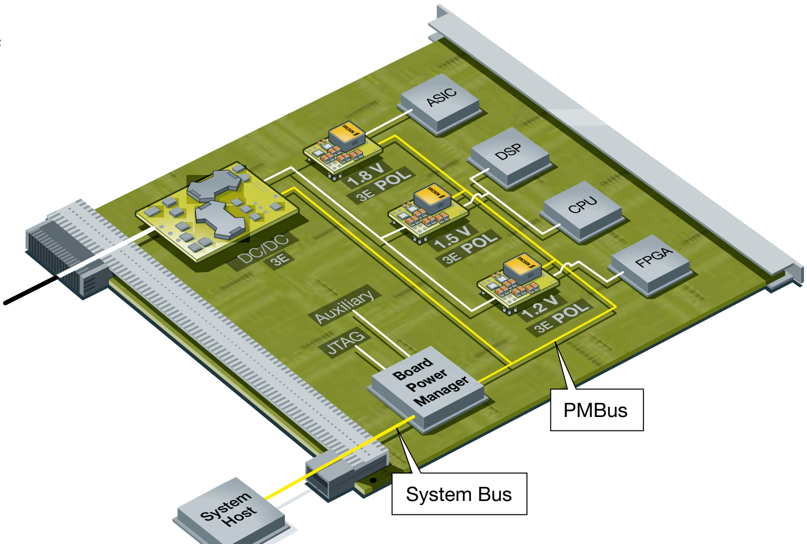


Figure 5 PMBus makes it easy to monitor and control compatible power-system devices such as the 3E family

To make development immediately available, Ericsson developed a PC-compatible evaluation kit for 3E products that includes a USB-to-PMBus adapter and driver software that substitutes for the board power manager in the figure. The PC and the kit's application software then assume the role of system host and user interface. This approach provides an extremely fast method for experimenting with parameters such as output voltage settings, power sequencing routines, voltage margining, and fault handling without any need for hardware changes on the board-under-test.

When the designer is satisfied with a set-up, the application software can save a configuration file for each 3E device for later use. **Figure 6** shows some of the options that the software presents within a single device configuration screen.

Figure 6 The 3E graphical user interface software greatly simplifies device configuration

While customers can request specific configurations, Ericsson most often delivers 3E parts pre-programmed with a default configuration that reflects a converter's typical application profile. For instance, users can order a point-of-load regulator such as the 20 A-rated BMR450 preset to output 1.0, 3.3, 5.0, or 5.5 VDC – **Figure 7**. It is subsequently possible to reprogram

Figure 7 20A PMBus compliant and digitally controlled point-of-load BMR450

the device to any level from 0.6 to 5.5 VDC with 1 mV resolution via the PMBus (it's also possible to set the product's output voltage from 0.7 to 5.0 VDC in 25 steps with a resistor). As a result, one device covers a range of output voltages, permitting inventory reductions and easing logistics management. It's also worth noting that the BMR450 and its 40 A companion BMR451 **Figure 8** can share a common PCB layout, allowing designers to exchange converters as a system's power needs

Figure 8 40A PMBus compliant and digitally controlled point-of-load BMR451

evolve – **Figure 9**. Similar benefits apply to all 3E family power converters.

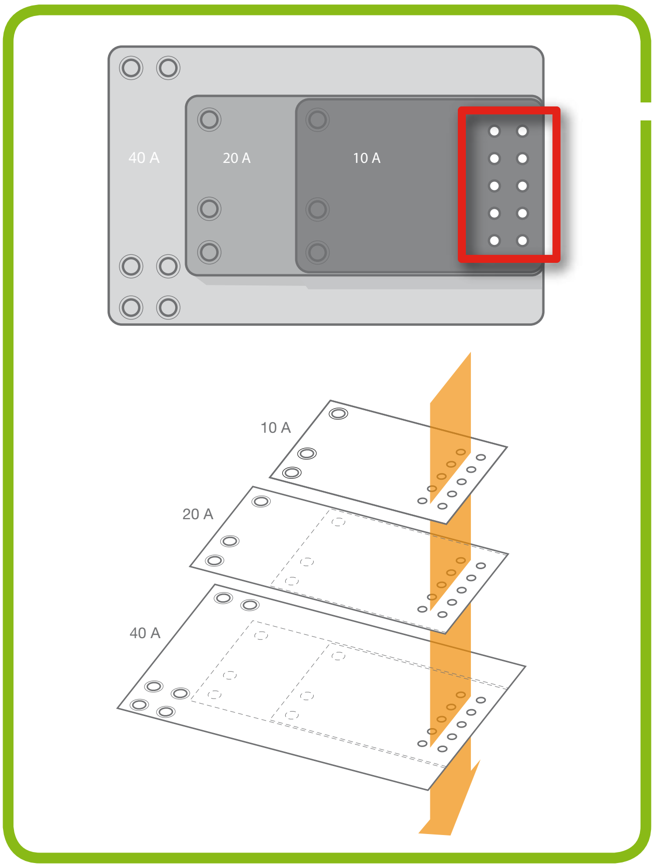


Figure 9 The footprint layouts of Ericsson 3E point-of-load regulators are scalable. A single PCB layout can accommodate the range of products improving flexibility

If a one-time change of output voltage or any other programmable parameter is all that's necessary, a logical time to do this is at the ATE phase of board manufacture. Alternatively, a distributor may offer a programming service. Assuming a simple end-user application such as upgrading an analogue design, it's possible to dispense with board power management logic on the target board. However, including full PMBus connectivity vastly improves the range of options that are available to power-system designers. As the PMBus requires just four conductors and a low-cost microcontroller easily accommodates the board power management logic, this approach is well worth considering.

Implementing PMBus connectivity allows the system host to monitor each PMBus-compatible device throughout the equipment's lifetime. Depending upon the sophistication of the system's supervisory software, this data-gathering ability might form the basis for energy cost analysis, root-cause failure analysis, or satisfy other user-specific functions. It may also help avoid system failures. For instance, if the supervisory software detects an unusually high pattern of warning conditions for a particular device, it may signal a service alert to swap out the suspect device before it fails. Similarly, if a power converter's output voltage drifts slightly over time or as a result of wide temperature variations, supervisory software could adjust the device back into full specification.

Another possibility that monitoring a board's power consumption offers is dynamic energy conservation, where supervisory software intelligently varies the output voltage that the intermediate bus converter supplies to the point-of-load regulators. Because virtually all power converters are least efficient at low loads, reprogramming the advanced bus converter from say 12 VDC down to 9 VDC saves power dissipation while the point-of-load regulators are running under light load – **Figure 10**. When more power is required, supervisory software can seamlessly ramp up the intermediate bus voltage to its optimal level for the new load conditions. Where a pair of power converters operate in a parallel current-sharing arrangement, it will save energy to turn off one if the load level falls within the capability of a single converter – **Figure 11**. This active approach to power management particularly suits systems that spend significant periods under widely different load conditions.

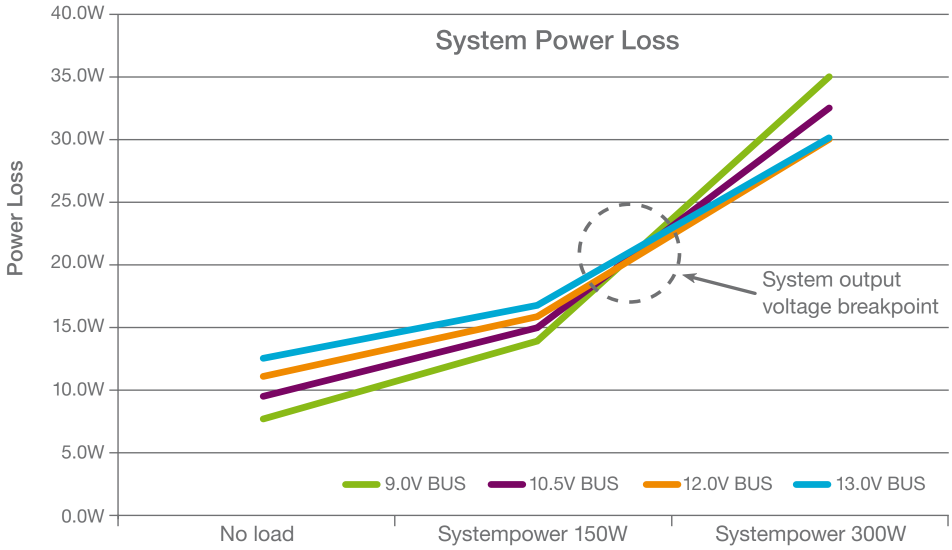


Figure 10 Adjusting an advanced bus converter's output voltage to payload condition reduces energy consumption

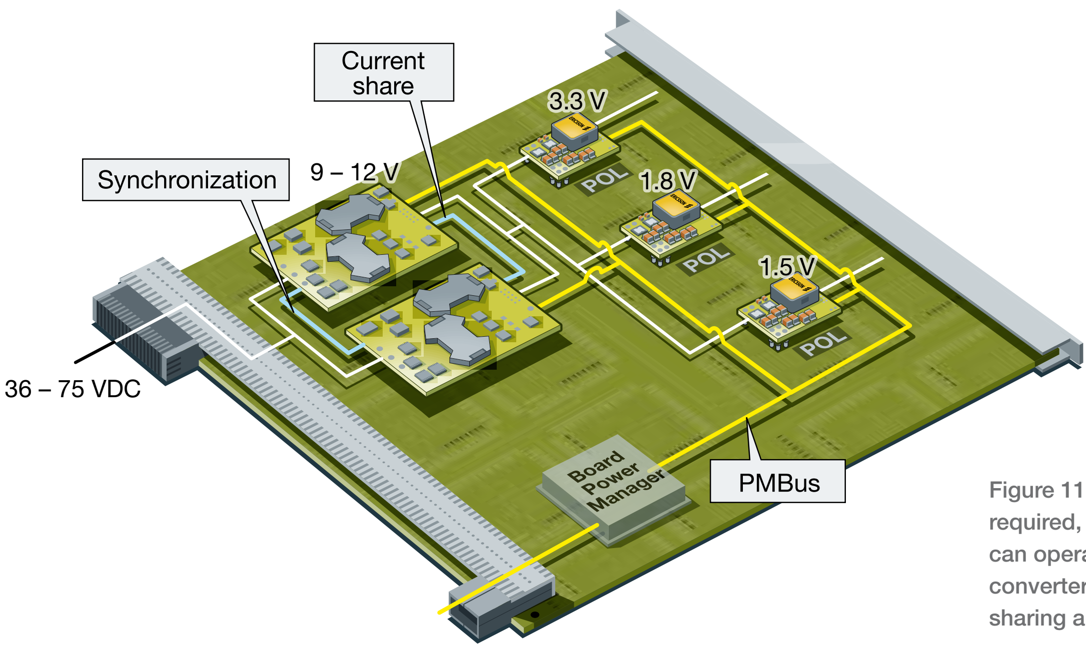


Figure 11 When more power is required, supervisory software can operate a pair of power converters in a parallel current-sharing arrangement

4. THIS IS JUST THE BEGINNING

It's important to emphasise that these example scenarios represent just a few of the possibilities 3E power converters with PMBus connectivity make possible, and innovative designers will doubtless find new ones. Also, any of these converters can upgrade analogue designs with no special effort on the designer's behalf. They can easily operate stand-alone as they offer analogue-style functions such as output voltage adjustment via a single resistor, remote voltage sensing, and single-pin hardware on/off control. The "set-and-forget" capability that PMBus mandates also means that any 3E power converter can be pre-programmed with user-defined parameters that the device then retains for its lifetime or until re-programmed. This makes it possible to fine-tune a converter for a particular application without requiring PMBus in the target system.

Compared with well-known analogue techniques, the downside of digital power conversion is the very substantial amount of R&D effort that's necessary to produce a production-worthy digital converter—which is a prime reason for selecting proven, pre-qualified solutions. To help ease users into the digital power environment, Ericsson offers application engineering assistance and complements its evaluation kit **Figure 12** with a large archive of technical papers and application information.

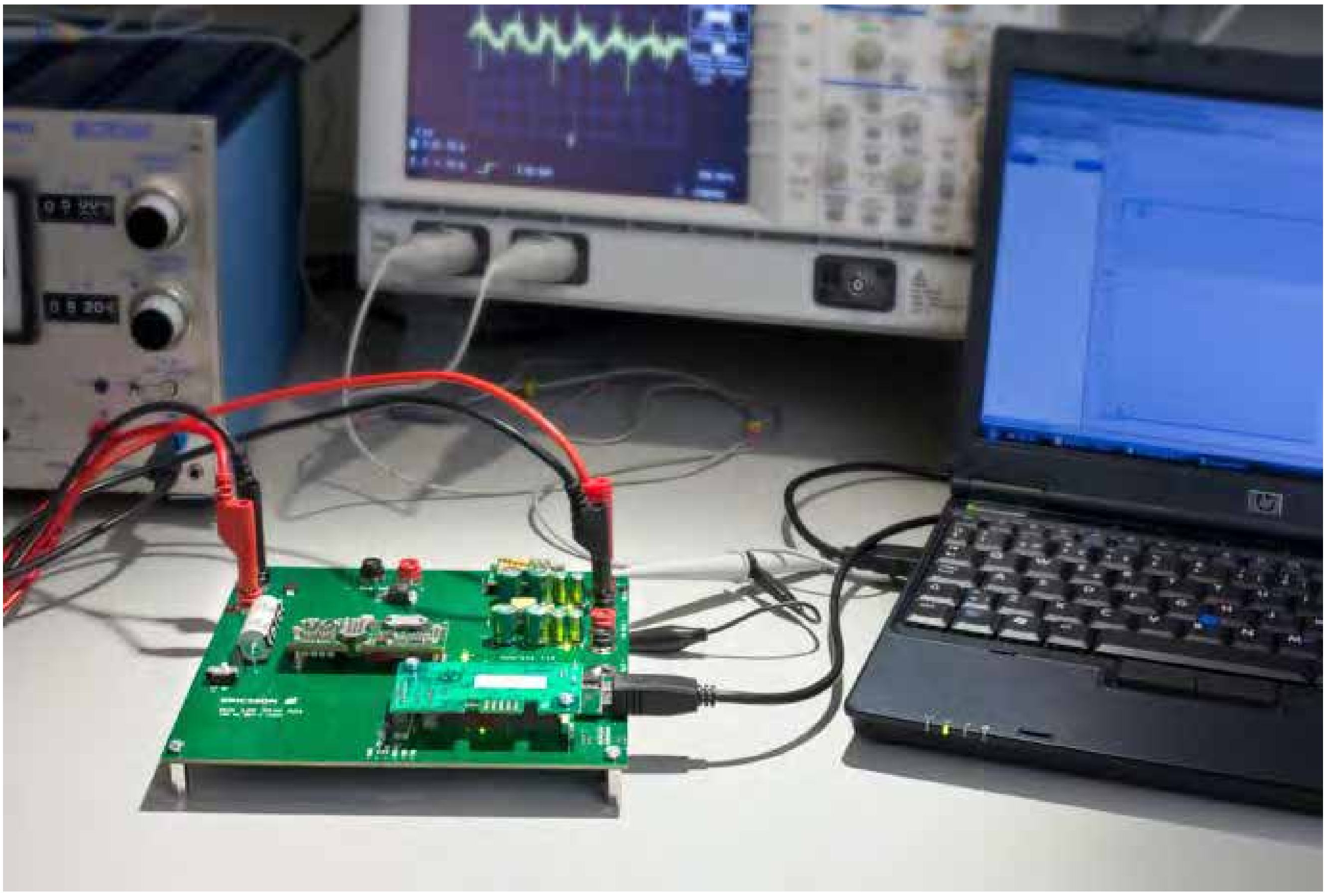


Figure 12 3E evaluation kit simplifies learning, testing and programming

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ERICSSON

DIGITALLY CONTROLLED BOARD MOUNTED POWER CONVERTERS

This paper addresses hardware designers of Information and Communication Technology equipment, i.e. the users of digitally controlled Board Mounted Power Supplies (BMPS). The intention of this paper is to explain how the digital power technology can be used in both existing and new designs.

CONTENTS

ABOUT THIS PAPER

The material contained in this paper was first presented on November 15, 2007 at Digital Power Europe, Munich. This focused three-day international conference served an audience of decision makers who are interested in learning about and contributing to the latest practical advancements related to the use of digital power control techniques in electronic systems and in power converters, and digital energy management and power management in enterprise-level installations and related digital equipment.

1. INTRODUCTION

Digital Power Technology covers both digital implementations of the dc-dc control IC as well as a possibility of controlling the dc-dc converter parameters with a digital interface.

A digital IC controls cycle-by-cycle the switching process of dc-dc converters. Instead of using the analog feedback signal, the digital controller uses digitalized measurements of the input and output electrical parameters and takes a proper switching decision.

When a digital interface is added to a digitally controlled BMPS, the power converter becomes flexible and new features are available. Protection functions can be re-defined depending on the application requirements. Input and output parameters can be modified either before the first power up or “online” (during operation).

Electrical parameters and temperature can be monitored. The possibility of controlling BMPS “online” can dramatically improve efficiency of BMPS on board and system level.

2. VENDOR CONFIGURED BMPS

Digitally controlled dc-dc modules can be completely programmed by the vendor. Both standard and customized configuration information can be put into the control IC memory. The modules may have a standard pinning and work in a stand alone mode. In this case, there is no need for any additional communication interface. The vendor configured digital power modules can be used as replacement of analog BMPS.

Contrary to the analog BMPS, the digitally controlled modules are much more flexible. It is dramatically easier to design and produce customized variants. For instance, a user can order a pre-programmed variant of a Point of Load module with 1.35 V/14 A output, 11 ms start-up time, 7 ms ramp-up time and the load transient response optimized for 1000 µF external ceramic capacitors.

Using vendor configured stand alone modules is the simplest way to take advantage of the digital power technology. No prior knowledge of the digital power is needed at the user site. The drawback of this design approach is that only the vendor can reconfigure the digital module when the user requirements are changed.

3. USING EVALUATION TOOLS

To speed up the development of the customized BMPS, it is required that the users can update the BMPS configuration themselves. The easiest way to do it is using preconfigured digital modules and dedicated design tools.

A typical design tool contains an evaluation board with sockets for one or more digital modules and Graphical User Interface (GUI) personal computer software. Each module on the evaluation board is equipped with an additional digital interface connector. This connector contains pins for serial communication bus as well as address pins. The address pins are necessary when several modules are evaluated at the same time.

The PMBus [1] is often used for internal (within evaluation board) communication and the USB is used for the communication between the evaluation board and the personal computer. The evaluation boards usually contain a PMBus / USB adapter.

Thanks to the GUI, the user does not need to know the PMBus commands. The GUI presents directly the BMPS electrical parameters on the PC display. The designer can change the parameters by typing new values and save them in the module's IC flash memory.

Typical parameters which may be changed by the user are: under and over voltage protection levels, output current limits, start and ramp up times and over temperature protection thresholds. The user can also define the behavior of the BMPS when a protection condition occurs. The user can chose a number of events before the protection is activated as well as the protection mode (e.g. latching or automatic restart).

Setting the protection parameters is particularly important since there is a significant difference between digital and analog BMPS as far as the sensing of the input/output voltage and current is concerned. In digital BMPS, the voltage level is measured with a very fast A/D converter. The results correspond to an instant value in the sampling moment. The voltage sensing in analog BMPS is rather slow, an average value over tens of microseconds is measured. High frequency noise is often present in the monitored voltages. To avoid activation of the protection functions in case of low energy spikes, necessary margins should be added to the protection threshold values.

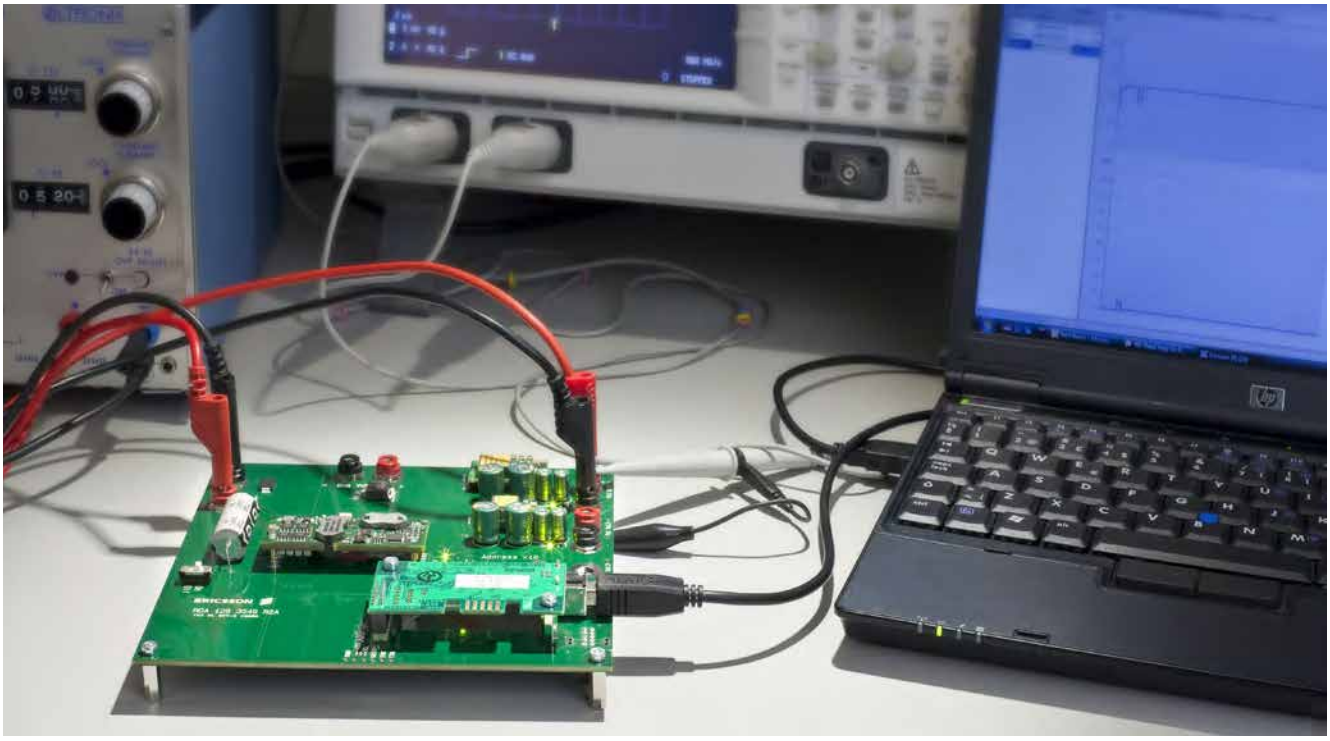

Figure 1 - 3E Evaluation Kit

4. CONFIGURING BMPS ON APPLICATION BOARDS

For more complex applications (particularly when several modules are used and they require a sophisticated sequencing or when the board power consumption must be minimized) it is not convenient to use a design evaluation board. Instead, it is recommended to add a dedicated serial communication bus (e.g. PMBus) to the application board. Each digital power converter connected to the bus should have a unique address. General design recommendation regarding signal integrity should be applied when routing the PMBus data and clock traces. It is also important to apply proper line terminations.
An external PMBus to USB adapter can be used to connect the board under development to a PC. The same GUI as provided with the evaluation board can be used for the BMPS development on the application board.

Once the power design is optimized it is not necessary to copy the PMBus signals and the addressing connections from the prototype to the final version of the application board. The devices once programmed can work in a stand alone mode. However, it is recommended to keep the PMBus lines and the module address configuration for future improvements. Besides, it is likely that new versions (e.g. with lower core voltage) of the application board key components like processors and DSP will arrive on the market. In this case re-configuration of the BMPS will be easier.

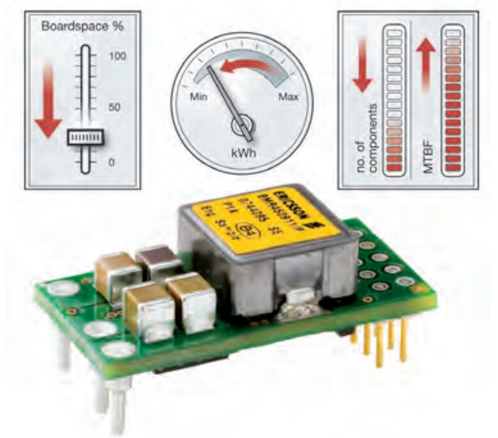

Figure 2 - Benefits of digital Point-of-Load design.

5. CONFIGURING FROM A HOST PROCESSOR

When application requires that the BMPS can be reconfigured "online", the digital power communication bus (e.g. PMBus) must be controlled from a host processor. This design approach is necessary when "online" Energy Management will be implemented. Complex application boards often have board management processors which can be partially used as a host processor for digital power management. It is not recommended to implement the PMBus interface using standard I/O ports and software blocks since it would be a complex task and would require processor resources. Dedicated ICs [2] or commercially available FPGA reference designs should be used instead.

Using host processors gives the designer a great possibility to optimize the BMPS on prototype boards. Parameters as switching frequency, intermediate bus voltage and dynamics of the control loop can be optimized for a specific application. Also, "real-time" monitoring of the BMPS parameters will be possible. It will enable energy management on board and system level.

The advantage of a host configuring is that the high volume manufacturing will not require additional efforts for power configuration. The BMPS can be configured during a Boundary-Scan test of the application board (In-System Programming [3]). The drawback of configuring the BMPS from a host processor is relatively complex software which could be time consuming. A close co-operation between software and power engineers is necessary.

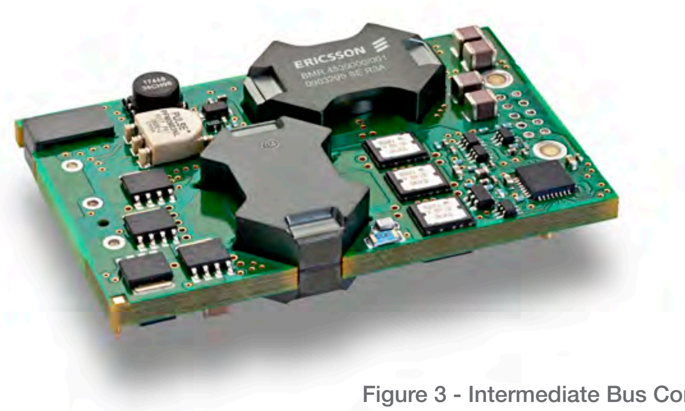

Figure 3 - Intermediate Bus Converter built with digital control & management capability.

6. CONCLUSIONS

Digital power technology makes Board Mounted Power Supplies flexible and more efficient. New features like parameter monitoring and Energy Management become available. On the other hand, the power design becomes more complex, at least, initially.

Digital power knowledge must be transferred form vendors to users. New software tools must be developed. Besides, it is necessary that the board power designers closely cooperate with system and software designers.

The end user of the ICT equipment will definitely benefit when digital power technology is fully implemented.

7. GLOSSARY

DSP	Digital Signal Processor
FPGA	Field Programmable Gate Array
GUI	Graphical User Interface
IC	Integrated Circuit
I2C	Inter-Integrated Circuit (multi-master serial computer bus)
ICT	Information Communication Technology
PMBus™	Power Management Bus
SMBus	System Management Bus
USB	Universal Serial Bus

8. REFERENCES

[1] PMBus: http://pmbus.org

[2] I2C Specification and User Manual, UM10204, Philips, 2007

[3] Manufacturing Test and In-System Programming, Data sheet, JTAG Technologies, www.jetag.com

All referenced papers and data sheets can be found at Ericsson Power Modules' web site: http://www.ericsson.com/powermodules

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QUALIFICATION AND VERIFICATION CONSIDERATIONS FOR DIGITAL POWER SUPPLIES

The introduction of digitally controlled power supplies have huge impact on the Quality Assurance process and solutions to the issues discussed in this paper will be vital to the success of digital power in the telecom and datacom markets.

CONTENTS

ABOUT THIS PAPER

Material contained in this paper was first presented on September 10, 2007 at Digital Power Forum 2007 – Plenary session.

This focused three-day international conference served an audience of decision makers who are interested in learning about and contributing to the latest practical advancements related to the use of digital power control techniques in electronic systems and in power converters, and digital energy management and power management in enterprise-level installations and related digital equipment.

1. INTRODUCTION

Digitally controlled and managed power supplies represent a rapidly growing part of the power conversion industry. It is an exciting and dynamic part of the market because of the many advantages it offers relative to conventional analog-based control methodologies. Hardware and system impacts of digital power are being addressed in the many conference papers and trade journal articles that have recently been appearing. But this highly configurable new approach to power supplies has other impacts both to suppliers of power hardware and to their OEM customers. One of these impacts is the Quality Assurance process, which faces new challenges with the introduction of digital power supplies.

A conventional power converter or regulator with an analog control system is “hard wired” to perform to a set of documented specifications, and the normal Quality Control processes are designed for this environment. With digital power, the converters and regulators are highly configurable via software resulting in an almost infinite number of possible performance attributes. Some of the Quality Assurance issues that arise from this change include management of software levels, verification of memory operation internal to power supplies, sourcing of critical digital control components, more complex verification testing, lifetime and reliability implications, software upgrade procedures, and failure analysis. Ericsson is one of the industry leaders in the design of digital power and recognizes that solutions to the kinds of Quality Assurance issues listed above will be vital to the success of digital power in the telecom and datacom markets. Ericsson therefore has a commitment to be proactive in identifying and resolving the Quality Assurance implications of digital power. This paper will describe the initial efforts.

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2. DIGITAL CONTROL

A comparison of the differences between analog and digital control is shown in *Figure 1*, which shows a generic example of a power converter, and briefly describes what "digital power" actually means in a typical power supply. Much of the content internal to the converter remains essentially unchanged when going from analog to digital control. Examples are input and output filtering, magnetics, and power semiconductors. The primary impact of digital control is in the control/feedback loop of the power supply. The analog control chip is removed and replaced by a micro controller (μC), memory support, and an interface bus for communication outside the power supply. Control algorithms for the power supply are contained in software loaded into the internal memory.

This approach provides several benefits:

- HIGHER EFFICIENCY
- HIGHER PACKAGING DENSITY
- INCREASED CONFIGURABILITY
- FEWER HARDWARE PART NUMBERS
- FIELD CONFIGURABILITY AND UPGRADEABILITY
- FASTER SYSTEM TIME-TO-MARKET

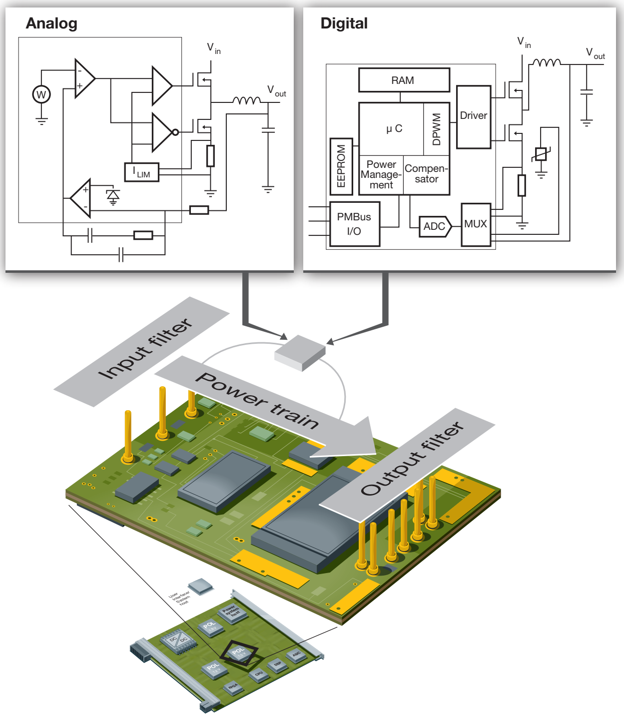


Figure 1 - Digital Power Control

Digital control also raises some risks or potential concerns from a Quality Assurance perspective, including:

- WITH ALMOST INFINITE CONFIGURABILITY, HOW ARE THE LOGISTICS MANAGED?
- THE NEW SOFTWARE "COMPONENT" MUST BE VERIFIED AND QUALIFIED.
- THE INTERNAL MEMORY MUST BE EXTREMELY RELIABLE. HOW IS IT VERIFIED THAT NO DATA IS LOST?
- HOW IS THE OPERATION CONFIGURATION OF THE POWER SUPPLY DONE DURING MANUFACTURING TESTING?

3. SOFTWARE

From an operational point-of-view, the biggest difference between analog control and digital control is the added component of software for the digital case. The software provides many benefits for the developers and users of digital power products, but it also adds complications to the qualification, manufacturing, and logistical support processes.

The µC used in Ericsson's digital power products is supported with onboard non-volatile memory. This memory is used to store the basic firmware that allows boot-up and operation of the µC. Obviously the robustness of this data is critical to the operation of the converter or regulator, as without it the µC cannot function at all. This basic firmware tends to be relatively stable in regard to change activity for any given hardware implementation of the µC. This firmware is loaded into the µC non-volatile memory during the manufacturing process of the µC.

The more interesting and flexible software in a digitally controlled power supply is the application programming. This code contains operating parameters for the power supply's feedback control loop, settings for output voltage, fault detector limits, error handling routines, sequencing information, etc. Each digital power supply is capable of operation over a broad range of many of these parameters. During the manufacturing process of a standard digital power supply, default settings are defined, entered and verified before product shipment. In addition, several other representative settings must be tested to insure that the power supply will operate reliably over its

intended range of functionality. A further complication is that some parts of the application programming can be done by the OEM user if they are using the product in a digital power management environment. Thus the software and the processes for its control and Quality Assurance must address usage by both Ericsson during manufacturing and by the customer during product development and field deployment.

4. QUALITY ASSURANCE IMPLICATIONS

The Quality Assurance implications of digital power extend through all stages of Ericsson's operational processes from the sourcing of raw materials through field support activities. A flow chart showing the areas affected is provided in *Figure 2*.

Each of these areas will be covered in more detail in the material that follows. The reference section at the end of the paper cites several sources of information about

Ericsson's general Quality Assurance programs. While they do not address digital power specifically, they will give a good overview of Ericsson's commitment to quality and of our level of attention to operational details.

4.1 MATERIAL SOURCING

Ericsson places a high degree of emphasis on quality in all of the material sourcing, as explained in the reference material. In the case of digital power, the biggest new challenge will be the management of the µC device, both from a sourcing security point-of-view and in terms of managing the included firmware. Digital µC chips intended for power supply applications are relatively few in number at this time. They are also highly complex devices with no standardization from supplier to supplier. Consequently, second sourcing is not an option. Instead, we will insist on "secure sourcing". The supplier of the chip will have to have two or more manufacturing sources, and regularly ship product from all of them to insure equivalency and to minimize start-up problems at any manufacturing site.

There will be very close contact and substantial dialog between Ericsson and the suppliers of the µC chips used in digitally controlled power supplies. The following are the types of provisions that will be required:

- TWO OR MORE EQUIVALENT MANUFACTURING SITES FOR µC CHIPS
- INCLUSION OF A VERY ROBUST NON-VOLATILE MEMORY AND COMMUNICATION INTERFACE
- BUILT-IN FAULT DETECTION AND DIAGNOSTIC CAPABILITY OF THE DIGITAL FUNCTIONALITY
- EXTENDED QUALITY TESTING DURING THE IC DESIGN AND MANUFACTURING PROCESSES
- INSURANCE OF LEVEL CONTROL FOR FIRMWARE LOADED DURING IC MANUFACTURING
- THOROUGH CONTROL OF LOGISTICS FLOW DURING IC MANUFACTURING AND SHIPMENT

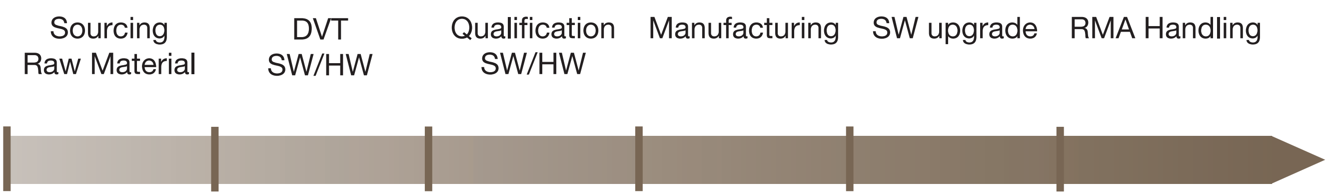


Figure 2 - Quality Assurance process

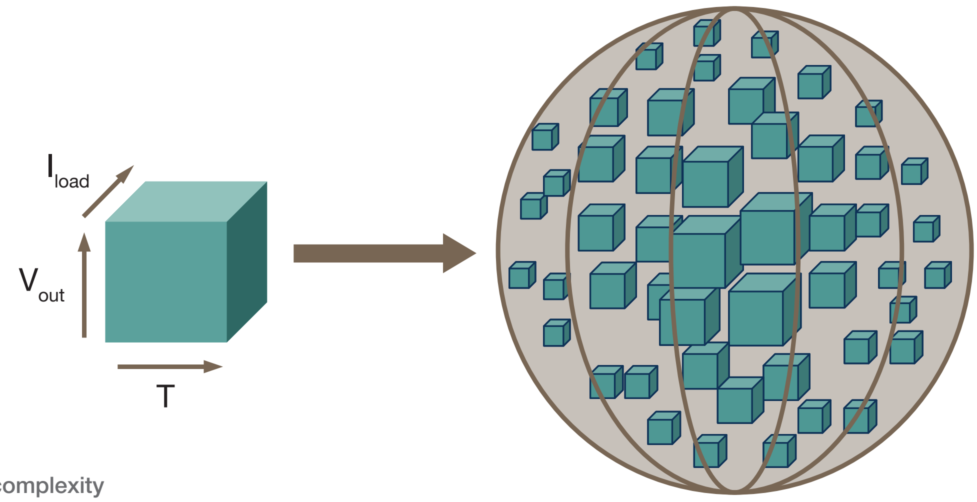


Figure 3 - DVT complexity

4.2 DESIGN VERIFICATION TESTING

Design Verification Testing (DVT) is done near the end of a product's design cycle for the purpose of insuring that the product, as designed, meets all of the requirements and specifications for the product. Both functionality and performance must be verified. With digital power, the DVT will also apply to the software content of the product. An analog product has a few well defined "corners" of its specification space. For example the parameters of output voltage, output current and temperature might be the key elements of the specification for an analog power supply. These three parameters define a three dimensional space such as the cube shown in *Figure 3*. By making measurements at each of the eight corners of the cube, operation of the product can be insured over the entire operational ranges of the three parameters.

The situation is entirely different with digital power. Because the software is highly configurable and can control dozens of individual parameters, the number of possible combinations is essentially infinite, and the number of "corners" expands exponentially as indicated by the graphic in *Figure 3*. In essence, the software makes it possible to define an almost infinite number of "products", not just one. Ericsson addresses this problem by using an "intelligent DVT" process.

The concept of an intelligent DVT is to define software for multiple platform implementations spanning the expected applications for the power supply. Each of these implementations will include specification of the external functionality of the product such as output voltage and fault monitoring/handling behavior. Each implementation will also define parameters and functionality within the power supply such as control loop compensation settings. A checksum will be generated for each configuration so that the operation of the memory can be verified.

Another area requiring exceptional focus during DVT is the electromagnetic susceptibility (EMS) performance of the µC and memory. These are very complex, small geometry ICs that are critical to the operation of the power supply and are located in close proximity to the large currents and fields resident within a switching power supply. Their robustness in such an environment must be carefully verified so that data integrity is not compromised. Ericsson plans to utilize a special test board for this purpose and conduct EMS testing at levels in excess of 10 volts per meter. X-ray, neutron and proton radiation testing will also be done.

Ericsson will also put emphasis on insuring that the communications bus interfacing the power supply to the outside world meets all the requirements of the appropriate specification. This is important to guarantee that the power supply will interface seamlessly with host controllers in customer systems and provide compatible communication with all other devices on the bus.

4.3 QUALIFICATION

Qualification testing insures that the design and manufacturing processes produce a product that will provide long-term reliability under a variety of environmental conditions. This testing can be done at more than one level in the process flow, both at the component supplier and after final assembly of the power supply, for example. The key qualification challenge for digital power will be the long-term performance of the µC and memory with regard to software data integrity.

The hardware qualification testing of a digital power product will be very similar to that of a conventional analog product, but with additional emphasis on those elements that can affect the reliability of the stored data. The IC supplier is of course required to conduct and document extensive qualification testing at the chip level. These tests will include Write Endurance and Data Retention.

Ericsson will also test the data retention and integrity of the memory by comparing the memory content via checksum both before and after the standard hardware environmental tests such as 1000 hr 85°C/85% RH and Life Testing. Extended EMS environmental tests will be defined to insure long-term reliability in a variety of intended application environments.

4.4 MANUFACTURING

The purpose of the quality focus during the manufacturing process is to eliminate all quality risks in every manufacturing step to ensure that customers receive products on time and within specification. "Making it right the first time" will save time and money for both Ericsson and customers in the long run. The changes to the manufacturing process to enable production of digital power products are actually rather minor. Changes relate to the software control component in terms of dealing with the software and memory verification. Software customization also means that now the same physical hardware can represent multiple part numbers. This customization will be done during the manufacturing electrical test process when the application software is loaded into the power supply memory.

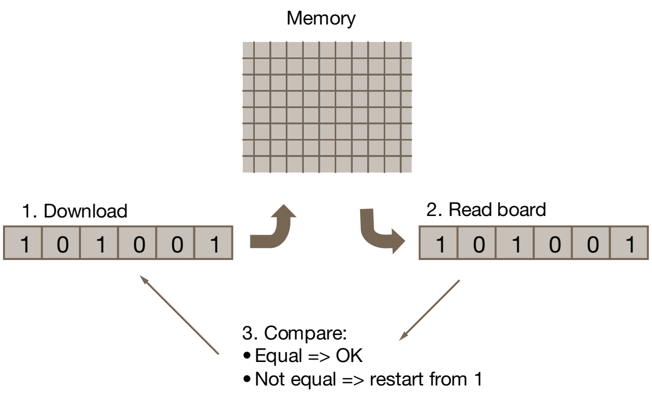


Figure 4 - Memory verification

To facilitate loading and verifying the software, the Automated Test Equipment (ATE) will be modified to include a standardized communication interface.

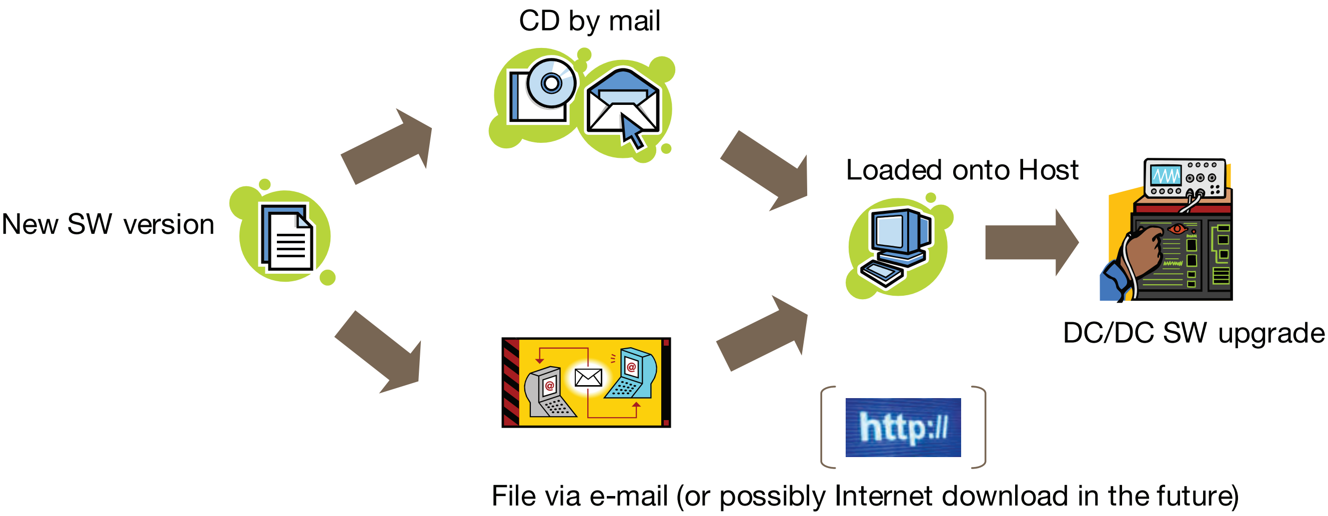
An integrated intelligent logistics system will be used during the manufacturing test process to insure that the correct application software is loaded into the power supply depending upon its intended purpose and functionality. The ATE will, by means of the communications interface, then conduct a memory check to verify that the software loaded into the power supply is the same as the memory content of the power supply. This is done via a bit-by-bit comparison of the input data and stored data read from the power supply memory as shown in *Figure 4*.

4.5 SOFTWARE UPGRADES

Our focus on Quality includes the period after the product is shipped. Software performance and functionality enhancements could occur after the product is in the customer's equipment. These changes could be driven by improvements developed at Ericsson or they could be the result of specific customer requests due to a change in the system requirements for their particular application. It is important to have a reliable system in place for managing this software change and upgrade activity.

Software upgrades can be distributed to the end user by multiple methods, as shown in *Figure 5*. A CD containing the new software can be sent via mail. A quicker option is to send the software as an Email attachment. Another possibility which may be explored in the future is the ability to have download files available on the Ericsson Power Module website. Regardless of the distribution method used, the new software version is first loaded into the customer's host computer. This computer, which could be part of a development system or the control computer in the system application, can then provide the update to the affected digital power supply via the standardized communication bus.

Figure 5 – Software upgrade process



4.6 CUSTOMER SUPPORT

The extensive Quality Assurance efforts within Ericsson that are described in this paper will guarantee product quality in the field environment. In case of a quality problem in the end-user product it may be related to a failure in the power supply hardware, or it could be created because of some anomaly in the end-user's product or system. In either case, it is important to have processes in place to make the proper determination accurately, quickly and with the minimum amount of disruption to the customer. All customer inquiries and concerns should be handled in a professional manner and resolved with a closed feedback loop so that corrective action is effectively communicated to the customer.

The method used by Ericsson for this process is the Return Material Authorization (RMA). It turns out that digital power actually will offer some advantages for this process relative to a conventional analog power supply because of the digital supply's ability to capture operational information within the customer's system and store it in memory. Analysis of the memory content of the power supply should be quite helpful in locating the cause of the problem. This can be accomplished quickly because of the ability to transmit this data electronically in real time rather than waiting for shipment of a power supply back to Ericsson. Furthermore, root-cause analysis and fixes for corrective action can also often be done while the power supply is still installed in the customer's application system, providing for very rapid response and resolution.

5. CONCLUSIONS AND SUMMARY

Ericsson's initial efforts at establishing Quality Assurance processes that address the new challenges that are a part of digital power have been described. There are indeed challenges, but the approaches outlined in this paper help to guarantee reliable digital power products. The following observations and conclusions can be made:

- DIGITAL POWER HAS MANY BENEFITS, AND WILL BECOME A MAJOR TREND FOR TELECOM AND DATACOM SYSTEMS.
- CONVERSION FROM ANALOG TO DIGITAL CONTROL IN A POWER SUPPLY RESULTS IN NEW DEMANDS FOR THE VERIFICATION AND QUALIFICATION PROCESSES.
- THE QUALITY ASSURANCE OF THE CRITICAL µC AND ITS SOURCING WILL BE VERY IMPORTANT.
- VERIFICATION OF THE INTERNAL MEMORY OPERATION AND RELIABILITY WILL BE CRITICAL.
- SOFTWARE IS A COMPONENT OF THE POWER SUPPLY AND WILL NEED TO BE MANAGED DURING THE SUPPLY CHAIN AND PRODUCT LIFE CYCLES.
- BOTH DVT AND PRODUCTION TESTING WILL BE MORE COMPLEX DUE TO INCREASED PRODUCT CONFIGURABILITY.
- A SYSTEM FOR MANAGED SOFTWARE UPGRADES IS POSSIBLE.
- RMA ACTIVITY WILL ACTUALLY BE ENHANCED DUE TO THE ABILITY OF DIGITAL POWER SUPPLIES TO CAPTURE DATA IN THE APPLICATION ENVIRONMENT AND COMMUNICATE WITH ERICSSON IN REAL TIME.

Being proactive in facing these Quality Assurance challenges is in the best interests of the customers, and maintaining an open dialog is the best way to proceed. Ericsson will continue to document and publish progress in this exciting new endeavor, and invite customers to share their experiences and ideas so that the benefits of digital power can be maximized in the transition from an analog to a digital environment.

6. GLOSSARY

ATE	Automated Test Equipment
DVT	Design Verification Test
EMS	Electromagnetic Susceptibility
HW	Hardware
IC	Integrated Circuit
MCU	Micro Controller Unit
PMBus™	Power Management Bus
PWM	Pulse Width Modulation
RMA	Return Material Authorization
SW	Software
µC	Micro Controller

7. REFERENCES

More information on related topics and some additional in-depth descriptions of the technology that this paper addresses can be found in the papers listed below.

[1] Performance Improvements for OEM System Designers – A Digital Control Case Study, DPF '07, Dallas USA, Sept 2007

[2] Implications of Digital Control and Management for a High-Performance Isolated DC/DC Converter – A Case Study, APEC '07, USA, Feb 2007

[3] Digital Control Techniques Enabling Power Density Improvements and Power Management Capabilities, PCIM China, Mar 2007

[4] Digital Power Technical Brief, Ericsson Power Modules, November 2006

[5] Quality Assurance – Overview Statement, Ericsson Power Modules

[6] Quality Assurance – Product Development, Ericsson Power Modules

[7] Quality Assurance – Supply Chain, Ericsson Power Modules

[8] Quality Assurance – Supporting Acitvities, Ericsson Power Modules

All referenced papers and data sheets can be found at Ericsson Power Modules' web site: http://www.ericsson.com/powermodules

EAB-08:001018 Uen Rev B 2010-06-23

ERICSSON

PERFORMANCE, COST AND RELIABILITY CONSIDERATIONS IN A MICROTCA POWER SYSTEM

A tutorial for designers considering their first use of products based on the MicroTCA standard, and for the experienced designer looking for detailed information regarding optimal solutions for the power module design.

CONTENTS

1. INTRODUCTION

Micro Telecommunications Computing Architecture (MicroTCATM) is a relatively new architectural specification for Information and Communications Technology (ICT) equipment, and is a complement to the Advanced Telecommunications Computing Architecture (AdvancedTCATM) specification, but with a different intended product market. After a brief summary of the history of these architectures and a comparison of the two, this paper will address the MicroTCA power system in more detail, with an emphasis on the MicroTCA power module. It will be shown that design considerations within the MicroTCA power module can have a significant effect on the performance, cost and reliability of the resulting MicroTCA system. These design details can be important to the OEM, because while the MicroTCA specification defines several mandatory requirements in terms of functionality, interfaces and thermal/mechanical design of the MicroTCA power module, it also allows for internal design flexibility for the MicroTCA power module supplier. The design choices made by the supplier or requested by the customer will affect the overall system performance.

This paper may serve as a general tutorial to Micro-TCA power systems for those who are knowledgeable about contemporary power system design but are considering their first designs to the MicroTCA specification. It should also be useful for those who are already conversant with MicroTCA but are looking for more information on the details of the power system implementation and choices in the power module design. In either instance, the reader must consult the latest version of the actual MicroTCA specification for the latest requirements before finalizing a system design choice. While the information contained in this paper represents our considered opinion, there may be new developments over time that allow alternative approaches to become more viable.

2. HISTORICAL PERSPECTIVE

MicroTCA, which was ratified by the PCI Industrial Computer Manufacters Group (PICMG™) in July 2006, is the latest generation of open-architecture platforms developed by the PICMG for ICT equipment. It builds upon the heritage of previous architectures and technology, namely AdvancedTCA and AdvancedMC, maintaining much of the same functionality but with different system partitioning and with optimization for applications with lower power levels such as Customer Premises Equipment (CPE), and Edge and Access equipment. The AdvancedTCA specification has been in existence since 2002. AdvancedTCA carrier-boards are large planar structures operating from -48 V and containing both power control/ conversion circuitry and some of the load electronics. Additional load electronics may be packaged in Advanced Mezzanine Card (AdvancedMC™) modules which are mounted to the carrier-boards. An AdvancedTCA system rack contains several of these carrier-boards. Up to 14 carrier-boards may be installed in a 13U high 19 inch shelf, while up to 16 carrier-boards may be used in an European Telecommunications Standards Institute (ETSI) 600 mm enclosure.

With MicroTCA, all load electronics are packaged on AdvancedMC modules. These mezzanine modules are identical to those used with AdvancedTCA systems, leveraging development costs between the two architectures, providing a migration path and providing economies of scale for the production of AdvancedMCs. Time-to-market and spares inventory costs are also reduced due to a smaller number of required unique module types. A key feature of the MicroTCA system is the power module, which contains the majority of the power conversion and control circuitry and eliminates the need for the large planar carrier-boards of the AdvancedTCA systems. MicroTCA systems may also be packaged in 19 inch racks, with a 6U height considered a large system. Smaller enclosures are also possible.

Figure 1 contains photographs of the two types of systems. The AdvancedMC module is a common element between them, plugging into the backplane of the MicroTCA rack and onto the carrier-board which is then plugged into the AdvancedTCA equipment rack. While our emphasis will be on the MicroTCA, a description of both architectures is given in the following section so that commonalities and differences can be better understood.

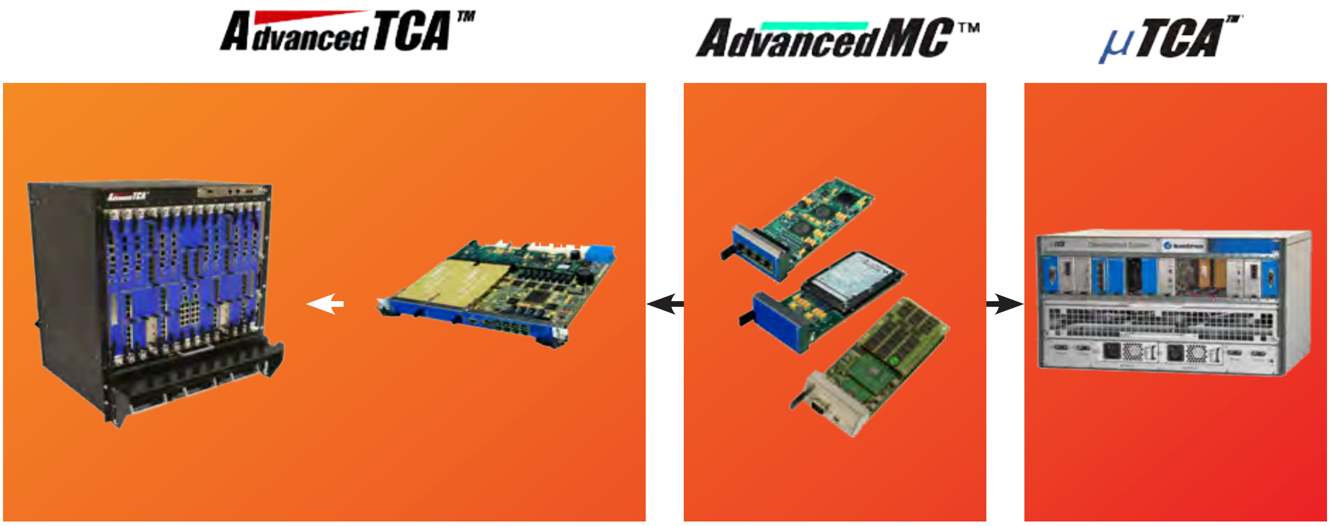


Figure 1 – AdvancedMC modules make use in both AdvnacedTCA and MicroTCA systems

3. ARCHITECTURAL OVERVIEW

The information below is intended to provide a basic overview of the architecture and power partitioning of AdvancedTCA and MicroTCA systems. The actual system specifications should be consulted for the latest detailed information.

3.1 AdvancedTCA

Figure 2 shows a typical power architecture for an AdvancedTCA system. Some power conditioning takes place prior to the individual carrier-boards. AC/DC conversion and battery backup is usually accomplished in a redundant fashion at a centralized location. The resulting -48 V DC power is then distributed to individual AdvancedTCA shelves. At the shelf level, a Power Entry Module is used to provide filtering and transient suppression. Then the individual redundant -48 V feeds are connected to the shelf backplane, which acts as an interface between the shelf level power conditioning and the power circuitry contained on each carrier-board.

Each carrier board provides fusing, O-Ring diodes, inrush current limiting, filtering, hold-up capacitance and input voltage monitO-Ring for the -48 V input power. The result is a reliable and robust source of input power for the rest of the carrier-board power system. The reader may recognize the remainder of the on-board power system as an example of an intermediate bus architecture (IBA). The main isolated DC/DC converter is normally selected to have an output of 12 V, since there are readily available Intermediate Bus Converter (IBC) modules marketed for this application and the AdvancedMC modules require 12 V as their main input voltage. The AdvancedTCA specification limits the total power consumption to a maximum of 200 W per carrier-board.

The load circuitry power is referred to as "payload" power in the AdvancedTCA specification. A carrier-board may contain payload circuitry mounted directly to its printed circuit board (PCB), in which case one or more Point of Load (POL) regulators are used to convert the 12 V intermediate bus to the voltages required by the payload circuitry. Another option is to mount one or more AdvancedMC modules on the carrier-board. These modules, by definition, will require 12 V as their payload power voltage. Any required POL regulation will be accomplished within the AdvancedMC module.

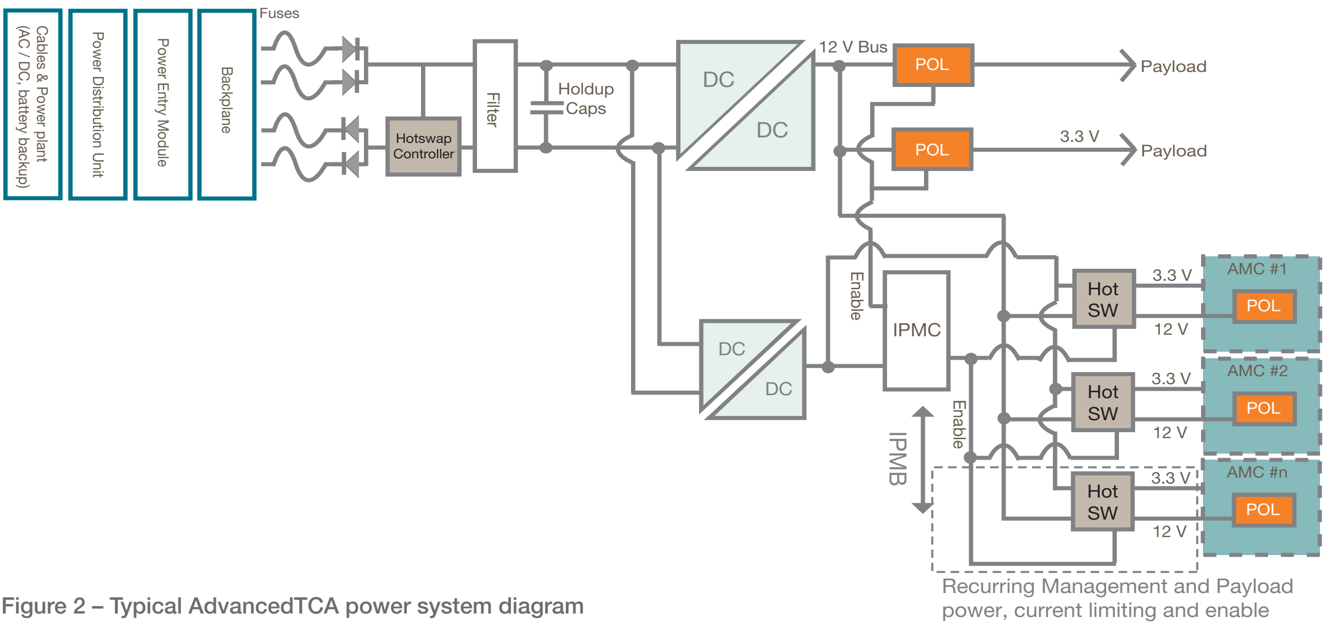


Figure 2 – Typical AdvancedTCA power system diagram

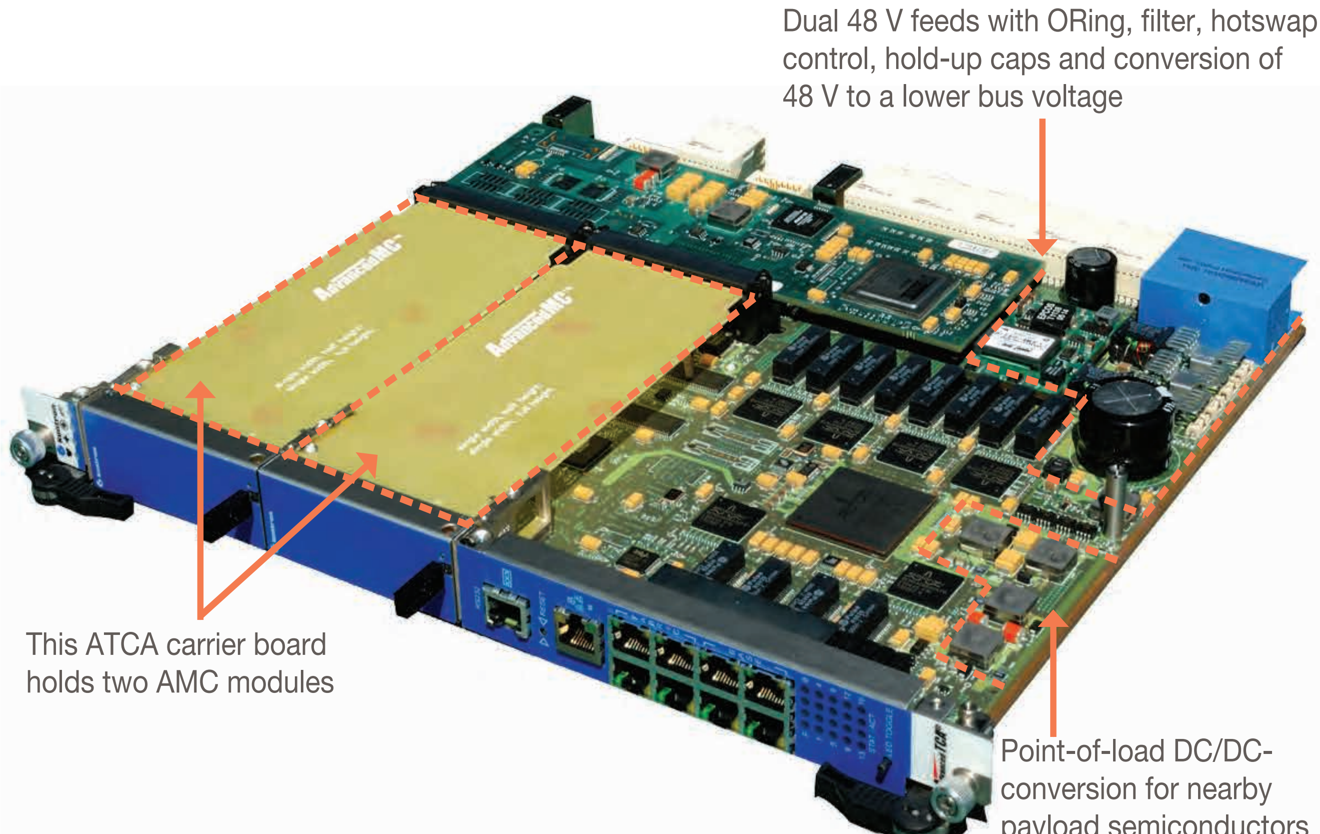


Figure 3 – AdvancedTCA carrier-board with AdvancedMC modules

Another function that must be provided on each carrier-board is power control, and each carrier-board will contain an Intelligent Platform Management Controller (IPMC) for this purpose. The specification requires that the control circuitry be active and in communication with shelf-level management to negotiate power-up rights before a maximum of 10 W of power is used by the carrier-board. This requirement could for example be accomplished by providing a separate 3.3 V isolated DC/DC converter on each carrier-board that is dedicated to powering the control circuitry, both the IPMC on the carrier-board and also the management power to each AdvancedMC that may be used. By this method, individual AdvancedMC modules can receive management power without the IPMC having powered up the full payload circuitry of the carrier-board. In addition, the carrier-board power control must provide the functions of voltage monitO-Ring, current limiting, power sequencing and hotswap control for each AdvancedMC location on the board.

Thus each carrier-board requires a high degree of power conditioning and control functionality, both for input power and for payload power located on either the carrier-board or on AdvancedMC modules. This high degree of functionality can result in a carrier-board assembly like the example shown in *Figure 3*. The carrier-board is a planar structure that is 280 mm deep and 322 mm high. In the example shown, the board contains DC/DC conversion from -48 V down to an intermediate bus voltage that provides payload power to two AdvancedMC slots. The bus voltage is also used to feed down-stream POL regulators for on-board payload circuitry.

3.2 MicroTCA

MicroTCA is intended to be a complement to AdvancedTCA rather than a replacement for it. The MicroTCA architecture offers several advantages for its intended markets. The smaller form factor and lower hardware cost makes it attractive for applications that require less processing power within an enclosure, for example, for edge, access and customer premises equipment. While smaller and more cost effective, the reliability and availability requirements for MicroTCA systems are typically just as stringent as those for equipment implemented with AdvancedTCA. The same basic functionality in terms of power conditioning and control is also required. One of the main differences between the two architectures is the degree of centralization and the physical partitioning of the power systems.

With AdvancedTCA, all power conversion functions are replicated on every carrier-board. There is also the flexibility to locate payload circuitry either on AdvancedMC modules, on the carrier-board PCB, or both. The MicroTCA approach simplifies this partitioning by requiring all payload circuitry to reside in AdvancedMC modules and by centralizing all the main power conversion/control functions for a sub-rack into one or more MicroTCA power modules. The overall architecture of a MicroTCA system is shown in *Figure 4*. A complete MicroTCA system is defined in the specification as follows:

"A MINIMUM MICROTCA SYSTEM IS DEFINED AS A COLLECTION OF INTERCONNECTED ELEMENTS CONSISTING OF AT LEAST ONE ADVANCEDMC, AT LEAST ONE MICROTCA CARRIER HUB (MCH), AND THE INTERCONNECT, POWER, COOLING AND MECHANICAL RESOURCES NEEDED TO SUPPORT THEM."

The system as shown in the figure supports up to a maximum of 12 AdvancedMC modules which contain the payload circuitry, and each of these AdvancedMCs is specified to require from 20 to 80 watts of payload power. Again quoting from the MicroTCA specification, "They provide the functional elements needed to implement useful system functions. Examples of AdvancedMCs that could be installed into a MicroTCA shelf include CPUs, Digital Signal Processing devices, packet processors, storage, and various sorts of I/O AdvancedMCs (including metallic and optical line units, RF devices, and interfaces to other boxes)."

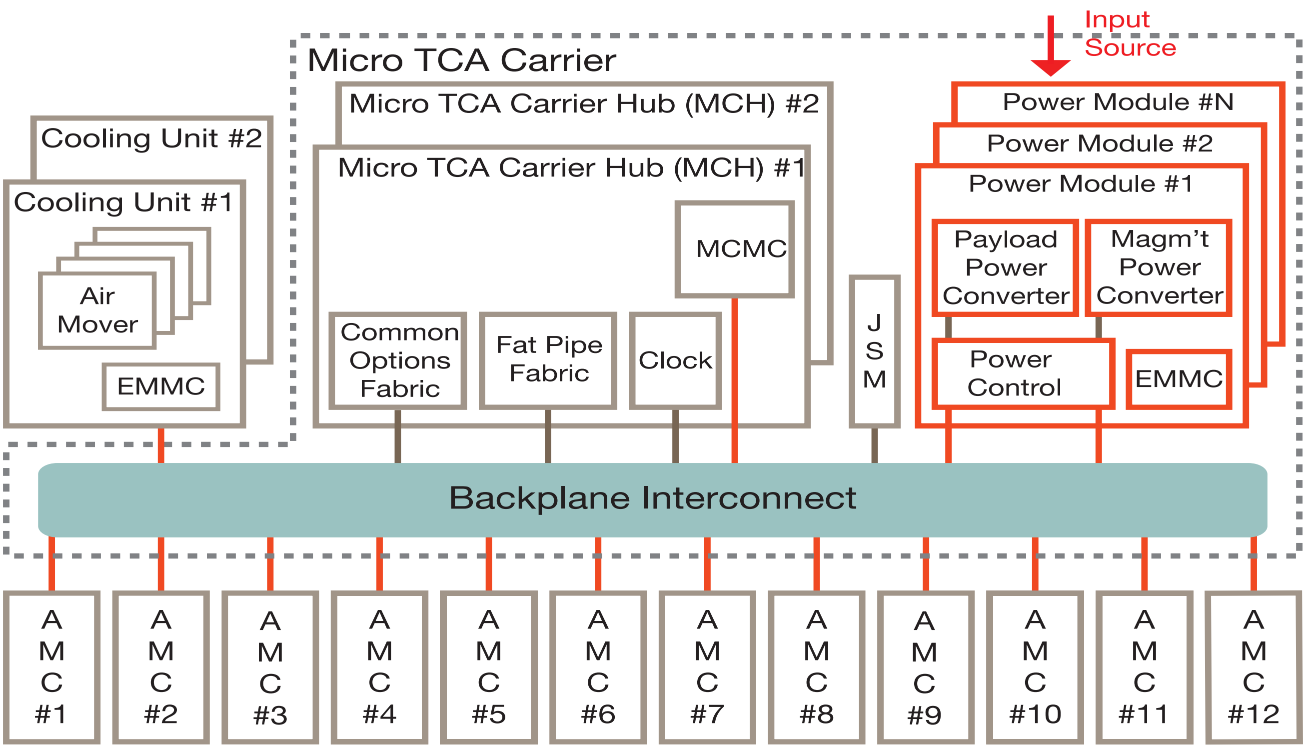


Figure 4 – MicroTCA overview with parts of the power system highlighted

The MCH function provides overall control for the interconnected AdvancedMCs. A second redundant MCH is often added for systems with high availability requirements. Similarly, a second redundant cooling system is sometimes used. The backplane is used as an interconnection mechanism for all of these elements. The power module is a very key element in the overall MicroTCA system. It serves as a centralized power conditioning, conversion and control block for the entire sub-rack. Anywhere from one to four power modules may be used in a single Micro-TCA system with more than one being used either because of the power demand or because of a desire for redundancy.

The MicroTCA specification provides a very clear description of the power module purpose and functionality:

"The MicroTCA power module(s) take the input supply and convert it to 12 V to provide payload power to each AdvancedMC. 3.3 V management power for AdvancedMCs is also supplied by the power subsystem. The power control logic on the power module performs sequencing, protection, and isolation functions. The Power Subsystem is controlled by the Carrier Manager which performs power budgeting to ensure adequate power is available prior to enabling Power Channels."

"POWER MODULES ALSO INCLUDE THE SUPERVISORY FUNCTIONS NECESSARY TO MANAGE THE POWER SUBSYSTEM. THEY HAVE CIRCUITRY TO DETECT THE PRESENCE OF ADVANCEDMCS, MCHS, AND COOLING UNITS (CU), AND TO ENERGIZE INDIVIDUAL POWER BRANCHES. POWER MODULES ALSO MONITOR THE POWER QUALITY OF EACH BRANCH AND PROTECT AGAINST OVERLOAD. IF A REDUNDANT POWER MODULE IS CONFIGURED, IT MAY AUTOMATICALLY TAKE OVER THE POWER CHANNEL RESPONSIBILITIES OF A FAILED PRIMARY POWER MODULE."

Figure 5 – MicroTCA sub-rack holding AdvancedMCs and power modules

In addition to supplying payload and management power to up to 12 AdvancedMC modules, the power modules must be capable of supplying payload and management power to up to two CUs and two MCHs. As a consequence, many power modules are designed to provide a total of 16 output power channels, or 32 channels if payload and management power are counted separately.

This is obviously a lot of functionality to include into one assembly, and as a consequence the power module is one of the most important elements of the overall MicroTCA system. It includes more power and control functionality than is required of the power elements on an AdvancedTCA carrier-board but is contained in a smaller package. Obviously the design of the power module will have a large impact on the overall system efficiency and reliability.

The power module will be the focus of the remainder of this paper. First the overall functionality and partitioning will be described and then some of the important design details will be discussed. *Figure 5* shows how power modules can be packaged in a MicroTCA sub-rack. The system shown uses two power modules and they are located at the extreme right and left ends of the upper row of plugged modules. DC input power is plugged to the connectors on the front panel of the power modules, while 12 V and 3.3 V payload and management power is connected to the MicroTCA backplane at the rear of the power modules.

4. MICROTCA POWER MODULE OVERVIEW

MicroTCA places a significant amount of functional content into the power module, including:

- INPUT POWER O-RING
- HOTSWAP CONTROL FOR INPUT POWER INRUSH PROTECTION
- INPUT POWER FILTERING
- POWER HOLD-UP CAPACITANCE
- 48 V TO 12 V DC/DC CONVERSION (PAYLOAD POWER)
- INPUT TO OUTPUT ISOLATION
- 12 V TO 3.3 V CONVERSION (MANAGEMENT POWER)
- OUTPUT POWER DISTRIBUTION
- HOTSWAP CONTROL FOR MULTIPLE ADVANCED MCS, CUS, MCHS
- OUTPUT POWER MONITO-RING AND CONTROL
- OUTPUT POWER PROTECTION CIRCUITRY

The consolidation of both power handling circuitry and system level control/management functionality from the large AdvancedTCA carrier-board into the relatively small MicroTCA power module means that the power module design, performance and reliability are all crucial to the success of the overall system. *Figure 6* is a block diagram showing the content of a typical MicroTCA power module. Most of the functionality is similar to that of an AdvancedTCA carrier-board power system, but there are differences.

With AdvancedTCA, there is a Power Entry Module (PEM) which provides some input power conditioning and protection in the form of transient protection and filtering before the power is distributed to the carrier-board. With MicroTCA, there is no PEM, so “raw” DC input power is supplied directly to the input connectors on the front of the power module. This means that the functionality of the PEM must be included in each power module. AdvancedTCA carrier-boards contain fuses on the -48 V inputs. In the case of MicroTCA, fusing is typically done in a power distribution unit by providing fuses for each of the cables that distribute input power to the front of the power modules. Consequently, no internal fuses are normally contained within a power module. Otherwise, the front-end functions are very similar to AdvancedTCA – O-Ring diodes, EMI filtering, inrush current limiting and hold-up capacitance. While AdvancedTCA is specified to always contain dual redundant -48 V input power feeds, MicroTCA may be configured with either a single feed or with two redundant feeds.

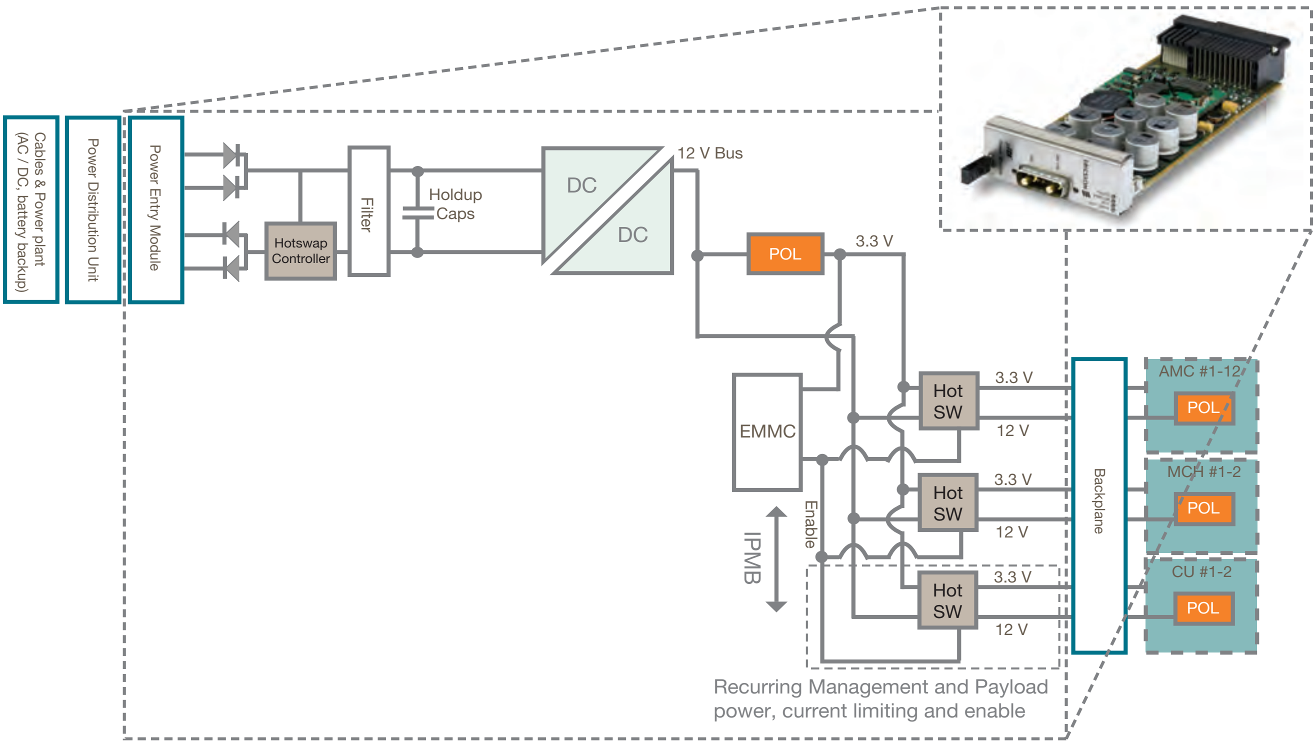


Figure 6 – Typical MicroTCA power module block-diagram

The power module contains a single -48 V to 12 V isolated DC/DC converter, similar to the approach taken with AdvancedTCA, but with power levels up to 600 W. A POL regulator from the 12 V output is used for generation of management power. Additional POLs, within the AdvancedMC modules are used to derive their needed low voltage power from the 12 V payload power. The control mechanism for MicroTCA power modules is the Enhanced Module Management Controller (EMMC), which monitors and controls both management and payload power for all of the AdvancedMCs, CUs and MCHs configured in the system.

A closer view of an actual MicroTCA power module is shown in *Figure 7*. This particular power module is configured in a single-width full-height form factor with approximate external dimensions of 73.5 by 186.6 by 28.9 mm. It is capable of supplying and controlling power to 12 AdvancedMCs, 2 CUs and 2 MCHs, for a total of 32 output voltage channels.

The repartitioning of the distributed power conversion functions from several AdvancedTCA carrier-boards into a relatively few (one to four) centralized MicroTCA power modules results in a higher power conversion density, with some power modules delivering up to 600 W. As a result, high efficiency design is extremely important both for packaging purposes and also to achieve the reliability requirements for these systems. Input power inrush, EMI control, and hold-up design are also more difficult in the MicroTCA environment since it must be done to the same standards but at a maximum power level of 600 W rather than the 200 W seen on an AdvancedTCA carrier-board. The control and management demands are also challenging, with the need to interface with up to 32 output voltage channels as well as with the shelf-level MCHs.

The above demands make the design and selection of the MicroTCA power module a critical element in the success of the overall system. In the following section we will explore in more detail some aspects of the power module design that can help insure successful system designs. While MicroTCA systems may be configured with other input voltage sources such as 24 VDC or universal AC, the following discussion will be limited to the most commonly used telecom -48 VDC input voltage.

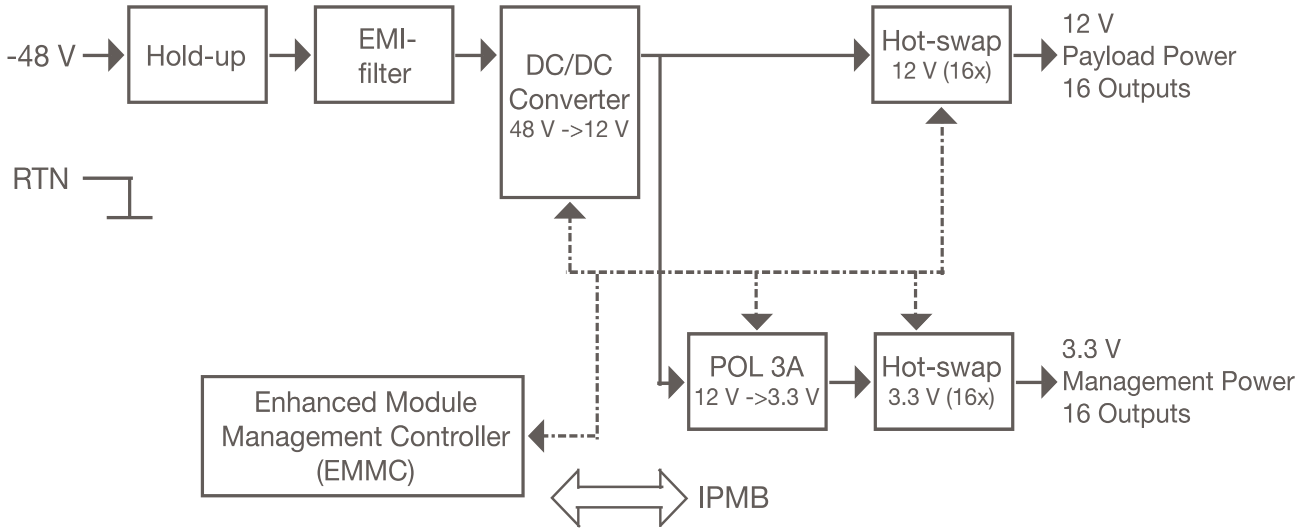


Figure 7 – Example of MicroTCA power module

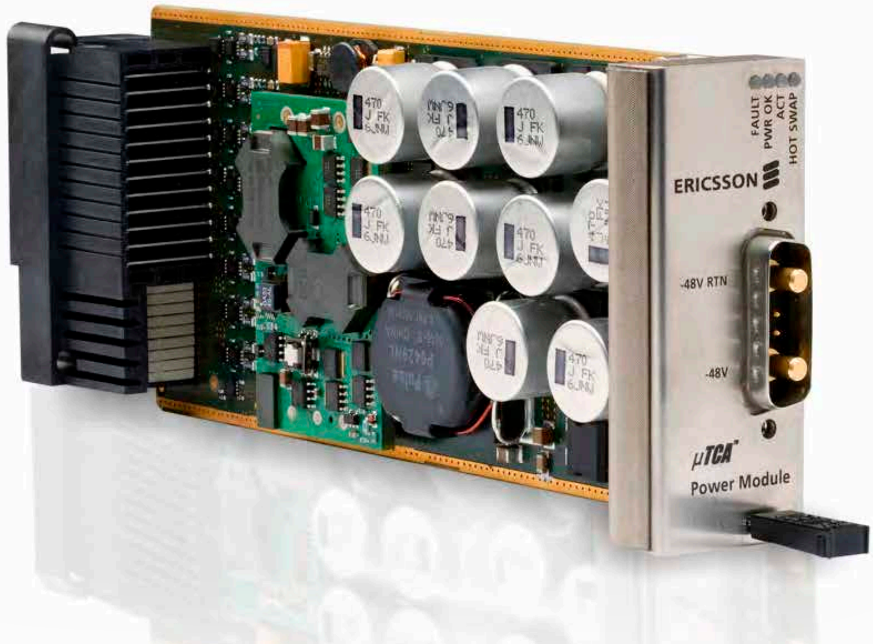


Figure 8 – Ericsson MicroTCA power module ROA 117 5078/1

5. MICROTCA POWER MODULE DESIGN CONSIDERATIONS

The MicroTCA specification actually contains three levels of designation, which in everyday language can be called “shall”, “should” and “may”. That is, it defines a level of absolute requirements and then two additional levels that are intended as recommendations and guidelines but which allow for some flexibility as to the implementation of MicroTCA component assemblies and systems so that they are best suited for the actual application. This flexibility is an advantage to the system designer who must balance performance, reliability and cost and in most cases must make some sort of trade-off between these attributes. The specification and design of MicroTCA power modules represents an example of this flexibility in that their parameters may vary and still meet the provisions of the MicroTCA specification. Ericsson has undertaken a detailed study of some of these parameters in order to determine how the selected performance level affects other attributes of the power module, including cost. This information is essential for the OEM system designers when specifying and selecting MicroTCA power modules. The design considerations to be discussed in this paper are hold-up capacitance, input voltage, redundancy and dual input feeds.

The baseline hardware used for this study is an Ericsson MicroTCA power module with an output power rating of 355 W as shown in *Figure 8*. The basic specifications for this unit, with its standard implementation, are as follows:

OUTPUT POWER	355 W
INPUT POWER	385 W
OUTPUT VOLTAGE CHANNELS	16 X 12 V & 16 X 3.3 V
EFFICIENCY AT 50% LOAD	95%
NORMAL INPUT VOLTAGE (FULL PERFORMANCE)	-40.5 V TO -57 V
HOLD-UP (54 V IN)	10 MS
CONDUCTED EMISSIONS	CLASS B
PACKAGE FORM FACTOR	SINGLE-WIDTH FULL-HEIGHT (6HP)

The term “cost unit” will be used to define cost. This unit is normalized based on the Q2-2007 cost estimate for the prototype power module, which is assigned a value of 400 cost units for the entire bill of material. If a design change results in a savings of 20 cost units, this would represent a 5% reduction in the total bill of material cost. Thus the cost conclusions stated in this paper, although represented in relative terms, should provide some guidance for the system designer when making power module specification trade-off decisions.

5.1 HOLD-UP CAPACITANCE

Inside a typical MicroTCA power module there is a number of fairly large electrolytic capacitors. The presence of most of this capacitance is due to one of the recommendations in the MicroTCA specification which addresses operating through an input power interruption that is caused by, for example, a short circuit fault on the input voltage bus.

The specification defines this outage under a worst-case scenario as a reduction in input voltage to a level of 5 V for a duration of 10 ms, and the power module is expected to operate without interruption through this fault condition. Power module designers normally accomplish this by including several “hold-up” capacitors on the -48 V input after the O-Ring diodes. The power module operates from the stored energy in these capacitors for up to 10 ms until the normal input voltage is restored.

The derivation of this recommendation can be better understood by referring to *Figure 9*, which represents a fairly typical MicroTCA system.

The system shown consists of one cabinet with two shelves. Each shelf contains one power module, which receives its -48 V power feed from a Power Distribution Unit (PDU) via a separate power cable. Assume that a short circuit occurs on the -48 V feed to shelf 1 as shown in the diagram.

Each cable is individually protected in the PDU, so the fuse or circuit breaker will open and isolate the fault condition from the remainder of the system. But the fault clearing is not instantaneous – there will be some time period before the fuse opens during which the fault current will pull the -48 V for the entire cabinet to a voltage below the operating voltage specification. Consequently, the power module in shelf 2 must operate through an interruption in its input voltage.

The hold-up time of 10 ms at a voltage of 5 V is recommended in the MicroTCA specification to represent the worst-case condition in terms of the fault clearing time and the robustness (voltage drop) of the -48 V power distribution system.

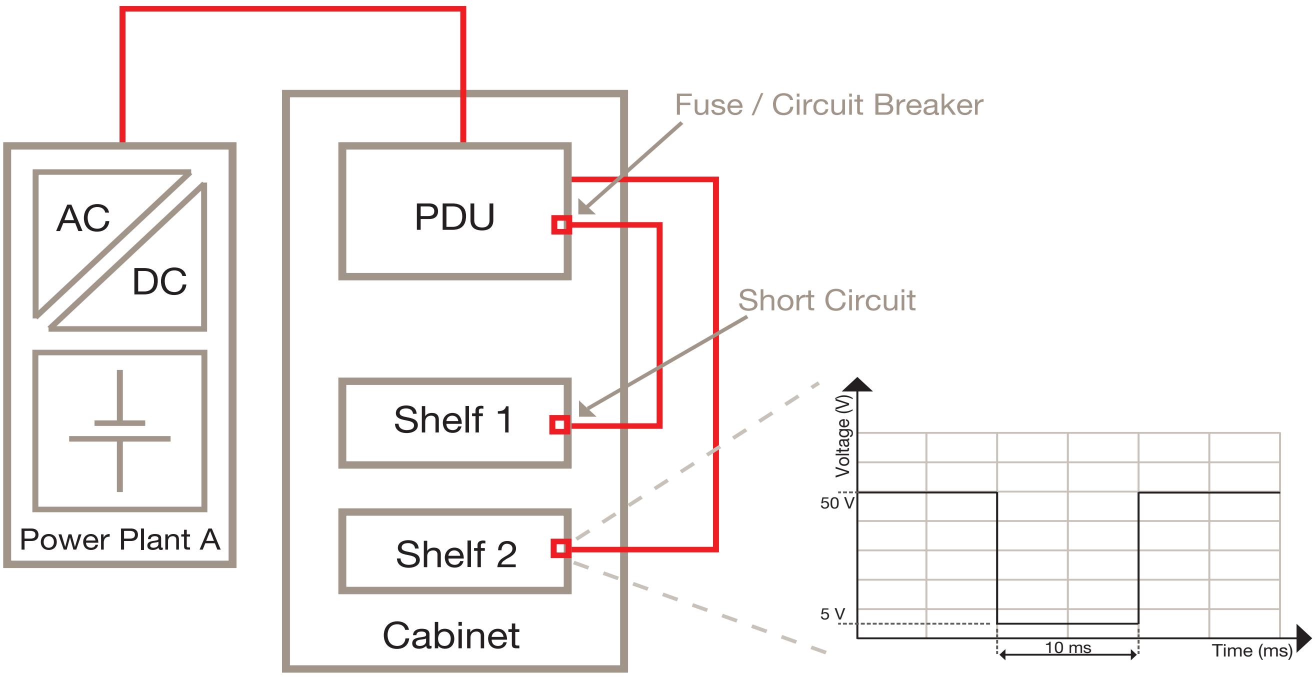


Figure 9 – Short circuit event resulting in voltage drop in power feed

The above specification is certainly a safe one and will result in a reliable system. But there are circumstances in which the same system reliability and performance can be obtained with less hold-up time and consequently less capacitance. Some examples are:

- IF THE CABINET IN THE APPLICATION ONLY CONTAINS ONE SHELF AND ONE POWER MODULE, THE FAULT CONDITION PRESENTED ABOVE IS NOT A VALID SCENARIO, SINCE THE ONLY POWER MODULE WOULD BE INOPERATIVE AFTER THE FUSE OPENS ANYHOW. IN THIS SITUATION, NO HOLD-UP CAPACITANCE AT ALL COULD BE AN ACCEPTABLE DESIGN.
- THE SYSTEM DESIGNER SHOULD UNDERSTAND THE FAULT CLEARING BEHAVIOR OF THE DEVICES IN THE PDU. THERE ARE FUSES AND CIRCUIT BREAKERS AVAILABLE THAT WILL OPEN IN LESS THAN 10 MS. IF, FOR EXAMPLE, THE DESIGN GUARANTEES FAULT CLEARING IN 5 MS, THE REQUIRED AMOUNT OF STORED ENERGY AND THE NUMBER OF HOLD-UP CAPACITORS COULD BE CUT IN HALF.
- THE SPECIFICATION ASSUMES THAT THE POWER MODULE IS OPERATING AT FULL RATED OUTPUT POWER DURING THE FAULT CONDITION. IN MOST PROPERLY DESIGNED SYSTEMS THIS IS NOT THE CASE, AS SOME DESIGN MARGIN IS ALLOWED FOR BY RUNNING THE POWER MODULES AT LESS THAN FULL LOAD. IF THE MAXIMUM ACTUAL LOAD IS LESS THAN THE RATED MAXIMUM LOAD, THEN THE AMOUNT OF HOLD-UP CAPACITANCE FOR A GIVEN HOLD-UP TIME WILL BE REDUCED ACCORDINGLY.
- SOME SYSTEM DESIGNERS USE WHAT IS REFERRED TO AS TWO-STEP HIGH OHMIC DISTRIBUTION (TS-HOD). WITH THIS TECHNIQUE, THE -48 V CABLING CONTAINS A PRE-DEFINED RESISTANCE. THIS WILL LIMIT THE FAULT CURRENT AND THE RESULTING VOLTAGE DROP WILL NOT GO BELOW -40.5 V, WHICH ENSURES THAT THE POWER MODULE STAYS WITHIN ITS NORMAL OPERATING RANGE.

These examples show situations in which the hold-up capacitance can be reduced without any degradation in system performance or reliability. Note, however, that they all depend upon the knowledge of the system designer about the actual application. Once this understanding is obtained, the system designer can work with the power module supplier to specify the appropriate hold-up time.

What are the cost impacts of the hold-up time specification? The power module used in the study is rated at 10 ms hold-up time at full load at an input voltage of -54 V, which is the nominal input voltage for a -48 V system with battery back-up. A short circuit fault during a static input voltage of less than that would represent a double fault condition which is not normally designed for. The hold-up capacitors in the subject power module are Nichicon 63 V LS series electrolytics. They consume 1100 mm2 of PCB area, which represents 10% of the total PCB. The cost of the hold-up capacitors is 2 cost units. Using fewer hold-up capacitors would only have a small effect on component cost but a very positive impact on PCB component area. The latter improvement could come to good use in other parts of the design.

Another design approach which is not pursued or quantified here would be the addition of a voltage boost circuit in the front end of the power module. Such a booster would charge the capacitors at a higher voltage such as -72 V. Then higher voltage capacitors would be used and a lower amount of capacitance would be required for a given hold-up time since the stored energy is proportional to the square of the capacitor charge voltage. Some of the savings would however be off-set since a given capacitor holds less capacitance when rated for a higher voltage. Plus, the design would also have to carry the extra circuitry for the booster.

5.2 INPUT VOLTAGE

Another parameter that needs to be specified by the system designer is the input operating voltage range. As a general rule, the narrower the voltage range, the more the power module design can be optimized in terms of performance, efficiency and cost. Most often, the input voltage is specified at the normal -48 V telecom range of -40.5 to -57 VDC, with a nominal value of -54 V. Some systems are required to also operate over the range of the less commonly used -60 V telecom power system, which can vary from -50 to -72 VDC. In this part of our study, we attempted to quantify the performance and cost impacts of extending the input voltage range to address both -48 V and -60 V systems versus designing for -48 V only.

The input and hold-up capacitors must of course be resized to operate at the higher input voltage by changing the capacitor voltage rating from 63 V to 80 V. Higher voltage capacitors have less volumetric efficiency in terms of capacitance per volume, so the higher voltage capacitors will require additional volume and PCB area within the power module. It is true that when operating from the -60 V system less total capacitance would be required for hold-up due to the larger amount of energy stored in a given capacitance. But since the analysis considers both -60 V and -48 V power sources, the amount of capacitance must be predicated on the worst case scenario (i.e. the -48 V application). It is worth mentioning that that this calculation was based on 80 V capacitors, while ones rated for 100 V would most likely be needed for the sake of design margin. That would make the higher input range even less favorable.

HOLD-UP CAPACITANCE		
OPERATING RANGE	40.5-57 VDC	40.5-72 VDC
NOMINAL INPUT	-54 VDC	
DURATION	10 MS	
OUTPUT POWER	355 W	
NICHICON LS-SERIES	63 V	80 V
PCB AREA	1100 MM²	1650 MM²
PCB AREA OF PM	10%	14%
COST	2 UNITS	2.5 UNITS

Figure 10 – Study results

The results of our study are shown in *Figure 10*. The data in the 40.5 – 57 VDC column represents the baseline design as presented in the previous section. When the capacitors are changed to 80 V rated devices to accommodate the -60 V system requirements, both the PCB area and the cost increase as shown in the rightmost column. An additional 550 mm2 of PCB area are required and the cost of the power module increases by approximately 0.5 cost units. If a voltage booster topology as described in the previous section were used, this analysis would not apply.

The effect of the maximum input voltage on the power module efficiency was also studied. Specifically, we examined the efficiency differences that could be measured in the main 48 V to 12 V DC/DC converter. As a general rule, a lower input voltage means that the primary switch transistors can have a lower voltage rating, which should imply a lower on resistance and less power losses. A PKM 4304B PI isolated DC/DC converter was used for this study. This design uses 100 V primary power transistors, suitable for both -48 V and -60 V power systems. As an experiment the 100 V devices were replaced with 60 V devices from the same supplier and product line. These 60 V transistors will only support operation with -48 V systems. There is a 2.5 milliohm reduction in on-resistance with the 60 V devices which should theoretically result in a 0.3 W reduction in power losses at maximum load. The results are shown in *Figure 11*.

Primary side transistors		
Unit 1	HAT 2173	100 V
Unit 2	HAT 2266	60 V

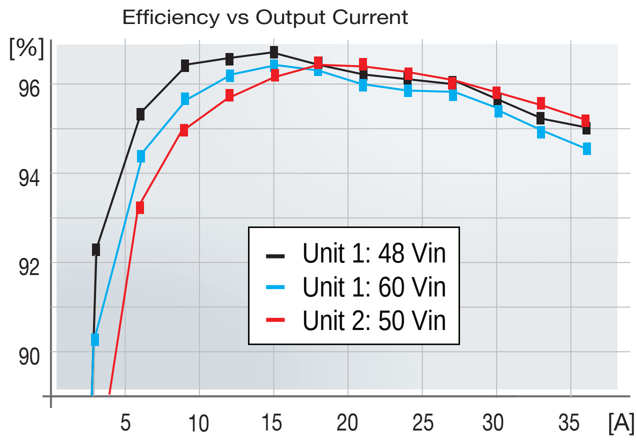


Figure 11 – PKM4304B PI and Efficiency dependent of input voltage

There was indeed a reduction in power losses at full load with the 60 V devices, but it was relatively small. However when operated at less than 50% load, the efficiency was actually less when using the 60 V transistors. The change in the shape of the efficiency curve is probably due to the voltage levels at which the lower rated transistors turn on and off rather than the actual DC resistance. The baseline design has been optimized for 100 V transistors. Expending significant additional engineering time with the 60 V devices might change the outcome shown. Nonetheless, for now we cannot conclude that the broader input voltage range required to address both -48 V and -60 V systems has any significant penalty on operating efficiency for this particular device.

5.3 REDUNDANCY

The MicroTCA specification includes provision for redundant power modules to increase system availability in critical applications. When needed, this capability can function quite well and achieve the system availability goals. It is important to understand, however, that power modules designed for redundant operation are inherently more complex and costly than power modules intended for stand-alone operation. The basic power module redundancy approach used with MicroTCA payload and management power channels will first be described for the benefit of those who may not be familiar with it. Then two aspects of the power module design that are affected by the redundancy decision, payload power channel control and DC/DC converter performance will be discussed.

The intent is to inform the OEM designer about the size, efficiency and cost impacts of redundancy to the power module design so that the redundancy approach is used when it is actually needed and the benefits of a non-redundant power module may be enjoyed in systems with lower availability requirements.

An example of a 2+1 redundant MicroTCA power module implementation is shown in *Figure 12*. In this system, two power modules are used to supply both payload and management power to a total of 16 output channels. A third power module is normally in a stand-by state and is available to provide power to any of the 16 channels (32 voltage outputs) in the event of a fault in either of the two main power modules. The MicroTCA specification contains very specific requirements for the implementation of power module redundancy. Techniques such as power paralleling and current sharing are not intended to be used, and only one power module may deliver current to any load channel at any given time. This restriction can be seen in the system shown in the figure. Power module 1 supplies the normal power to only channels 1 through 8, while power module 2 does the same for channels 9 through 16. The redundant power module 3 can supply power to any of the 16 output channels, but only in case of failure in one of the primary power modules or if one of the two has been disabled. This architectural restriction was established so that the maximum overcurrent possible to any channel is limited. If two power modules were paralleled, the maximum fault current could be doubled, which would expose the system backplane and connectors to excessive current and possibility of damage.

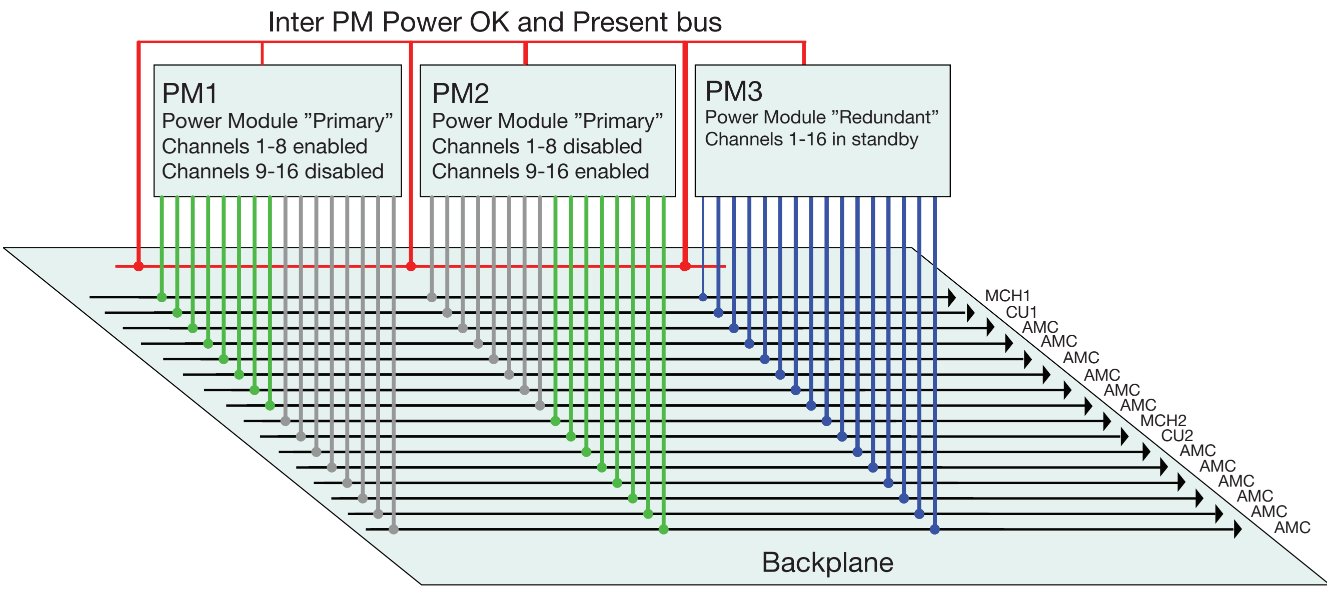


Figure 12 – Example of 2+1 redundant MicroTCA power module implementation

The MicroTCA specification requires that any given power module be identified to the system as either a primary power module or a redundant power module. A given power module within the system may transition between these two roles as decided by the MCH, but one power module could not maintain both roles at the same time. In the event of a failure in any output channel of a primary power module, the redundant power module will take over responsibility for all output channels of that primary power module, not just the failed channel. Automatic transition between a failed primary power module and the redundant power module is accomplished by the settings of their output voltages.

Primary power modules are set to a higher output voltage than redundant power modules, the two nominal settings being perhaps 12.5 V and 11.5 V. This output O-Ring allows instantaneous and automatic transition in the event of a failure due to the power module with the higher output voltage delivering power to the loads. This technique also imposes much more stringent voltage budgets and output regulation requirements on power modules (including the primary power modules) used in redundant systems. This impact on the power module design will be discussed later in this section.

To understand the impacts of redundancy on the power module output channel control, it is easiest to first examine a typical implementation for a non-redundant power module, which is shown in *Figure 13*. The drawing is for only one payload channel, but all of the elements shown other than the DC/DC converter and the EMMC would need to be replicated for each of the payload power channels as well as for each of the management power channels – i.e. up to 32 times. Due to the significantly lower current levels, the management power channels do not pose as much of a design challenge, so concentrating on a single payload channel is sufficient to gain an understanding of the situation. There is a single DC/DC and a single EMMC in each power module, and these functions are shared with all 32 output channels.

The circuit block shown between the EMMC and the current sense resistor and output control transistors is most often some kind of hotswap control IC. Often these ICs can handle multiple channels, so the number of chips required will vary but the described functionality is independently required for each of the up to 32 output voltage channels. Each channel has two semiconductor switches in series. The switch to the left is the pass device and the one on the right is the O-Ring device. The O-Ring device prevents current from flowing in the reverse direction from the load into the power module. The pass device is used to enable or inhibit the output current and also to limit the value of the current to provide for functions such as soft start for hotswap and fault current limiting.

Since this is a non-redundant power module, its outputs will be either on or off. There is no need for it to be in a stand-by state ready to take over for another power module. Therefore both of the transistors can be driven by the same control line as shown in the figure. This results in a fairly simple implementation, with only two control lines (enable and power good), and only a total of three defined conditions for this payload power channel.

The three conditions are:

- CHANNEL OFF
- CHANNEL ON AND FUNCTIONAL
- CHANNEL ON WITH FAULT

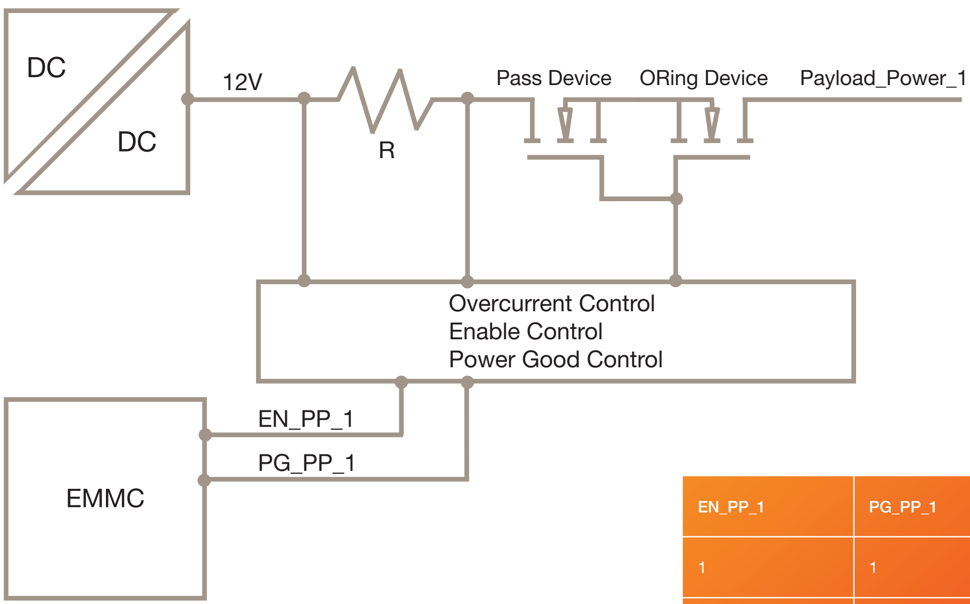


Figure 13 – Payload channel that only allows for non-redundant operation

EN_PP_1	PG_PP_1	STATUS
1	1	PAYLOAD POWER 1 ON AND FUNCTIONAL
1	0	PAYLOAD POWER 1 ON AND FUNCTIONAL
0	0	PAYLOAD POWER 1 OFF

Note that non-redundancy does not limit the number of power modules in a given sub-rack. There can be more than one, but each power module needs to be assigned to specific AdvancedMCs, CUs or MCHs and there would be no hand-over between the power modules in the event of a failure.

The typical implementation of the output channels for redundant operation is much more complex, as shown in *Figure 14*. The same circuit elements are used, but there are more interconnections and control states. The EMMC might need to be connected to the 12 V DC/DC converter so that the converter output voltage can be set to the appropriate value as a function of the power module's definition as either primary or redundant. In *Figure 14* this connection is exemplified by a Power Management Bus (PMBusTM). The PMBus may also connect to the hotswap control function in order to obtain data collection capability from the output channels. There is also a control line between the EMMC and the hotswap control function that sets the primary/redundant definition to the hotswap controller. Note that for the redundant implementation, the O-Ring switch is driven separately from the pass device.

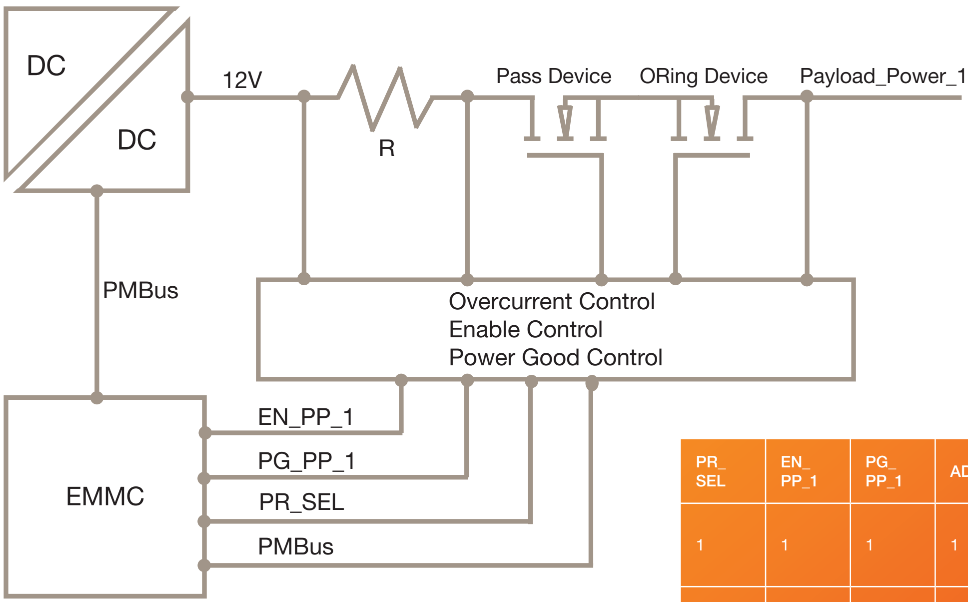


Figure 14 – Payload channel that allows for redundant operation

If the specific power module in question is defined as a redundant device, this O-Ring switch is normally turned off, and the intrinsic diode of the switch is reverse biased due to the lower voltage setting of the redundant DC/DC converter. This intrinsic diode will become forward biased to automatically deliver current from the redundant power module in the event of a failure in the primary power module. The O-Ring transistor is then turned on by the control logic to reduce the on-resistance of the connection and to reduce power dissipation in the concerned component.

The net of all this is that the redundant implementation results in considerable extra complexity. There are now four interface lines between the EMMC and hotswap function instead of two, and the number of defined states that need to be controlled is now seven rather than three. The PMBus connection to the DC/DC converter may also be needed. In addition, the accuracy of the current limiting needs to be much higher when using redundancy. Compared with the non-redundant setup shown in *Figure 13*, the redundant solution requires an additional 300 mm2 of PCB area to accommodate the hardware for the increased control complexity. This represents about 2.5% of the total PCB area in the power module.

The control cost impact for the redundant solution is about 10 cost units over and above that required for the non-redundant power module. These estimates are for the 16 payload channels. The impact of the lower current management channels is relatively minor. It should also be noted that the above analysis is predicated on the hotswap hardware available in 2006. As semiconductor vendors develop more highly integrated and flexible channel control devices for the MicroTCA market this situation may change. In additional to the cost differentials for each power module as described here, a redundant solution will of course require at least one additional power module compared to a non-redundant system.

PR_ SEL	EN_ PP_1	PG_ PP_1	AD_1	STATUS
1	1	1	1	PM IS PRIMARY PAYLOAD POWER 1 ON, FUNCTIONAL AND POWER IS DELIVERED
1	1	0	0	PM IS PRIMARY PAYLOAD POWER 1 ON AND NOT FUNCTIONAL
1	0	0	0	PM IS PRIMARY PAYLOAD POWER 1 OFF
0	1	1	0	PM IS REDUNDANT PAYLOAD POWER 1 ON AND FUNCTIONAL, NO POWER DELIVERED
0	1	1	1	PM IS REDUNDANT PAYLOAD POWER 1 ON AND FUNCTIONAL, POWER IS DELIVERED
0	1	0	0	PM IS REDUNDANT PAYLOAD POWER 1 ON AND NOT FUNCTIONAL
0	0	0	0	PM IS REDUNDANT PAYLOAD POWER 1 OFF

We will now examine the impacts of redundancy on the 12 V DC/DC converter. The basic MicroTCA specification defines the tolerance range for the AdvancedMC module input voltage as 10 V to 14 V. Since the load module will operate at any voltage in this range, the 12 V DC/DC converter could have a +/- 10% tolerance in a non-redundant system. In a redundant system, the situation becomes more challenging. In order to keep the voltage budgets of both the primary and the redundant power modules within the same overall range at the AdvancedMC inputs without possibility of overlap, the tolerance ranges for the primary power module would be approximately 12.25 V to 12.95 V and the range for the redundant power module from 11.6 V to 12.0 V. These ranges include the effects of line and load regulation as well as temperature. This means that the DC/DC converter in a power module intended for operation in a redundant system must have a +/- 2% output voltage tolerance. Going from a +/- 10% to a +/- 2% regulation tolerance has a significant impact on the DC/DC converter design.

A redesign of the baseline converter used in this study was not done to quantify this impact, but a meaningful analysis can be obtained by looking at two other DC/DC converters in the Ericsson product line.

Figures 15 and *16* summarize the parameters of two Ericsson DC/DC converters with 12 V outputs and approximately the same input voltage range.

They are both very contemporary designs and are highly regarded as representing industry-leading performance in terms of efficiency and power density given their respective design assumptions. They both have exactly the same form factors and total volume. The PKM 4304 is more loosely regulated with only feed-forward regulation from the input line voltage and no load regulation feedback loop. This greatly simplifies the module's control system, but does create a droop in its output load characteristic as shown in the figure. The additional space freed up by the less complex control system was used to enhance the power train resulting in high efficiency (95.3%) and output power (380 W). This converter would be well suited for usage in a power module not intended for redundant applications.

The PKM 4313, in the same sized physical package, contains output voltage feedback and features output voltage regulation of +/- 2.5%, making it suitable for usage in a power module for redundant applications. But there are penalties for this enhanced performance. The efficiency is 93.3%, significantly lower than that of the PKM 4304. Also, the maximum power output is 204 W. The power density is only 54% that of the PKM 4304. We can conclude from this that power modules used in redundant systems will have higher power losses than those intended for non-redundant systems, and that their internal packaging will be more challenging.

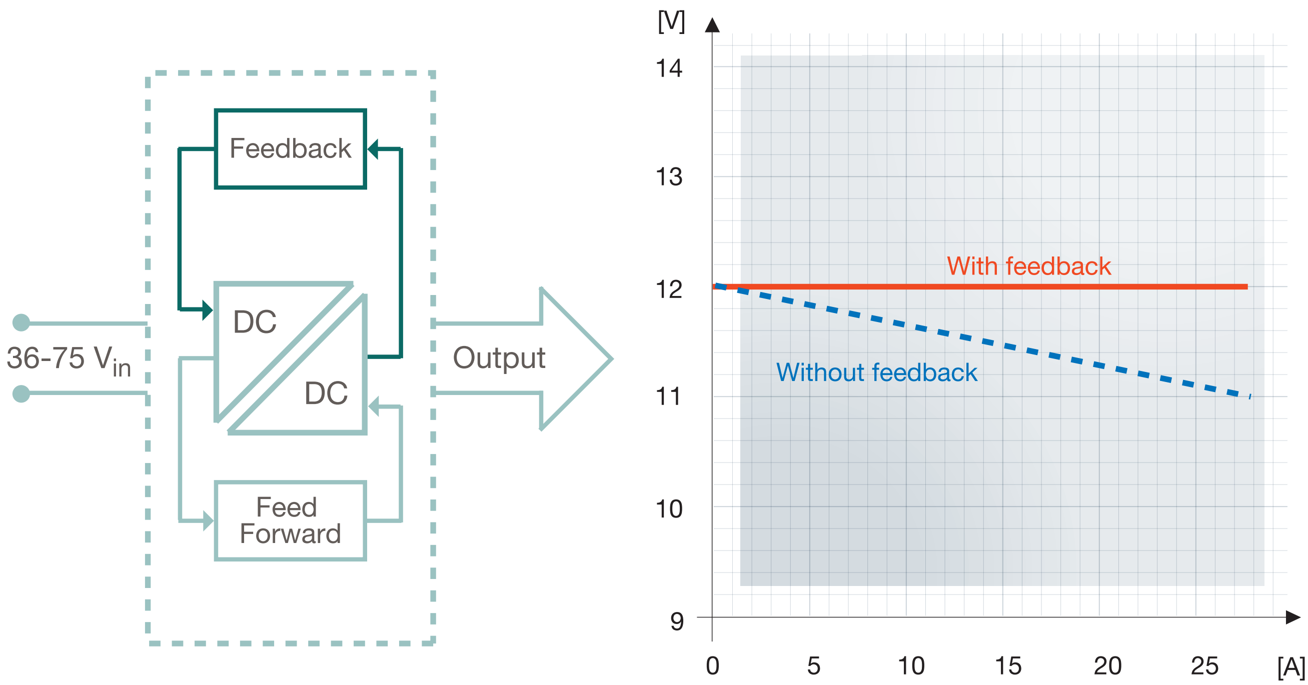


Figure 15 – Performance comparison with and without feedback loop.

These numbers are of course continuously improving as new technologies are being developed. The fact, however, remains that tighter control of the output voltage will require additional control circuitry in the DC/DC converter, thus affecting power density and efficiency.

5.4 DUAL INPUT FEEDS

The unique physical partitioning of MicroTCA actually provides some opportunity for enhanced system availability by means of redundant DC/DC conversion. Other types of systems based on a -48 V bus voltage in the backplane normally utilize redundant -48 V power feeds, but contain only one 48 V to low voltage DC/DC converter on each carrier-board. This DC/DC converter represents a single-point-failure source with no redundancy. Providing redundancy in the form of a second DC/DC converter on each carrier-board would be prohibitive in terms of cost and board space, since it would need to be replicated for every carrier-board in the system.

MicroTCA provides a neat and effective solution for this dilemma. MicroTCA equipment racks are normally designed with provision for two power modules. If each power module position is fed from a separate -48 V power feed, the power modules can be easily configured into a redundant arrangement so that complete redundancy is provided for both loss of one power feed and for all power conditioning, conversion and control functions servicing all AdvancedMCs in the system.

PKM 4313C PI	
INPUT RANGE	38 - 75 VDC
SIZE	36.8 X 57.9 MM (WXL)
VOUT TOLERANCE	+/- 2.5%
EFFICIENCY	93.3% (48 V IN, MAX LOAD)
OUTPUT POWER	204 W

PKM 4304B PI	
INPUT RANGE	36 - 75 VDC
SIZE	36.8 X 57.9 MM (WXL)
VOUT TOLERANCE	- 10.8 / +4.2%
EFFICIENCY	95.3% (48 V IN, MAX LOAD)
OUTPUT POWER	380 W

Figure 16 – Summary of performance parameters

This can all be accomplished with only one additional power module assembly, rather than the multiple additional high power DC/DC converters that would be required in a system based on a -48 V backplane. This approach gives OEMs using MicroTCA an opportunity to offer complete power system redundancy and extremely high rack level system availability all within a small enclosure and at a reasonable cost. It is important to emphasize that the -48 V backplane analogy is only included to explain the architectural differences. Actual effects on system level reliability cannot be compared as a DC/DC converter feeds a single board in one case, while in the other a complete shelf. Further examination of the redundancy options available with MicroTCA should help clarify the possible system design decisions. One very key point to keep in mind is that providing power feed redundancy does not automatically imply that power modules will require dual power feed input capability.

A generalized drawing of a dual power feed situation is shown in *Figure 17*. Here the cabinet and shelves are supported with dual feeds. The main question to be addressed next is how to utilize these dual feeds. Three possibilities will be considered, as follows:

- ONE DUAL INPUT POWER MODULE
- TWO REDUNDANT SINGLE INPUT POWER MODULES
- TWO REDUNDANT DUAL INPUT POWER MODULES

One dual input power module

This is a non-redundant power module implementation, where a single power module supplies the entire shelf. The power module has dual input power feeds, which does provide for redundancy in the event of a loss of one of the power feeds, but no redundancy exists for the loss of the main DC/DC converter. That is, the DC/DC converter represents a single point-of-failure. The system designer should have the data to determine if this is a viable design direction, but it could be argued that the failure rate of a power feed may be less than that of the DC/DC converter, making one of the other options below more attractive.

Two redundant single input power modules

This is a 1+1 power module redundancy implementation where power feed A is connected to one power module and power feed B to the other. Both power modules only have a single input power feed connection, and only one power module is required to supply all of the system loads. Redundancy is provided for both DC/DC converters and input power feeds. This solution is an improvement over the previous scenario because of the DC/DC converter redundancy.

Two redundant dual input power modules
This solution differs from the previous one only in that both power feeds go to both power modules and both power modules require dual input power feed capability. As with the previous method, this approach provides redundancy for both single point DC/DC converter and power feed failures. It does offer additional protection from multiple point failures, essentially providing 1+3 redundancy for input power feed faults along with the 1+1 redundancy for power module faults. This really represents protection against multiple failures at the same time, such as up to three blown fuses or cable faults in the PDU or a simultaneous failure of a power feed and a DC/DC converter. There may be a few systems where this level of protection is desirable, but many MicroTCA applications will achieve their availability targets with only protection from a single simultaneous failure.

While only the system designer will be in a position to make the above trade-offs for a particular application, it is our contention that many MicroTCA systems requiring dual power feed redundancy may be best served by the second option. It provides single failure protection for both input power feeds and for DC/DC converters but does not require dual feeds to each power module. This analysis only applies to the assumed 1+1 power module redundancy. In other cases the conclusions will vary. For example in a 3+1 redundant power module system with single feed power modules, the loss of one DC power source will disable two power modules, resulting in an output current overload to the remaining two modules. The cost, efficiency and size impacts of providing dual input feed capability to a power module will be examined below. The system designer must essentially trade off these impacts vs. the capability of protection from multiple simultaneous failures.

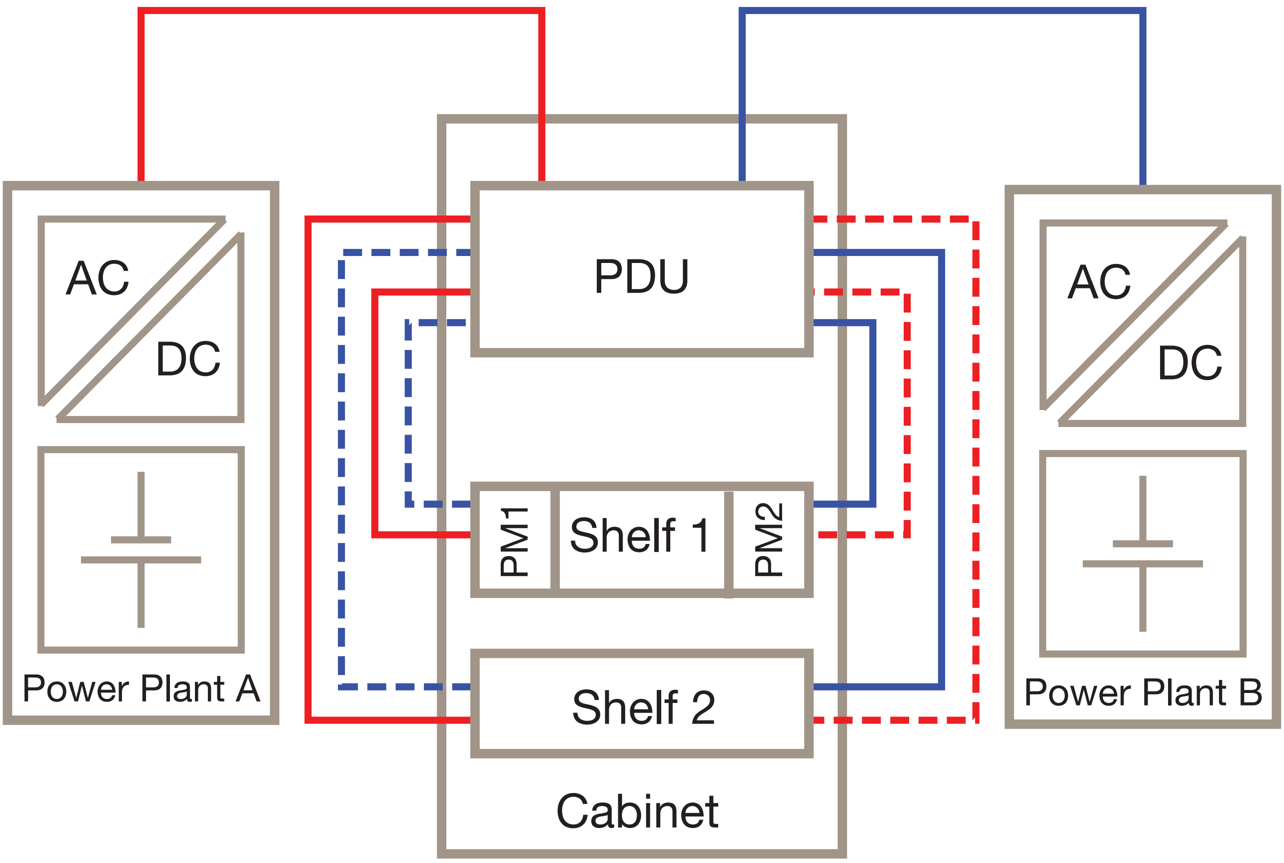
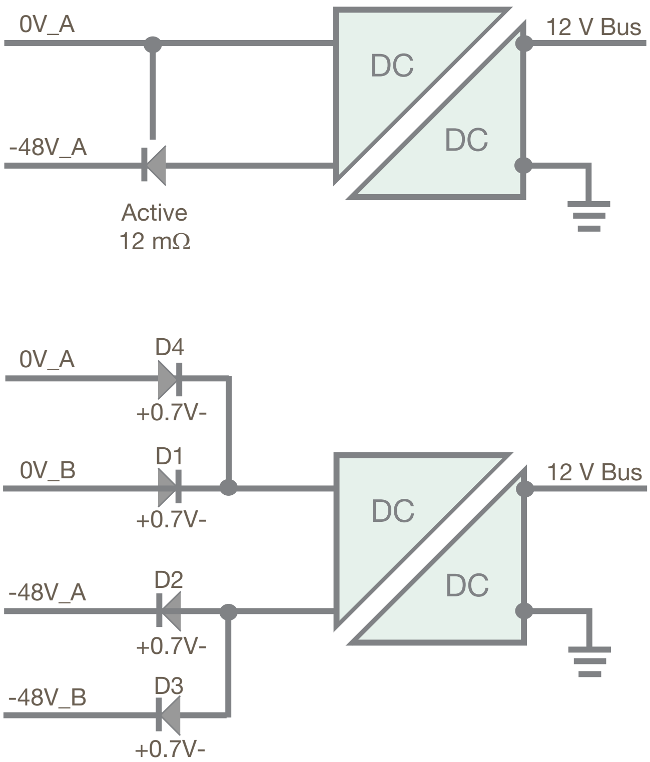


Figure 17 – Dual power feed general set-up

A comparison of the front end implementations for single feed and dual feed power modules is shown in *Figure 18*. The single feed system uses an “active diode” with a forward resistance of only 12 milliohms for reverse polarity protection. This device is actually a transistor connected to simulate a diode with only connection to the input voltage (no external control needed). Providing input polarity protection for the dual feed input is considerably more complex, requiring a total of four conventional diodes to reliably address all the provisions of the MicroTCA specification. The difference in power loss and efficiency is significant, with the dual feed input dissipating 10 W in diode losses vs. only 1 W for the single feed power module. The net efficiency reduction for the dual feed module is 2.7%. Using the dual feed design requires an additional 750 mm2 of PCB area as well as increasing the cost by 12 cost units.

Much of this additional cost is driven by the need for a second input power connector. These penalties may outweigh the advantage of protection from some multiple simultaneous failures in many system designs.

There are techniques that would allow for transistors to be used even in dual input configurations, thus eliminating the power dissipation generated by the diodes. Such an implementation would however require a rather complex control system to ensure that the transistors are turned on when they are supposed to be turned on. And even more importantly, turned off when they are supposed to be turned off. Making sure that this is the case at the same time as providing reverse polarity protection and eliminating cross conduction between the two power feeds is quite a challenge using transistors. Diodes on the other hand, would naturally provide the robustness and reliability needed.



SINGLE INPUT	
PCB AREA	200 MM²
PCB AREA OF POWER MODULE	1.7%
LOSS @ 380 W; 54 V IN	1 W
EFFICIENCY LOSS	0.3%
COST	9 UNITS

DUAL INPUT	
PCB AREA	950 MM²
PCB AREA OF POWER MODULE	8%
LOSS @ 380 W; 54 V IN	10 W
EFFICIENCY LOSS	3%
COST	21 UNITS

Figure 18 – Single feed and Dual feed power modules

6. CONCLUSIONS AND SUMMARY

It is difficult to form valid generalizations about many of the topics discussed in this paper because the MicroTCA power module cannot be viewed as a stand-alone entity, but rather must be considered as an element in the overall system. Consequently, the system requirements for the particular application being considered will be the primary driver for determining the correct answer in any given situation. As such, the system designer will be the person who determines the requirements for system elements such as power modules. The intent of this paper was to communicate to the system designer how some of these decisions can affect the cost, performance, efficiency and power density of the power module so that more informed decisions are possible. Keeping in mind that they will not be universally applicable, the following conclusions are offered in the spirit of some general guidelines that may be useful. *Figure 19* contains a summary of the power module impacts.

- MICROTCA IS AN EXCITING AND SUCCESSFUL COMPLEMENT TO THE MORE ESTABLISHED ADVANCEDTCA, OFFERING SIGNIFICANT BENEFITS FOR SMALLER, LOWER POWERED, LOWER COST SYSTEMS.
- MICROTCA IS CAPABLE OF HIGH-AVAILABILITY REDUNDANT POWER SYSTEM SOLUTIONS, AND CAN EVEN PROVIDE ENHANCED AVAILABILITY BY MEANS OF REDUNDANT DC/DC CONVERSION.
- COMMERCIALLY AVAILABLE MICROTCA COMPONENTS AND SYSTEM ELEMENTS, INCLUDING POWER MODULES, WILL CONTINUE TO EVOLVE BASED ON USER DEMAND AND TECHNOLOGY ENHANCEMENT. PROBABLE TRENDS INCLUDE INCREASED SILICON INTEGRATION, HIGHER PACKAGING DENSITY AND LOWER PRODUCTION COSTS AND PRICING.
- BECAUSE IT CONTAINS AN EXTENSIVE AMOUNT OF POWER CONDITIONING, CONVERSION AND CONTROL FUNCTIONS, THE POWER MODULE IS A VERY KEY ELEMENT IN ACHIEVING A SUCCESSFUL AND RELIABLE MICROTCA SYSTEM DESIGN.
- SYSTEM DESIGN DECISIONS CAN AFFECT THE PERFORMANCE, EFFICIENCY, SIZE AND COST OF A MICROTCA POWER MODULE.
- **HOLD-UP CAPACITANCE** - THE 2 COST UNITS REQUIRED TO IMPLEMENT THE FULL 10 MS HOLD-UP REQUIREMENT IS NOT IN ITSELF A MAJOR DETERRENT. THE CAPACITORS USED ARE HIGH QUALITY LOW FAILURE RATE UNITS AND CONSERVATIVE DESIGN DERATING IS USED, SO THE RELIABILITY IMPACT OF THE NUMBER OF CAPACITORS IS ALSO NOT A CONCERN. THE MAIN IMPACT TO THE OVERALL POWER MODULE DESIGN IS THE AMOUNT OF PCB AREA NEEDED FOR THE IMPLEMENTATION OF THE HOLD-UP FUNCTION, WHICH IS ALREADY APPROXIMATELY 10% OF THE TOTAL PCB IN A 355 W OUTPUT POWER MODULE. WITH THE POWER OUTPUT OF A SINGLE-WIDTH FULL-HEIGHT POWER MODULE PROJECTED TO REACH 600 W IN THE FUTURE, A CORRESPONDING INCREASE IN HOLD-UP PCB AREA WILL CREATE SIGNIFICANT DESIGN CHALLENGES. USING ONE OR MORE OF THE HOLD-UP SPECIFICATION APPROACHES DISCUSSED IN THIS PAPER CAN MITIGATE THIS CONCERN.

HOLD-UP CAPACITANCE (10 MS SHORT-CIRCUIT)

- 10% OF POWER MODULE AREA & 2 UNITS IN COST
- NEED FOR HOLD-UP RELATED TO MULTIPLE POWER MODULES ON THE SAME -48 VDC SUPPLY
- AMOUNT OF HOLD-UP DEPENDENT ON POWER CONSUMPTION, INPUT VOLTAGE AND SHORT-CIRCUIT DURATION

INPUT VOLTAGE (-48 VDC AND -60 VDC)

- MINOR EFFECTS ON DC/DC CONVERTER EFFICIENCY
- SLIGHT INCREASE IN COST AND REAL-ESTATE OF HOLD-UP CAPACITANCE

REDUNDANCY (REDUNDANT OPERATION OF POWER MODULE)

- 2.5% INCREASE IN REAL-ESTATE AND 10 UNITS IN COST ADDED
- MORE ADVANCED CONTROL LOGIC
- SIGNIFICANT REDUCTION IN DC/DC CONVERTER POWER DENSITY AND EFFICIENCY

DUAL INPUT FEEDS (-48 VDC INTO POWER MODULE)

- 10 W OF POWER LOSS
- 21 UNITS IN COST & 8% OF POWER MODULE AREA
- RELIABILITY IMPROVEMENT IN NON-REDUNDANT SYSTEM
- RELIABILITY IMPROVEMENT NEGLIGIBLE IN REDUNDANT SYSTEM

Figure 19 – Power module impact summary

- **INPUT VOLTAGE** - DESIGNING THE POWER MODULE FOR BOTH -48 V AND -60 V POWER SYSTEMS RATHER THAN ONLY FOR -48 V DOES NOT RESULT IN SIGNIFICANT IMPACTS ON EITHER COST OR PERFORMANCE. THERE MAY BE A SLIGHT CHANGE TO THE EFFICIENCY CURVE AND AN INCREMENTAL IMPACT TO THE AMOUNT OF HOLD-UP CAPACITANCE REQUIRED. PERHAPS A MORE SIGNIFICANT IMPACT OF THIS DECISION, WHICH IS OUTSIDE THE SCOPE OF THIS PAPER'S ANALYSIS, IS THE COMPLICATION THAT INCLUDING -60 V MAY HAVE IN TERMS OF SAFETY AGENCY APPROVAL. IT WILL ENTAIL DESIGNING FOR OPERATING VOLTAGES GOING ABOVE SAFETY EXTRA LOW VOLTAGE (SELV) STANDARDS WHICH WILL REQUIRE ADDITIONAL TESTING AND GREATER CREEPAGE AND CLEARANCE DISTANCES INSIDE THE POWER MODULE.

- **REDUNDANCY** - THE COST DIFFERENTIAL FOR PROVIDING REDUNDANT POWER MODULE OPERATION IS PRESENTLY SOMEWHAT SIGNIFICANT AT 10 COST UNITS. THIS COST, ALONG WITH THE PCB REAL ESTATE REQUIREMENT, IS EXPECTED TO DIMINISH OVER TIME AS MORE HIGHLY INTEGRATED HOTSWAP SEMICONDUCTOR SOLUTIONS BECOME AVAILABLE. A LARGER COST TO THE SYSTEM DESIGNER, WHICH MAY NOT DIMINISH, IS THE NEED FOR MORE EXTENSIVE SOFTWARE DEVELOPMENT, PERFORMANCE VERIFICATION AND INTEROPERABILITY TESTING FOR THE SIGNIFICANTLY MORE COMPLEX REDUNDANT POWER MODULE IMPLEMENTATION. FROM A POWER MODULE PERSPECTIVE, THE MOST SIGNIFICANT IMPACT OF PROVIDING REDUNDANT OPERATION IS THE SUBSTANTIALLY TIGHTER REGULATION REQUIREMENTS IMPOSED ON THE DC/DC CONVERTER. THE TIGHTER REQUIREMENTS ARE TECHNICALLY VERY FEASIBLE EVEN WITH TODAY'S TECHNOLOGY, BUT RESULT IN SIGNIFICANTLY LOWER POWER DENSITY AND CONVERSION EFFICIENCY. AND, OF COURSE, USING A REDUNDANT POWER MODULE CONFIGURATION WILL REQUIRE THE COST OF AT LEAST ONE ADDITIONAL POWER MODULE.

- **DUAL INPUT FEEDS** - OF THE FOUR POWER MODULE DESIGN AREAS EXPLORED, THIS ONE HAS PERHAPS THE HIGHEST OVERALL IMPACT. DUAL FEED INPUTS TO A POWER MODULE ADD APPROXIMATELY 12 COST UNITS AS WELL AS 9 WATTS OF ADDITIONAL POWER DISSIPATION AND A CORRESPONDINGLY LOWER EFFICIENCY. FOR MANY MICROTCA SYSTEMS THESE PENALTIES NEED NOT BE INCURRED SINCE A SOLUTION IS OFFERED THAT PROVIDES DUAL FEED REDUNDANCY AND REDUNDANT DC/DC OPERATION AT THE SHELF LEVEL WITHOUT THE NEED FOR DUAL FEEDS TO ANY POWER MODULE.

This paper will hopefully be a useful guide to some of the design decisions that need to be made when configuring a MicroTCA power system. The content, however, should not be considered as the final authority on the issues presented. The system designer should always consult with the latest version of the appropriate MicroTCA specification when determining design requirements. Ericsson intends to continue its investment in developing industry-leading MicroTCA power solutions as well as to continue our commitment to providing open dialog with our customers about the design trade-offs inherent with this exciting new architecture.

7. GLOSSARY

AdvancedMC™, AMC	Advanced Mezzanine Card
AdvancedTCA™, ATCA	Advanced Telecommunications Computing Architecture
PCB	Printed Circuit Board
CPE	Customer Premises Equipment
CU	Cooling Unit
EMMC	Enhanced Module Management Controller
ETSI	European Telecommunications Standards Institute
IBA	Intermediate Bus Architecture
IBC	Intermediate Bus Converter
IC	Integrated Circuit
ICT	Information and Communications Technology
IPMB	Intelligent Platform Management Bus
IPMC	Intelligent Platform Management Controller
IPMI	Intelligent Platform Management Interface
MCH	MicroTCA Carrier Hub
MicroTCA™	Micro Telecommunications Computing Architecture
PDU	Power Distribution Unit
PEM	Power Entry Module
PICMG™	PCI Industrial Computer Manufacturers Group
PMBus™	Power Management Bus
POL	Point of Load
SELV	Safety Extra Low Voltage
TS-HOD	Two-Step High Ohmic Distribution

8. REFERENCES

1. AdvancedMC base specification R2.0, PICMG, 15 November 2006

2. AdvancedTCA base specification R2.0 ECN001 & ECN002, PICMG, 26 May 2006

3. MicroTCA base specification R1.0, PICMG, 6 July 2006

All referenced papers and data sheets can be found at Ericsson Power Modules' web site: http://www.ericsson.com/powermodules

MPM-07:000535 Uen Rev B 2010-06-23

INTELLIGENT ENERGY MANAGEMENT FOR IMPROVED EFFICIENCY

A look at possible energy efficiency improvements brought forth by the introduction of digital control and monitoring of power supplies.

CONTENTS

ABOUT THIS PAPER

Material contained in this paper was first presented on September 11, 2007 at Digital Power Forum 2007 - Practical Benefits of PMBus and Digital Control session.

This focused three-day international conference served an audience of decision makers who are interested in learning about and contributing to the latest practical advancements related to the use of digital power control techniques in electronic systems and in power converters, and digital energy management and power management in enterprise-level installations and related digital equipment.

1. INTRODUCTION

This paper will address the two converging trends of digital control and management of power conversion systems and the recognition of the importance of energy conservation. It will be shown that using digital techniques can increase the efficiency of power supplies and of the systems that use them. Efficiency, in turn, is the primary driver for energy conservation so that optimization of efficiency leads to the concept of Energy Management rather than just power management. The relationship between increased power supply efficiency and quantifiable measures of energy conservation will be explored.

An analytical study was done using actual present-day DC/DC converters and POL regulators in order to obtain the data presented. These devices were configured into a board level power system in order to simulate a typical user system application. In addition to simulating the power delivery hardware, the evaluation system included a software interface to allow for adjustment of system and power supply parameters in a manner similar to that used by a system developer. It is further demonstrated that power supplies utilizing control ICs from different manufacturers can be successfully integrated into one system and communicate effectively over the system management bus.

All the objectives of the study were successfully met, with power and energy savings established by means of multiple techniques. Even greater savings should be possible in the future. The trends and indicators are that advancements in power conversion technology, power control/management hardware and power/energy management software show great potential as an environmental resource.

2. EFFICIENCY, ENERGY, THE ENVIRONMENT AND COST

Everyone embraces the concept of high efficiency and energy conservation, but we do not often calibrate our desire for achieving them with quantifiable measurements of their benefits. A simple example will be useful in this regard. Using a similar methodology, the reader can easily calculate the benefits for any degree of efficiency improvement in their particular system or application of interest.

Assume a power saving of only 1 watt on one circuit board. With continual operation and at an energy rate of $0.1 per kWh, the cost saving would be $4.38 over a 5 year operating period. This is only the savings due to the power dissipation on the board. Each watt of power at the board most likely represents 2 to 3 watts at the input to the total system, due to the series inefficiencies of such components as AC/DC conversion, battery backup, cooling hardware, additional system volume and floor space, etc. Consequently 1 watt on 1 board can cost $13 over the 5 year period. Of course a typical system contains dozens or hundreds of boards and most user facilities contain more than one system, so the cumulative effect is meaningful for most end users – well into the thousands of dollars in most situations.

From an environmental point-of-view, electrical energy is not free. Energy Star estimates the average environmental impact of electrical generation and consumption as 0.7 kg of CO2 for each kWh [1]. One watt of power savings on one board, plus the system overhead reduction of 2 watts, translates into over 18 kg per year less CO2 released into the atmosphere. With 300 to 400 such boards in operation, the savings in emissions is equivalent to the CO2 produced by driving a typical gasoline powered automobile for an entire year [2].

High efficiency obviously pays high dividends to the pocketbook and to the environment. Higher efficiency and lower energy consumption also result in long system lifetimes, more benign thermal management conditions and higher reliability. Using the minimum number of power conversion stages and selecting power supplies that feature the highest available efficiency are both important techniques for achieving these objectives. In the remainder of this paper it will be shown how digital control and management techniques can help achieve the desired optimization of power supply and power system efficiency and result in true Energy Management.

3. DEFINITION OF TERMINOLOGY

There is no industry-wide standardization of naming conventions and terminology in the field of “digital power”. It will therefore be useful to summarize how Ericsson defines the terminology used in this paper and elsewhere in our product development and marketing activities. One key concept that must be understood is the distinction between digital power control and digital power management.

3.1 DIGITAL POWER CONTROL

Ericsson uses the term “power control” to address the control functions internal to a power supply, especially the cycle-by-cycle management of the energy flow within the DC/DC converter or POL regulator. This will include the feedback loop and internal housekeeping functions. The power control function is “real-time” in comparison to the switching frequency of the power supply. These types of control functions can be implemented with either analog or digital techniques. Note that a DC/DC converter or POL regulator could use digital power control techniques and appear identical to the end user to a similar product using analog power control techniques. That is, the usage of digital power control may not require any changes or new design on the part of the end user.

Figure 1 depicts a generalized DC/DC converter or POL regulator, and shows how the internal power control functions could be implemented with either analog or digital based circuitry. In either case, the external functionality of the unit would be the same and indistinguishable by the casual user. The analog implementation

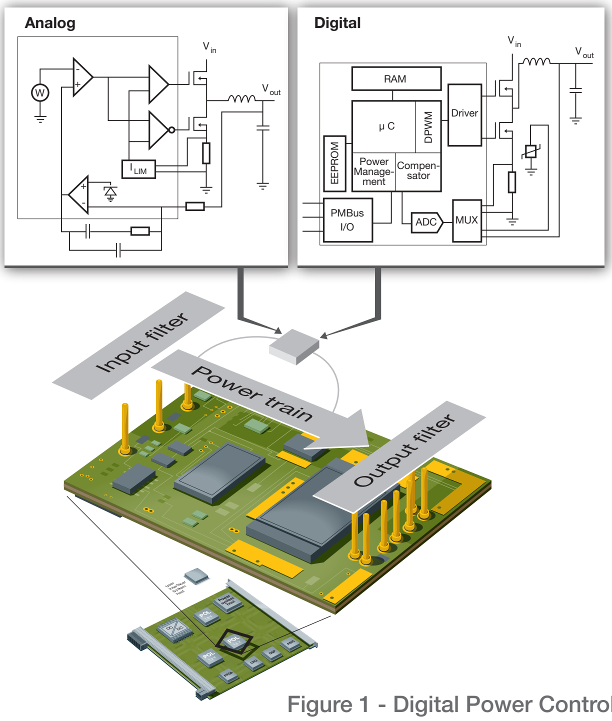


Figure 1 - Digital Power Control

shown on the left side uses a PWM IC as the primary control element. The DC/DC converter output voltage is sampled by means of a resistive voltage divider and compared with a DC reference voltage by an error amplifier. The error amplifier output is an analog signal that has a magnitude proportional to the needed correction in output voltage. This signal is used as an input to the PWM device, which produces an output pulse whose width is defined by the error signal. This PWM output pulse then is used to control the "on time" of the power handling semiconductors. It is important to note that the input and output filters and the power devices will remain essentially the same with either an analog or a digital control structure.

The right side of the figure shows a digital control implementation. The sensing of the output voltage is similar to that in an analog system. Rather than an error amplifier, however, the sensed analog voltage is converted to a binary digital number with an analog to digital converter (ADC). In addition to output voltage, it is useful to know the value of other analog parameters such as output current, temperatures in the power supply, etc. Separate ADCs could be used for each parameter to be sensed, but it is often more advantageous to use just a single ADC and precede it with a multiplexer (MUX). The MUX will then sequence between the analog inputs to be measured and feed each one in sequence to the ADC.

The output of the ADC will be a series of digital numbers, each representing the value of a parameter at a specific time. Since the clock frequency or sampling rate of the MUX and ADC is fixed, the result is a series of numbers for each parameter each separated by a known time period. The digital outputs from the ADC are fed to a microcontroller (µC) which provides the processing for the system. On board Read-Only-Memory (ROM) is used to store the control algorithms for the µC. These algorithms allow the µC to perform a series of calculations on the digital outputs from the ADC. The results of these calculations are such parameters as the error signal, the desired pulse widths for the drivers, optimized values for delay in the various drive outputs, and also the loop compensation parameters. Digital control is considerably more flexible than analog control in its ability to adapt to changes in line and load conditions. Generally analog approaches are configured with only one "compromise" setting for a given control parameter whereas digital control systems have the ability to change the control parameters as a function of the power supply operating conditions.

3.2 DIGITAL POWER MANAGEMENT

Ericsson uses the term "power management" to address communication and/or control outside of one or more power supplies. This would include such items as power system configuration, control and monitoring of individual power supplies, fault detection communication, etc. The power management functions are not real-time to the conversion circuitry, because they operate on a time scale that is slower than the power supply switching frequencies. Presently, these functions, when implemented, tend to be a combination of analog and digital. Output voltage programming of power supplies is often done with external resistors (analog). Power sequencing is typically done with dedicated control lines to each power supply (digital). Digital power management, as defined by Ericsson, implies that all of these functions are implemented with digital techniques. Furthermore, rather than using multiple customized interconnections to each power supply for sequencing and fault monitoring, some type of data communications bus structure is used to minimize the interconnection complexity.

Figure 2 shows a board level assembly that contains one DC/DC converter and three POL regulators and is implemented using digital power management techniques. The control structure communicates with the power supplies by means of a standardized communications bus. This same bus interface can be used at several times during the life cycle of the power supplies, the board and the system into which the board is integrated. The power supply manufacturer may use the digital interface during manufacturing and testing to assure conformance to specifications and to optimize the performance of the unit. The user of the power supplies can use the interface to optimize the board level power design during development.

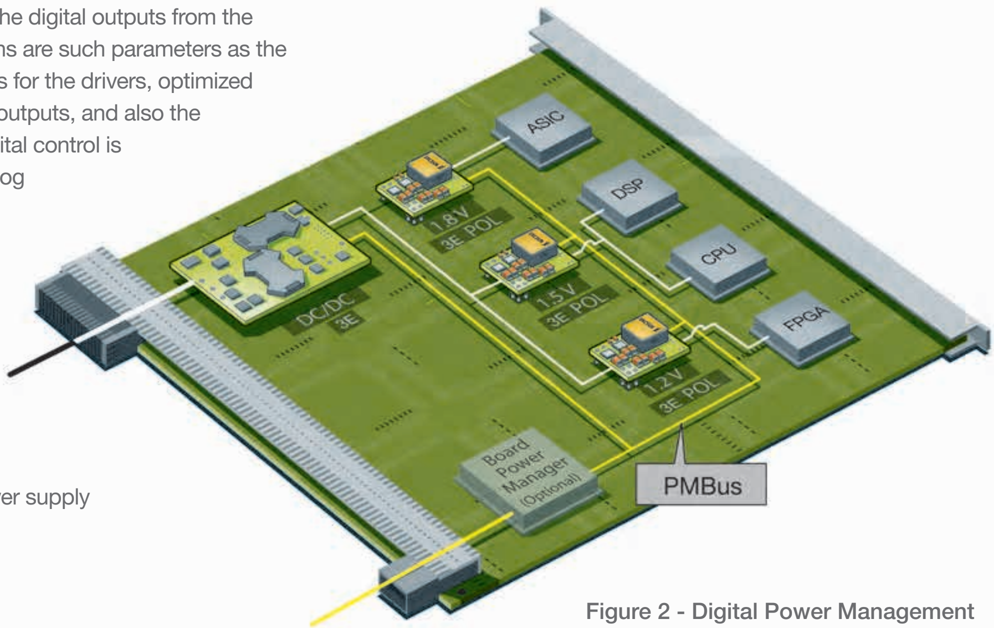


Figure 2 - Digital Power Management

The digital interface can also be used during production of the board for the purpose of final testing and loading of board level operational parameters. In the top level system, the digital power management capability can be used for power sequencing, power monitoring, fault protection routines and field maintenance troubleshooting.

Thus digital power management is very broad in nature, and can be used anywhere from the individual power supply to the final system. Unlike digital power control, digital power management is very much under the control of the end user. The board and/or system designer will decide what, if any, of the digital power management capabilities to implement. This degree of flexibility is one of the biggest advantages of digital power management. It allows for easily changing power sequencing routines without making hardware changes. Voltage margin testing to increase the robustness of power systems is easy to automate. Development time and consequently time-to-market is considerably shortened because of configurability via software rather than hardware [3].

3.3 ENERGY MANAGEMENT

Energy Management is a relatively new term and concept that integrates both power control and power management, with an emphasis on total energy conservation rather than just the efficiency of a specific system component. Energy Management is defined as "the intelligent usage of both digital power control and digital power management for the purpose of optimizing overall performance and efficiency during operation of Information and Communications Technology (ICT) equipment". As was described in the previous section of this paper, seemingly small improvements in efficiency or power dissipation within a power product can have significant ramifications at the system level both in terms of cost of energy and environmental impacts. The system designer is urged to take a holistic approach and to think in terms of optimizing Energy Management for the end user of the equipment being designed. Ericsson, in turn, is dedicated to developing and marketing power products that will facilitate this effort. The remainder of this paper describes an evaluation of some of the Energy Management techniques made possible by using digital power control and digital power management.

Figure 3 – POL used in system study

4. EVALUATION SYSTEM

For the purpose of gathering the data used in this analysis, a simple evaluation system was configured and constructed that replicates the environment seen in a typical larger system application. The power supplies used consisted of two POL regulators and one isolated DC/DC converter. The power supplies were mounted to a PCB and interconnected with a Power Management Bus (PMBus™) so that digital power management techniques could be used. The components of the evaluation system and an overview of their performance are described below.

The POL regulator used in the evaluation is a non-isolated synchronous buck regulator with a programmable output voltage, a wide input voltage range, and operates at a switching frequency of 320 kHz. This is a recent design with very competitive specifications, and is a good representation of a state-of-the-art POL regulator using digital control [4].

The dimensions of the finished POL regulator are 25.4 x 12.7 x 7.65 mm and it is capable of supplying a maximum output current of 20 A. Much of the size reduction that became possible in this design compared to its predecessors was due to the lower component count associated with the digital control implementation. The higher level of integration eliminated several discrete house-keeping components used in previous analog designs. The efficiency was optimized by careful selection of the MOSFET devices and by minimizing the sum of MOSFET switching losses and conduction losses. The digital PWM IC features an "efficiency optimized dead-time control", a capability that will be discussed later in this paper. A signal interface connector for the digital power management bus is used in the design. This is a small standard 10 pin connector that does not add appreciably to the size or cost of the power supply.
A photograph and specification summary of the digitally controlled POL regulator are shown in *Figure 3*.

POINT OF LOAD	
OUTPUT CURRENT	20 A
TOPOLOGY	SYNCHRONOUS BUCK
CONTROL	DIGITAL PWM
INPUT VOLTAGE RANGE	4.5 TO 14 V
OUTPUT VOLTAGE RANGE	0.6 TO 5.5 V
SWITCHING FREQUENCY	320 KHZ
DIMENSIONS	25.4 X 12.7 X 7.65 MM (1.00 X 0.50 X 0.301 IN.)

Measured efficiency curves for the POL regulators are presented in *Figure 4*. With a buck converter the efficiency is greater at lower values of input voltage since the duty cycle is greater. Data is presented for both the normal 12 V input voltage and also for an input voltage of 9 V for output voltages of 1.0 V and 3.3 V. As expected, the efficiencies are higher when the POL regulators are operated from 9 V. This characteristic will later be used as an Energy Management technique.

The isolated DC/DC converter is based on a full-bridge topology with secondary side control and synchronous output rectification. This design is the result of previous research conducted by Ericsson in the field of digital control [5]. It provides a tightly regulated output voltage and unprecedented power density. An interface connector for the digital power management bus was also installed.

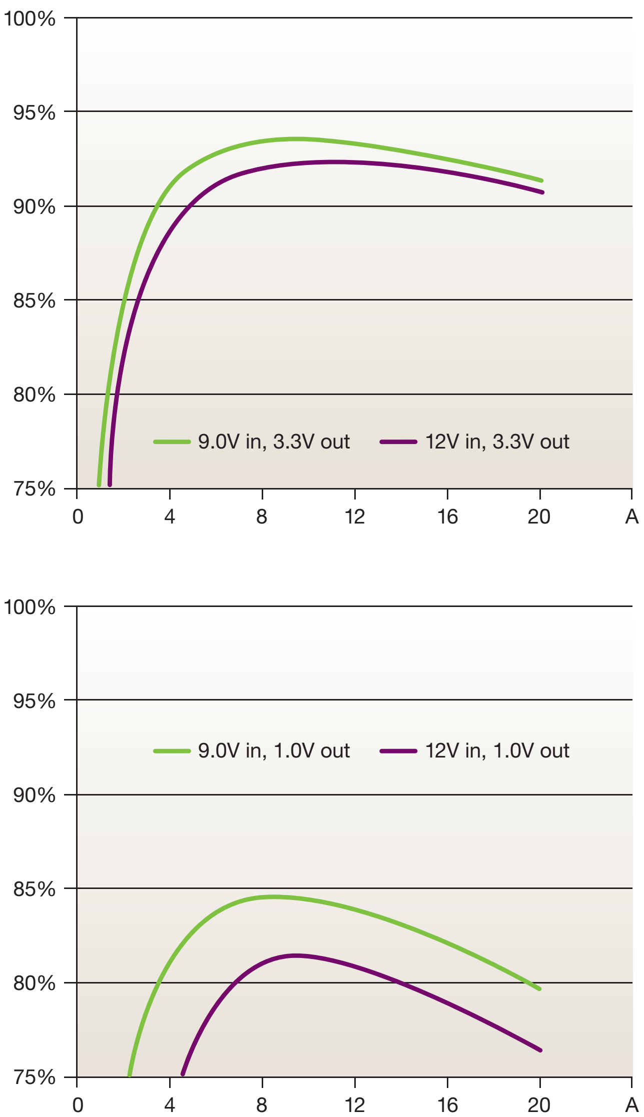
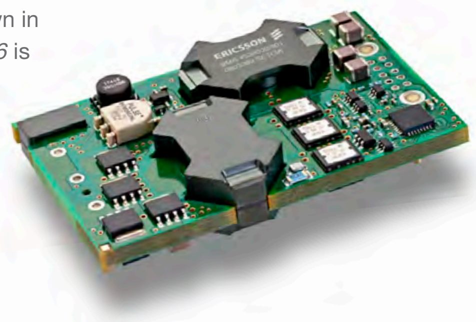


Figure 4 – PoL efficiency

The resulting DC/DC converter is in a ¼ brick package and can supply a maximum of 396 W output at a nominal 12 V. The switching frequency is 150 kHz. Its output voltage may be adjusted between 9 V and 12 V.

A photograph and specification summary is shown in *Figure 5*. *Figure 6* is the efficiency curve of the digitally controlled DC/DC converter.



DC/DC CONVERTER	
FORM FACTOR	¼ BRICK (2.28 X 1.45 IN.)
INPUT VOLTAGE	36 - 75 V DC
OUTPUT VOLTAGE	12 V DC ± 2%
OUTPUT ADJUST	9 - 12 V
OUTPUT POWER	396 W
SWITCHING FREQUENCY	150 KHZ
CONTROL IC	DIGITAL µC
REGULATION	V OUT FEEDBACK
TOPOLOGY	FULL-BRIDGE

Figure 5 – DC/DC converter used in system study

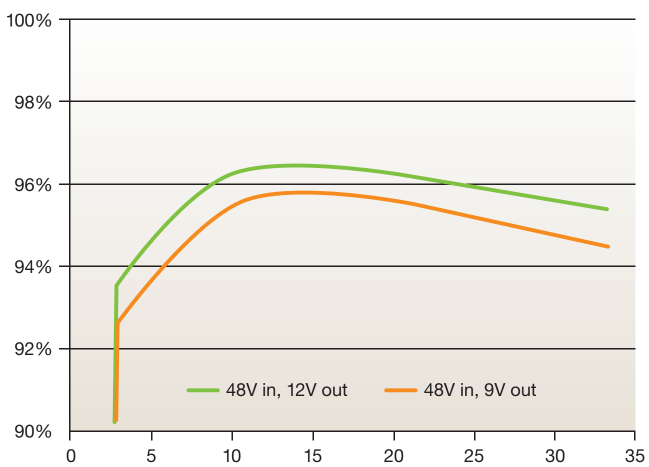


Figure 6 – DC/DC efficiency

An overview of the evaluation system is shown in *Figure 7*. The PCB is an evaluation board developed by Ericsson for conveniently developing and demonstrating the capabilities of digital power management. The DC/DC converter and the two POL regulators are mounted to this board. One of the POL regulators is programmed for an output voltage of 1.0 V and the other to 3.3 V. These two 20 A POL regulators will only draw a little under 100 W maximum of input power and the DC/DC converter is capable of almost 400 W of output power. In order to operate the DC/DC converter at a more typical system load, an adjustable external bulk load was added to the system. The amount of this external loading will be defined in the test results.

A Graphical User Interface (GUI) was used to communicate with the evaluation system power management bus. This capability made it easy to program the power supplies in the system
and to change the system operating conditions in order to evaluate Energy Management techniques. The GUI was run on a laptop computer and connected to the evaluation board via a USB interface. Circuitry on the evaluation board translated between the USB and PMBus protocols. A screen photograph of the GUI is shown in *Figure 8*.

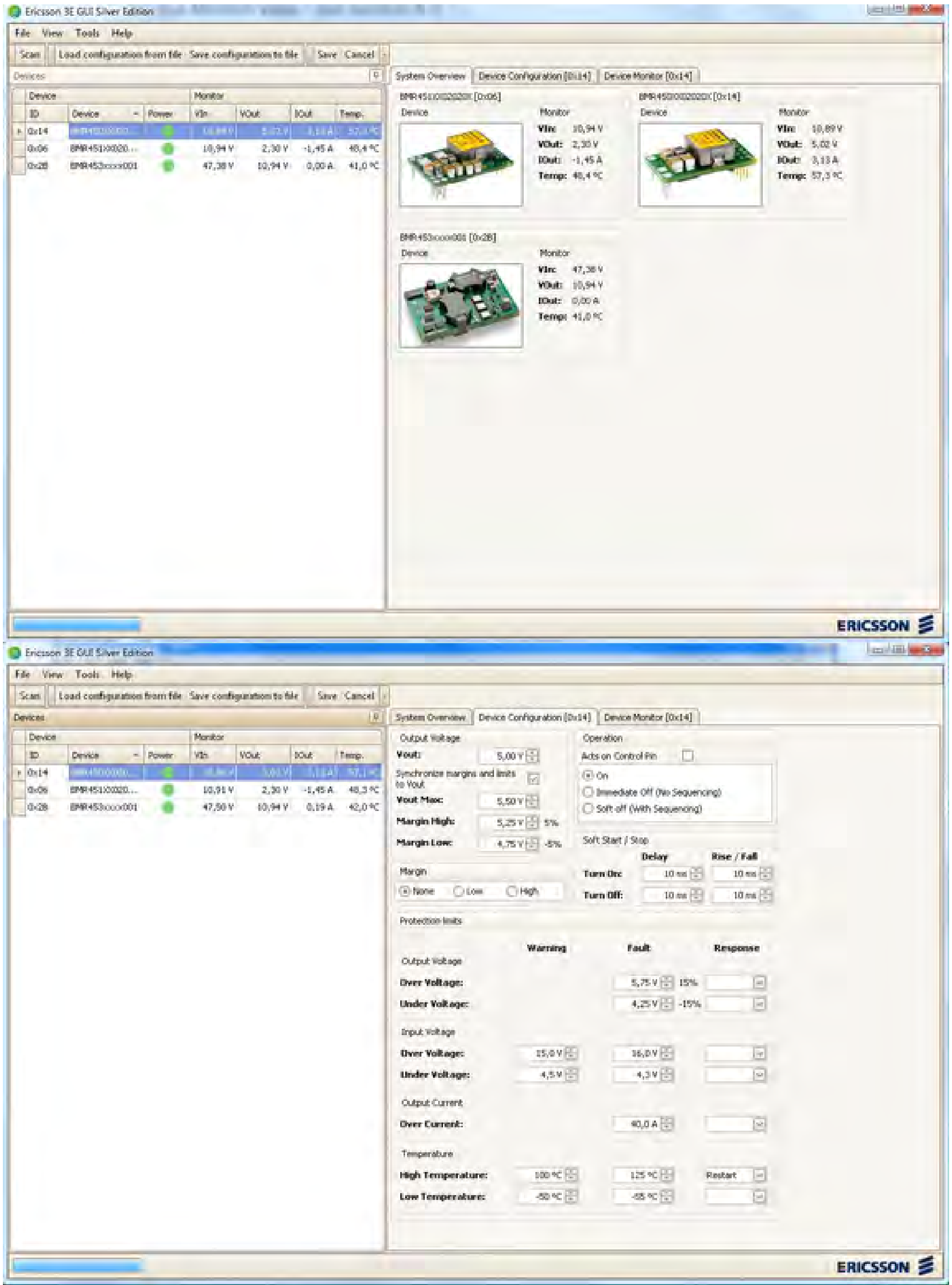
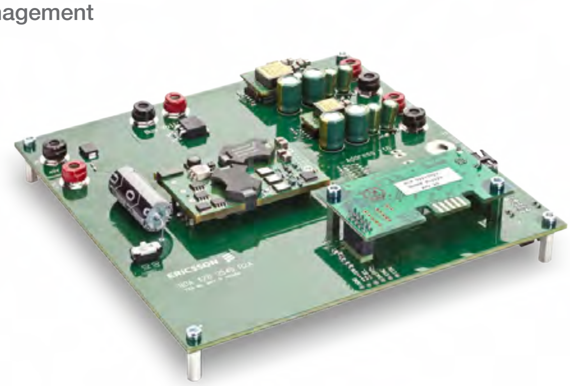


Figure 8 – GUI used for Power Management

Figure 7 – System components



5. ENERGY MANAGEMENT RESULTS

The possible techniques for Energy Management made available by digital power control and management have just begun to be explored. The next few years should see an incredible amount of progress in this area, including many ideas not even thought of as yet. This paper will discuss some of the techniques explored at Ericsson and report on the data resulting from the evaluation system. The investigation spanned two areas: optimization of a "stand-alone" power supply using digital power control, and system level optimization using digital power management.

5.1 POL REGULATOR OPTIMIZATION

The digital PWM control IC used in the evaluation POL regulators includes a feature called "efficiency optimized dead-time control" [6]. Dead-time in a switching POL regulator is introduced to avoid conduction overlap of the switching devices. Ideally, the dead-time should be as small as possible in order to achieve maximum efficiency. But the dead-time must be set long enough to encompass the variability of component tolerances, resulting in a fair degree of margin in conventional analog control loop designs. With the feature in this digital control IC, the dead-time can be automatically programmed for each individual POL regulator to the optimum value for the actual components in that particular unit. This essentially removes the allowance needed for component-to-component variability and creates a net increase in efficiency.

This technique was used during the manufacturing process of these prototype digital POL regulators. First, each POL regulator was set to its full-load datasheet parameters, 12 V input and 20 A output. When the optimized dead-time feature was enabled, the increase in efficiency was in the range of 0.6 to 0.7 %. This would represent the type of improvement expected in the manufacturing environment for a standard POL regulator if there were no knowledge of the conditions of its actual end application. All users of the POL regulator would receive this benefit, even if they participated in no digital power management at the system level.

Secondly, the dead-time efficiency optimization feature was used to set the dead-time for the POL regulator under conditions reflecting the intended usage of the unit. For example, the "standard" optimization setting for a 1.0 V output POL regulator would be done at 12 V input and 100 % load. A "custom" setting could be done with 9 V input and 50 % load if it was known that that was the typical condition for its system application. When this was done, the "custom" setting resulted in 1.4% greater efficiency than the "standard" optimization under the same operating conditions. A net power dissipation saving of 150 mW was achieved. These types of improvements can, in the aggregate, be significant for a large system. To achieve these benefits, the system designer would either need to request customization at the power supply manufacturer or do the optimization in-house via a digital power management interface.

5.2 SYSTEM OPTIMIZATION

The investigation also explored Energy Management techniques at the evaluation system level by means of the digital power management bus. The first technique tried was reduction in the intermediate bus voltage by programming of the DC/DC converter output voltage. From *Figure 4* you could expect that the POL regulators would exhibit a gain in efficiency when operated at this lower input voltage. The baseline for the test was operation of each POL regulator at its full 20 A output load and also setting the bulk load to 66.81 W to provide a representative load for the DC/DC converter, which was operating at a nominal 12 V output. The total output power was 152.81 W. The POL regulators had received the "standard" (12 V input, 100 % load) efficiency optimization. Under these conditions, the input power was 171.75 W resulting in an overall system conversion efficiency of 89.0 %. A summary of the test conditions and measured data is shown in *Figure 9*.

The DC/DC converter was then programmed to an output voltage of 9 V. The power of the bulk load remained at 66.81 W and the output voltages and loading of each POL regulator remained the same, so the total output power was held constant at 152.81 W. The input power was measured at 170.18 W, for a system conversion efficiency of 89.8 %, a 0.8 % increase from the baseline condition. The 1.57 W reduction in input power represents a 0.91 % decrease. That is the combined effect of improved efficiency in the POL regulators but also higher I2R losses due to the lower bus voltage.

A very similar test was done at light system loading as shown in *Figure 10*. The POL regulators were loaded at 2 A each and no bulk load was used. This would represent a system condition such as "sleep mode" or standby. The efficiency increase at lower input voltage for the POL regulators is more pronounced at light load, so this condition yields a higher improvement in relative efficiency and input power. The efficiency increased 4.1 % from 63.8 % to 67.9 %. The input power was reduced by 0.83 W, a 6.08 % improvement.

It would appear that operating at a bus voltage of 9 V would be the wiser choice under most conditions. Only at extremely high system loading requirements would operation at 12 V be needed. This is because the specification for the DC/DC converter is a maximum of 33 A output current over the entire 9 V to 12 V output voltage range, giving it a maximum output power capability of 396 W at 12 V vs. 297 W at 9 V. So in a typical application it could be kept at 9 V and then dynamically increased towards 12 V to manage peak load conditions. The 9 V and 12 V levels tested only represent the extreme limits of the range. The DC/DC converter could be operated at any voltage between these limits, allowing for optimization for the actual system.

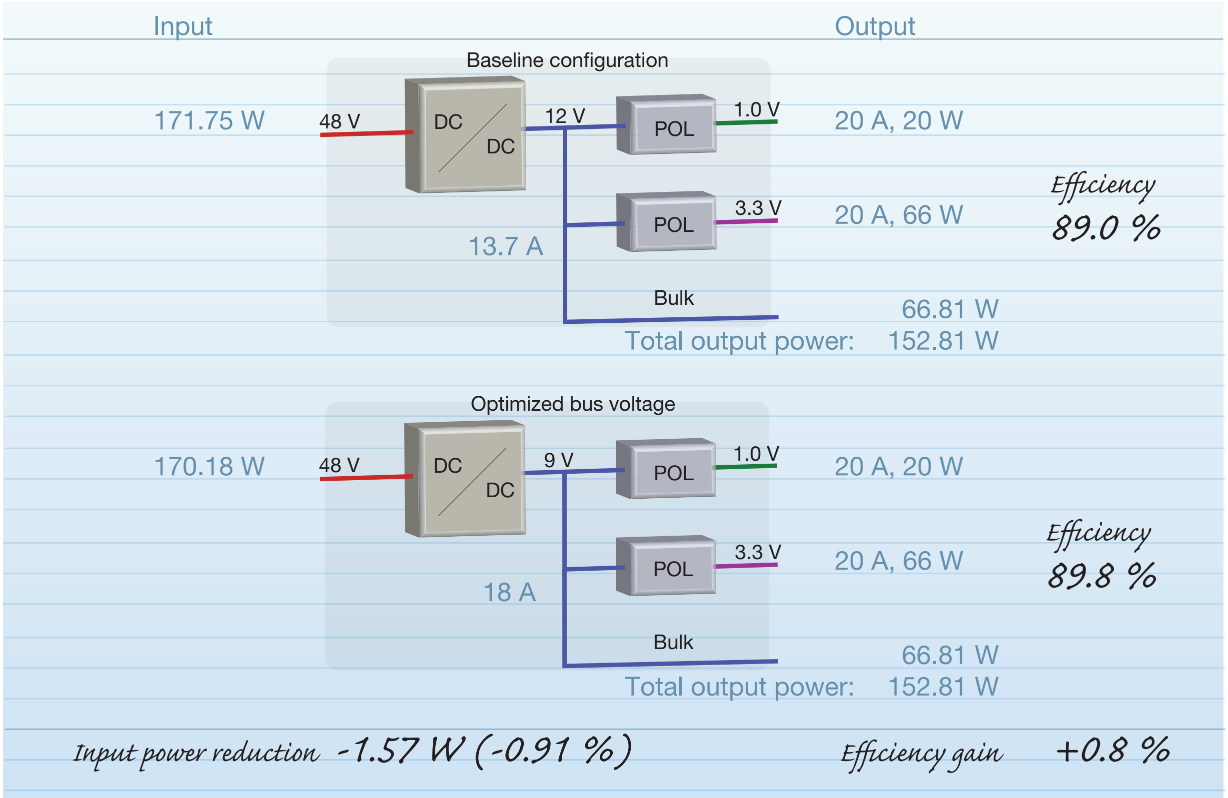


Figure 9 – System efficiency data - optimized bus voltage

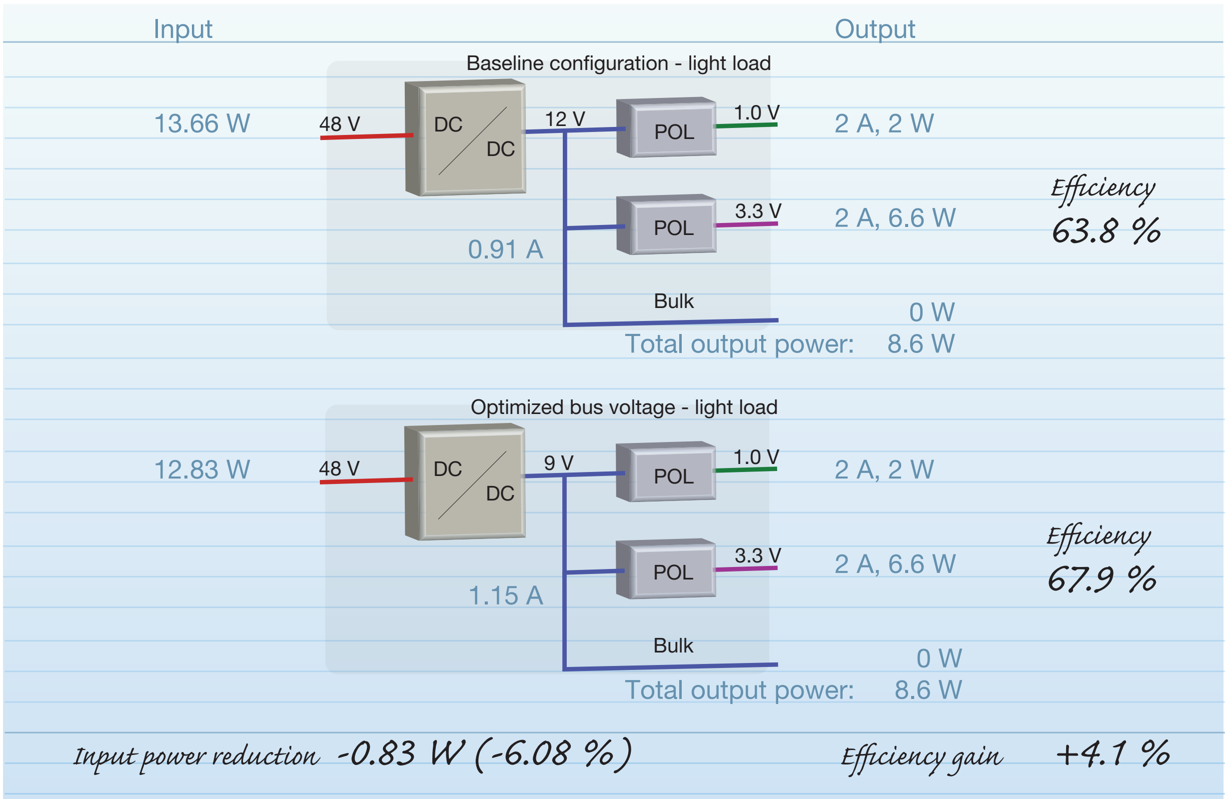


Figure 10 – System efficiency data - optimized bus voltage at light load

A third system level experiment was done to determine the effect of re-optimizing the dead-time of the POL regulators to reflect actual system operating conditions. These tests were done with a 9 V bus and at 50 % loading (10 A) on the POL regulators and a 123.8 W bulk load as shown in *Figure 11*. The baseline input power and efficiency measurements were made with the "standard" POL regulator dead-time optimization done at 12 V in and 100 % load, but with the system operating with a 9 V bus and 50 % load as shown in the figure. The POL regulators were then re-optimized to the actual 9 V in and 50 % load system conditions and the input power and efficiency were again measured. The result of this re-optimization was a 0.3 % increase in efficiency from 94.0 % up to 94.3 %. This corresponds to a reduction in input power by 0.51 W, a 0.29 % improvement.

This ability to optimize the efficiency of a POL regulator or DC/DC converter based on actual system operating conditions is very important and is a powerful tool for total system Energy Management. It could be done one time during system build or configuration based on the expected average operating conditions for the unit. For systems with stringent efficiency requirements, it could be reconfigured dynamically as the system operating conditions change. It could also be done periodically to compensate for component ageing effects.

This investigation has demonstrated the ability to use digital power management techniques at the system level for the purpose of Energy Management optimization. It was accomplished via the PMBus using digital control ICs from two different suppliers, showing that interoperability is possible. The GUI provides a convenient method for the system developer to monitor the system conditions and to reprogram the power supplies as desired. But there is at least one further possible extension – adaptive control of Energy Management.

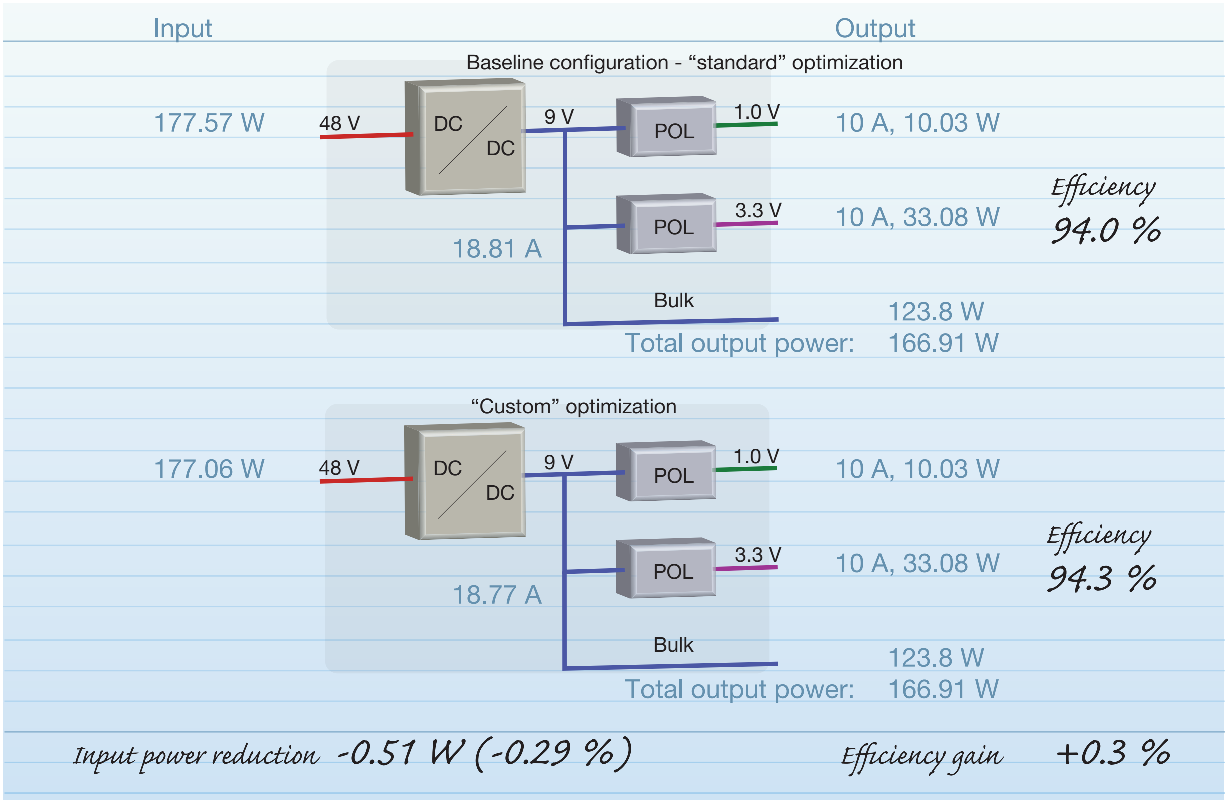


Figure 11 – System efficiency data – re-optimized POL regulators

6. ADAPTIVE CONTROL OF ENERGY MANAGEMENT

Adaptive Control of Energy Management essentially replaces the GUI with an automated system hosted by a system level management controller or FPGA. The ease of connecting to the PMBus makes this possible. This approach would give the system the capability to monitor the operating conditions during usage and utilize adaptive control of the power system configuration parameters as needed in order to optimize overall efficiency without any manual intervention. In addition to using this technique on an event-driven basis, it could also be done periodically to re-optimize the system or be done during a system reconfiguration or upgrade in the field. These powerful digital power management techniques should enable system designers to make significant advances in the field of automatically reconfigurable systems.

7. CONCLUSIONS AND SUMMARY

This paper has demonstrated the feasibility of power and energy efficiency optimization at the individual power supply level using digital power control and at the system level using digital power management. Some of our conclusions are as follows:

- EVEN SMALL EFFICIENCY AND POWER LOSS IMPROVEMENTS ON AN INDIVIDUAL ASSEMBLY CAN HAVE SIGNIFICANTLY LARGE EFFECTS AT THE SYSTEM LEVEL
- ENERGY MANAGEMENT COMBINES THE BENEFITS OF DIGITAL POWER CONTROL AND DIGITAL POWER MANAGEMENT FOR THE PURPOSE OF HIGH LEVEL SYSTEM OPTIMIZATION
- ENERGY MANAGEMENT PAYS BIG DIVIDENDS IN BOTH COST AND ENVIRONMENTAL IMPACTS
- FOR INDIVIDUAL POWER SUPPLIES, DIGITAL POWER CONTROL CAN BE USED TO COMPENSATE FOR COMPONENT VARIATIONS AND AGEING
- AT THE SYSTEM LEVEL, DIGITAL POWER MANAGEMENT CAN BE USED TO RECONFIGURE THE BUS VOLTAGE AND RE-OPTIMIZE THE EFFICIENCY OF POL REGULATORS
- DIGITAL POWER MANAGEMENT IS POSSIBLE WHEN USING CONTROL ICS FROM DIFFERENT MANUFACTURERS
- DIGITAL POWER MANAGEMENT SHOULD BE CAPABLE OF DYNAMIC AS WELL AS STATIC OPERATION

The next few years should be very exciting at both the power supply level and at the system level as designers make use of these new capabilities. Ericsson is dedicated to continuing the development and marketing of power products that can be used to optimize Energy Management.

8. GLOSSARY

ADC	Analog to Digital Converter
FPGA	Field Programmable Gate Array
GUI	Graphical User Interface
IC	Integrated Circuit
ICT	Information and Communications Technology
MUX	Multiplexer
PMBus™	Power Management Bus
POL	Point of Load
PWM	Pulse Width Modulation
ROM	Read-Only-Memory
USB	Universal Serial Bus
µC	Microcontroller

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All referenced papers and data sheets can be found at Ericsson Power Modules' web site: http://www.ericsson.com/powermodules

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ERICSSON

DIGITAL CONTROL TECHNIQUES ENABLING POWER DENSITY IMPROVEMENTS AND POWER MANAGEMENT CAPABILITIES

Digital control can be used as an enabling technology to offer performance, value, reliability and power density improvements to the end user. A system power management interface may also be added to a BMPS without compromising cost or packaging density.

CONTENTS

ABOUT THIS PAPER

Material contained in this document has been presented first in March 22, 2007 at PCIM China, session 3 – Future DC/DC Converter Concepts – Part I.

PCIM China is an independent event within Electronica & Productronica China, organized by Munich Exhibitions. Like PCIM Europe, which takes place annually in Nuremberg in Germany, the PCIM event in China is an international meeting ground for specialists in power electronics and its applications in drive technologies and power quality. The event offers a chance to see the latest developments in power electronics components and systems.

ABSTRACT

This paper presents a detailed analysis of how digital techniques compare with traditional analog approaches in a Board Mounted Power Supply (BMPS). The analysis is based on a case study of a product from an actual production batch. It is shown that replacing some of the analog content with digital circuitry can provide performance benefits to the end user without incurring any penalties in the form of additional cost or design complexity. Power density, in particular, is significantly improved. In addition, work is presented showing how a simple cost effective communication interface can be added to the basic design so that the additional functionality of digital power management can be made available.

1. INTRODUCTION

Digital techniques can be applied at several points within a power system, both internal to power supplies and at the system level for purposes of implementing management and monitoring functions [4]. This paper elaborates on the former situation. It compares the effects at the system level of implementation of control functions internal to a Board Mounted Power Supply (BMPS) with digital techniques vs. the more traditional analog approaches. With either of the approaches considered in this comparison, the end user of the BMPS may treat the device in a traditional way without any need for digital techniques at the system level. The comparison is done by means of a case study using an actual production unit as a baseline design. Two digital designs are used in the study. One is a size-optimized design that offers a power output comparable to the analog product but with smaller physical dimensions. The second output-optimized design maintains a form factor similar to the analog version but increases the power output. The basic power train topologies remain constant across all three versions so that the focus of the comparison is the design flexibility made available due to the utilization of digital control techniques. Some of the areas of interest in the comparison are electrical performance and efficiency, parts count, power density, cost and reliability. The comparison is done from an end-user's perspective rather than focusing on benefits to the BMPS designer.

The BMPS used in the case study comparison is an Ericsson PMH8918L Point of Load (POL) regulator [1]. This is an 18 amp non-isolated synchronous buck regulator with a programmable output voltage and a nominal 12 V input voltage. This is a recent product with competitive specifications, so it is a good representation of a POL regulator using analog control. A previously published paper [3], estimated that digital techniques could reduce the required Printed-Circuit-Board (PCB) area by 40 to 50% for the same 18 A output current or allow an output current of 35 A in the same package size. This paper will show that these estimates were in fact too conservative and that even higher power and current densities are possible when using digital control techniques.

In addition to considering the user benefits of the digital control design internal to the POL regulator, a new interface connector was added to the digital versions so that digital power management techniques could optionally be used in the power system. The addition of this connector does not change the measured performance of the POL regulator or the results of the comparison between analog and digital control methodologies. The connector addition was done to demonstrate that providing this optional system capability could be accomplished without substantive negative impact on the cost or size of the BMPS.

The content of this paper is limited to the technical and performance trade-offs at the BMPS level as described above. To provide a broader context, including extension of digital techniques into the arena of power system management, the reader is directed to the white paper in reference [4].

2. CASE STUDY DESIGNS

2.1 EXISTING 18 A ANALOG PRODUCT

The Ericsson PMH8918L Point of Load (POL) regulator has a nominal output current of 18 A. It uses a non-isolated synchronous buck topology with a traditional analog control loop and operates at a switching frequency of 320 kHz. The output voltage is programmable between 1.2 and 5.5 V and the input voltage is nominally 12 V. The typical efficiency at 3.3 V output is over 92% and the calculated MTBF is 3.8 million hours.

The upper MOSFET has an $R_{DS\text{-}ON}$ specification of 8.8 mΩ and a gate charge specification, Qg, of 11 nC. The corresponding values for the lower MOSFET are 4.0 mΩ and 27 nC. The output inductor has a nominal value of 1.2 µH and a resistance of 2.3 mΩ.

The dimensions of the PMH8918L POL regulator are 38.1 x 22.1 x 9.0 mm. A photograph of the through hole version is shown in *Figure 1*.

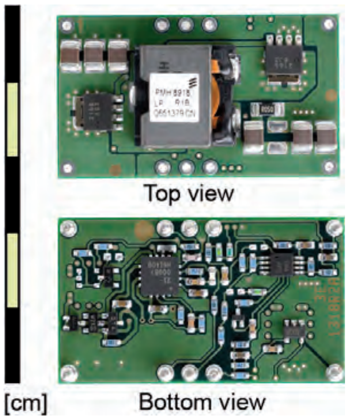


Figure 1 – PMH8918L analog design

2.2 SIZE-OPTIMIZED 20 A DIGITAL

A digitally controlled POL regulator was constructed that was capable of approximately the same output current and power as the analog PMH8918L. The basic topology was the same. A new PCB layout was used in order to optimize the size. The dimensions of the finished POL regulator were 25.4 x 12.7 x 8.5 mm and it was capable of supplying a maximum output current of 20 A.

It is important to be aware that much of the size reduction that became possible in this design was due to the lower component count associated with the digital control implementation. The higher level of integration eliminated several discrete housekeeping components used in the analog design. The efficiency was optimized by careful selection of the MOSFET devices and by minimizing the sum of MOSFET switching losses and conduction losses. The upper FET has an $R_{DS\text{-}ON}$ of 3.4 mΩ and a Qg of 30 nC. The lower FET has values of 1.8 mΩ and 47 nC. The lower RDS-ON values in combination with lower source inductance of the new devices result in a lower total for combined conduction and switching losses and optimize efficiency at full load. The output inductor is 1.0 µH with a resistance of 2.3 mΩ. The amount of copper in the PCB was also changed to allow for improved thermal management and minimized conduction losses.

The control chip used in this design features an "efficiency optimized dead time control". This feature results in enhanced efficiency as will be demonstrated later in this paper. More information about this technique can be found in reference [2]. This POL regulator operates at a switching frequency of 320 kHz.

Although they do not affect the performance of the designs and are not needed for basic functionality, a new signal interface connector was added to the digitally controlled POL regulators in this case study. Rather than using high current pins suitable for power connections, a simple standardized cost-effective 10 pin connector was designed. If desired by the end user, this connector can be used for purposes of communicating with system level power management circuitry and configuration of the POL regulator. By including the connector in these designs, it can be shown that it will not adversely affect the package size. A photograph of the completed 20 A size-optimized digital design is shown in *Figure 2*.

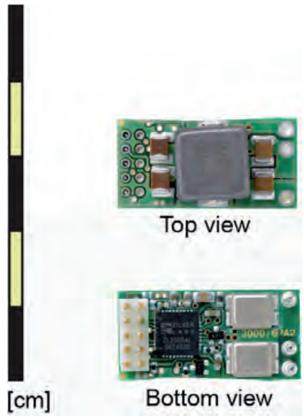


Figure 2 – Size-optimized digital design

2.3 OUTPUT-OPTIMIZED 40 A DIGITAL

Another digitally controlled POL regulator was constructed in a size similar to that of the analog PMH8918L but with enhanced output current capability. The final size was slightly less than the analog version, with final dimensions of 30.0 x 20.0 x 8.5 mm. The output current capability of this POL regulator was 40 A.

In order to support the higher current level, parallel MOSFETs are used in this design. The FET devices were selected based on the same criteria as the size-optimized design. The upper FETs have a combined RDS-ON of 1.7 mΩ and Qg of 60 nC. The lower devices' combined values are 0.6 mΩ and 141 nC. The inductor is 0.82 µH with a resistance of 1.7 mΩ to further minimizing the resistive losses. This design also operates at a frequency of 320 kHz using the same control chip as the 20 A digital design.

A photograph of the 40 A output-optimized design is shown in *Figure 3*.

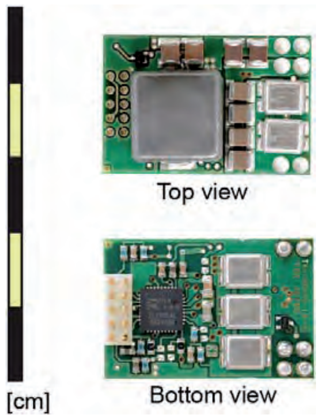


Figure 3 – Output-optimized digital design

3. PERFORMANCE COMPARISON

The three designs used in this case study are being characterized in terms of the normally accepted electrical performance parameters. These include output line and load regulation, efficiency, ripple and noise, and dynamic response. Due to the space limitations of this paper, we will only discuss efficiency in detail since it is a critical parameter that is of high importance to the end user. We can summarize the other electrical parameters identified above by saying that in all cases the performance of the two digital designs are equal to or better than the analog baseline design. Some of the preliminary comparative data can be found in reference [3].

3.1 EFFICIENCY

The PMH8918L used in this design comparison is a high current POL regulator. For this type of product, conversion efficiency is extremely important as it has a large influence on the system thermal design and ultimate packaging density as well as determining the input power required by the end equipment. Consequently, if digital control techniques compromise the efficiency they would not be an acceptable approach.

Curves showing the efficiency vs. output current for the three designs used in this study are shown in *Figures 4, 5 and 6*. The data for each of these curves was taken with an input voltage of 12 V, an output voltage of 3.3 V, and at an ambient temperature of +25°C. Comparing the 20 A digital design with the 18 A analog design shows that the digital implementation resulted in an efficiency improvement across the entire load range in spite of the significantly smaller size of the digital module. At half load, the digital POL regulator was 1.1% more efficient (93.8%) and at full load it was 1.2% more efficient (92.5%). The efficiency improvement in the digital design is achieved thanks to elimination of house-keeping circuitry and the dead-time control, but also thanks to a more optimized power-train.

Because the baseline analog POL regulator is designed and characterized at 12 V input, we used this input voltage to get comparable data for the digital design. As a side note, the efficiency of the digital design is even higher at lower input voltages. For example, its efficiency is approximately 1% better (94.8%) at half load when operated at an input voltage of 9.6 V. This could be an interesting area to explore for purposes of optimization of overall power system efficiency.

The 40 A digital design was optimized for higher current, and this is reflected in its efficiency performance between 15 and 30 A as shown in *Figure 6*. At under 10 A output, which includes much of the useful operating range of the 18 A analog design, its efficiency will be somewhat less than that of the analog POL regulator duo to higher switching losses. Its efficiency at half load (20 A) is 93.7% which is a 2.4% improvement over the efficiency of the analog design at a comparable current. At a full load output of 40 A, the efficiency is 91.9%, which is still 0.6% better than the analog POL regulator at full load. So over its intended design range, the 40 A digital also outperforms the analog design in terms of efficiency. The improvement can be attributed to the same elements as with the 20 A design. The 40 A design is also up to 1% more efficient when operated at 9.6 V input.

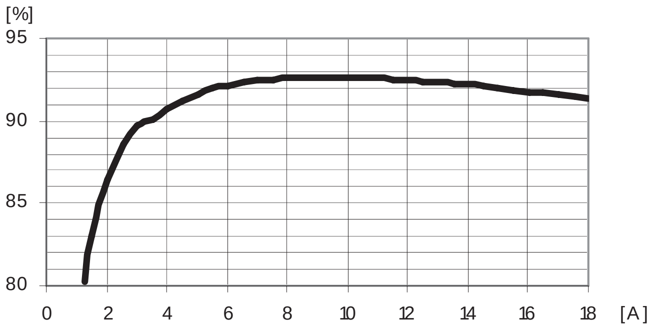


Figure 4 – Analog design Efficiency, Vout=3.3 V, T=25°C

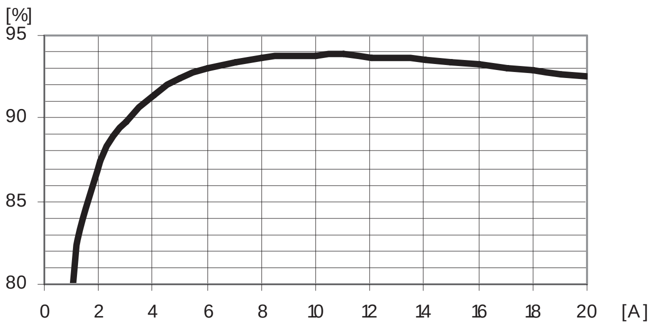


Figure 5 – 20 A Digital design Efficiency, Vout=3.3 V, T=25°C

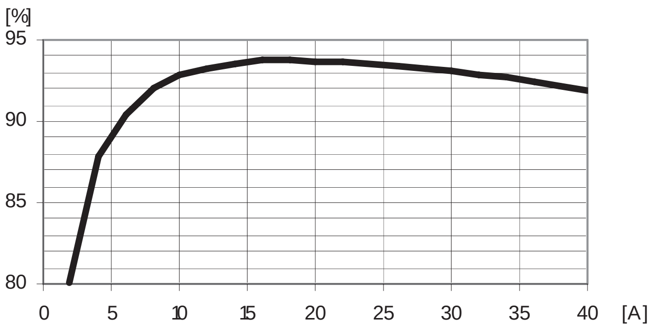


Figure 6 – 40 A Digital design Efficiency, Vout=3.3 V, T=25°C

Even though the 40 A digital design is more efficient than the analog POL regulator and is approximately similar in size, it will have a larger power dissipation because it is capable of over twice the output power and current. This results in a larger power density in terms of heat that needs to be removed from the BMPS. While the previous analog designs were size limited by the component packaging density, this type of digital design could be size limited by the heat transfer mechanisms for cooling the BMPS. That is, if conventional packaging materials and cooling paths are used, generating 40 A from a BMPS of this size could require additional attention to thermal management and ambient temperatures in the end-user's equipment.

3.2 PACKAGING DENSITY

Packaging density is heavily influenced by efficiency and is equally important to the end user. The reduction in component count in the digital designs, to be discussed below, contributes significantly to the higher packaging densities obtained. We have calculated density in two ways. The first is area current density expressed in terms of output amps per cm^2 of board area used by the POL regulator. The second is traditional power density calculated from the POL regulator maximum output power at 3.3 V and expressed in terms of watts per cm^3.

The 20 A digital POL regulator has a 289% better area current density and a 307% better power density than the baseline analog design. The 40 A digital POL regulator has a 312% better area current density and a 330% better power density than the baseline analog design. Stated another way, the 20 A digital design provides an additional 2 A of output current along with a reduction of 61% in board area vs. the analog product. The 40 A design provides a 22 A (122%) increase in current with a board area reduction of 28% compared to the analog design.

3.3 COMPONENT COUNT

The baseline POL regulator design using analog control used a total of 58 components excluding connector pins but including the PCB as one component. Using the same ground rules, the 20 A digital design has 24 components and the 40 A digital design has 41 components. As noted previously, this major reduction in parts was primarily responsible for the enhanced power densities achievable with the digital designs. In addition to the packaging improvements, the reduced parts count is expected to play a major positive role in the cost and reliability of future designs using digital control.

3.4 COST

Since PMH8918L is a production unit, the cost structure of the analog design is known with a high degree of accuracy. The digital designs are in prototype form and utilize some components, such as the digital control chip, that have been quite recently introduced and consequently do not have a well established pricing history. Furthermore, we expect that as digital control techniques receive wider acceptance the prices for some of the specialized components will decline. We therefore do not present a detailed cost analysis here. But because of the much higher degree of integration shown to be possible with digital techniques, along with their higher level of electrical and packaging performance, we are convinced that digital solutions will soon provide a much higher level of value to most users.

3.5 RELIABILITY

Detailed reliability calculations have not as yet been done for the prototype digital designs. The 18 A analog design has a calculated MTBF of 3.8 million hours. The two digital designs were done with the same component derating practices as used in the analog version. The lower parts count should more than offset the higher current levels in some areas of the digital designs. In general, the high degree of integration and fewer component interconnections of the digital designs should bode well for their reliability.

4. CONCLUSIONS

As a result of this case study several conclusions can be made about the viability of digital control in POL regulators relative to analog designs:

- THE GENERAL ELECTRICAL PERFORMANCE OF THE DIGITALLY CONTROLLED REGULATORS IS EQUAL TO OR BETTER THAN THE ANALOG VERSION.
- AT THE SAME CURRENT LEVEL, THE EFFICIENCY OF THE DIGITAL DESIGNS IS HIGHER THAN THAT OF THE ANALOG VERSION. EFFICIENCY IMPROVEMENTS IN EXCESS OF 1% ARE POSSIBLE.
- THE DIGITAL DESIGNS HAVE A DEFINITE ADVANTAGE IN TERMS OF PACKAGING DENSITY. THIS CAN BE USED TO MAKE BMPS SMALLER OR TO INCREASE THE POWER AVAILABLE WITHIN A STANDARDIZED PACKAGE SIZE.
- THE DIGITAL DESIGNS EXHIBIT DRASTICALLY IMPROVED CURRENT AND POWER DENSITIES WHEN COMPARED TO THE ANALOG POL REGULATOR, RANGING FROM 289% TO 330%.
- WITH THE INCREASED INTEGRATION OF THE 40 A DIGITAL DESIGN, THE PACKAGING LIMITATION BECOMES HEAT REMOVAL RATHER THAN COMPONENT AREA.
- THE DIGITAL DESIGNS SUBSTANTIALLY REDUCE THE PARTS COUNT, A 58% REDUCTION FOR THE 20 A DESIGN AND 29% FOR THE 40 A VERSION.
- ALTHOUGH DETAILED COST ANALYSIS IS NOT YET VIABLE, DIGITAL DESIGNS ARE EXPECTED TO OFFER OUTSTANDING VALUE TO THE USER WHEN COMPARED TO ANALOG BMPS.
- DUE TO LOW PARTS COUNT AND INCREASED INTEGRATION DIGITAL DESIGNS SHOULD PROVE TO BE EVEN MORE RELIABLE THAN ANALOG IMPLEMENTATIONS WHEN PREDICTIVE MTBF CALCULATIONS ARE USED.

In conclusion, digital control can be used as an enabling technology to offer performance, value, reliability and power density improvements to the end user with no additional design effort required from the OEM system designer. If desired, a system power management interface may be added to BMPS without compromising cost or packaging density.

5. REFERENCES

[1] Ericsson Power Modules: PMH8918L Technical Specification, April 2006, www.ericsson.com

[2] Zilker Labs, Inc.: ZL2005 Datasheet, 2006, www.zilkerlabs.com

[3] Ericsson Power Modules: “Performance Improvements for OEM System Designers – a Digital Control Case Study”, September, 2006, www.ericsson.com

[4] Ericsson AB: “Power supply goes digital”, October 2006, www.ericsson.com

All referenced papers and data sheets can be found at Ericsson Power Modules’ web site: http://www.ericsson.com/powermodules

10/287 01-FGB 101 378 Uen Rev B 2010-06-30

ERICSSON

IMPLICATIONS OF DIGITAL CONTROL AND MANAGEMENT FOR A HIGH PERFORMANCE ISOLATED DC/DC CONVERTER

Digital control implemented in an isolated DC/DC converter provides equal or better performance compared to an analog design. It also offers additional advantages in system energy management, improved flexibility and increased functionality.

CONTENTS

1. EXECUTIVE SUMMARY

Application of digital control techniques in power conversion is a development that is receiving a significant amount of attention. Ericsson has been working extensively in this field and believes that digital approaches can provide an overall benefit to the power system designer [1, 2]. Using digital techniques within a power supply for the purposes of implementing the control loop and control/monitoring functions is referred to as “digital power control”. Digital power control is completely transparent to the user of the power supply, as all of the external interfaces may be kept the same as those of one implemented with a conventional analog control scheme. “Digital power management” refers to the usage of digital techniques at the system level to monitor and control individual power supplies. This paper will focus primarily on digital control within a Board Mounted Power Supply (BMPS), but reference will be made to the possibility of extending the subject design to include digital power management.

This paper is a case study that compares digital control vs. analog control for usage in an isolated DC/DC converter. The analog control version is an existing high performance DC/DC converter that exemplifies the current state-of-the-art in terms of size, efficiency and reliability for telecom systems. The study methodology was to implement a new design within the same package size using digital control techniques. The main objective was to obtain performance that was equal to or better than that of the analog reference design. In addition, it will be shown that new features and capabilities can be added to the digitally controlled BMPS that are not possible when using the analog approach. Test data was taken to make performance comparisons between the two versions.

The study shows that the digital and analog designs are roughly similar in terms of efficiency, size, output ripple, component count and predicted failure rate. The digital version was superior in terms of output power, output regulation and dynamic load response. New features and capabilities that were possible with the digital design include output voltage feedback for enhanced regulation capability, adjustable output voltage, programmable output droop, and an optional interface for usage with digital power management at the system level. We conclude that the digital approach offers several overall advantages that are not possible with an analog design.

2. STUDY METHODOLOGY

A quarter brick sized BMPS supplying a bus voltage of 12 V was selected as the subject for this study. It is a fairly recent product that is already highly evolved in terms of efficiency and power density and is also expected to be in continued demand in the coming years. The reference analog design is an existing product which was recently released to the market, the Ericsson PKM 4304B PI [3]. Our ground rules for this study were to maintain the same physical package size and to include as much improved performance and added functionality as possible by using digital control techniques. As a preface to the details of our design decisions, it is important to understand the distinction between the various types of available DC/DC converters out of which some are referred to as Intermediate Bus Converters (IBC).

DC/DC converters in present production fall into three categories based on differences in control system and regulation of the output voltage. The first is the fixed ratio type, which is also sometimes referred to as a DC/DC transformer. This is the simplest type used for supplying a bus voltage in an Intermediate Bus Architecture (IBA) and has the advantages of minimal component count, highest efficiency and highest power density. This type of DC/DC converter is "free running" without any feedback from the source voltage or from the load, and delivers a DC voltage conversion based on the turns ratio of the high frequency converter transformer. For example, if a 4:1 turns ratio is used with a nominal 48 V input, the nominal output voltage will be 12 V. This output voltage, however, will vary directly with the input voltage and also will be very "soft" in terms of load regulation. Consequently, this type of DC/DC converter is not suitable for use in battery powered telecom systems with wide ranging input voltages.

The second type, called a semi-regulated DC/DC converter, is more complex and adds line voltage regulation by using a feed-forward control loop. This technique will isolate the output voltage from effects of the input source voltage so that the DC/DC converter is suitable for usage with wide range input voltages. The PKM 4304B PI falls into this category. The load regulation of this type will still be soft as defined by the output resistance of the DC/DC converter, so the output voltage will "droop" as the output load increases. This droop is sometimes used to provide automatic current sharing when two or more DC/DC converters are operated in parallel.

The third type of DC/DC converter, referred to as fully-regulated, is regulated by means of a feedback from the output voltage. Such a design may be used both for supplying a bus voltage but also lower voltages with tight regulation needed to power semiconductors and other payload components. This design decision increases the number of components and the circuit complexity as well as reducing the power density of the BMPS. However, it also provides the benefits of an adjustable output voltage and option of either a fixed output voltage or a programmed droop with any desired slope. It will be shown that the digital design approach used in this study was capable of implementing a full-featured and fully-regulated DC/DC converter with higher output power in the same power train and package as the semi-regulated reference analog design. *Figure 1* is a comparison of the reference analog DC/DC converter and the one with digital control. Note the much tighter output voltage tolerance band of the digital fully-regulated DC/DC converter.

	ANALOG REFERENCE (PKM 4304B PI)	DIGITAL
FORM-FACTOR	¼-BRICK (2.28"X1.45")	¼-BRICK (2.28"X1.45")
INPUT VOLTAGE	36 - 75 VDC	36 - 75 VDC
OUTPUT VOLTAGE	12 VDC +4/-9%	12 VDC +/-2% *
OUTPUT ADJUST	N/A	9 - 12 V
OUTPUT POWER	377 W**	396 W
SWITCHING FREQUENCY	125 KHZ	150 KHZ
CONTROL IC	ANALOG ASIC	DIGITAL µC
REGULATION	V_{IN} FEED FORWARD	V_{OUT} FEEDBACK
TOPOLOGY	FULL-BRIDGE	FULL-BRIDGE

Figure 1 - Comparison of DC/DC converter designs in case study (* From input voltage 38 V to 75 V; ** At input voltage 53 V)

3. REFERENCE ANALOG DESIGN

A block diagram of the PKM 4304B PI DC/DC converter with analog control is shown in *Figure 2*. This full-bridge converter has primary side control. The secondary side synchronous rectifier FETs are controlled via a signal form the primary PWM controller, transferred via an isolated signal transformer. The circuit also includes an isolated over voltage protection circuit. A small auxiliary supply is used to power the primary controller and both primary and secondary drivers. This is a very successful design within the telecom and datacom markets. The primary side control with feed-forward line regulation results in a fairly simple circuit requiring minimal board area for the control system. The slope on the output regulation curve allows for convenient current sharing by multiple converters.

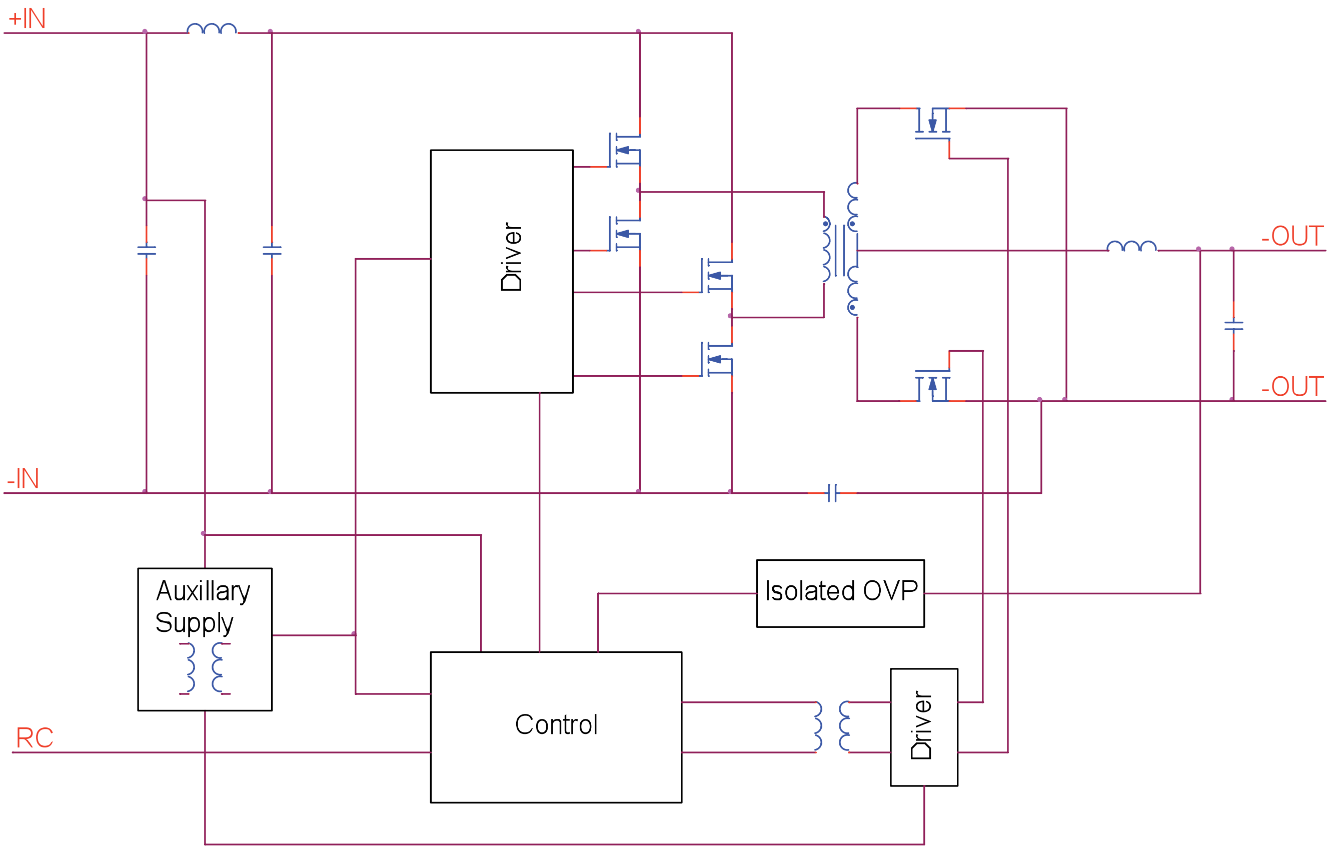


Figure 2 - PKM 4304B PI Analog Design

4. DIGITAL DESIGN

The digital design uses the same power train structure as that of the reference analog design. That is, the same topology and transformer but with some changes necessary to implement the new control system. This was done to keep the comparison as "apples-to-apples" as possible so that the differences in performance and functionality could be attributed to the control methodology. The control section is moved to the secondary side of the converter and is designed around a digital μC [4]. With the control circuitry on the secondary side, there is no longer a need to isolate the over-voltage circuit, but now isolation is required for the remote control interface line.

For purposes of establishing feasibility, an interface connector for digital power management was installed. This interface was primarily used when optimizing and configuring the control system during the design phase. Implementing it also concludes that it is possible to provide this interface within the confines of the quarter brick package which will enable the end-user to configure, control and monitor the BMPS. As shown in *Figure 3*, this digital DC/DC converter operates at a slightly higher switching frequency and is capable of an additional 19 W of power compared to the analog reference design. The increase can be attributed to the regulated 12 V output since the current rating remains the same.

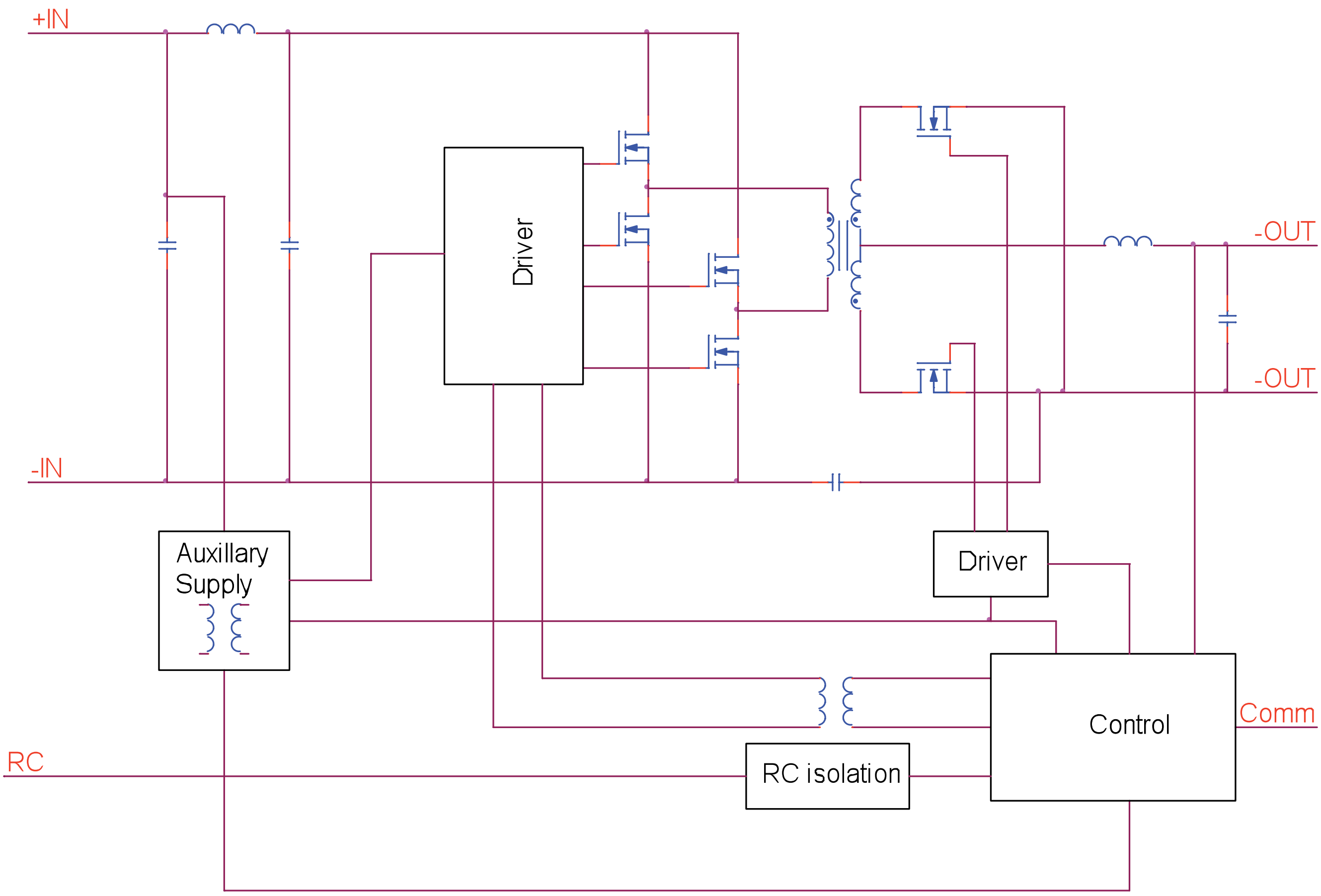


Figure 3 - Digital DC/DC Converter Design

5. PERFORMANCE EVALUATION

The main performance attributes of the two DC/DC converters were measured. In this section these data will be presented and compared.

5.1 EFFICIENCY

Efficiency is probably the most important parameter for this type of DC/DC converter. By definition, an IBC is used in a power architecture that has two or more stages of power conversion, so that total conversion losses must be tightly monitored. The PKM 4304B PI is a recent design and has one of the best efficiency curves in the market. As shown in *Figure 4*, its efficiency is over 96% over the most useful load current range and it has excellent efficiency over the full 36 to 75 V input range. This is a difficult standard to meet, but it is important that a successful digitally controlled design do as well in order to gain market acceptance.

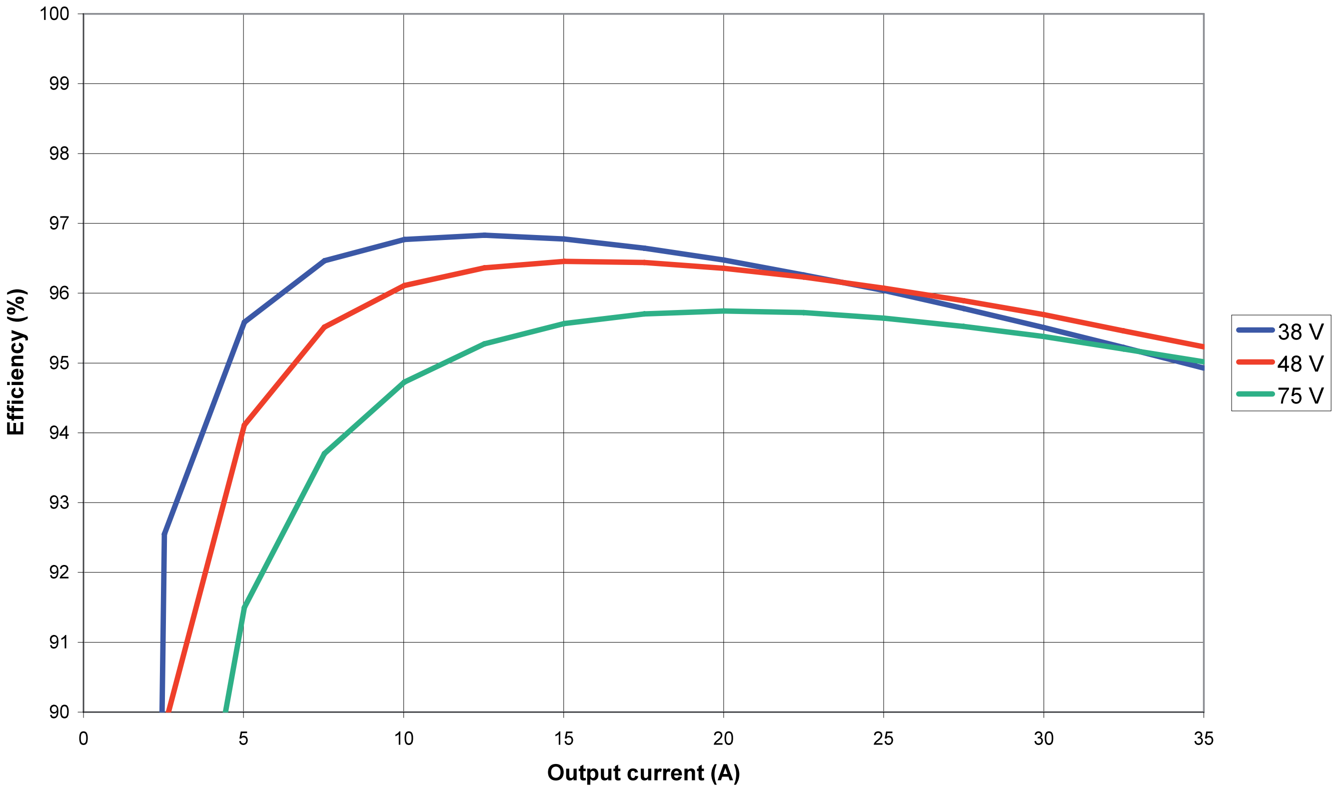


Figure 4 - Efficiency of PKM 4304B PI Analog Design

The efficiency curves for the digitally controlled DC/DC converter are shown in *Figure 5*. Note that the efficiency is over 96% over the same load current range as in the analog design. This is an excellent result, given that additional space normally is needed for the voltage feedback control loop. In the analog semi-regulated design, this space can be used to lower conduction losses in the power train. The dip in the efficiency curve at 75 V input between 5 and 10 amps output is not a measurement error. This is an artefact from the capability of the digital controller to change the transistor dead-time settings of the converter in an adaptive manner. This feature is actually in place to allow for optimization of efficiency vs. load current, but needs additional work to maximize its effectiveness in this application. We expect that a smoother curve will be possible in future versions of this design.

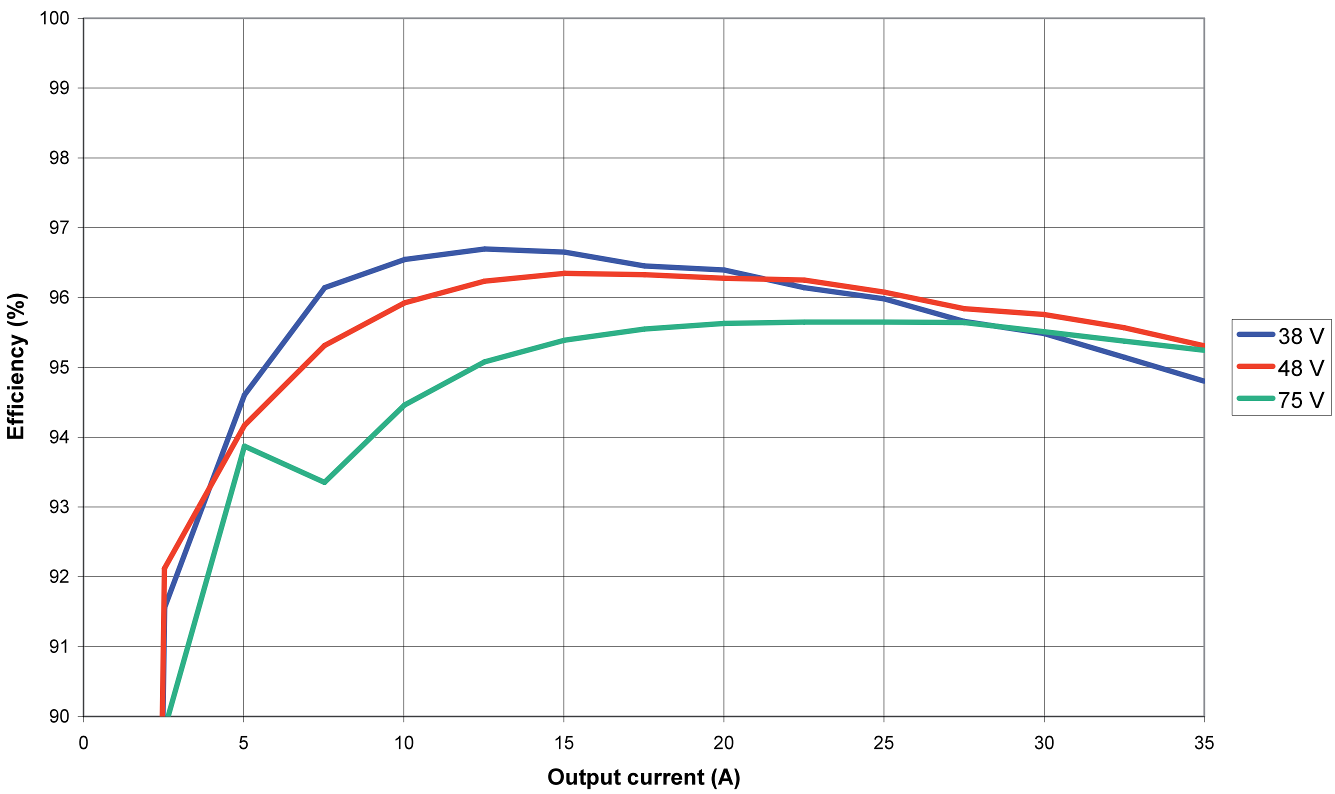


Figure 5 - Efficiency of Digital DC/DC Converter Design

The adaptive dead-time feature is actually an interesting and useful one. In a conventional analog design, the dead-time is fixed at a value that is a good compromise over the entire output load range. The digital control IC allows for the dead-time to be mapped as a function of output load in an adaptive fashion, resulting in meaningful reduction in power losses, especially at light loads. *Figure 6* shows a plot of this characteristic as a function of output load and source voltage. The curves represent the change in power dissipation relative to a fixed dead-time implementation within the same digital design. As can be seen, reductions in power loss of up to 2 watts are possible at light loads as well as some improvements at high load. We feel that this type of capability, although in its infancy, can be one of the major benefits of using digital control techniques.

Figure 6 - Benefit of Dead-Time Control in Digital DC/DC Converter Design

5.2 OUTPUT REGULATION

The output voltage regulation for the analog DC/DC converter is shown in *Figure 7*. The slope of the regulation curve is a result of the duty cycle being controlled by the primary voltage. As was noted earlier, this slope can actually be useful for the purpose of automatic current sharing between multiple DC/DC converters. The slope is mainly determined by the equivalent resistance of the BMPS which is a function of the resistance of the different components in the power train. At high input voltages the duty cycle will be smaller and the output impedance lower. The converse is true at low values of input voltage. Impedance will also be affected by temperature. It will increase at higher temperatures since both FETs and copper have positive temperature coefficients.

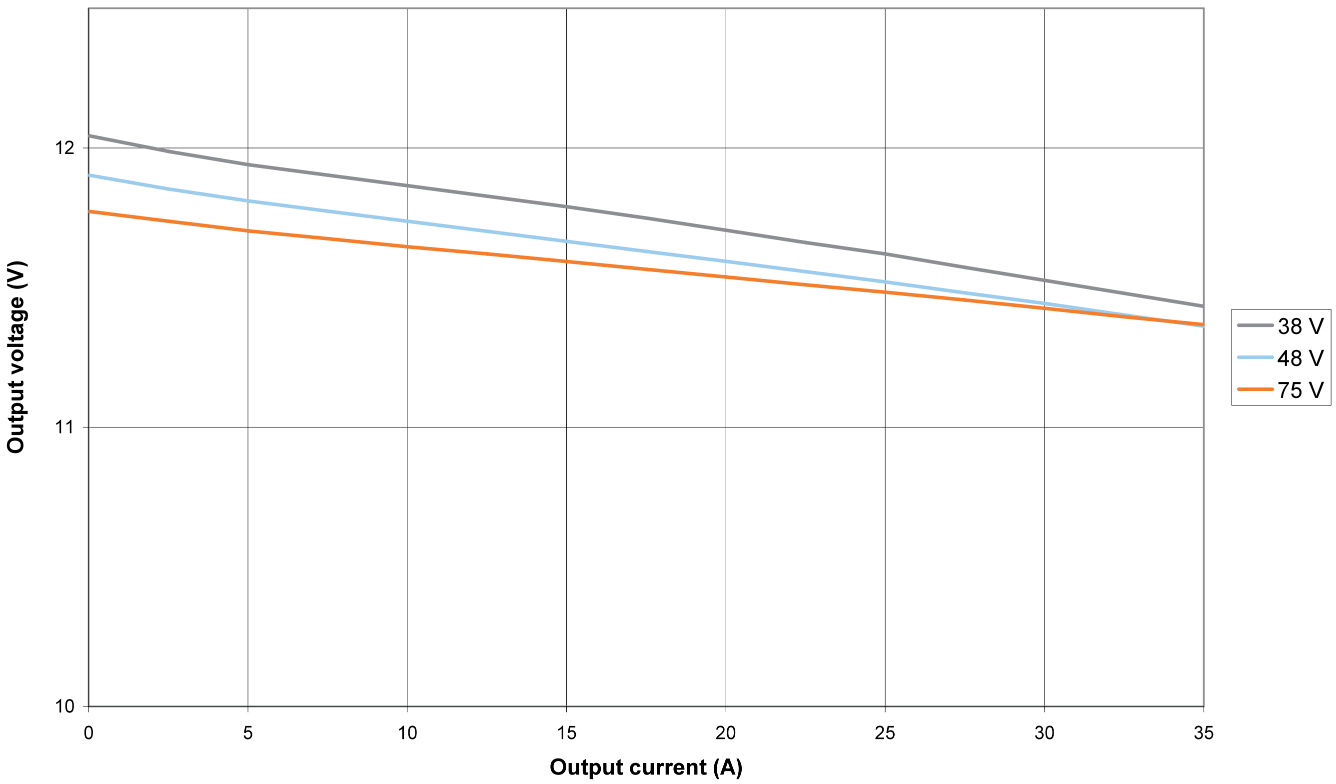


Figure 7 - Output Voltage Regulation of PKM 4304B PI Analog Design

A set of curves showing voltage regulation for the digital DC/DC converter is displayed in *Figure 8*. Because of the programmable slope capability of the digital design, any number of droop characteristics are possible of which three are shown. The upper curve, with essentially no droop, would be used in the case where the DC/DC converter was used independently without paralleling. When paralleling is used, the user would select the desired amount of droop. Note that the variation in output voltage vs. input voltage is tighter than was the case in the analog design. Also, the feedback loop can correct for variations in operating temperature, making for extremely accurate current sharing between converters. The best possible current sharing with the analog design is in the range of 90% of rated output power. With the digital techniques used here, sharing approaching 96% could be possible.

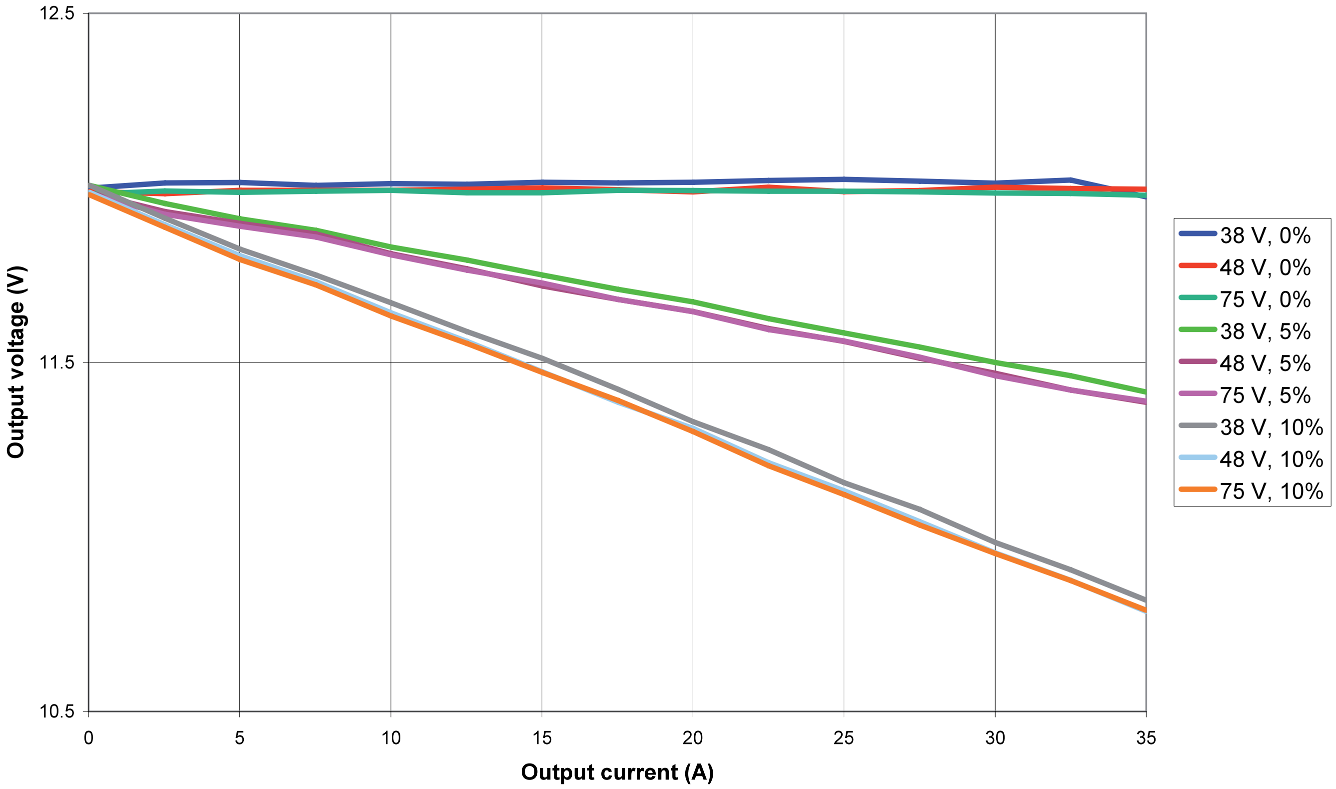
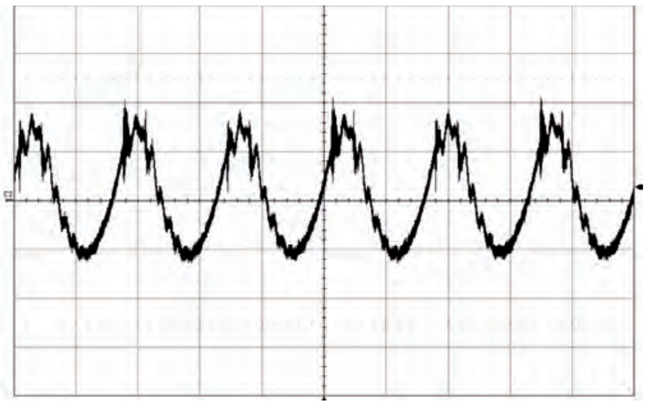


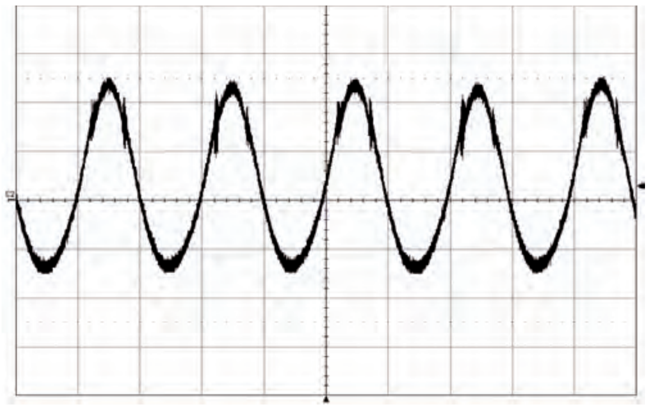
Figure 8 - Output Voltage Regulation of Digital DC/DC Converter Design

5.3 OUTPUT RIPPLE

The output voltage ripple for both the analog and digital DC/DC converter is shown in *Figure 9.* They are actually quite comparable, with the digital version being slightly better with a ripple of about 55 mV vs. approximately 70 mV for the analog design. The digital design had 80 µF of output capacitance vs. 70 µF for the analog version which along with the higher switching frequency account for the improvement. The lower ripple on the digital version could have an advantage for the user because less decoupling capacitance would be required at the load.



Digital, 150 kHz 80 µF output capacitance



Analog, 125 kHz 70 µF output capacitance

Test set up [5]:

Top trace Output voltage (20 mV / div)

Time-scale (2 µs / div)

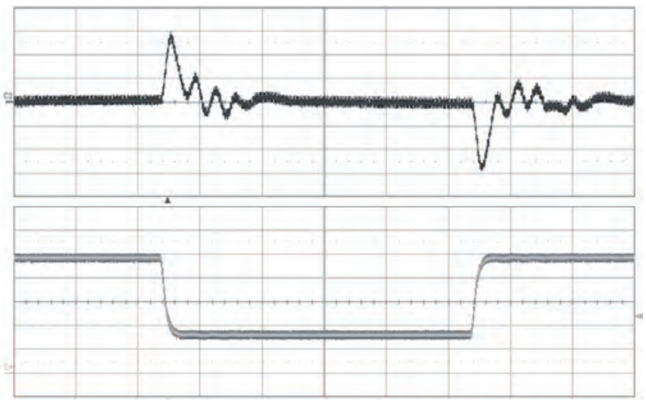
IOUT = 33 A load; TA = +25°C; VIN = 53 V

Figure 9 - Output Voltage Ripple

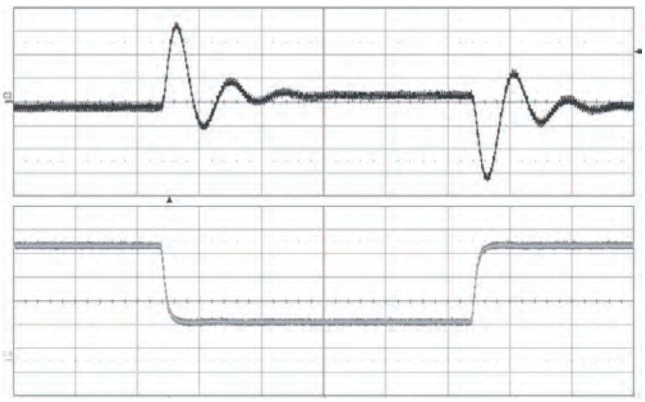
5.4 DYNAMIC RESPONSE

Dynamic response was measured using a 16 A change in output current with a 1 A/µs ramp rate. For both DC/DC converters, an external capacitor was used to simulate the bulk decoupling capacitance in a typical application. The external capacitor had a value of 68 µF with a 50 mΩ equivalent series resistance. Photos of the dynamic response characteristics of the two DC/DC converters are shown in *Figure 10*. The digital design provides a slightly better dynamic response than the analog version both in terms of the peak deviation and the settling time. Note that the nature of the voltage waveforms is different in the two versions.

Since it has no feedback from the output, the response of the analog DC/DC converter is dependent solely on the output capacitance internal and external to the BMPS and the output impedance of the DC/DC converter. In the case of the digital design, the feedback loop helps the DC/DC converter recover from the transitory current more rapidly. The digital design also uses non-linear settings of the PID controller in its feedback loop. This improves transient recovery even further by distributing the voltage deviation over time, generating a burst of peaks smaller than it would have been without the non-linear settings. The better response characteristics of the digital implementation should allow the system designer to use less decoupling capacitance to stay within a given tolerance band with some attendant cost savings. We feel that there is potential to further optimize the dynamic response characteristics of the digital design as part of the effort to increase the effectiveness of the non-linear PID controller.



Digital: 68 µF, 50 mOhm external cap



Analog: 68 µF, 50 mOhm external cap

Test set up:
Top trace Output voltage (500 mV / div)
Bottom trace Load current (5 A / div)
Time-scale (100 µs / div)
Load step 24 – 8 – 24 A (1 A / µs)
TA = +25°C; VIN = 53 V

Figure 10 – Dynamic Response

5.5 COMPONENT COUNT AND MTBF

In general, a DC/DC converter with a given functionality will require fewer components with digital control than with analog. This is due to the much higher level of integration within the digital control IC compared to the more discrete analog implementation. In this study, however, we did not keep the functionality constant. In the digital DC/DC converter it was possible to include secondary feedback which added greatly to the performance and somewhat to the complexity. The total component count for the PKM 4304B PI analog
DC/DC converter is 120, while the component count for the digital DC/DC converter is 132. In both cases, the count does not include interconnection pins.

A more detailed analysis was done to determine the actual benefit of using digital techniques within the control system. A second reference analog design was used. This new design was similar to the PKM 4304B PI with the addition of output voltage feedback and secondary side control so that its functionality was similar to the digital design. The number of components in the control section of this second analog reference design was used as a measurement standard. Compared with this control system reference, the PKM 4304B PI had 29% fewer components in its control section and the digital design had 31% fewer components. So the
net result is that by using digital control there was a reduction in control components even though there was more functionality in the digital design. The 12 additional parts in the raw component count for the digital design was actually due to a slightly different implementation of the power train details which offset the savings of components
in the control section. Further optimization of the digital design should allow these additional parts to be eliminated. A summary of the component count analysis along with photographs of both converters is shown in *Figure 11*.

A reliability prediction calculation was done for both DC/DC converter designs using the methodology in Telcordia SR332, issue 1, black box technique. The result for the analog design was 1.13 million hours vs. 1.03 million hours for the digital version. These results are very close especially considering the increased functionality of the digital design. The slight difference is related to the previously mentioned component counts.

ANALOG REFERENCE (PKM 4304B PI)

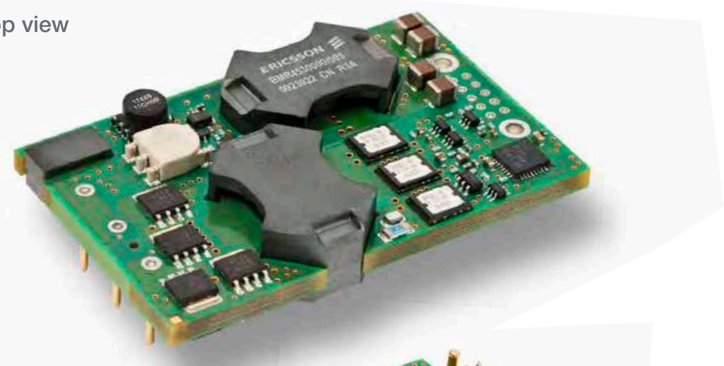
Top view

Bottom view

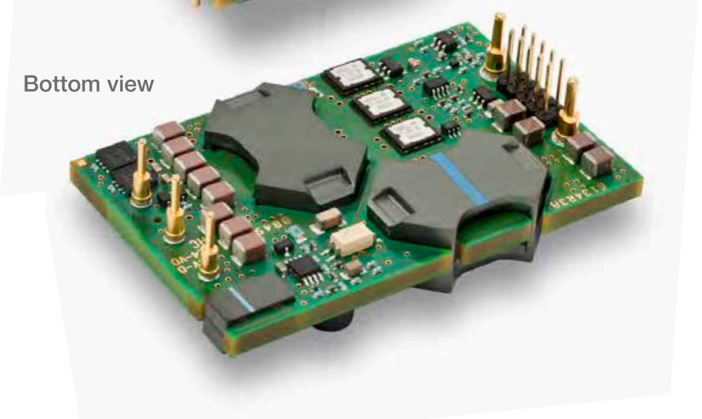
Component count: 120 pcs; MTBF: 1.13 million hours;
Control system -29%

DIGITAL DESIGN (BMR453)

Top view



Bottom view



Component count: 132 pcs; MTBF: 1.03 million hours;
Control system -31%

Figure 11 - Component Count and MTBF

6. CONCLUSION

The digital design was equal to or better than the analog reference design in almost all respects. Component count for the digital design is somewhat higher due to a slightly different implementation of the power train details which offset the savings of components in the control section. Further optimization of the design should eliminate the difference in component count.

The performance of the analog and digital designs was similar in the following areas:

- EFFICIENCY
- OUTPUT VOLTAGE RIPPLE
- SIZE
- PREDICTED RELIABILITY

The performance of the digital design was measured to be significantly better than that of the analog version in these areas:

- OUTPUT POWER
- OUTPUT VOLTAGE REGULATION
- DYNAMIC RESPONSE

In addition to the measured data, the digital design offers benefits not available with the analog implementation such as:

- REDUCED POWER DISSIPATION DUE TO ADAPTIVE DEAD-TIME CONTROL
- ABILITY TO ADJUST THE OUTPUT VOLTAGE
- PROGRAMMABLE DROOP FOR ENHANCED CURRENT SHARING PERFORMANCE
- INCREASED FLEXIBILITY AND FASTER IMPLEMENTATION OF DESIGN CHANGES
- OPTION OF DIGITAL POWER MANAGEMENT INTERFACE WITHOUT SIZE PENALTY

The performance attributes and additional benefits of digital power control summarized above reconfirm Ericsson's belief that digital power techniques have an exciting future in high performance power electronic equipment. We will continue to explore and optimize the usage of digital power techniques within our product offerings with a strong focus on higher total system efficiency and reduced energy consumption. We also expect that digital power management techniques utilized at a power system level will bring additional end-user value and spur the adoption of digital techniques forward.

7. GLOSSARY

ASIC	Application Specific Integrated Circuit
BMPS	Board Mounted Power Supply
BOM	Bill of Material
FET	Field Effect Transistor
IBA	Intermediate Bus Architecture
IBC	Intermediate Bus Converter
IC	Integrated Circuit
MTBF	Mean Time Between Failure
OEM	Original Equipment Manufacturer
PID controller	Proportional-Integral-Derivative controller
µC	Micro controller

8. REFERENCES

1. Ericsson Power Modules: “Performance Improvements for OEM System Designers – a Digital Control Case Study”, September, 2006, www.ericsson.com

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All referenced papers and data sheets can be found at Ericsson Power Modules’ web site: http://www.ericsson.com/powermodules

MPM-07:000199 Uen Rev B 2010-06-29

ERICSSON

PERFORMANCE IMPROVEMENTS FOR OEM SYSTEM DESIGNERS

A Digital Control Case Study

Digital control can be used as an enabling technology to offer cost, reliability and power density improvements to the end user with no additional design effort required from the OEM system designer.

CONTENTS

1. EXECUTIVE SUMMARY

Digital control techniques can be applied at several points within a power system, both internal to power converters and at the system level for purposes of implementing control and monitoring functions. This paper elaborates on the former situation. It compares the effects at the system level of implementation of control functions internal to a dc/dc regulator with digital techniques vs. the more traditional analog approaches. With either of the approaches considered in this comparison, the end user of the regulator may treat the device in a traditional way without any need for digital techniques at the system level. The comparison is done by means of a case study using an actual production product with only the minimal required changes to the power train so that the effects of the control system implementation are highlighted. Some of the areas of interest in the comparison are electrical performance including efficiency, parts count, power density, cost and reliability. The comparison is done from an end-user's perspective rather than focusing on benefits to the regulator designer.

The power module used in the case study comparison is an Ericsson PMH8918L Point of Load (POL) regulator. This is an 18 amp non-isolated synchronous buck regulator with a programmable output voltage and a nominal 12 V input voltage. Most of the power train components were kept common between the analog and digital control designs, as described later. Electrical performance parameters were measured directly on the two designs. Calculations were used to estimate the differences between the regulators for parameters related to the respective parts counts of the two approaches.

The comparison results can be summarized as follows:

- THE ELECTRICAL PERFORMANCE, INCLUDING EFFICIENCY, OF THE DIGITALLY CONTROLLED REGULATOR IS EQUAL TO OR BETTER THAN THE ANALOG VERSION.
- THE DIGITAL SOLUTION RESULTS IN MORE THAN A 60% REDUCTION IN PARTS COUNT. THIS INCREASED INTEGRATION WILL REDUCE THE COST OF THE REGULATOR.
- THE REDUCED PARTS COUNT RESULTS IN A REDUCTION IN REQUIRED REAL ESTATE FOR THE REGULATOR CIRCUITRY. THIS CAN BE USED EITHER TO REDUCE THE SIZE OF THE DEVICE OR TO INCREASE THE POWER OUTPUT WITHIN THE PRESENT SIZE ENVELOPE.
- THE REDUCED PARTS COUNT WILL INCREASE THE PREDICTED RELIABILITY.

In conclusion, digital control can be used as an enabling technology to offer cost, reliability and power density improvements to the end user with no additional design effort required from the OEM system designer.

2. TEST CONFIGURATION AND CONDITIONS

An Ericsson PMH8918L non-isolated POL regulator was selected as a baseline for the comparative study of differences between analog and digital control. This regulator has the following basic specifications:

OUTPUT CURRENT	18 A
TOPOLOGY	SYNCHRONOUS BUCK
CONTROL	TRADITIONAL ANALOG PWM
INPUT VOLTAGE	10.8 TO 13.2 V
OUTPUT VOLTAGE	1.2 TO 5.5 V (USER PROGRAMMABLE)
SWITCHING FREQUENCY	320 KHZ
DIMENSIONS	38.1 X 22.1 X 9.0 MM (1.50 X 0.87 X 0.35 IN)

The output voltage was adjusted by means of a resistor between the Vadj pin and ground. The remote sense pin was tied to the output pin (local sensing). This device was selected because it fits into a very popular voltage and current range for POL regulators and should provide useful data for a wide range of customers. It should be noted that while Ericsson expects that the conclusions shown in this paper should apply over a fairly broad range of operating currents and power modules, the testing to date was only done on a small group of samples of this specific regulator device.

The digital control implementation is based upon the ZL2005 chip developed by Zilker Labs, Inc.. The PCB has the same area as the PCB used in the PMH8918L. The switching frequency of this digital implementation is 333 kHz, very similar to that of the analog regulator. To obtain the most objective comparison, the power train components used in both versions were kept the same except as noted below.

The PMH8918L uses a set of Renesas FETs for the high side and low side switches. The digital control implementation was made with the same Renesas FETs. These test results are labelled as "Digital Renesas". In order to make a small test of the "Efficiency Optimized Driver Dead time Control" (see section 5.12 in the referenced Zilker Labs datasheet) capabilities a second digital implementation was made using a set of Infineon FETs. These FETs have a higher gate resistance (1.2 ohms rather than 0.5 ohms) but are otherwise very similar in terms of important parameters such as drain-source on resistance and switching losses. In the data that follow, the digital control results using the Infineon FETs will be referred to as "Digital Infineon".

It was found that using ZL2005 "Efficiency Optimized Driver Dead time Control" the dead time setting capabilities can be used for a quick replacement of FETs, and, which is shown in this case study, can be used for efficiency improvements.

The actual FETs used in our evaluation are summarized in the table below, and references to the FET datasheets are also contained in the references section.

	ANALOG	DIGITAL INFINEON	DIGITAL RENESAS
LOW SIDE	HAT2166H	BSC029N025S	HAT2166H
HIGH SIDE	HAT2168H	BSC072N025S	HAT2168H

3. MEASUREMENT RESULTS

This section contains the results of the electrical measurements performed on the various regulator configurations. Test data for the Renesas FET digital configuration is less complete than that of the Infineon FET digital configuration due to time constraints. All measurements were taken with an input voltage of 12V and at room ambient temperature. The regulator output voltage was set to either 3.3V or 1.5V by means of the appropriate programming resistor.

3.1 EFFICIENCY AND POWER DISSIPATION

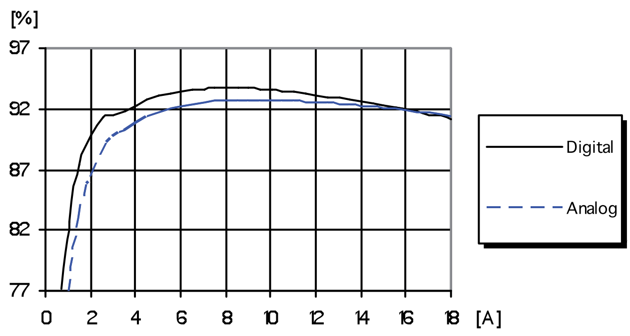

Figure 1 - Eff at 3.3 V - Renesas Digital

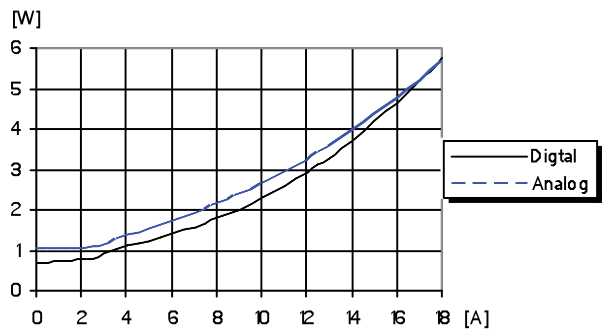

Figure 2 - Pwr Disp at 3.3 V - Renesas Digital

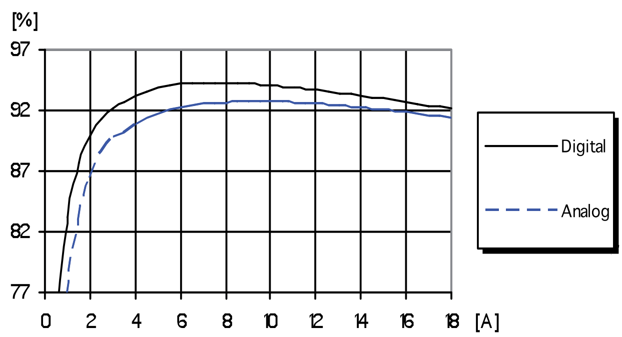

Figure 3 - Eff at 3.3 V - Infineon Digital

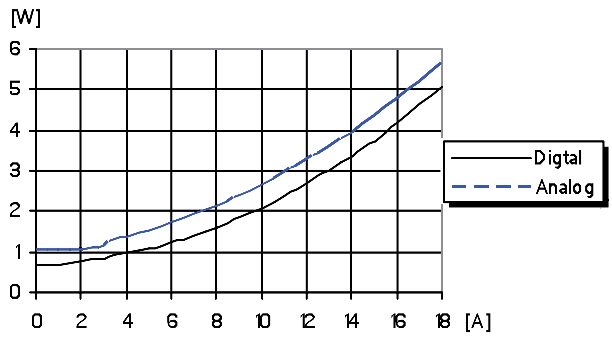

Figure 4 - Pwr Disp at 3.3 V - Infineon Digital

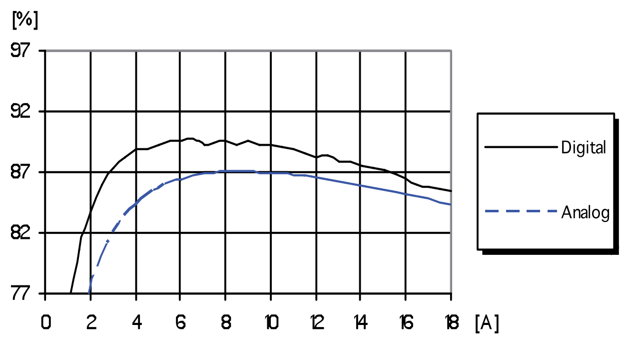

Figure 5 - Eff at 1.5 V - Infineon Digital

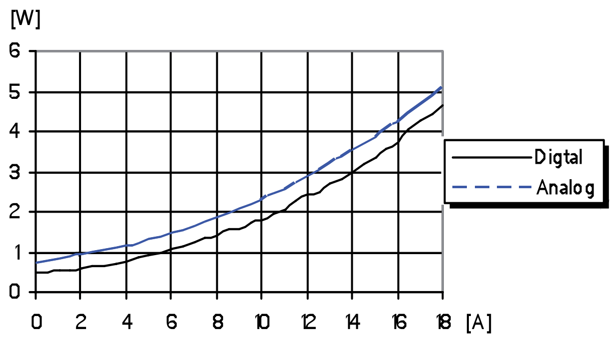

Figure 6 - Pwr Disp at 1.5 V - Infineon Digital

COMPARISON OF DIGITAL PERFORMANCE VS. ANALOG

	DIGITAL INFINEON		DIGITAL RENESAS	
	EFF	PWR DISP	EFF	PWR DISP
3.3V 18A	+ 0.8%	- 0.57 W	SAME	SAME
1.5V 18A	+1.2%	- 0.45 W	NO DATA	NO DATA

At full load, the Renesas digital configuration is equal to the analog solution, but does exhibit some improvement at lower load currents. The Infineon FET digital implementation is clearly better than the benchmark analog solution for both efficiency and power dissipation.

As can be seen from the Power dissipation diagrams in *Figures 2, 4 and 6*, there is a reduction in power dissipation in the digital implementation. This is due to the elimination of house-keeping and protection circuitry, which is necessary for the analog DC/DC solution.

3.2 OUTPUT REGULATION

The output regulation vs. load for Infineon and Renesas Digital implementation were identical. For simplicity, only Infineon digital measurements are shown, see *Figures 7 and 8*. The output regulation vs. load current of the Infineon digital and the analog solution are essentially the same. The slightly better performance for the digital solution exhibited in the above figures is due to small differences in the test setup used for the measurement of the analog and digital regulator.

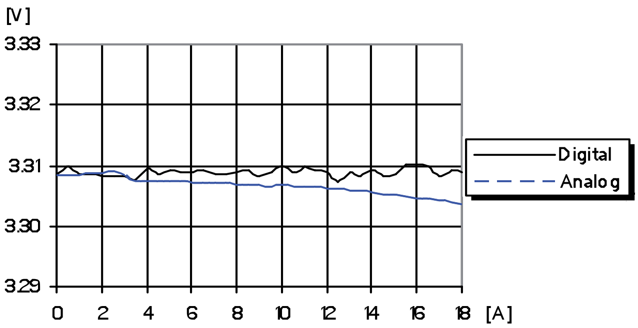

Figure 7 - Regulation at 3.3 V – Infineon Digital

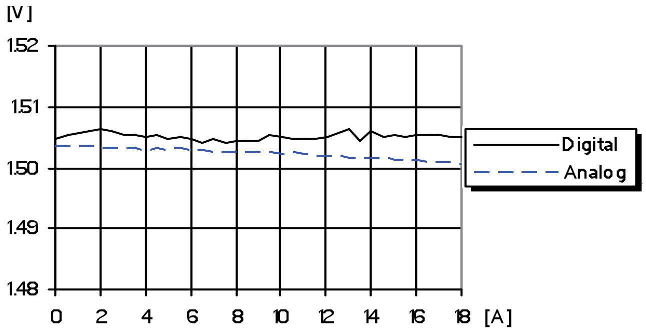

Figure 8 - Regulation at 1.5 V - Infineon Digital

3.3 DYNAMIC PERFORMANCE

Output ripple and noise and output load transient response were measured for both the analog and the Infineon Digital regulators. This testing was done at an output voltage of 3.3V. The filter used for the ripple and noise measurement consisted of a 0.1 uF ceramic and a 10 uF tantalum capacitor in parallel as defined in the datasheet for the PMH regulator. The dynamic load used for the transient response measurement consisted of a step change from 18A to 9A and then back to 18A.

The measured ripple and noise for the digital solution is slightly higher than the analog. The main reason for this is the difference in capacitance value, due to component tolerances in the external 330˚F capacitor. There is also a minor variation in-between the two due to the previously mentioned small difference in switching frequency. For practical reasons the ripple and noise may be considered the same. The analog solution provided a traditional smooth voltage response to the dynamic load current change as can be seen in *Figure 11*.

The peak amplitude is in the range of ±70 mV. The digital solution, which was programmed to work in Non-Linear Response mode (see section 5.11 of the referenced Zilker Labs datasheet), shows similar peak amplitude at low-to-high load transitions, and somewhat higher peak amplitude at high-to-low load transitions as can be seen in *Figure 12*. Due to the NLR mode operation, the peak is distributed over time generating a burst of peaks smaller than it would have been with the NLR turned off. Time did not permit optimization of the NLR settings, but we feel that the dynamic response waveform can be improved. Even as it is now, the amplitude of the voltage response is similar to that of the analog regulator response.

Our overall conclusion is that the digital approach offers similar or improved electrical performance when compared to an analog control design.

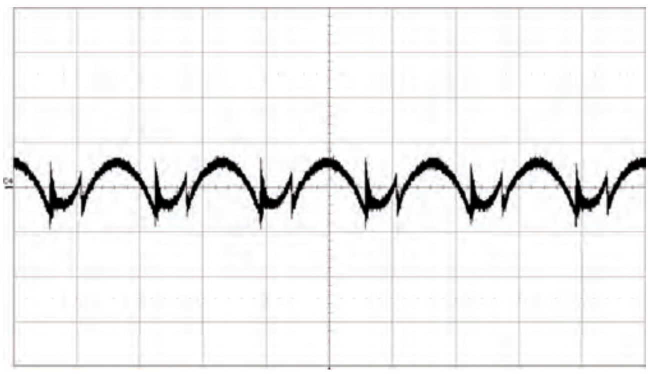

Figure 9 - Ripple & Noise – Analog (20mV/div, 2µs/div)

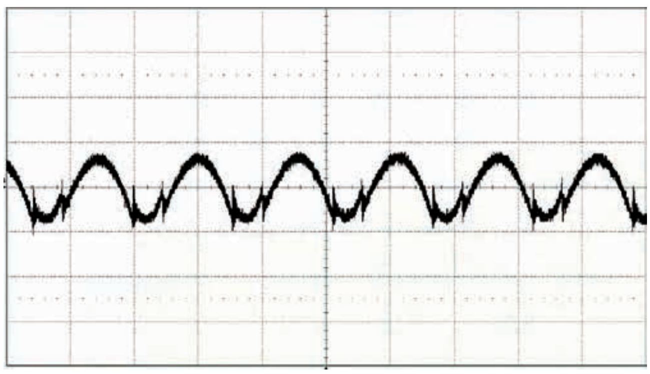

Figure 10 - Ripple & Noise - Infineon Digital (20mV/div, 2µs/div)

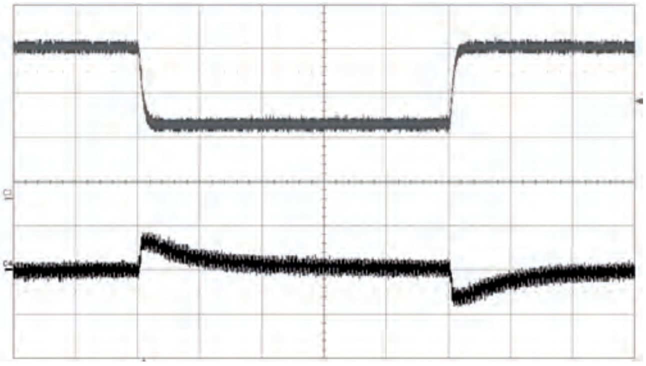

Figure 11 - Transient Response – Analog. Top trace: Load current (10A/div). Bottom trace: Output voltage (100mV/div)

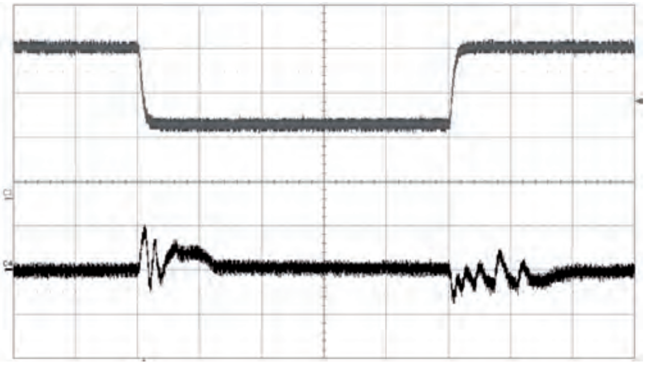

Figure 12 - Transient Response - Infineon Digital Top trace: Load current (10A/div). Bottom trace: Output voltage (100mV/div)

4. CALCULATED RESULTS

By using the BOM of the respective analog and digital designs, estimates can be obtained for such items as packaging area, cost and reliability. The comparisons in this section are between the benchmark PMH analog regulator and the digital control regulator using the Renesas FETs. The cost estimates in this paper are general in nature due to the uncertain trends in component costing, but there is sufficient data to project relative cost differences between the two approaches.

4.1 COMPONENT COUNT AND PACKAGING

The digital implementation resulted in a very significant reduction in component count relative to the benchmark analog regulator. Neglecting I/O pins (to be discussed later), the component count for the digital regulator is 21 vs. 58 for the PMH analog regulator, constituting a 64% reduction. This reduction will drive improvements in cost, packaging size and reliability.

One of the main assumptions of this particular case study is that we are only addressing the user benefit of using digital control internal to the POL regulator without any system level digital power management functions. Consequently there does not need to be any dedicated I/O pins for the purpose of digital communication between the regulator and the user's system. This is consistent with the pin design of the PMH regulator module (10 total pins). The PCB used in the digital implementation includes 3 additional pins dedicated to a digital interface between the regulator and the system (13 total pins). Since these pins were not used in this study, it was felt that the most meaningful comparison could be obtained by ignoring the pins.

Even though the PCBs of the two regulators have the same area, there is a significant difference in their packaging density due to the lower component count of the digital solution. Below are photographs of both sides of the populated analog and digital regulator PCBs.

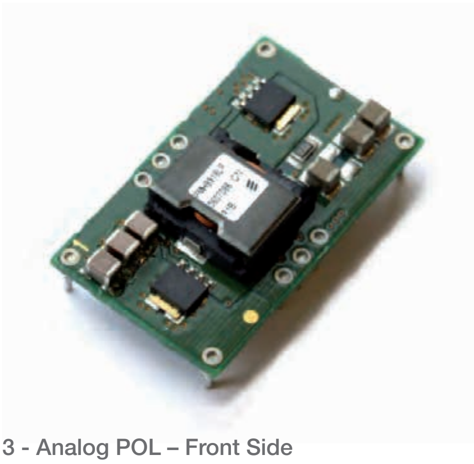

Figure 13 - Analog POL – Front Side

Figure 14 - Analog POL – Back Side

Figure 15 - Digital POL – Front Side

Figure 16 - Digital POL – Back Side

Obviously the digital POL regulator layout is not optimized in terms of packaging and would not be used for a production unit. We estimate that a production version of the digital design could be vastly improved in either of two ways:

- THE PCB BOARD AREA COULD BE REDUCED BY 40 TO 50% WHILE MAINTAINING THE 18 A CURRENT RATING, RESULTING IN SIGNIFICANT IMPROVEMENTS IN PACKAGING DENSITY FOR THE END USER.
- IF THE PCB BOARD AREA IS MAINTAINED WITH THE SAME DIMENSIONS AS THE PMH MODULES, THE OUTPUT CURRENT RATING COULD BE APPROXIMATELY DOUBLED, RESULTING IN OVER 35 A OF OUTPUT CURRENT. THIS OF COURSE WILL REQUIRE CHANGES TO THE POWER TRAIN COMPONENTS TO ACCOMMODATE THE INCREASED CURRENT LEVELS.

We conclude that the digital approach results in very significant benefits in terms of component count and packaging density when compared to the analog design.

4.2 COST ESTIMATES

It is premature to do an accurate quantitative assessment of BOM costs of the two approaches since the digital design is new and Ericsson does not yet have experience with large quantity production purchases of the required components. However, our preliminary, and forward-looking, analysis convinces us that there will be definite overall cost savings associated with the digital design.

In terms of BOM cost, the 10 pin version of a digital regulator should be definitely less than the present PMH design, due to the reduction in parts count. A 13 pin version with a communication interface, while slightly more expensive, should also be less than the analog implementation. There should also be cost savings during the assembly process due to the reduction in the number of components.

Our conclusion is that the production cost (and corresponding customer price) of a digital regulator should be less than that of a unit with the same functionality using analog control once quantities increase.

4.3 RELIABILITY ESTIMATES

Ericsson does extensive failure rate analysis and reliability predictions for all of its products. We use the methodology described in Telecordia SR332, issue 1, black box technique. MTBF predictions are made under the conditions of full output power at an ambient operating temperature of +40°C.

Using the above assumptions and methodology, the predicted reliability for the PMH analog and Zilker Labs ZL2005 digital approach are as shown below:

PMH8918L ANALOG	3.87 MILLION HOURS
DIGITAL	4.31 MILLION HOURS

The vast reduction in component count makes the digital version more reliable even with the addition of some complex components such as memory in the digital control chip. In an 18 A digital version built on the existing PCB area such as shown in *Figures 15 and 16*, the lowered component density would result in lower operating temperatures for the circuitry. This would further decrease the failure rate and increase the MTBF. This effect is not included in the above calculated reliability estimates.

We conclude that a digital control approach exhibits meaningful improvements in reliability when compared with a traditional analog regulator.

5. CONCLUSION

This paper is a case study that compares the differences, as seen by the end user, between power regulators implemented with analog and digital control techniques. We have tried to keep the comparison as fair and "apples to apples" as possible. While focused on a single design at an output current of 18 A, we believe that it is likely that many of the conclusions may, in general, be extended to other power module families.

Based upon the electrical measurements and calculations performed during the study, we conclude the following:

- THE ELECTRICAL PERFORMANCE, INCLUDING EFFICIENCY, OF THE DIGITALLY CONTROLLED CONVERTER IS EQUAL TO OR BETTER THAN THE ANALOG VERSION. ADDITIONAL WORK NEEDS TO BE DONE TO OPTIMIZE THE DYNAMIC LOAD RESPONSE OF THE DIGITAL DESIGN.
- THE DIGITAL SOLUTION RESULTS IN MORE THAN A 60% REDUCTION IN PARTS COUNT. THIS SIGNIFICANTLY INCREASED LEVEL OF INTEGRATION WILL REDUCE THE MATERIALS AND ASSEMBLY COSTS OF THE CONVERTER.
- THE REDUCED PARTS COUNT RESULTS IN A REDUCTION IN REQUIRED REAL ESTATE FOR THE CONVERTER CIRCUITRY. THIS CAN BE USED EITHER TO REDUCE THE SIZE OF THE CONVERTER OR TO INCREASE THE POWER OUTPUT WITHIN THE PRESENT SIZE ENVELOPE. IN ANY CASE, THE POWER DENSITY CAN BE SIGNIFICANTLY INCREASED USING DIGITAL CONTROL TECHNIQUES.
- THE REDUCED PARTS COUNT WILL INCREASE THE PREDICTED RELIABILITY.

These user benefits are achieved without any extra effort on the part of the OEM customer. The digital regulator module may be used interchangeably with the analog version and requires no specialized interface or design accommodation.

This study was conducted in Q2 – Q3 of 2006 and to the best of our ability reflects the situation in the 2006/2007 timeframe. If history is a guide, we expect that the benefits will swing even more in favour of a digital approach in subsequent years as parts availability, design experience and component pricing for digital control designs reach a higher level of maturity.

Ericsson plans to continue to explore the design of regulators and converters using digital controls. In the near future we will build, characterize and qualify designs using larger volume pilot runs. We also plan to further optimize the control designs and power train configurations to offer the most possible benefit to our customers.

6. GLOSSARY

BOM	Bill of Material
FET	Field Effect Transistor
I/O	Input / Output
MTBF	Mean Time Between Failure
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
POL	Point of Load
PWM	Pulse Width Modulation

7. REFERENCES

- Ericsson PMH8918L Datasheet
- Zilker Labs ZL2005 Datasheet
- Infineon BSC029N025S G FET Datasheet
- Infineon BSC072N025S G FET Datasheet
- Renesas HAT2166H FET Datasheet
- Renesas HAT2168H FET Datasheet

All referenced papers and data sheets can be found at Ericsson Power Modules' web site: http://www.ericsson.com/powermodules

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DIGITAL CONTROL IN A MICROTCA POWER SYSTEM

A look at the significant performance enhancements made available by using digitally controlled DC/DC converters in a MicroTCA power system.

CONTENTS

ABOUT THIS PAPER

Material contained in this document was first presented on November 13, 2007 at Digital Power Europe 2007 – Digital Power Applications session. Digital Power Europe (DPE) is a European-specific, three-day conference that served an international audience of decision makers who are interested in learning about and contributing to the latest practical advancements in digital power control techniques in electronics systems and power converters, along with digital energy management and power management in enterprise-level installations and related digital equipment.

1. INTRODUCTION

Micro Telecommunications Computing Architecture (MicroTCA™) is a relatively new architectural specification for Information and Communications Technology (ICT) equipment, intended for relatively small low power applications where it can be more cost effective than other ICT architectures. The key power assembly in MicroTCA is called the "power module". After a brief description of MicroTCA, this paper will address the MicroTCA power module in more detail, with an emphasis on how digital control techniques can enhance its performance. The design of the 12 V DC/DC converter function within the power module will receive particular attention. It will be shown that the output power density and efficiency of the power module can be significantly enhanced by techniques such as paralleling two converters with sophisticated current sharing and synchronization capabilities. It will also be shown that the Power Management Bus (PMBus™) can be an effective tool for communication within the power module.

This paper may serve as a general introduction to MicroTCA power systems for those readers who are knowledgeable about contemporary power system design but are considering their first designs to the MicroTCA specification. It should also be useful for those who are already conversant with MicroTCA but are looking for more information on the details of the power system implementation and choices in the power module design. The design challenges and proposed solutions will in many cases also apply to other more generic products such as Intermediated Bus Converters (IBC) intended for distributed power systems.

2. MICROTCA OVERVIEW

MicroTCA, which was ratified by the PCI Industrial Computer Manufacters Group (PICMG™) in July 2006, is the latest generation of open-architecture platforms developed by the PICMG for ICT equipment. It builds upon the heritage of previous architectures and technology such as Advanced Telecommunications Computing Architecture (AdvancedTCA™), maintaining much of the same functionality but with different system partitioning and with optimization to support systems with lower power levels such as Customer Premises Equipment (CPE) and Edge and Access equipment. While smaller and more cost effective than AdvancedTCA, the reliability and availability requirements for MicroTCA systems are typically just as stringent as those for equipment implemented with AdvancedTCA. The same basic functionality in terms of power conditioning and control is also required. One of the main differences between the two architectures is the degree of centralization and the physical partitioning of the power systems.

A typical MicroTCA equipment enclosure is shown in *Figure 1*. MicroTCA systems may be packaged in either 600 mm ETSI enclosures or 19 inch racks, with a 6U height considered a large system. Smaller enclosures are also possible. Most MicroTCA systems operate from -48 V DC telecom power, and this power source will be assumed in the remainder of the paper. +24 V and universal AC line power sources are also possible. Advanced Mezzanine Card (AdvancedMC™) modules are used to package the load electronics. These mezzanine modules are identical to those used with AdvancedTCA carrier-boards, leveraging development costs between the two architectures, providing a migration path and economies of scale for the production of AdvancedMCs. The AdvancedMC modules plug into the upper row of slots in the enclosure shown.

A key feature of the MicroTCA system is the power module, which contains the majority of the power conversion and control circuitry and eliminates the need for the large planar carrier-boards of the AdvancedTCA systems. The power module includes the functions of power filtering, DC/DC conversion, as well as power management. The system shown uses two power modules and they are located at the extreme right and left ends of the upper row of plugged modules. DC input power is plugged to the connectors on the front panel of the power modules, while 12 V and 3.3 V payload and management power is connected to the MicroTCA backplane at the rear of the power modules.

The power module is the focus of this paper and will be described in more detail in the following sections. The reader is referred to references [2] and [5] for more detail about MicroTCA.

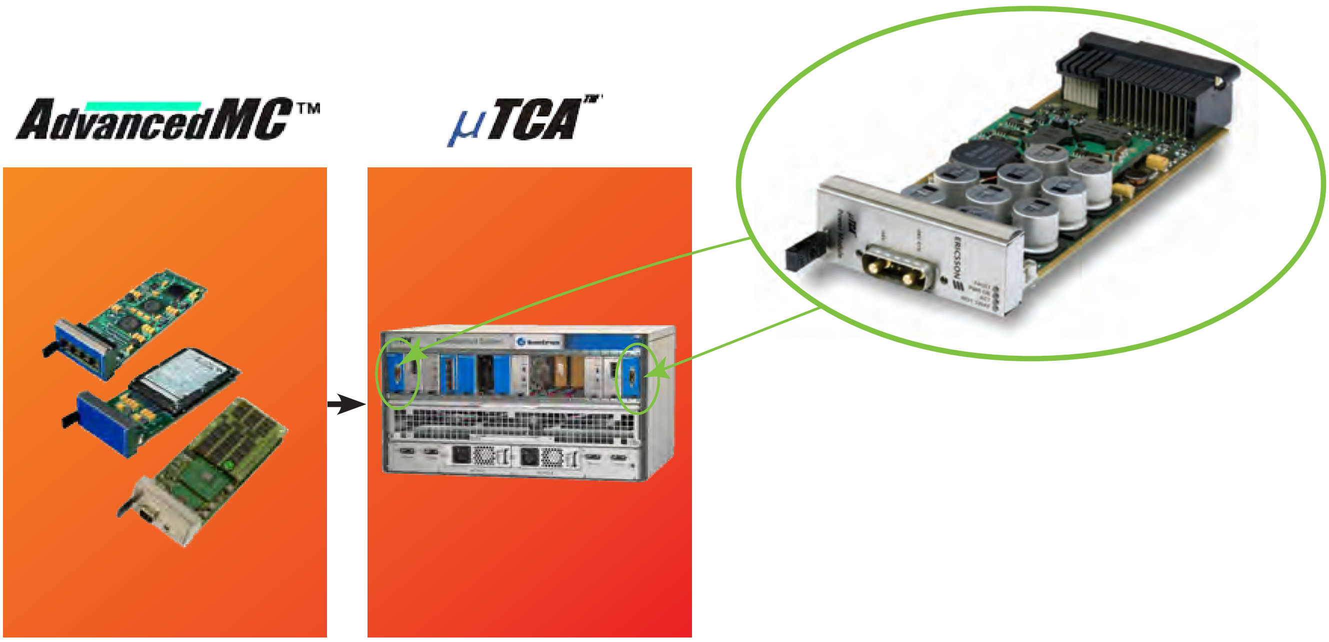


Figure 1 – MicroTCA sub-rack holding AdvancedMCs and power modules

3. MICROTCA POWER MODULE

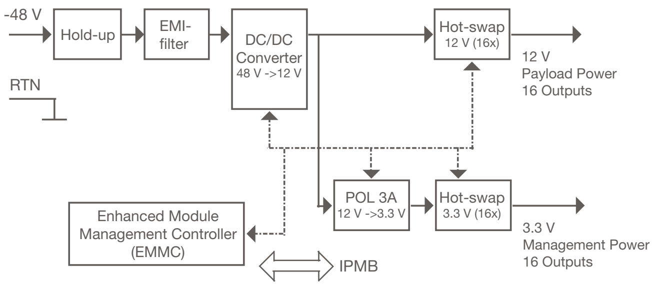
The power module provides both payload (12 V) and management (3.3 V) power for all of the loads in the MicroTCA enclosure. These loads may include 2 Cooling Units (CU) and 2 shelf-level MicroTCA Carrier Hubs (MCH) in addition to the maximum of 12 AdvancedMC modules, resulting in a maximum of 16 "channels" of output power. Over and above the power channels, the MicroTCA specification requires other functional content in the power module, resulting in the following list of functional requirements:

- INPUT POWER O-RING
- HOTSWAP CONTROL FOR INPUT POWER INRUSH PROTECTION
- INPUT POWER FILTERING
- POWER HOLD-UP CAPACITANCE
- 48 V TO 12 V DC/DC CONVERSION (PAYLOAD POWER)
- INPUT TO OUTPUT ISOLATION
- 12 V TO 3.3 V CONVERSION (MANAGEMENT POWER)
- OUTPUT POWER DISTRIBUTION
- HOTSWAP CONTROL FOR MULTIPLE ADVANCED MCS,CUS, MCHS
- OUTPUT POWER MONITO-RING AND CONTROL
- OUTPUT POWER PROTECTION CIRCUITRY

The consolidation of both power handling circuitry and system level control/management functionality into the relatively small centralized MicroTCA power module means that the power module design, performance and reliability are all crucial to the success of the overall system. The power module and particularly the 12 V Intermediate Bus Converter (IBC) function internal to it will be described in more detail in the remainder of this paper. *Figure 2* contains a block diagram showing the content of a typical MicroTCA power module.

In MicroTCA "raw" DC input power is supplied directly to the input connectors on the front of the power module. Therefore the power module must contain the necessary power conditioning and filtering that is done externally with some other architectures. Fusing in MicroTCA systems is typically done in a power distribution unit by providing fuses for each of the cables that distribute input power to the front of the power modules. Consequently, no internal fuses are normally contained within a power module. Other front-end functions are EMI filtering, inrush current limiting, hold-up capacitance and input power feed O-Ring diodes if used. A MicroTCA power module may be configured with either a single feed or with two redundant feeds.

The power module contains a -48 V to 12 V isolated DC/DC converter function with power levels up to 600 W. A Point of Load (POL) regulator from the 12 V output is used for generation of 3.3 V management power. Additional POLs, within the AdvancedMC modules are used to derive their needed low voltage power from the 12 V payload power. The control mechanism for MicroTCA power modules is the Enhanced Module Management Controller (EMMC), which monitors and controls both management and payload power for all of the AdvancedMCs, CUs and MCHs configured in the system. Communication between the EMMC and the external MCHs is done by means of the Intelligent Platform Management Bus (IPMB).



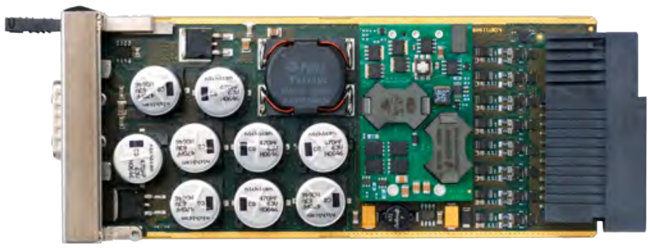


Figure 2 – Block diagram and overview of the Ericsson ROA 117 5078/1 power module

Figure 2 also contains a photograph of an actual power module, an Ericsson ROA 117 5078/1. This is an existing production module capable of up to 355 W of output power and is packaged in a "Single-Width Full-Height" form factor with approximate external dimensions of 74 by 187 by 29 mm. Some MicroTCA systems require power modules with up to 600 W of output power in the same package size. This requirement results in very high power conversion density and substantial design challenges for the power module if the desired reliability levels are to be maintained. Consequently, high efficiency is at the top of the list of design requirements. The remainder of this paper will delineate some of the design challenges posed by delivering more power in this same form factor and discuss proposed solutions to them. It will be demonstrated that digital control techniques offer opportunities for optimization of such a 600 W power module. For more complete information on the specification and implementation of MicroTCA power modules, the reader is directed to references [5] and [7].

4. POWER MODULE DESIGN CHALLENGES

The introduction summarizes the content of a MicroTCA power module and indicates that the design of a 600 W product is not a trivial exercise. We will next examine the design challenges of such a product in more detail, with emphasis on four different areas. Later, we will examine how digital control techniques can be used to turn these challenges into opportunities for enhanced performance and exciting products. While this information is presented within the context of a MicroTCA power module, the design challenges and proposed solutions will in many cases also apply to other more generic products such as IBCs intended for distributed power systems.

4.1 POWER DENSITY AND EFFICIENCY

Our goal of increasing the power module output power from 355 W to 600 W within the same physical form factor results in a significant increase in power density. The higher power demand has ramifications beyond the ratings of the 12 V DC/DC converter and 3.3 V POL regulator, as the capacity of the input filtering and hold-up capacitance must be correspondingly increased. The limitation, of course, is thermal dissipation within the confines of the power module, which should not exceed a total of 40 W for the single-width form factor. Our goal is to achieve an ambitious efficiency of 96% for the DC/DC converter function which will result in a maximum of 25 W of dissipation for this function, leaving 15 W of the 40 W budget available for dissipation in areas such as input filtering, power management components and output distribution losses.

4.2 CONDUCTED EMI

The power module must meet the class B conducted Electromagnetic Interference (EMI) requirements of EN55022 (CISPR22) and Telcordia GR-1089. A class B EMI filter at the 600 W power level can occupy a significant amount of circuit board area when used with conventional DC/DC converters, resulting in contention for space within the power module. To help solve this problem, our engineering objective is to design the DC/DC converter so that it is “filter friendly”, imposing a minimal demand on the conducted emission filter with a goal of minimizing its size and cost.

4.3 OUTPUT VOLTAGE TOLERANCE

The required output voltage tolerance on the power module 12 V payload output depends on whether power module redundancy is used in the MicroTCA system design. The MicroTCA specification does include provision for redundant power modules to increase system availability in critical applications. When needed, this capability can function quite well and achieve the system availability goals. It is important to understand, however, that power modules designed for redundant operation are inherently more complex and costly than power modules intended for stand-alone operation. A brief description of the MicroTCA power module redundancy scheme and its impact on output voltage tolerance requirements is presented here. Readers desiring more detail on the redundancy implementation and other power related impacts of the redundancy trade-off are directed to reference [5].

The MicroTCA specification requires that any given power module be identified to the system as either a primary power module or a redundant power module. In the event of a failure in any output channel of a primary power module, the redundant power module will take over responsibility for all output channels of that primary power module, not just the failed channel. Automatic transition between a failed primary power module and the redundant power module is accomplished by the settings of their output voltages. Primary power modules are set to a higher output voltage than redundant power modules, the two nominal settings being perhaps 12.5 V and 11.5 V. This output O-Ring allows instantaneous and automatic transition in the event of a failure due to the power module with the higher output voltage delivering power to the loads. This technique also imposes much more stringent voltage budgets and output regulation requirements on power modules used in redundant systems.

We will now examine the impacts of redundancy on the 12 V DC/DC converter. The basic MicroTCA specification defines the tolerance range for the AdvancedMC module input voltage as 10 V to 14 V. Since the load module will operate at any voltage in this range, the 12 V DC/DC converter could have a +/- 10% tolerance in a non-redundant system. In a redundant system, the situation becomes more challenging. In order to keep the voltage budgets of both the primary and the redundant power modules within the same overall range at the AdvancedMC inputs without possibility of overlap, the tolerance ranges for the primary power module would be approximately 12.25 V to 12.95 V and the range for the redundant power module from 11.6 V to 12.0 V. These ranges include the effects of line and load regulation as well as temperature. This means that the DC/DC converter in a power module intended for operation in a redundant system must have a +/- 2% output voltage tolerance. Going from a +/- 10% to a regulation tolerance of about +/- 2% has a significant impact on the DC/DC converter design.

A meaningful analysis and quantification of the above impact can be obtained by looking at two production DC/DC converters in the Ericsson product line.

Figure 3 summarizes the parameters of two Ericsson DC/DC converters with 12 V outputs and approximately the same input voltage range. They are both very contemporary designs and are highly regarded as representing industry-leading performance in terms of efficiency and power density given their respective design assumptions. They both have exactly the same form factors and total PCB area. The PKM 4304B is more loosely regulated with only feed-forward regulation from the input line voltage and no load regulation feedback loop. This greatly simplifies the module's control system, but does create a droop in its output load characteristic as shown in *Figure 4*. The additional space freed up by the less complex control system was used to enhance the power train resulting in high efficiency (95.3%) and output power (380 W). This converter could be used in a power module not intended for redundant applications.

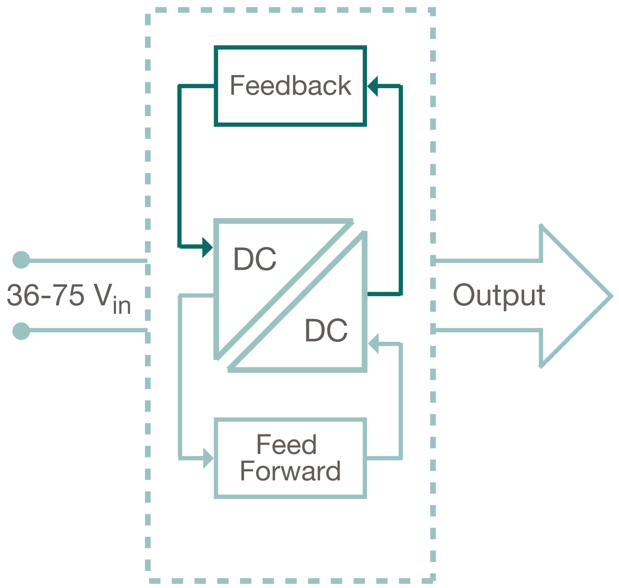
The PKM 4313C, in the same size physical package, contains output voltage feedback and features output voltage regulation of +/- 2.5%, close to the performance suitable for usage in a power module for redundant applications. But there are penalties for this enhanced performance.

The efficiency is 93.3%, significantly lower than that of the PKM 4304B. Also, the maximum power output is 204 W. The power density is only 54% that of the PKM 4304B. We can conclude from this that power modules used in redundant systems will have higher power losses than those intended for non-redundant systems, and that their internal packaging will be more challenging.

PKM 4313C PI	
INPUT RANGE	38 - 75 VDC
SIZE	36.8 X 57.9 MM (WXL)
VOUT TOLERANCE	+/- 2.5%
EFFICIENCY	93.3% (48 V IN, MAX LOAD)
OUTPUT POWER	204 W

PKM 4304B PI	
INPUT RANGE	36 - 75 VDC
SIZE	36.8 X 57.9 MM (WXL)
VOUT TOLERANCE	- 10.8 / +4.2%
EFFICIENCY	95.3% (48 V IN, MAX LOAD)
OUTPUT POWER	380 W

Figure 3 – DC/DC converters with 12 V outputs



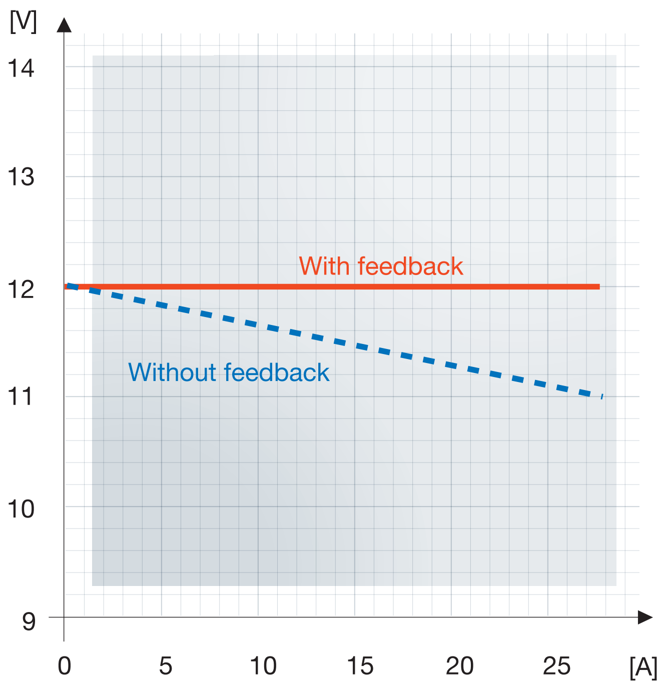


Figure 4 – Performance comparison with and without feedback loop

Consequently, our design goal of achieving 96% conversion efficiency at 600 W output in a restrictive power module form factor in conjunction with +/- 2% regulation for redundant applications is indeed a challenging one!

4.4 ENERGY MANAGEMENT

The power module contains an EMMC which communicates with the shelf-level MCH via two redundant 2 wire serial IPMBs as shown in *Figure 2*. The EMMC also communicates with the DC/DC converter. Since the DC/DC converter function is being done with a new design, it is possible that an innovative approach to the converter and its interconnection with the EMMC could achieve new capabilities in terms of intelligent energy management for the converter and result in benefits to the entire MicroTCA system. The new converter design then creates an opportunity for enhanced system level performance.

5. DIGITAL SOLUTIONS TO DESIGN CHALLENGES

Now that the challenges and objectives have been identified, we will describe an approach that provides solutions to all of them. After an overview of the proposed general implementation of the converter and control functions of the MicroTCA power module, more detailed data will be supplied showing how each of the four areas of concern have been addressed. In addition, it will be shown that the proposed solution may offer additional benefits to the power module and the MicroTCA system over and above the stated objectives.

5.1 OVERALL APPROACH

The solution proposed for the high performance MicroTCA power module is configured around a new Ericsson isolated DC/DC converter operating from the -48 V telecom input source and providing 12 V output at up to 396 W. The converter features a +/- 2% output voltage tolerance and is packaged in a ¼ brick package. It utilizes a full-bridge topology operating at a switching frequency of 150 kHz. A summary of the converter features and photographs of its construction are shown in *Figure 5*.

KEY FEATURES OF NEW DC/DC CONVERTER	
FORM FACTOR	¼-BRICK (2.28 X 1.45 IN.)
INPUT VOLTAGE	36 - 75 V
OUTPUT VOLTAGE	12 V ± 2%
OUTPUT POWER	396 W
SWITCHING FREQUENCY	150 KHZ
CONTROL IC	DIGITAL MICRO CONTROLLER
REGULATION	V_{OUT} FEEDBACK
TOPOLOGY	FULL-BRIDGE

Figure 5 – DC/DC converter with digital control

For comparison purposes, the PKM 4304B and the PKM 4313C mentioned previously use the same package size, but with significantly different power levels and output voltage tolerances. The PKM 4304B is capable of 380 W of output power but is loosely regulated with no output voltage feedback. Consequently it would not be suitable for use in a power module for a redundant MicroTCA system. The PKM 4313C is capable of tight output regulation, but can only deliver a maximum of 204 W under these conditions. Therefore, the new converter to be discussed here represents a substantial performance breakthrough even when compared to the referenced converters, which were considered state-of-the-art just a year ago.

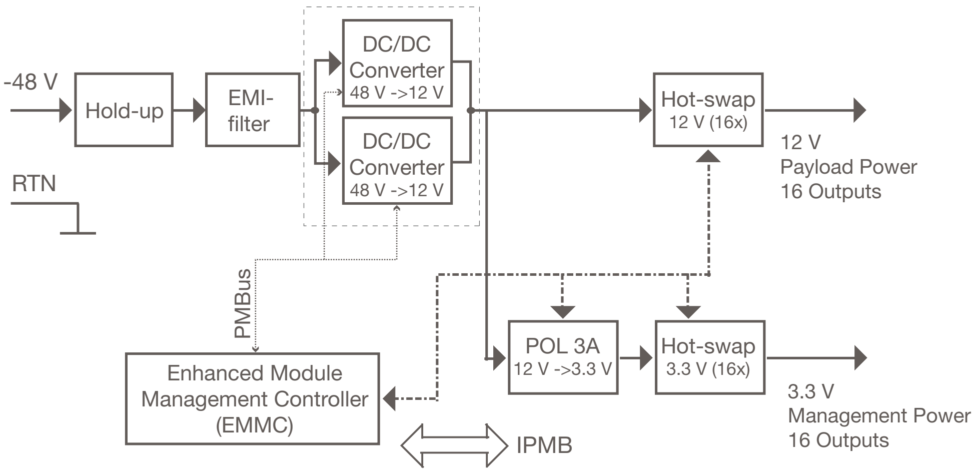
The enabling technology that allows for this significant advancement is digital control within the DC/DC converter. The conventional analog control IC was replaced with a digital micro controller. This technique has just recently become viable due to the better availability of lower cost high performance micro controllers suitable for use in power supplies. Most of the power train components of the converter remain the same as with an analog implementation. The micro controller, however, sweeps up a large quantity of discrete control and overhead components resulting in better integration, lower component count, less PCB area, and improved reliability. All this is reflected in the higher power density achieved by this converter. Additional detail about this converter design can be found in reference [6].

For this MicroTCA power module application two of these converters are operated in parallel to form a single high output power converter function that is capable of supplying the desired 600 W output power level. A PMBus is used for communication between the two converters and to the EMMC. A block diagram of the resulting power module architecture is shown in *Figure 6*. The dashed lines surrounding the two converter blocks indicate that they should be functionally considered as a single 600 W converter. The details of how this is accomplished and the resulting benefits are discussed below.

5.2 POWER DENSITY AND EFFICIENCY

The goal of 96% efficiency is a difficult one, but the paralleled converters are able to achieve it. The two converters normally behave as one higher power converter by means of an active current sharing connection between them. This connection is established via the communication interface connector that connects the dedicated current share pins on the converters, and the converters themselves regulate the current sharing without intervention from the EMMC. The PMBus connection from the converters to the EMMC is however used for other purposes as will be described later. Neither the converter to converter current sharing operation nor the EMMC to converter PMBus traffic interferes with the MCH to EMMC communication on the IPMB. No external components are required for the current sharing implementation, and current sharing to within 7-10% is targeted. The projected maximum current capability of two of these paralleled converters in other applications is up to 736 W.

The measured efficiency of the paralleled converter implementation is shown in *Figure 7*. The 96% efficiency objective is met at output loads from 40% to 100% of full load (20 to 50 A), which is outstanding performance. Note that the paralleled converters with current sharing can actually supply over 60 A of current, well above the rating for this power module application. This can be considered either as extra margin for increased reliability or as an opportunity for higher output power in future applications.



ENERGY MANAGEMENT FEATURES	
PMBUS INTERFACE	EMMC <-> DC/DC
SYNCHRONIZATION	DC/DC <-> DC/DC
CURRENT SHARE	DC/DC <-> DC/DC

Figure 6 – DC/DC converters with PMBus interfaces operating in parallel

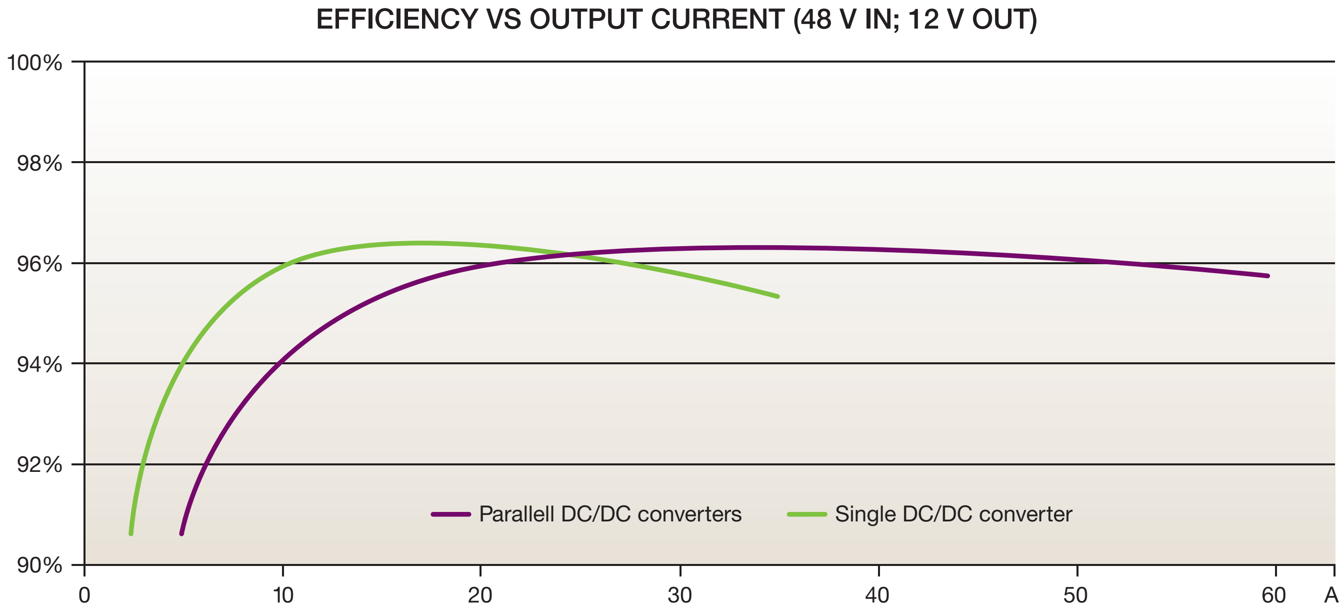


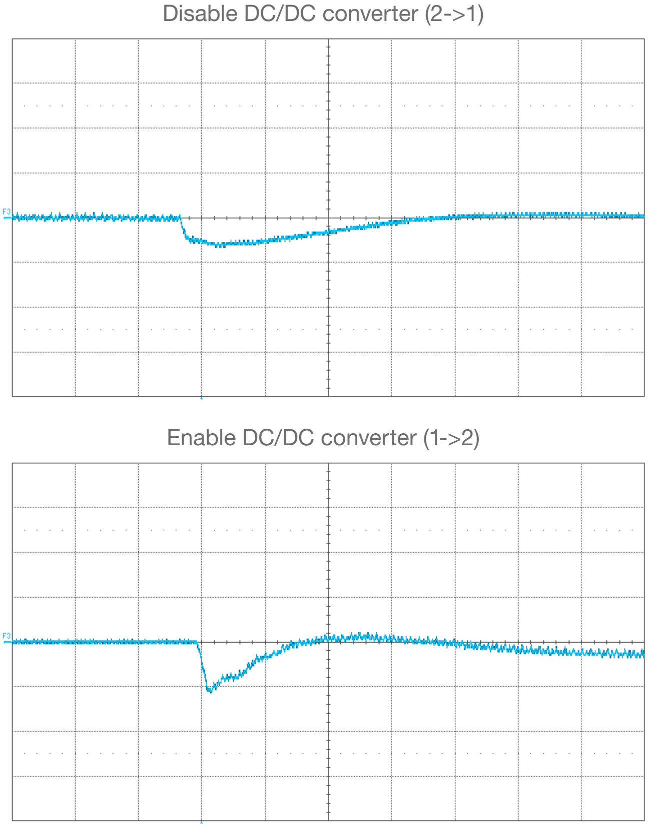
Figure 7 – Efficiency of the paralleled DC/DC converter implementation

Note that there is a second efficiency curve displayed in *Figure 7*. This is the measured efficiency of a single converter with output currents up to 33 A. As would be expected, the efficiency peak is at a lower current value than that of the paralleled converters. We believe that this characteristic creates an opportunity for further enhancing the performance of the power module. Consider a scenario where the EMMC determines the system current demand via communication with the MCH and automatically switches the DC/DC converter function from a current shared paralleled connection to a single converter when the system current requirements are low. This communication would be done via the PMBus. The negotiated switching point would need to contain a fair amount of "overlap" so that a single converter would not be operated near its maximum current rating to avoid overcurrent conditions.

With the automated converter changeover capability described above, the composite efficiency curve is truly impressive. The 96% efficiency objective is met with output loads from 20% to 100%. The efficiency is above 90% even at loads down to 2.5 A. This approach results in a significant savings in power losses. At light system loads, the switching losses of a single converter will be about half those of two paralleled converters. This is a very exciting result and should create exceptional benefit for MicroTCA system designers as well as other DC/DC converter users. It is a good example of how digital power control can create unexpected new capabilities and functionality.

Practical implementation of this automated converter selection capability will require seamless switchover without disruption to the system 12 V load or generation of any fault conditions. Some preliminary testing was done to assess the performance of the switchover from individual to paralleled operation. The upper oscilloscope trace in *Figure 8* shows the effect on the output voltage of switching from a paralleled converter connection to an individual converter. The test was done at an output load current of 20 A, so the operational converter sees an output current transition from 10 A to 20 A. This current change results in a slight depression in the output voltage – about 300 mV for a duration of 170 µs. This should not create any difficulties for the system.

OUTPUT VOLTAGE



Test conditions

48 V in & 12 V out	2.2 mF output capacitance
20 A output	No O-Ring on output
500 mV/div	Current share: DC/DC <-> DC/DC
50 µs/div	Enable: EMMC <-> DC/DC

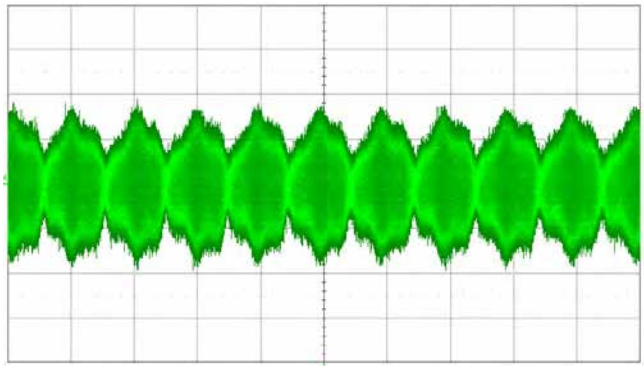
Figure 8 – Transition between single and parallel DC/DC converter operation

A more demanding condition occurs when switching from one converter to a paralleled connection. Synchronous rectification is used in the converters to maximize efficiency, so the output rectification is implemented with MOSFETs, which can conduct current in either direction. This can create difficulties when starting up into a pre-biased load, which is exactly the scenario presented with the start-up of the second converter in the paralleled configuration. Without proper management of the start-up, the converter could be overstressed or damaged by a reversed current and there could be a significant dip in the output voltage. O-Ring diodes could be used as a solution, but were rejected due to their negative impact on efficiency and component space. Instead, the O-Ring function is implemented with intelligent control of the output transistors. This approach would normally require the addition of a specialized controller IC, but with the digital control implementation of these converters the start-up control is handled by the existing on-board micro controller without the need for any additional components. The feasibility of this approach is demonstrated in the lower oscilloscope trace in *Figure 8*. The dip in the output voltage is due to some current being conducted into the second converter on start-up, but this current is at a safe level for the converter. The 500 mV dip in output voltage is more than desirable, however, and further work is under way to improve this aspect of the performance. We do believe, however, that these initial results are very encouraging and represent a meaningful advancement in the ability to achieve high efficiency over a very wide range of output current.

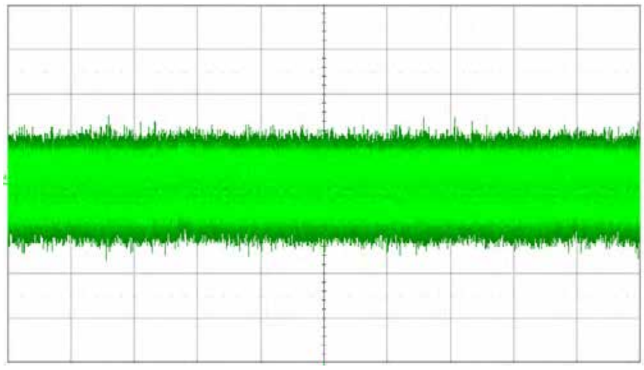
Another possible extension of this implementation would be to automatically reconfigure the power module to operate at a lower power level (up to 396 W) in the event of a failure in one of the paralleled DC/DC converters. This could achieve a temporary reduced performance mode until the power module could be replaced. This operation is currently not supported by the MicroTCA specification and would need to be collaborated with the design of the MCH. However it could be a possible way to create some additional redundancy and reliability within MicroTCA for those systems with a scalable output power.

AC INPUT RIPPLE CURRENT

Synchronization disabled



Synchronization enabled



Test conditions	
48 V in & 12 V out	150 kHz
0 A output	90° Interleaving
200 mV/div	No filter on input
5 ms/div	

Figure 9 – Synchronization and interleaving

5.3 CONDUCTED EMI

One of the objectives of this project was to design the DC/DC converter function of the power module so that the size and complexity of the class B conducted EMI filter is minimized. This objective was accomplished by designing the paralleled DC/DC converters to automatically synchronize their switching frequencies. The synchronization is accomplished with a direct connection between the two converters so that no intervention is needed from the EMMC via the PMBus. The synchronization is done in a “master-slave” implementation. The slave converter assumes the same operating frequency as the “master”, but with a 90 degree phase shift between them. This phase shift is critical for the purpose of minimizing the input ripple current of the combined converters with the interleaved full-bride topology.

The effect of this approach on the input ripple current is dramatic as shown in *Figure 9*. The maximum ripple current (and most stringent EMI criteria) for this topology actually occurs at light load, so the testing was done with no load on the output. The upper trace displays the input current with the synchronization feature disabled, and the lower trace the input current with the synchronization feature enabled. The significant reduction in ripple current in the lower trace demonstrates the effectiveness of this solution, and allows for a very small and compact implementation of the conducted EMI filter function.

5.4 OUTPUT VOLTAGE TOLERANCE

The objective of a +/- 2% output voltage tolerance while maintaining excellent efficiency as identified in section 4.3 has been met in this design, and documented in the discussion and test data presented in section 5.2

5.5 ENERGY MANAGEMENT

We have already described the two bus structures used in conjunction with the power module, the internal PMBus from the EMMC to the DC/DC converters and the external IPMB from the EMMC to the system MCH. We will now look at their implementation in more detail and also consider how they may be utilized in order to maximize the functionality of the power module and the total MicroTCA system. The EMMC could be implemented with a FPGA chip. Not all of the chip’s gates and I/O pins are required to configure the EMMC functions. The unused portion of the chip may instead be used to create the PMBus host controller, which primarily communicates with the two DC/DC converters via the two wire serial PMBus. This sharing of the FPGA between two functions results in a net reduction of needed components.

The EMMC would normally be connected to sensors located within the confines of the power module to measure data such as the system input voltage and internal power module temperatures. This information would then be sent to the MCH via the IPMB. With the implementation shown in *Figure 6*, some of these sensors and associated interconnections are not needed. Instead, the required data can be obtained directly from the DC/DC converters via the PMBus, resulting in additional hardware savings. There is also an opportunity to leverage the PMBus further by connecting it to functions such as the hotswap controllers.

In addition to reducing the number of discrete components in the system, the usage of the PMBus creates an opportunity for increased functionality and flexibility during all phases of the product life cycle. Some of these are summarized below.

CONVERTER DESIGN

- CHANGE OPERATING PARAMETERS SUCH AS OVERCURRENT LIMIT, FEEDBACK COMPENSATION, START-UP PROFILES, AND CONTROL OF OUTPUT RECTIFIERS
- CHANGES VIA SOFTWARE RATHER THAN SOLDERING IRONS AND PCB LAYOUT CHANGES
- FASTER DESIGN AND TIME-TO-MARKET

CONVERTER AND POWER MODULE MANUFACTURING

- SET OUTPUT VOLTAGE, CURRENT LIMITS, ETC.
- ADJUST FOR PROCESS VARIATIONS
- CONDUCT MARGIN TESTING

SYSTEM INTEGRATION AND FIELD DEPLOYMENT

- MONITOR AND ADJUST SYSTEM VOLTAGES
- DETECT AND RESPOND TO FAULT CONDITIONS

The above is only an abbreviated indication of the rich possibilities afforded by the usage of digital control for energy management purposes. References [4], [5], and [6] contain additional detail about these areas and are a source of many more ideas for utilizing the capabilities of the communication busses during the product life cycle.

6. CONCLUSIONS AND SUMMARY

This paper has set some aggressive objectives for various aspects of a new 600 W output MicroTCA power module. We have demonstrated that the design meets all these objectives as well as offering opportunities for additional features. The solutions to the stated objectives can be summarized as follows:

- THE 96% EFFICIENCY TARGET WAS MET OVER AN EXTREMELY WIDE RANGE OF OUTPUT CURRENT – 20 TO 50 A FOR THE CURRENT-SHARED PARALLELED CONVERTER IMPLEMENTATION, AND 10 TO 50 A WHEN AUTOMATED CONVERTER RECONFIGURATION IS USED
- TOTAL CONVERTER POWER DISSIPATION IS LESS THAN 25 W, WHICH GIVES APPROXIMATELY 12.5 W PER ¼- BRICK.
- A "FILTER FRIENDLY" CONVERTER DESIGN FEATURING SYNCHRONIZATION AND PHASED INTERLEAVING WAS ACCOMPLISHED, RESULTING IN MINIMAL INPUT RIPPLE CURRENT AND SIZE/COMPLEXITY/COST SAVINGS FOR THE CLASS B CONDUCTED EMISSIONS EMI FILTER
- +/- 2% OUTPUT VOLTAGE REGULATION WAS DEMONSTRATED, MAKING THE POWER MODULE SUITABLE FOR REDUNDANT APPLICATIONS
- EXCEPTIONAL POWER DENSITY WAS ACHIEVED, EVEN WITH THE TIGHT REGULATION VIA OUTPUT VOLTAGE FEEDBACK
- ENERGY MANAGEMENT TECHNIQUES WERE DEMONSTRATED, MAKING USE OF THE EMMC AND PMBUS SERIAL INTERFACE

Accomplishments over and above the stated objectives include:

- IMPLEMENTATION OF SYNCHRONIZATION, CURRENT SHARING AND THE PMBUS WITHOUT THE NEED FOR ADDITIONAL COMPONENTS
- SHARING A SINGLE FPGA FOR BOTH EMMC AND PMBUS HOST FUNCTIONALITY
- A TECHNIQUE WAS PRESENTED FOR AUTOMATED RECONFIGURATION OF THE DC/DC CONVERTERS TO OPTIMIZE EFFICIENCY OVER AN EXTREMELY WIDE CURRENT AND POWER RANGE
- A PROPOSED EXTENSION OF THE MICROTCA SPECIFICATION WAS PRESENTED THAT COULD INEXPENSIVELY ADD REDUNDANCY AND RELIABILITY TO POWER MODULES BY AUTOMATICALLY OPERATING AT REDUCED POWER WITH A SINGLE CONVERTER IN THE EVENT OF A CONVERTER FAILURE

The ability to automatically switch from one to two operating DC/DC converters was demonstrated, but the resulting output voltage dip was higher than desired due to the current into the second converter during start-up. Additional effort and design improvements are needed to optimize this operation.

While each of the above individual objectives and features could have been accomplished in any of several ways, including analog approaches, we feel that the digital control approach presented here was instrumental in meeting all of them within the confines of this high density package. High efficiency, high power density, tight output regulation, easy EMI filtering and an extensive list of digitally controlled features was accomplished along with a significant reduction in parts count. In summary, the work presented here has been very successful, and we are excited about its use in 600 W MicroTCA power modules as well as in traditional distributed power architectures.

7. GLOSSARY

AdvancedMC™, AMC	Advanced Mezzanine Card
AdvancedTCA™, ATCA	Advanced Telecommunications Computing Architecture
CPE	Customer Premises Equipment
CU	Cooling Unit
EMI	Electromagnetic Interference
EMMC	Enhanced Module Management Controller
ETSI	European Telecommunications Standards Institute
FPGA	Field Programmable Gate Array
IBC	Intermediate Bus Converter
IC	Integrated Circuit
ICT	Information and Communications Technology
I/O	Input/Output
IPMB	Intelligent Platform Management Bus
MCH	MicroTCA Carrier Hub
MicroTCA™	Micro Telecommunications Computing Architecture
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PCB	Printed Circuit Board
PICMG™	PCI Industrial Computer Manufacturers Group
PMBus™	Power Management Bus
POL	Point of Load

8. REFERENCES

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7. MicroTCA Power Module Preliminary Datasheet, Ericsson Power Modules, September 2007

All referenced papers and data sheets can be found at Ericsson Power Modules' web site: http://www.ericsson.com/powermodules

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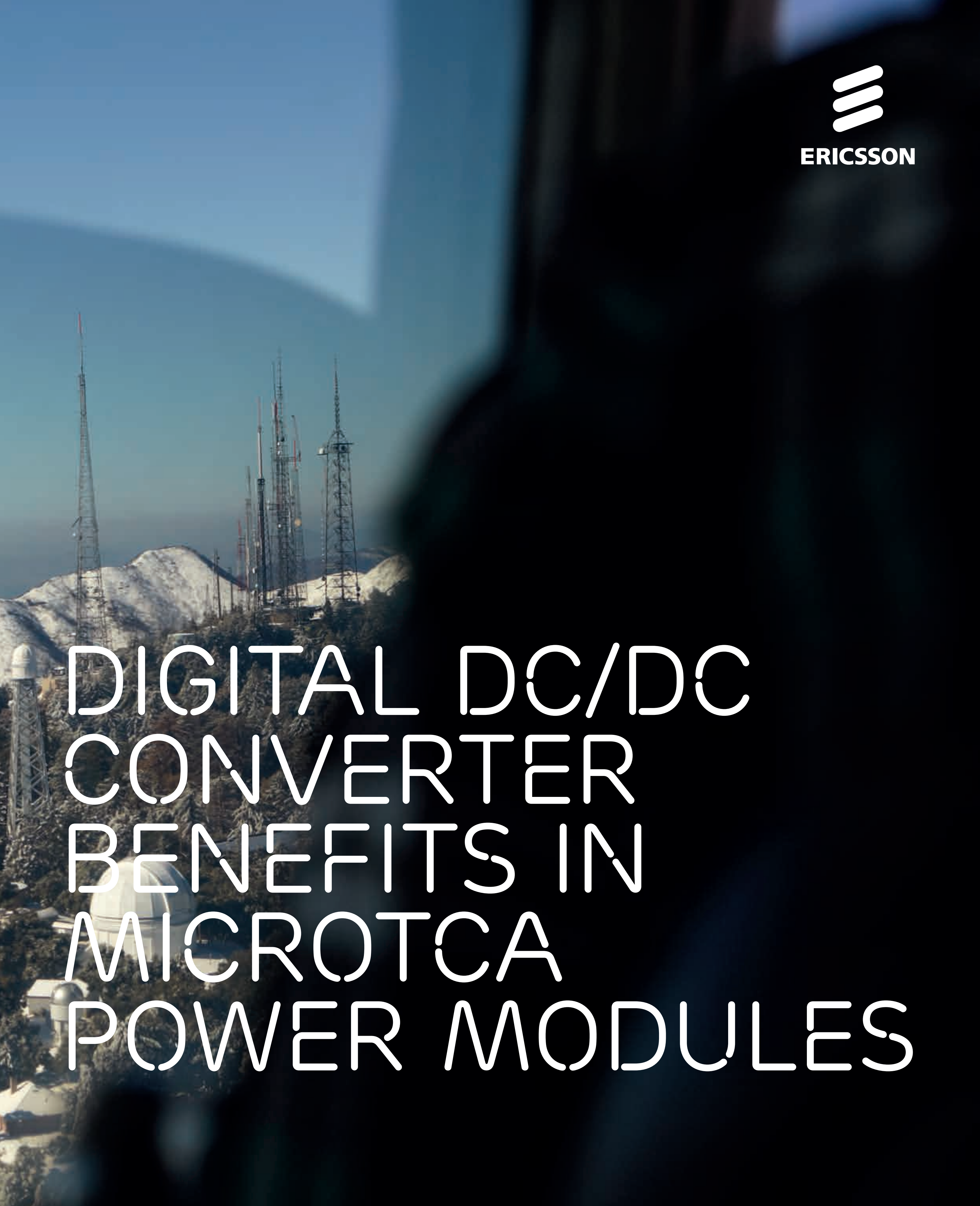

DIGITAL DC/DC CONVERTER BENEFITS IN MICROTCA POWER MODULES

Micro Telecommunications Computing Architecture (MicroTCA) is a relatively new architectural specification for Information and Communications Technology (ICT).

CONTENTS

Industrial equipment intended for relatively small, low power applications where it can be more cost effective than other architectures. The key power assembly in MicroTCA is called the ‘MicroTCA power module’ , which, by its own definition has to deliver and secure the power required by Advanced Mezzanine Cards and other accessories that plug-into the MicroTCA enclosure.

1. INTRODUCTION

The MicroTCA power module, which contains the majority of the power conversion and control-circuitry, eliminates the need for the large planar carrier-boards required in the AdvancedTCA systems. The MicroTCA power module includes the functions of power filtering,

DC/DC conversion, as well as power management. DC input power is plugged to the connectors on the front panel of the power modules, while 12 V and 3.3 V payload and management power is connected to the MicroTCA backplane at the rear of the MicroTCA power modules.

2. THE MICROTCA MODULE

MicroTCA power module (figure 1), provides both payload (12 V) and management (3.3 V) power for all of the loads in the MicroTCA enclosure. These loads may include two Cooling Units (CU) and two shelf-level MicroTCA Carrier Hubs (MCH) in addition to the maximum of 12 AdvancedMC modules, resulting in a maximum of 16 ‘channels’ of output power. Over and above the power channels, the MicroTCA specification requires other functional content in the power module, resulting in a list of functional requirements not detailed with here.

Figure 1 Ericsson MicroTCA power module
BMR 911 483/1

In order to meet MicroTCA specifications, and to consolidate both power handling circuitry and system level control/ management functionality into the relatively small centralized MicroTCA, it requires highly integrated power conversion modules, which, on top of converting the system 48 V to an

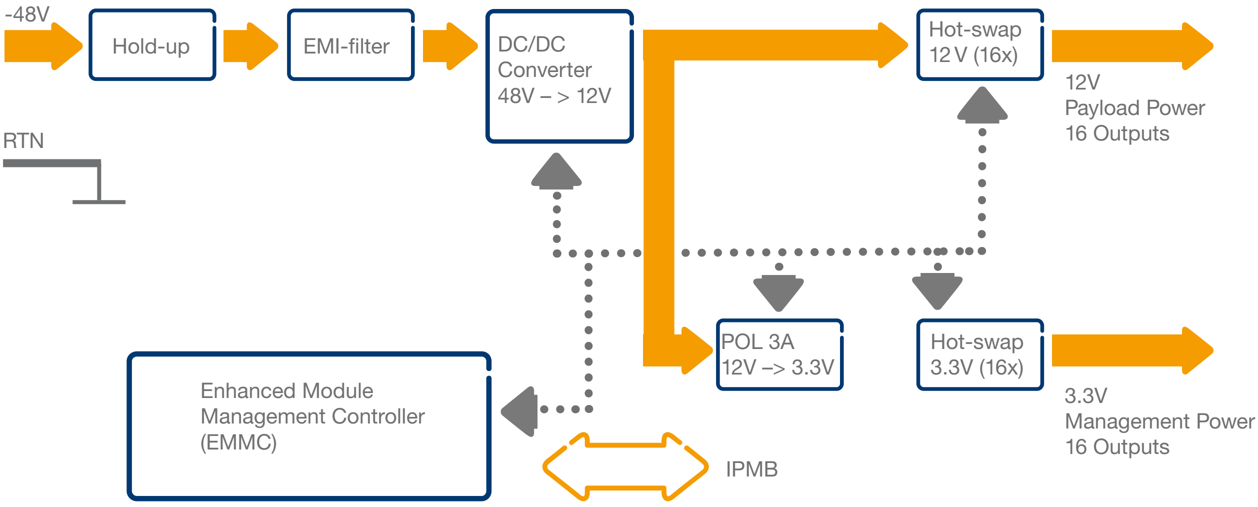

Figure 2 - MicroTCA power module block diagram

intermediate voltage of 12 V with high efficiency, has the ability to communicate with the rest of the system through the Enhanced Module Management Controller (EMMC) (figure 2).

3. SYSTEM REQUIREMENT FOR PARALLELING

The MicroTCA specification includes provision for redundant power modules to increase system availability in critical applications. When needed, this capability can function quite well and achieve the system availability goals. It is important to understand however, that power modules designed for redundant operation are inherently more complex and costly than power modules intended for stand-alone operation.

The required output voltage tolerance on the power module's 12 V payload output depends on whether power module redundancy is used in the MicroTCA system design or not. But to guarantee the highest flexibility for system architects, Ericsson decided to consider all options built-in one unit, which puts a higher demand on the internal DC/DC converter.

So, does the evidence really suggest that nothing is changing, when simultaneously the number of control circuits devoted to add digital performances to power conversion and to optimize power management as never been so high?

Let's considering the impact of redundancy on the 12 V DC/DC converter. The basic MicroTCA specification defines the tolerance range for the AdvancedMC module input voltage as 10 V to 14 V. Since the load module will operate at any voltage in this range, the 12 V DC/DC converter could have a +/-10% tolerance in a non-redundant system.

As highlighted earlier, in a redundant system the situation becomes more challenging, and in order to keep the voltage budgets of both the primary and the redundant power modules within the same overall range at the AdvancedMC inputs without possibility of overlap, the tolerance ranges for the primary power module would be approximately 12.25 V to 12.95 V and the range for the redundant power module from 11.6 V to 12.0 V. These ranges include the effects of line and load regulation as well as temperature. This means that the DC/DC converter in a power module intended for operation in a redundant system must have a +/-2% output voltage tolerance. Going from a +/-10% to a regulation tolerance of about +/-2% has a significant impact on the DC/DC converter design.

The first generation of MicroTCA power modules integrated a standard intermediate bus converter with the external complex analogue circuitry that was required to meet the tight specification inherent to redundancy. When considering the challenging requirement to meet such specifications, but as well to lower energy consumption by optimizing parameters to various load conditions while reducing cost, Ericsson considered the implementation of a brand new digitally controlled DC/DC converter, the BMR453 (figure 3).

Figure 3 - BMR453 top and bottom view

The BMR453 is a digitally controlled, isolated DC/DC converter operating from the -48 V telecom input source and providing 12 V output at up to 400 W, featuring a +/-2% output voltage tolerance and packaged in a quarter brick footprint equivalent to the previous analogue DC/DC powering the first generation of MicroTCA power modules. The BMR453 is based on a digital controller, which combined with a very efficient power-train, and adaptive control confers a flat efficiency curve in the region of 95% efficiency, from low load to high load conditions.

4. INCREASING EFFICIENCY AND FLEXIBILITY

At this point, it is important to pause to review the reasoning behind the different parameters that conducted Ericsson to implement digital power control and power management within the DC/DC power module, and how such development resulted in outstanding performance.

The combination of electrical performance and embedded control requirements led Ericsson to consider a fully digital approach to power-converter design that culminated in the BMR453 quarter-brick module. By comparison with the already highly efficient PKM4304BI module that uses a traditional analogue control loop, substituting a digital core results in as much as a 2% improvement in conversion efficiency with an approximately 5% increase in power-handling capacity. Better yet, the BMR453's digital core includes a PMBus interface that integrates a previously unprecedented level of control and monitoring functions.

In terms of power-conversion efficiency, the principal advantage that a digital core offers over its analogue counterpart is the ability to intelligently adapt to input-line and output-load conditions to optimize conversion efficiency across a wider range of operating conditions. In a buck converter, a unique mechanism that the digital core offers is the ability to vary the dead-time between the upper ('control') and lower ('sync') MOSFETs switching. By comparison, passive components establish the timing constants within an analogue control loop, which are then fixed. While it is essential to prevent the control and sync MOSFETs simultaneously conducting - which would assure mutual destruction - it's also desirable to minimize the dead-time period, during which the sync MOSFET is off and a relatively inefficient Schottky freewheeling diode conducts (figure 4).

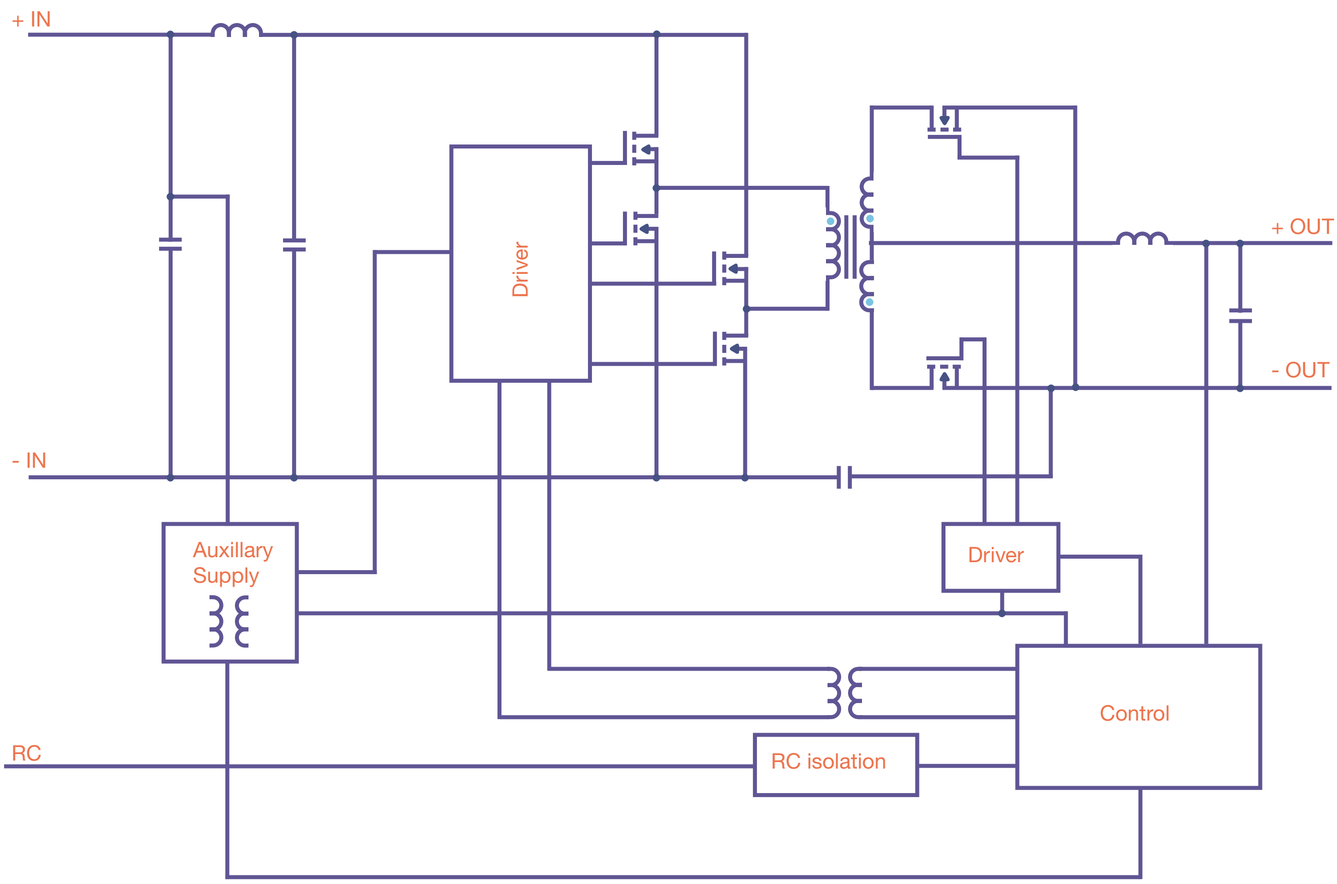

Figure 4 - BMR453 block diagram

Some literature claims as much as 5% efficiency improvement due to this adaptive ability, but with highly-developed converters such as the PKM4304BI, Ericsson's experience is that 1% – 1.5% is more realistic. Comparing the BMR453 with its analogue predecessor, the digital converter achieves 96% or better efficiency from about 3A upwards for a 48V input, and reduces losses at high input voltages by more than 2% (figure 5).

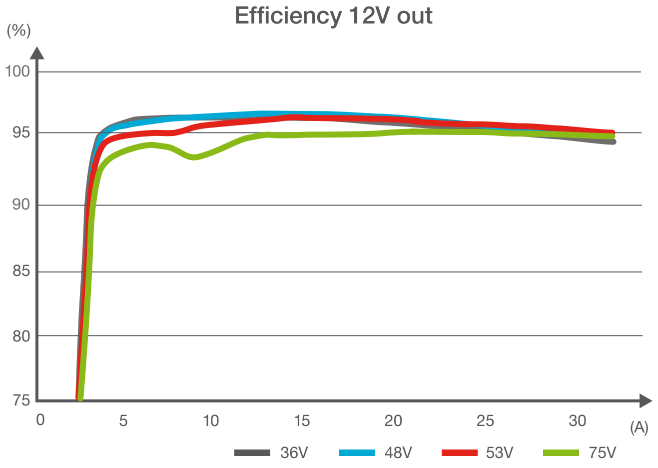

Figure 5 - BMR453 efficiency and voltage regulation illustrating the flat curve through the range of operation

Also, power handling capability increases from around 377 W to 400 W - or some 5% - while regulation improves from +4% -10%, to just ±2% with similar maximum noise-and-ripple levels of around 200 mV.

Adopting digital control enables a raft of benefits such as slashing component count, improving reliability, and lowering cost-of-ownership as well as supporting all the traditional analogue functions such as remote sensing and protection mechanisms. In addition, the BMR453 has an active current sharing facility that ensures equal load-current distribution between modules operating in parallel, making it easy to implement load-sharing or redundancy schemes - no additional OR-ing diodes or MOSFETs are necessary, greatly improving efficiency in parallel operation. Furthermore, digital supervision and control makes it possible to intelligently enable and disable paralleled converters, which is one of the toughest requirements that the internal DC/DC converter needs to manage within the MicroTCA power module.

But in the case of complying with MicroTCA specifications, the digital core's major advantage is easy integration with digital power-management schemes that require additional support circuitry when using an analogue converter. Usable with any standard two-wire I2C or SMBus hardware, the BMR453 includes a PMBus interface providing the ability to set numerous operating characteristics including soft-start ramp times and voltage margining thresholds. The EMMC controller can interrogate the module to extract a wealth of data such as input and output voltages, output current, internal junction temperatures, switching frequency, duty cycle, and instruct the module to adjust certain parameters to load or environmental conditions.

5. BENEFITS IN PRACTICE

Considering the original requirement, and users' demands to power MicroTCA enclosures with efficient and flexible MicroTCA power modules, the implementation of the digitally controlled BMR453 has been a major step.

The list of benefits such implementations have contributed to the end-user could be made long. But, besides the flexibility and the simplicity offered by highly integrated features within the DC/DC power module, which contributes to reduce the number of sub-boards and components, reducing cost and increasing reliability, the conclusion of the most important parameter must undoubtably be the benefit of combining an outstanding power-train with adaptive control, from which results a flat efficiency curve, meaning less power consumption, which contributes to reduce CO2 emissions.

At a time when due to market circumstances the electronics industry is facing new challenges, the MicroTCA is seen as a very promising solution to reduce time-to-market when speed is required to deploy new equipment in various industries. Having a system powered by very efficient MicroTCA power modules embedding a digitally controlled DC/DC converter will guarantee to end-users the highest performance while respecting the environment.

6. GLOSSARY

AdvancedTCA	Advanced Telecommunications Computing Architecture
AMC	Advanced Mezzanine Cards
CO2	Carbon dioxide
CU	Cooling Unit
MCH	MicroTCA Carrier Hubs
MicroTCA	Micro Telecommunications Computing Architecture
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
I^2C	Inter-Integrated Circuit (multi-master serial computer bus)
ICT	Information Communication Technology
PMBus	Power Management Bus
SMBus	System Management Bus
EMMC	Enhanced Module Management Controller

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ERICSSON

FROM DIGITAL CONFUSION TO DIGITAL CONVERSION

It is now several years since commercial products with ‘added digital performance’ have been around in the marketplace. However, the debate around how such products will change the face of the world has never been so intense, resulting in a certain kind of confusion.

CONTENTS

ABOUT THIS PAPER

Part of the material contained in this paper was presented on September 10, 2007 at Digital Power Forum 2007 - Plenary Session. This focused three-day international conference served an audience of decision makers who are interested in learning about and contributing to the latest practical advancements related to the use of digital power control techniques in electronic systems and in power converters, and digital energy management and power management in enterprise-level installations and related digital equipment.

Original material was first published in Power Electronics Europe, issue 1/2006, page 14-18 and 21-26, issue 6/2006 page 42-45.

1. INTRODUCTION

Energized by the marketing buzz surrounding 'the new power revolution', many articles and column inches have often forcibly expressed the details and benefits of implementing such technology into an industry that has for some time been considered as commodity, and slow moving in terms of innovation when compared to others.

Thus fuelled by the force of marketing led arguments about the inevitable replacement of analogue by digital, digital aficionados predict that as it has been for other market segments, the power industry will not be able to avoid the inevitable digital revolution, comparing it to other industries such as the music industry and the death of vinyl, replaced by the CD [1].

Looking at the other side of the argument, analogue aficionados claim that digital power is nothing new, and that adding digital functionalities to a power supply is as old as the launch by Philips of the world famous Inter-IC Bus (I2C) introduced in early eighties [2], and that nothing will drastically change just because digital marketing is in the air.

2. HALFWAY

Analogue supporters highlight the lack of market success of products released throughout the years - especially some recent ones that were backed by high power marketing - questioning how such products have contributed to the predicted power revolution.

In fact, for some time the VRM (voltage regulator module) industry has used five bit bus technology (VID or voltage identification) to control the output voltage of the VRM, new generations of VRM and VRD (voltage regulator down) include SMBus for power management, and most of the Telecom and Datacom applications already include digital power management.

So, does the evidence really suggest that nothing is changing, when simultaneously the number of control circuits devoted to add digital performances to power conversion and to optimize power management as never been so high?

It's a paradox that at a time when the semiconductor industry is investing so much money in developing this area, and as major processor manufacturers invest in start-ups and established companies to develop the next generation of digital power management control ICs (e.g. June 2006, Intel Capital invest in FyreStorm) aiming to optimize performance/watt, that end products such as board-mounted ones are so slow at gaining market adoption.

However, strengthened by the number of product releases, press announcements, and motivated by different interests, digital supporters are promoting 'full digital power is the only way to go', and that end-users will very soon have no other choice than to adopt existing products and technologies.

In fact, both arguments are right and wrong; the truth lies in between.

3. EVOLUTION NOT REVOLUTION

Taking into consideration the arguments from both camps, the power industry generally behaves similar to others, following the same rules in terms of technical evolution, technology transition, and marketing.

However, instead of comparing drastic evolution and technology revolution such as that experienced in the vinyl versus CD debate, it would be more relevant to compare the power industry to the car industry.

As it is for the motorcar, the power industry is composed of several elements that have always worked in a certain way and would continue to work that way, unchanged, without major evolution, whilst other industries will evolve and develop bringing significant benefits.

Compared to the car of 1900, today's car still has wheels, an engine, and seats, though automobile manufacturers have gradually introduced new technologies that have improved comfort, performance and safety while reducing energy consumption - and many more improvements are in progress.

The introduction of fuel injection and electronic control in commercial cars is comparable to the introduction of synchronous rectification and the implementation of digital power management in the power industry. Furthermore, electronic intelligence such as navigation systems and performance optimizations gained by adding computerized controls in cars are akin to what has been called the digital revolution in the electronics power industry.

While the wheels have continued to turn, step-by-step the car industry has implemented new technologies, moving from pure analogue control to digital. Adopting this comparison makes it easier to understand that any confusion resulting from information from different sources in the power industry may not be relevant. After filtering out this noise we get nearer to the truth about the evolution of power conversion.

4. DRIVING FACTORS

In the car industry, the level of evolution and the amount of improvements have been driven by competition and demand from customers. However the most significant improvements, the ones that drove the move from analogue to digital control occurred when fuel prices reached a peak.

Computerized ignition and the optimization of fuel injection to suit driver profiles and traffic conditions took place during an energy crisis, and new technologies to further improve performance per liter of fuel are very similar to what we see in other industries such as microprocessors finding ways to escape the 'suicide curve' by developing Dual-Core technologies bringing in more performance per watt whilst reducing overall power consumption [3].

Less visible for decades, the power industry is now facing similar challenges, and from site management down to on-board power solutions, every watt saved contributes to reduce the total cost of ownership and global energy consumption.

As it was in the car industry, analogue control reached performance standards that will be difficult to improve upon without changing ways of working, ways of designing products, and by introducing new technologies.

Also, pressure from end-customers to reduce the time-to-market while simultaneously decreasing cost and increasing performance per watt has placed new demands on power supply manufacturers, who must now consider more than pure power conversion by integrating power management and energy saving into the complex equation.

Taking all these aspects into consideration, it is clear that the power industry is now ready to take a serious step forward in digital power - while the wheels are still turning.

Driven by the explosion of portable equipment such as mobile phones, game terminals, MP3-players, and also the increased level of functionalities such as video and online multi-services, the mobile industry has a very high requirement on performance optimization and particularly, the amount of usable power one can eke out of the battery. After all, who would buy a portable equipment that functionally does virtually anything, but offers a battery time as short as a spark?!

As an example of the complexity attained by mobile equipments, combining all modes and functions, the latest mobile phones require no less than 18 voltages, often adjusted to be within a couple of millivolts. Taking into consideration that all those voltages are derived from a single voltage battery, that gives some idea of how complex energy management can be, and evidence if it were needed that only digital control can do the job.

Recent announcements that mobile player manufacturers have signed partnerships and licensing agreements with semiconductor and IP developers to implement the most advanced digital power management into the next generation of portable equipment are evidence that; digital conversion has become a true reality (eg. June 2006, Samsung and National Semiconductor).

Over the last two years, semiconductor manufacturers have taken serious steps to integrate digital functions into the latest generation of control ICs [4] (*figure 1*), step-by-step adding all the necessary elements to simplify the development of efficient power solutions, and already tangible benefits are evident in other segments as well as mobile.

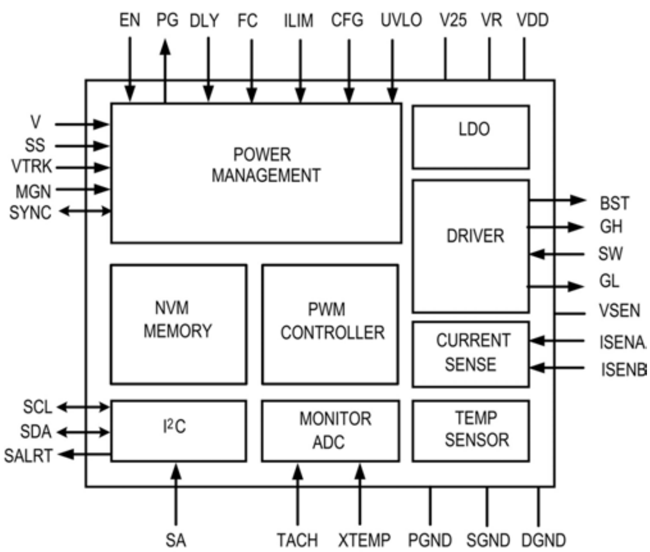

Figure 1 - Integrated PWM with digital control and interface

Simultaneously, in the consumer industry, areas such as plasma/flat screen have started to implement digital techniques to gradually replace analogue PWM with digital PWM and ultimately to use a digital DC controller (*figures 2, 3, and 4*).

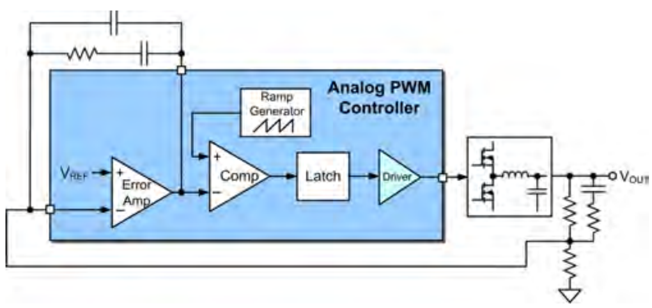

Figure 2 - Conventional analogue PWM controller block diagram

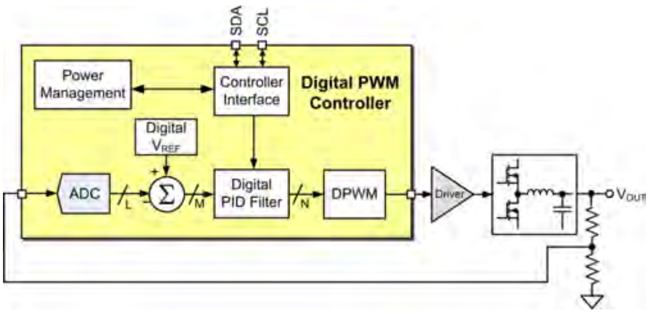

Figure 3 - Digital PWM controller block diagram

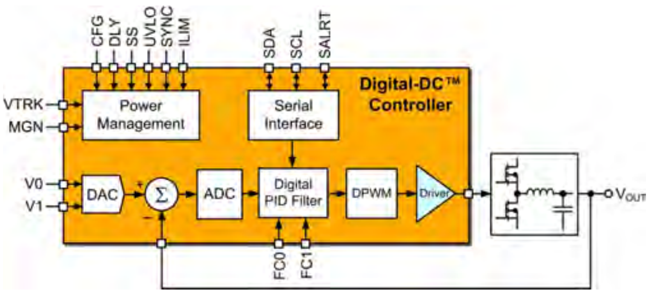

Figure 4 - Fully digital controller

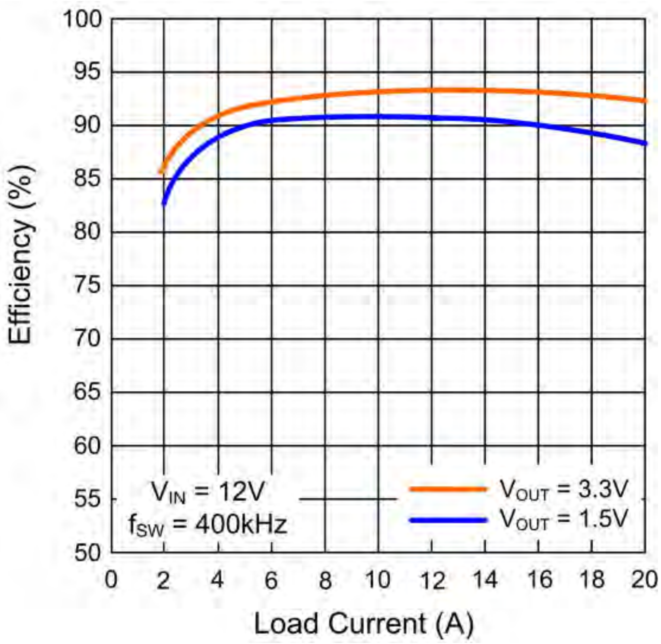

Figure 5 - Efficiency of POL device

The immediate benefit of this transition has been the reduction of power consumption achieved by supplying time controlled, extremely accurate voltages to control specific functions, facilitating compliance with the forthcoming European Directive 2005/32/EC, that encourages manufacturers to produce products that are designed to minimize their overall environmental impact.

Implementing optimized power management and higher efficiency converters and regulators at all points on the curve is the only way to meet future requirements. As well, the results of optimizing such parameters will improve thermal performance, reducing un-necessary power burn, increasing equipment life time, and avoiding noisy cooling equipment resulting from previous forced air circulation, etc.

A further benefit of digital DC controllers is the ability to adjust switching parameters to match load requirement, and that loads as low as 10% of the maximum allowed by the constructor can be accommodated (*figure 5*).

Knowing that most DC/DC converters and regulators are operated in the range of 40 to 70% of the maximum specified by manufacturers, efficiency improvements at lower load levels have a direct impact on the total cost of ownership.

Other sectors such as aeronautical and transportation already reap the benefits from the new generation of digital DC controllers that include integrated interfaces such as SMBus [5] or PMBus [6], simplifying the designer's job when considering power management at board and systems level (*figure 6 & 7*).

Figure 6 shows a conventional power architecture using external power and function monitoring, whereas *figure 7* highlights the benefits of a fully integrated, digitally controlled power architecture that is obviously much simpler for a designer to implement.

In fact, exploring different segments, we see that digital confusion has already efficiently moved on to digital conversion - again while the wheels have kept turning.

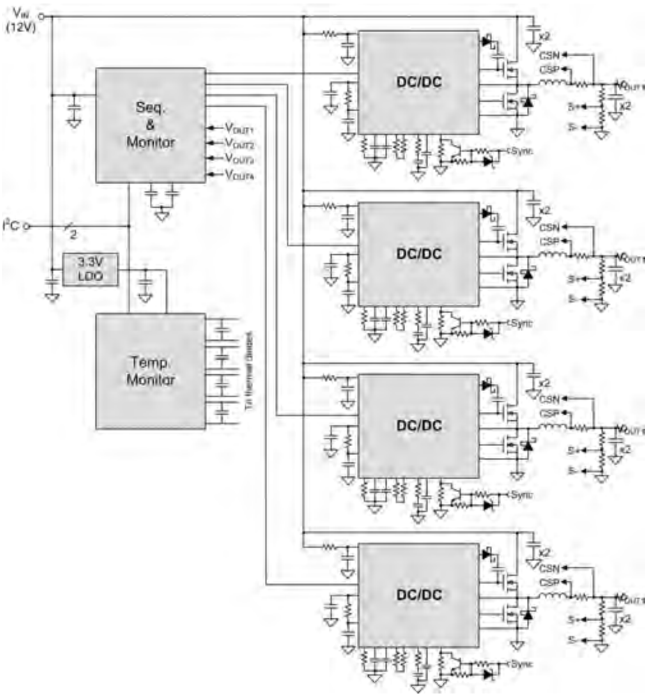

Figure 6 - Conventional power architecture using external power and function monitoring

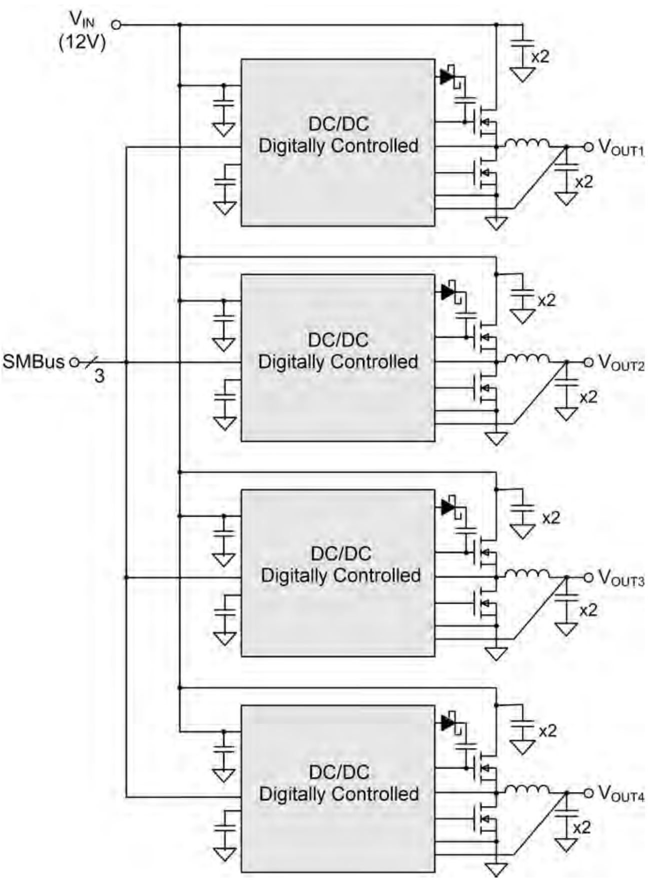

Figure 7 - Power architecture with fully integrated power and function monitoring

5. SUCCESS WHILE MOVING

In the introduction, I mentioned the analogue aficionados' comments about the number of products released over the years aimed at addressing digital power solutions, and them not being seen as being revolutionary because of slow market adoption.

IS THAT REALLY THE CASE, OR PART OF THE DIGITAL CONFUSION?!

As for all industries - including car - the power industry follows the rules of a marketplace driven by demand, and new products addressing developing segments are always a challenge.

Mentioned earlier, the transition from vinyl to recordable CD has always been highlighted as a reference, but that is without considering other products and standards, where despite technical benefits and leading edge technology haven't encountered expected market recognition.

As the data-storage industry presently battles with the standardization of the next generation of high density DVD format (Blue-Ray versus HD-DVD), we should remember that a few years ago Betamax lost the battle against VHS - despite Betamax's better performance.

As it was for the adoption of a video standard, even at it's relatively modest level, digital power conversion is following the same rules and the principle of 'R.G. Cooper's Law' [7];

"FOR EVERY FOUR PRODUCTS THAT ENTER DEVELOPMENT, ONLY ONE BECOMES A COMMERCIAL SUCCESS."

As we've seen, digital power management and conversion is already a reality for a number of segments where standardization is considered at a different level. World leading companies in consumers' high-end equipments are following a business model based on strong partnerships between power supply vendors and equipment manufacturers, in the best mutual interests of the parties involved.

The Telecom and Datacom industries have placed strong demands on on-board power supply manufacturers, demanding strong interoperability between products.

The result of these demands in an industry where time and resources are as important as technology, are the alliances POLA, DOSA and PMBus.

These are aiming to support the power industry with appropriate specifications, footprints, and a communication bus protocol that will result in full interoperability.

6. CONCLUSIONS

Driven by growing concerns about energy preservation and reduction of CO_2 released during the operation by the Information Communication Technology (ICT) industry, power supply manufacturers have seriously taken the measure of the situation and initiated number of projects contributing to reduce environmental impacts.

The development of efficient power conversion systems associated to active energy management made possible by digital technologies are the most evident way to go, which will contribute to the rapid development of commercial "digital power solutions."

Despite some to believe that one technology will prevail on another, it will not be a war between analogue and digital, but more a cohabitation between both and a smooth transition at time equipment manufacturers consider new systems or major updates.

We should remember that volume applications such as radio base stations or datacenters have longer life cycle than most of the consumer's products and that requirement on inter-operability and make such product longer to design as well.

Whatsoever, and to conclude, as it has been for other industries (remember why Bluetooth and WiFi turned into success), the migration to digital power will require the power industry to consider new ways of working and efforts to standardize the basic principle.

That is the only way to go to guarantee market adoption by designers and end-users of digital power technology, and nothing will happen by magic.

We should all remember that; whatever good products will be, they will not escape 'R. G. Cooper's Law' strengthening the demand on all players to work together - while the wheels are turning.

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7. GLOSSARY

CD	Compact Disc
DOSA	Distributed-power Open Standards Alliance
DVD	Digital Versatile Disc
IC	Integrated Circuit
I2C	Inter-Integrated Circuit (multi-master serial computer bus)
ICT	Information Communication Technology
PMBus™	Power Management Bus
POLA	Point Of Load Alliance
PWM	Pulse Width Modulation
SMBus	System Management Bus
VID	Voltage Identification
VRD	Voltage Regulator Down
VRM	Voltage Regulator Module

8. REFERENCES

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[2] Philips / DesignCon 2003 TecForum I2C Bus Overview / Jean-Marc Irazabal / Steve Blozis

[3] APEC 2006 – INTEL – Ed Stanford - Power Delivery Challenges in Computer Platforms

[4] Zilker Labs / June 2006 / Digital Power presentation http://www.zilkerlabs.com

[5] SMBus: http://smbus.org

[6] PMBus: http://pmbus.org

[7] R.G. Cooper, Winning at New products (Reading, MA, Perseus Books, 1993), page 9

All referenced papers and data sheets can be found at Ericsson Power Modules' web site: http://www.ericsson.com/powermodules

ERICSSON

DIGITAL POWER

A proactive stance in terms of defining the approach Ericsson Power Modules is taking to enable the implementation of converters and systems using digital power.

CONTENTS

1. INTRODUCTION

The concept of "digital power" has been receiving significant attention and promotion in the past few years by both semiconductor suppliers and power converter manufacturers. Marketing literature is starting to focus on digital techniques as the answer to today's increasingly complex power systems. But many end users are adopting a "wait and see" attitude. Different converter manufacturers are promoting alternative approaches and architectures. "Digital power" is defined differently by various suppliers. There is not yet an appreciable field history of successful large-scale designs using digital approaches. The result is an atmosphere of uncertainty and perhaps confusion, resulting in the OEM power system designer asking the following types of questions about digital power:

- IS IT COST EFFECTIVE
- HOW DOES THE PERFORMANCE COMPARE TO CONVENTIONAL ANALOG APPROACHES?
- WHAT ABOUT RELIABILITY?

  HOW DOES IT AFFECT THE COMPLEXITY OF THE DESIGN AND DEVELOPMENT PROCESS?
- DO I NEED DEVELOPERS WITH SPECIALIZED SKILLS?
- HOW "STANDARDIZED" IS IT?
- HOW WILL IT AFFECT SECOND SOURCING?

Ericsson feels that this is the right time to take a more proactive stance in terms of defining the approach we are taking to enable the implementation of converters and systems using digital power. This paper will explain the concepts of digital power as practiced at Ericsson, explore the advantages and tradeoffs of digital techniques compared to analog approaches, discuss some of the standardization directions that Ericsson supports and explore possible future directions that digital power may make possible. Most importantly, we hope to answer the types of questions shown above so that our customers can move forward confidently with the appropriate uses of digital power.