

Intelligent Energy Management for Improved Efficiency

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Technical Paper

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

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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 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

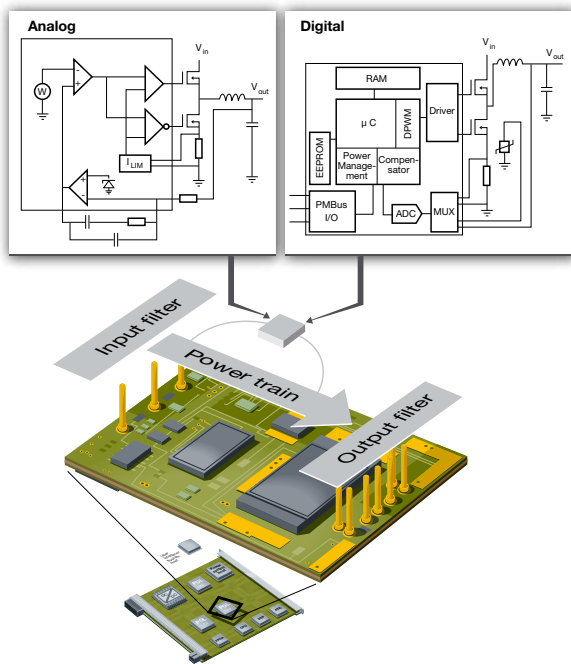


Figure 1 - Digital Power Control

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

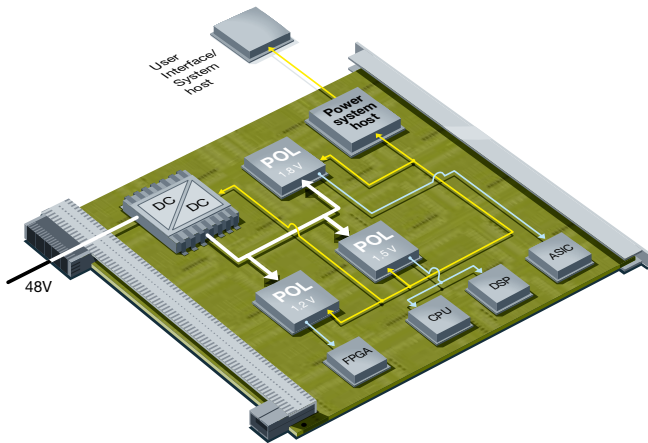


Figure 2 - Digital Power Management

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. 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.

4. Evaluation System

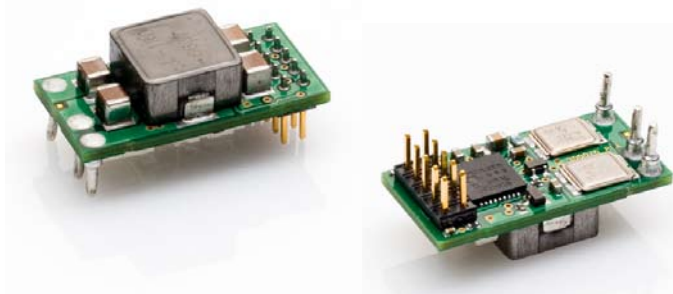
For the purpose of gathering the data used in this analysis, a simple evaluation system was configured and constructed that replicates the environment seen in a typical larger system application. The power supplies used consisted of two POL regulators and one isolated DC/DC converter. The power supplies 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.

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.



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.)

Figure 3 – POL used in system study

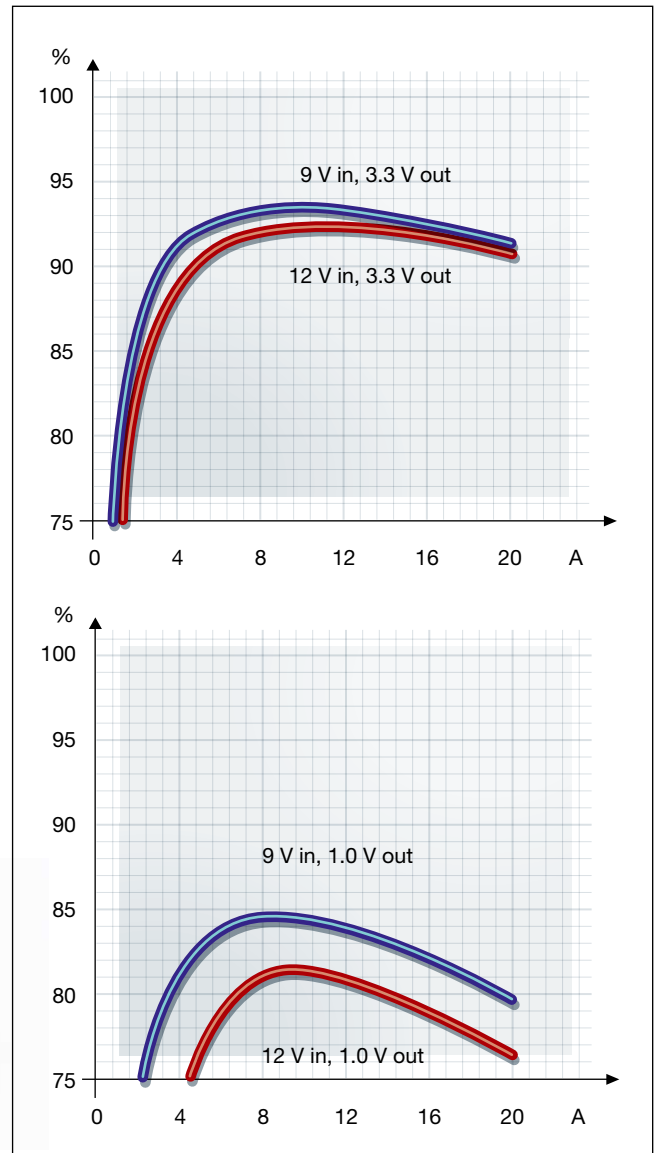
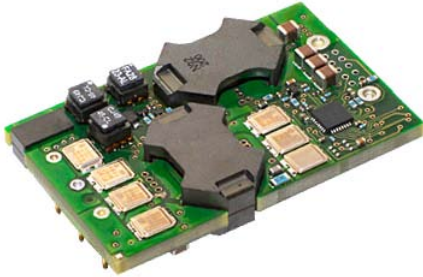


Figure 4 – PoL efficiency

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. 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

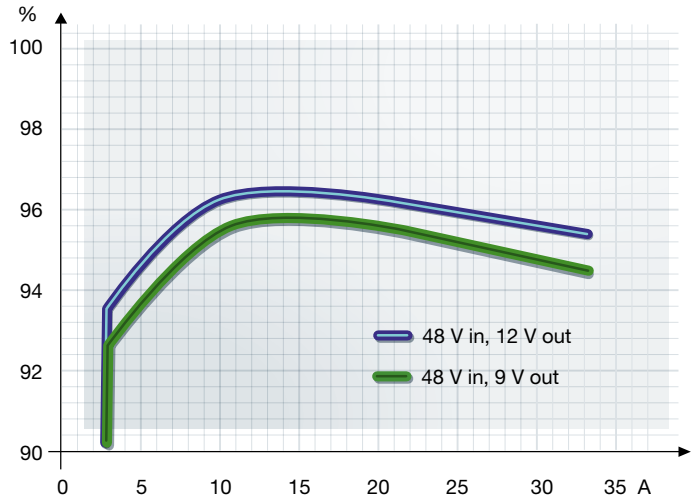


Figure 6 – DC/DC efficiency

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

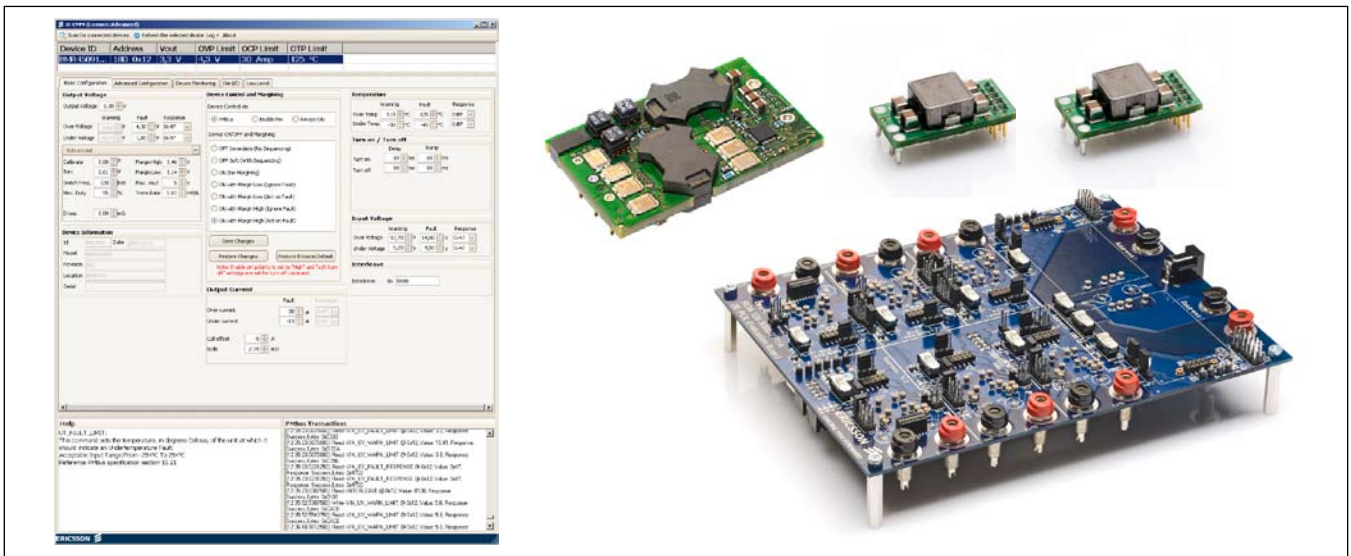


Figure 7 – System components

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 sys-

tem 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.

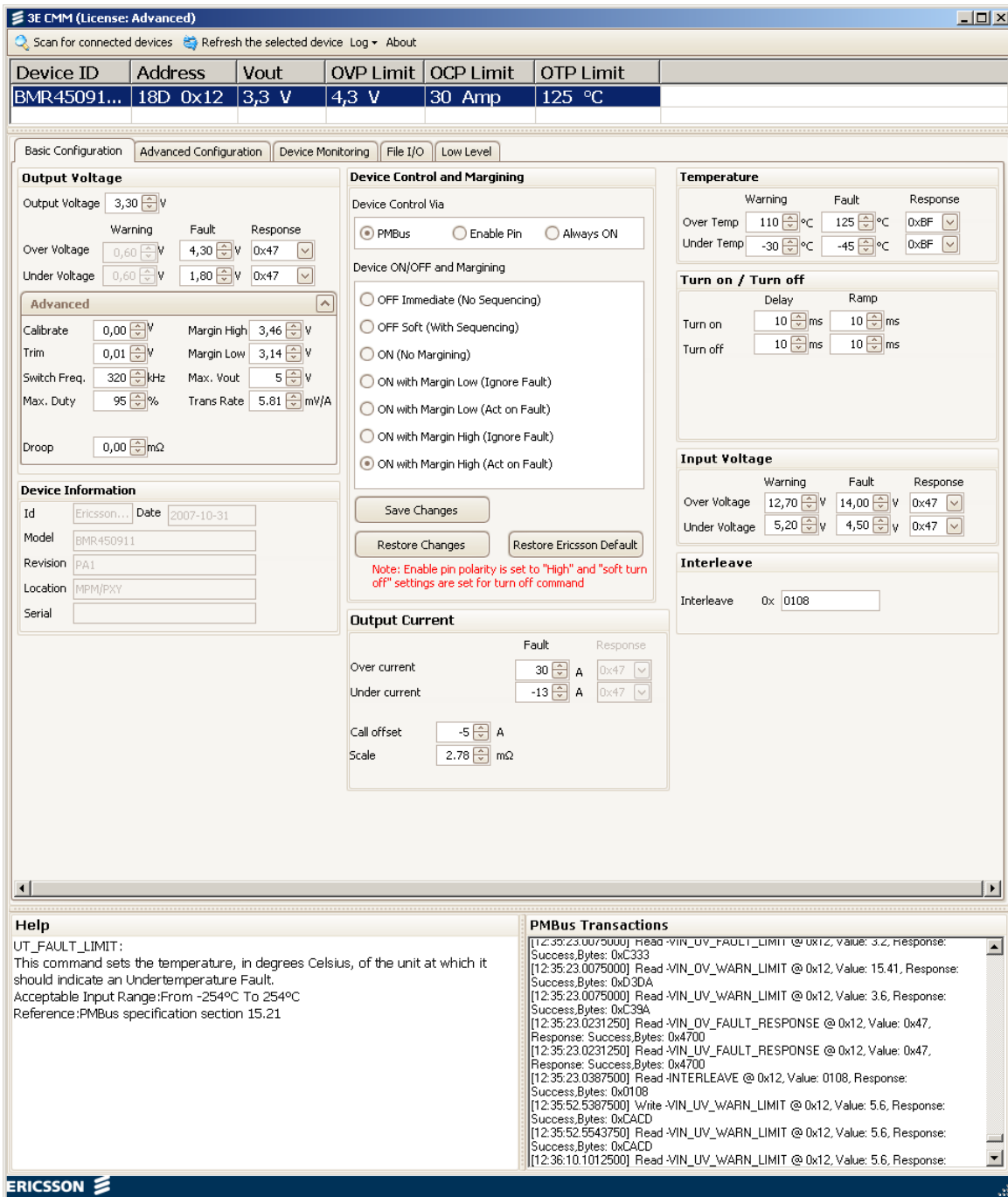


Figure 8 – GUI used for Power Management

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” optimi-

zation 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

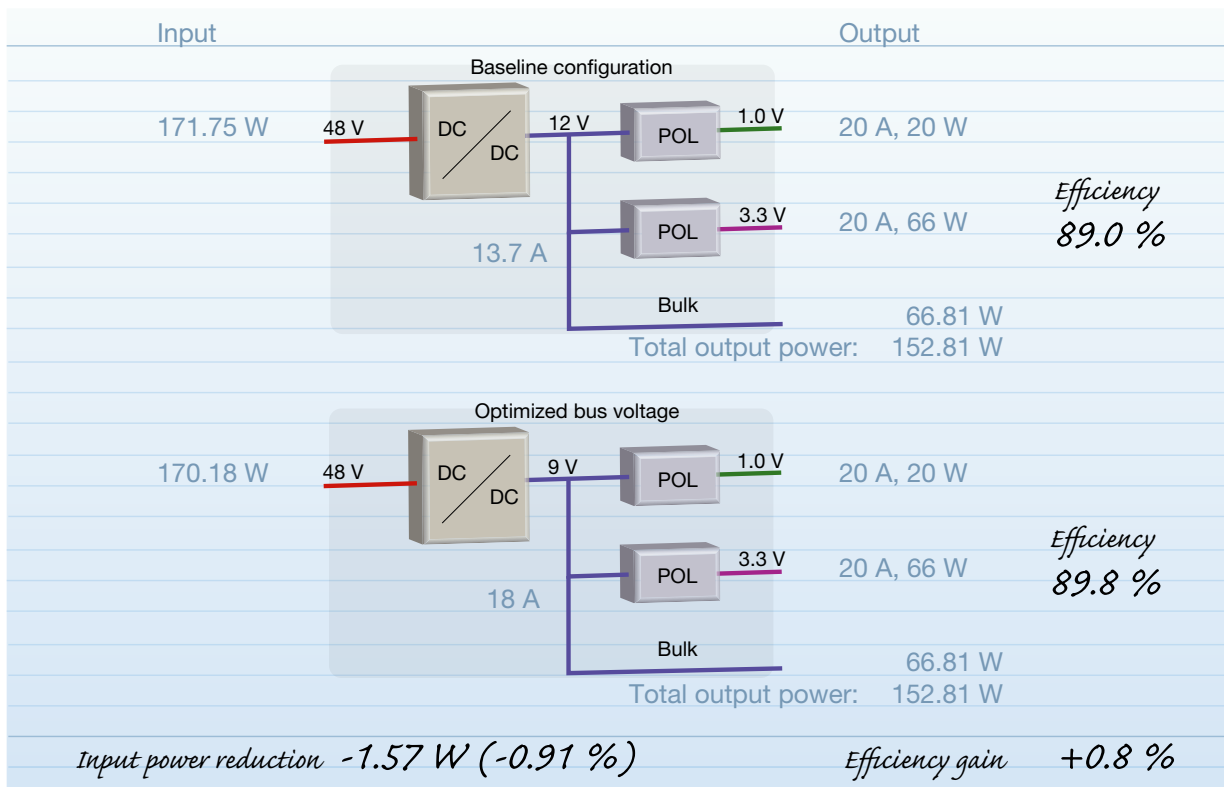


Figure 9 – System efficiency data - optimized bus voltage

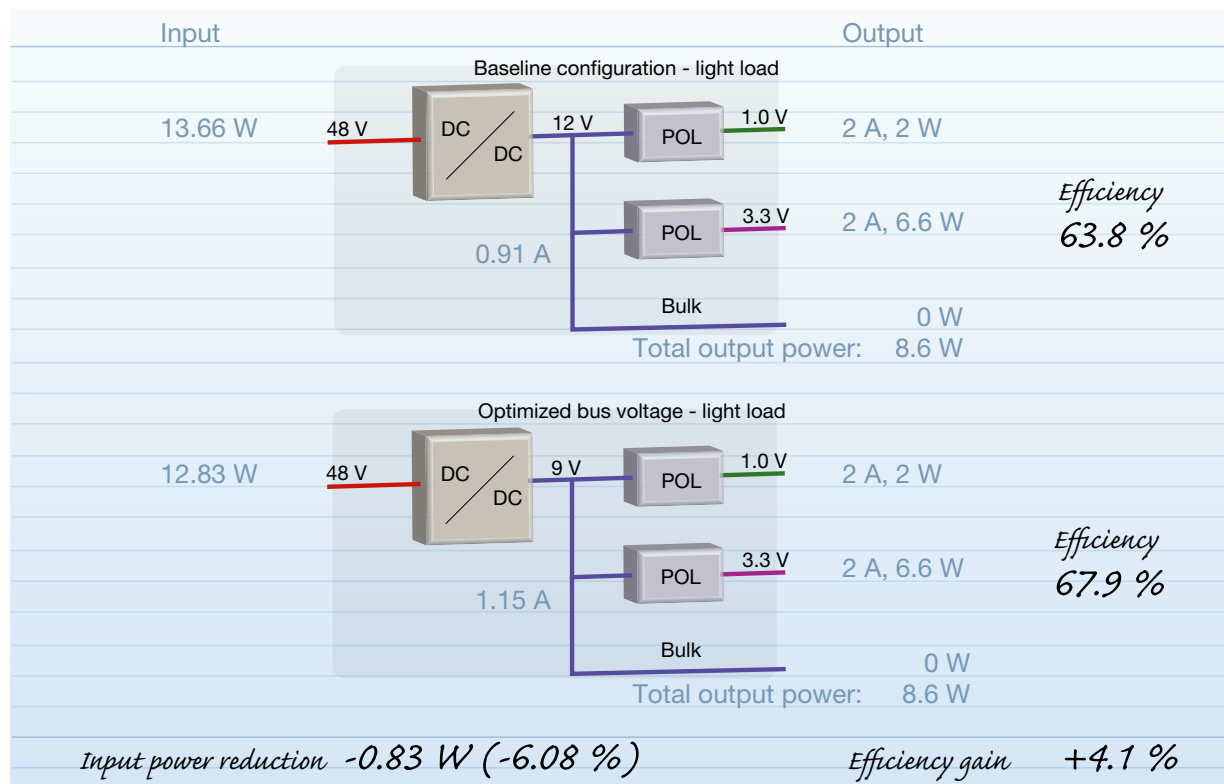


Figure 10 – System efficiency data - optimized bus voltage at light load

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.

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.

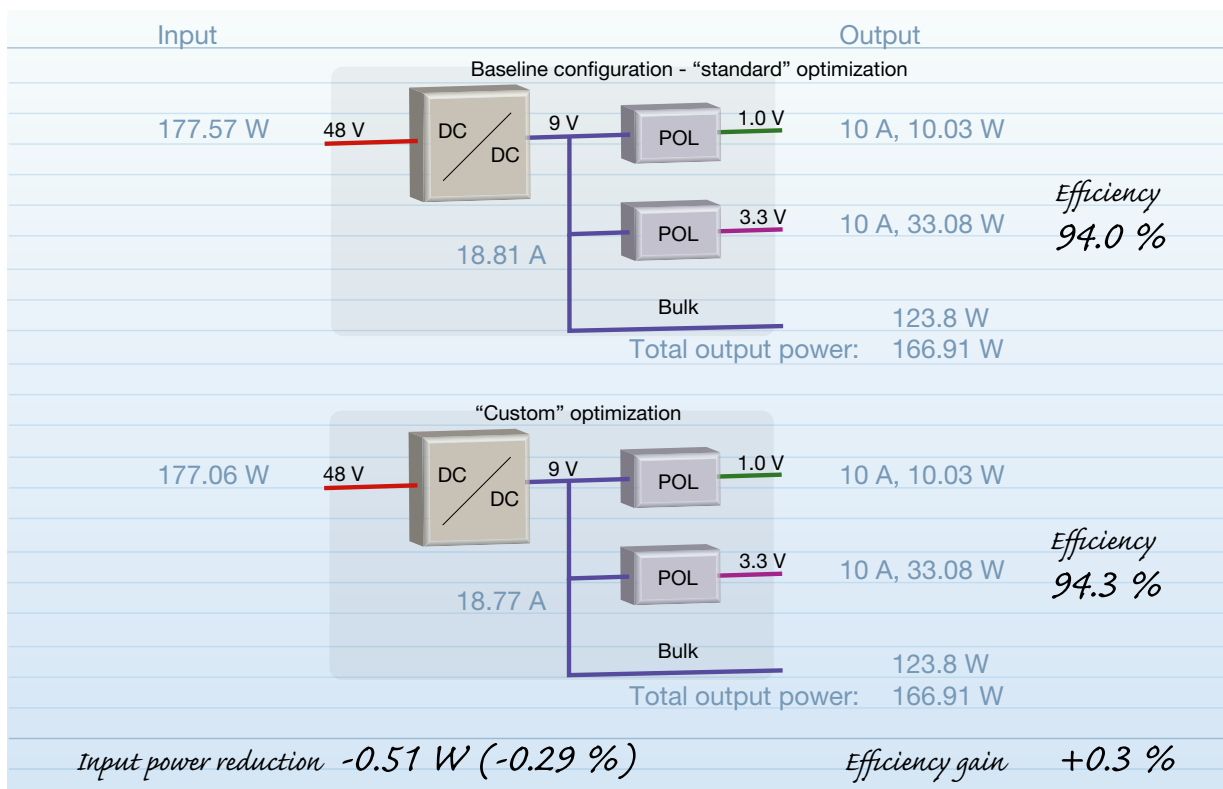


Figure 11 – System efficiency data - re-optimized POL regulators

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.

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.

Trademarks

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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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