MPM-07:000199 Uen Rev A

Implications of Digital Control and Management for a High Performance Isolated DC/DC Converter

March 2007

Technical Paper

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.

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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 implementation**
• 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 freq.:	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.

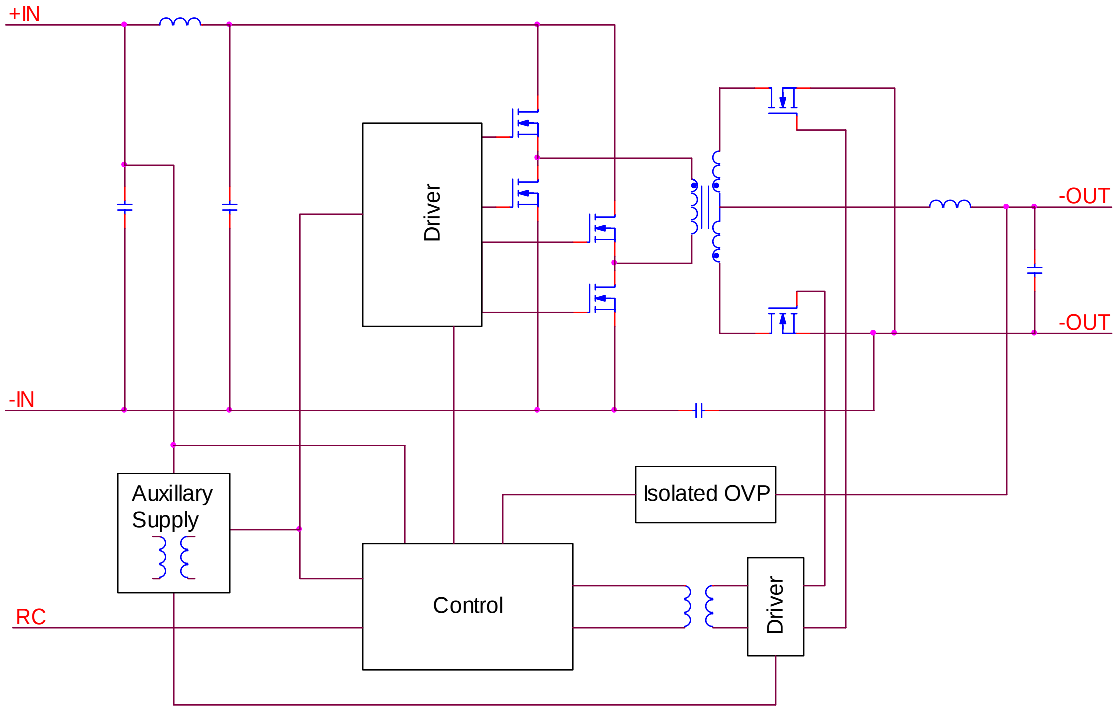


Figure 2 - PKM 4304B PI Analog Design

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 1, 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.

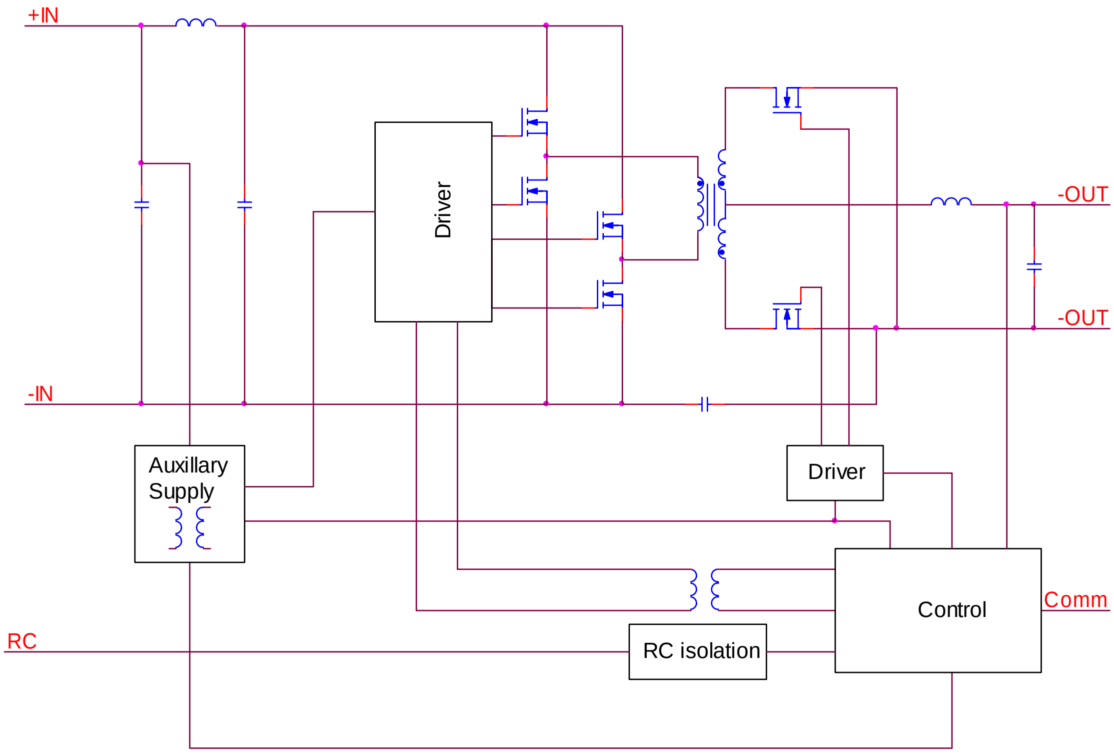


Figure 3 - Digital DC/DC Converter Design

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.

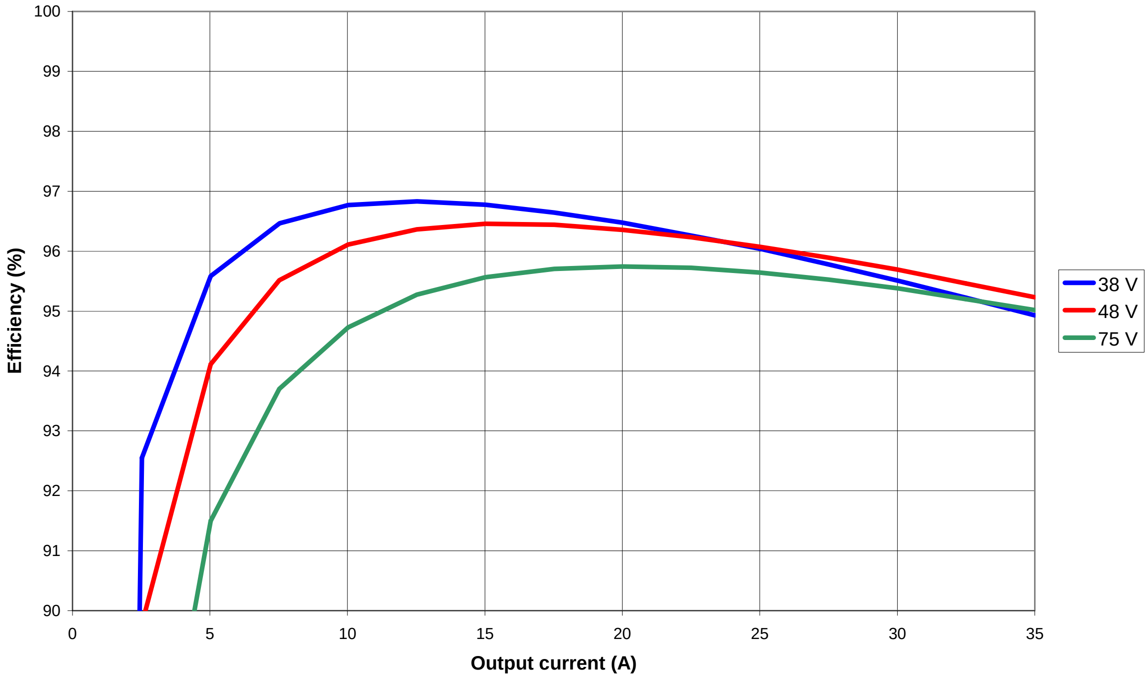


Figure 4 - Efficiency of PKM 4304B PI Analog Design

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.

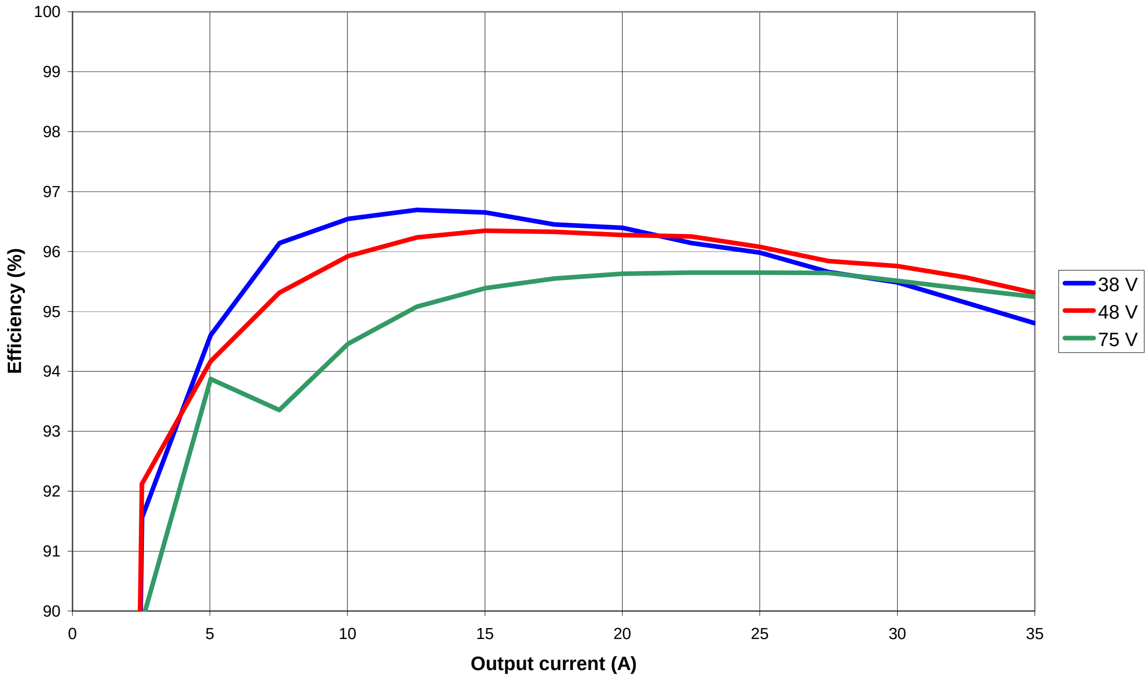


Figure 5 - Efficiency of Digital DC/DC Converter Design

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.

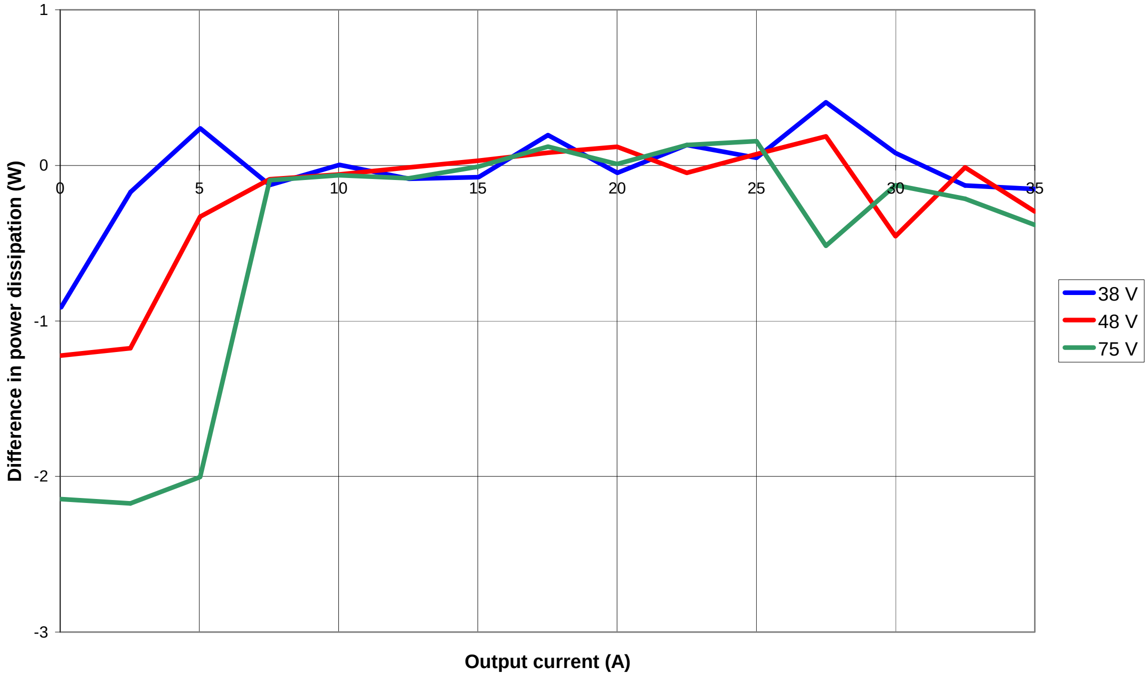


Figure 6 - Benefit of Dead-Time Control in Digital DC/DC Converter Design

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.

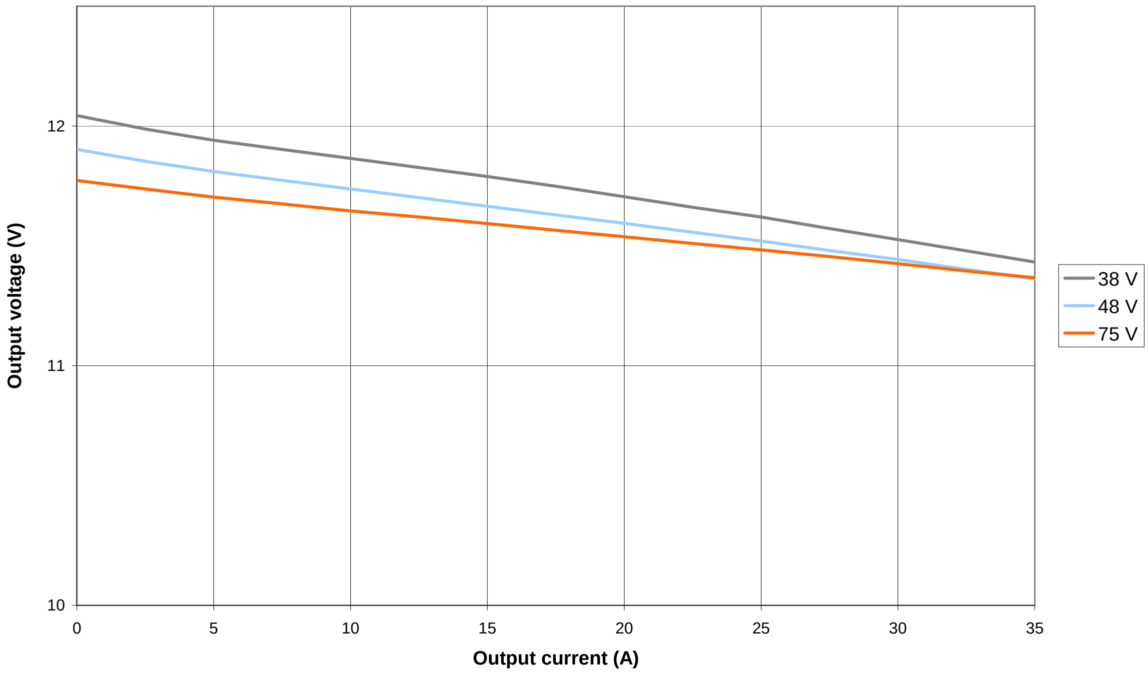


Figure 7 - Output Voltage Regulation of PKM 4304B PI Analog Design

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.

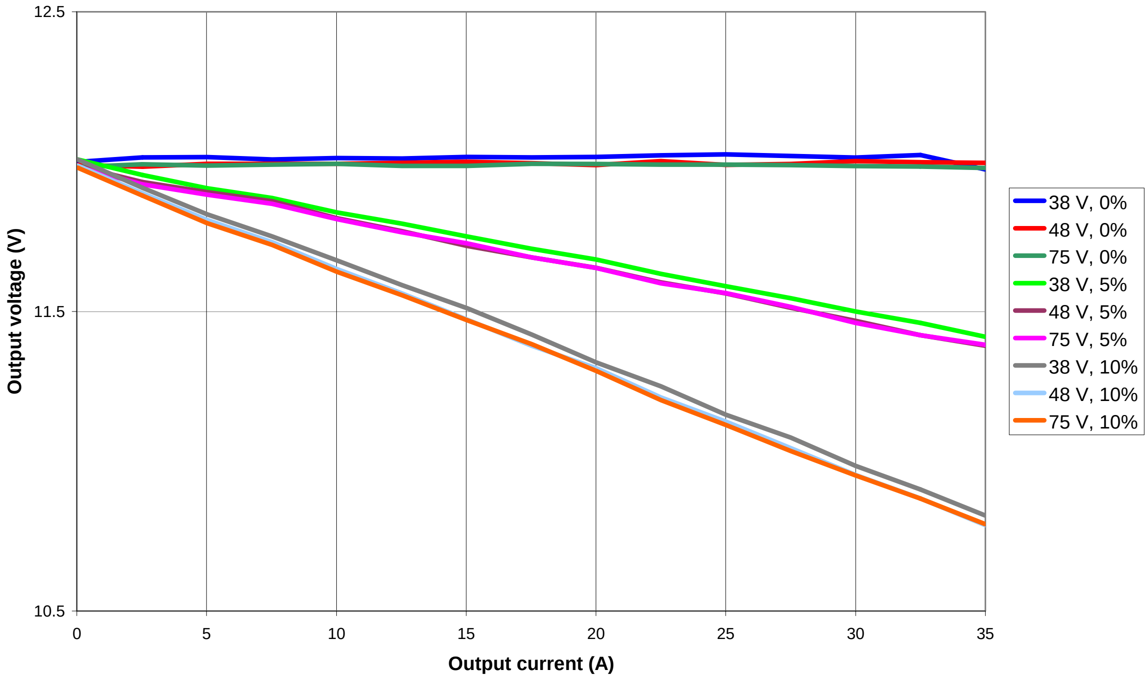
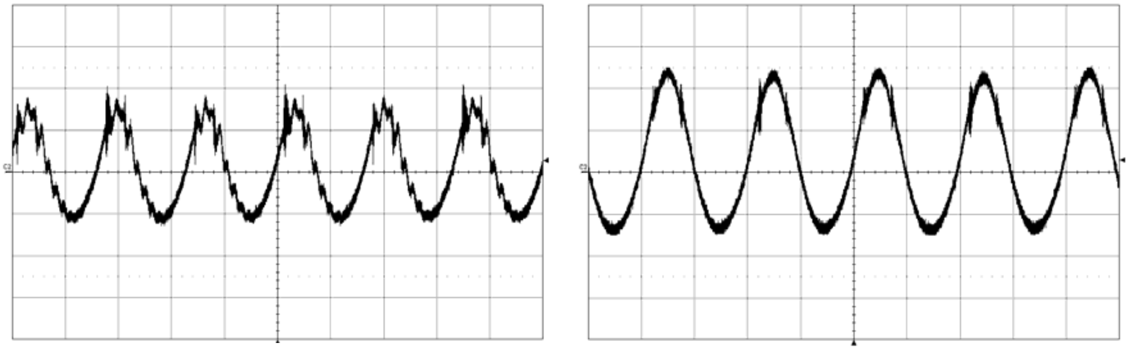


Figure 8 - Output Voltage Regulation of Digital DC/DC Converter Design

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

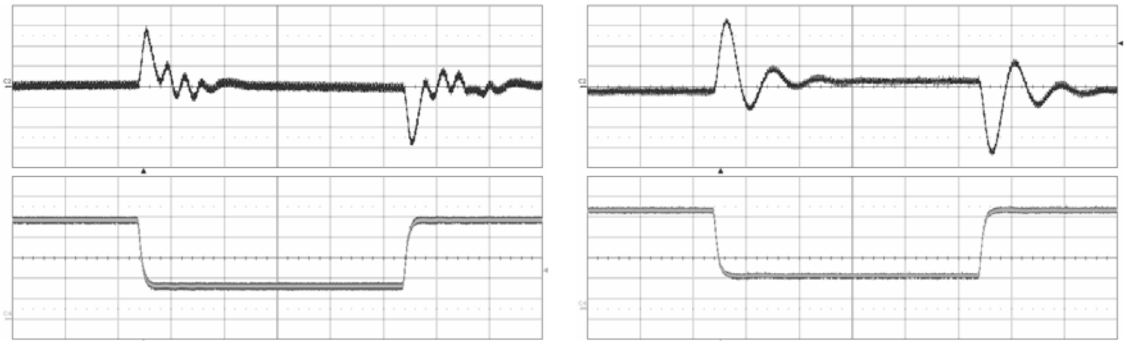
Test set up [5]: Top trace Output voltage (20 mV / div)
Time-scale (2 µs / div)
I_{OUT} = 33 A load; T_A = +25°C; V_{IN} = 53 V

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)
T_A = +25°C; V_{IN} = 53 V

Figure 10 – Dynamic Response

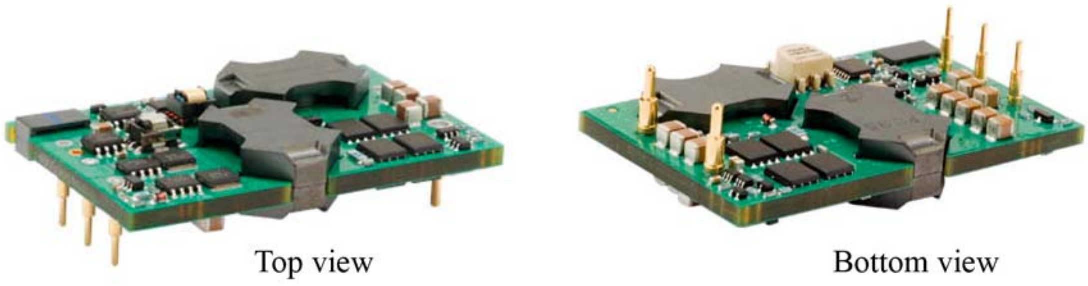
5.5 Component Count and MTBF

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.

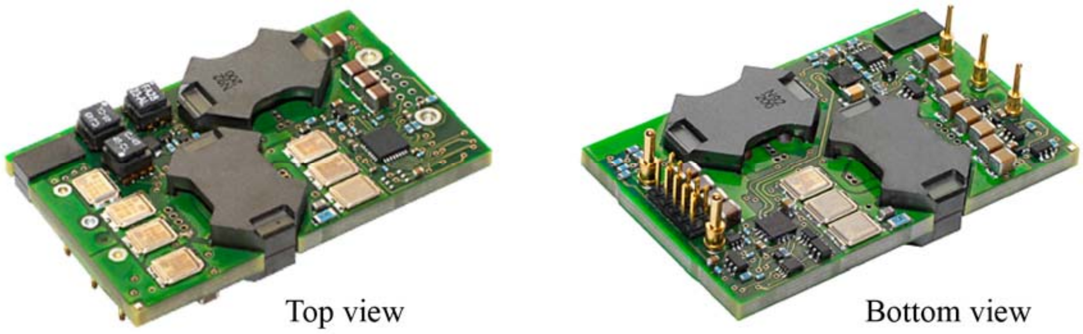
A reliability prediction calculation was done for both DC/DC converter designs using the methodology in Telcordia SR332, issue 1, black box technique. The result for the analog design was 1.13 million hours vs. 1.03 million hours for the digital version. These results are very close especially considering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

Analog reference (PKM 4304B PI)



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

Digital design



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

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