High-Temperature Versatile Voltage-Mode PWM Controller

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Abstract

In this paper we present the operation of the XTR30011 device, a high-temperature, versatile, PWM controller with in-specification performance achieved from -60°C to 230°C using a CMOS SOI process. The circuit features a voltage-mode PWM controller that can be used in Buck-mode converters as well as in Boost, Buck-boost, Push-pull and Flyback. Several functional features are implemented including duty-cycle limitation allowing cycle-by-cycle current limitation, hiccup short-circuit protection and complex functionalities for improved efficiency at low load currents.

These advanced features for improved efficiency include automatic synchronous-asynchronous mode transition in Buck-mode, pulse skipping logic with adjustable threshold, low-power mode with capability to receiving the 5V converter output voltage.

Efficiency in DC-DC converters operated at low load currents is dominated by switching as well as intrinsic consumption losses. The XTR3011, in addition to having a low intrinsic current consumption, allows reaching very good efficiencies at low load currents thanks to its functional features.

We present here the operation of several functional features and experimental results across temperature of the efficiency in several configuration modes, and in particular for low load currents.

Keywords: High-temperature electronics, DC-DC converters, PWM, controller, high-efficiency

Introduction

DC-DC converters are today an unavoidable and critical block in nearly every high-temperature system. From down-hole to aerospace applications, the efficient use of the available energy is crucial, and not only at high load conditions, but also at moderate and low load currents, where the intrinsic low power characteristics and the smart functional features of the PWM make the difference.

In a buck DC-DC converter several loss centers can be identified [1]. Losses can be mainly grouped into:

- Conduction losses: high-side switch, low-side-switch (or diode), inductor, capacitor.
- Switching losses: high-side switch, low-side-switch, drivers, parasitic capacitors.
- Other losses: quiescent current, dead time, reverse recovery.

Conduction losses, mainly determined by high-side and low side on-resistance, are dominant at moderate and high loads and are quite straightforward to determine. Switching losses, however, are determined by much subtle parameters such as rise and fall times, dead time, as well as the charge and discharge of several capacitors (gate of switches and parasitic). At the lower end of load currents, the intrinsic current consumption of the active parts plays also a role in the losses to account for accurate efficiency calculation.

Depending on the conduction regime of the converter (continuous or discontinuous conduction modes), several alternatives exist to improve efficiency along different load conditions. These alternatives have also an impact on the noise spectrum generated by the DC-DC converter and must be considered on a case-by-case basis.

In the following sections, we present several functional features of the XTR30011 PWM controller and how these features allow a safe and high efficiency implementation of a buck DC-DC converter.

Description of the XTR30011

Figure 1 depicts the simplified block diagram of the XT30011 showing its many functional features. A full description of these features can be found in the product datasheet [2].

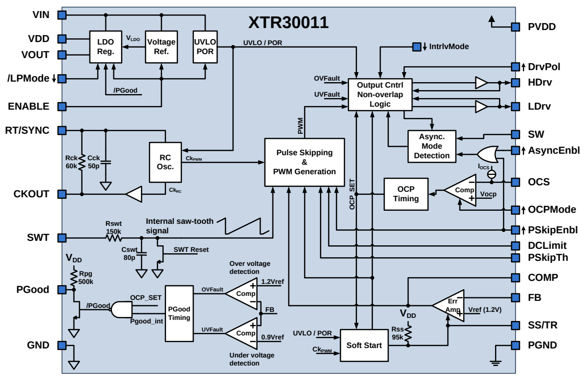

Figure 1. Block diagram of XTR30011.

Hereunder we describe some of the features allowing the implementation of a safe and high efficiency buck DC-DC converter.

The following figure shows the architecture of a standard buck DC-DC converter. The XTR30011 PWM controller sends the corresponding control signals to the drivers, which drive the high- and low-side switches on and off.

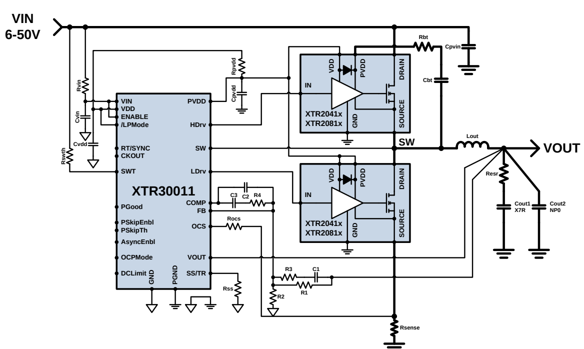

Figure 2. Buck DC-DC converter.

One of the most important features of the XTR30011 controller is the possibility to automatically toggle between synchronous and asynchronous modes. Indeed, depending upon the setting of input AsyncEnbl, the XTR30011 controller monitors the SW node (switching node of the inductor), and decides to turn the low-side switch on only if current through the inductor is strictly positive (operation in continuous current mode; CCM). If at the end of a cycle the current through the inductor comes to reverse (current flowing from the load to ground through low-side switch) the low-side switch is set off during the next clock cycle. Monitoring of the SW node continues on a cycle-by-cycle basis, detecting whether it is positive or negative at the end of each cycle. In Figure 3, the trace SW shows the lower level of the envelope of SW node when switching every cycle. When SW is negative, the XTR30011 operates in synchronous mode (CCM). When SW is positive at the end of the conduction of the low-side switch, the low-side switch is no longer turned on as long as this condition remains, and the DC-DC converter operates in discontinuous current mode (DCM). In an extreme case where the average inductor current is too low, the bootstrap capacitor could no longer be charged, compromising the good operation of the high-side switch. With the XTR30011, this case is removed by imposing a forced charge of the bootstrap capacitor if the SW lower end goes above about 1.2V during at least 16 consecutive clock periods. In this case, some activity is detected on the low-side switch for housekeeping reasons. The fact of having a reduced activity or not activity at all on the low side switch, greatly improves overall efficiency at moderate and light loads.

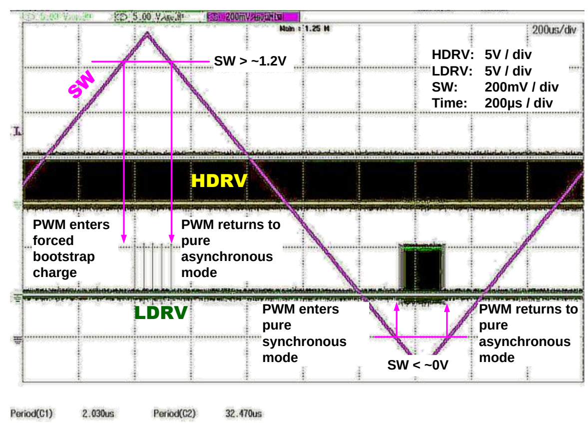

Figure 3. Automatic transition between synchronous and asynchronous modes.

Once the DC-DC converter operates in DCM, a further efficiency improvement can be obtained by operating in pulse skipping mode.

Figure 4 shows the operation in pulse-skipping mode. Pulse-skipping is controlled by the voltage on the COMP terminal (output of the error amplifier) and its value with respect to the pulse-skipping threshold (voltage on PSkipTh node). If COMP is smaller than PSkipTh by about 40mV, no energy is needed on the inductor and the high-side switch is kept off. However, the low-side switch continues with its housekeeping activity of keeping the bootstrap capacitor charged. Once COMP gets closer than 40mV to PSkipTh, the PWM controller starts to activate the high-side switch at a constant Ton and frequency. When COMP is greater than PSkipTh, the XTR30011 provides an output duty cycle proportional to COMP.

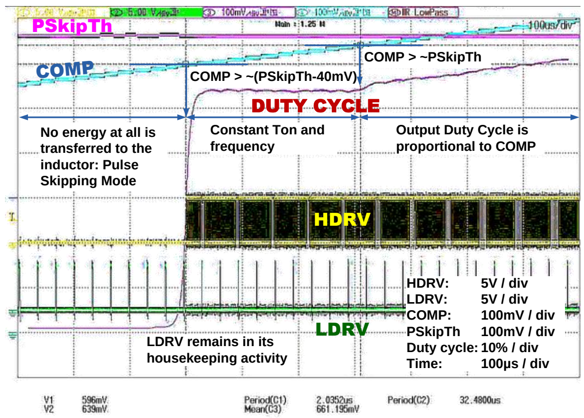

Figure 4. Transition from pulse-skipping to pure asynchronous mode.

Still another efficiency improvement can be obtained from the fact of supplying the PWM controller with the output voltage of the DC-DC converter, provided this voltage is 5V. In the XTR30011, this is achieved by means of a dedicated input (VOUT) to supply back the controller with the DC-DC output. At that moment, the internal low drop out regulator is set to a lower value (4V) so that it becomes inactive in practice.

Figure 5 shows a standard start-up where the soft-start functionality can be observed. After the output reaches 90% of its nominal value, PGood is asserted. In this case /LPMode=1.

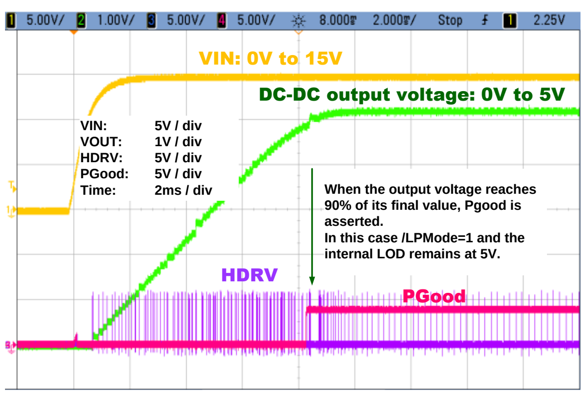

Figure 5. Standard start-up. Internal LDO remains at 5V after PGood is asserted. Rload=200 Ohm.

Figure 6 shows a start-up in low-power mode (/LPMode=0). In this case, after the output of the DC-DC converter reaching 90% of its nominal output voltage, PGood is asserted and the on-chip LDO supplies 4V to the internal circuitry.

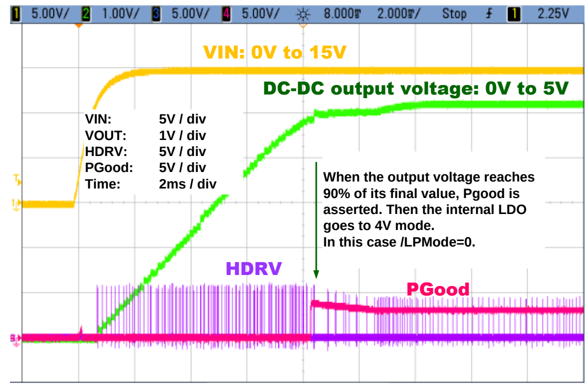

Figure 6. Start-up in low-power mode (/LPMode=0). Internal LDO provides 4V. Rload=200 Ohm.

Figure 7 shows a start-up in low-power mode (/LPMode=0) but in this case the output of the DC-DC converter is fed back to the VOUT terminal of the XTR30011 to keep its internal circuitry supplied at 5V.

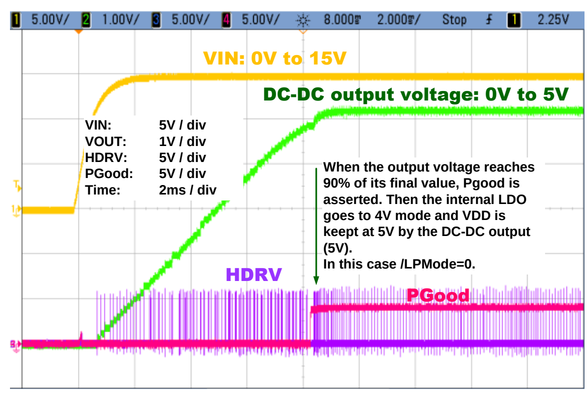

Figure 7. Start-up in low-power mode (/LPMode=0) with DC-DC output (5V) fed back to VOUT of the XTR30011. Rload=200 Ohm.

Figure 8 shows two different start-up sequences with the output of the DC-DC precharged to 1.8V and 3.0V. This figure shows the absolutely predictable start-up sequence of the XTR30011 under two distinct initial conditions.

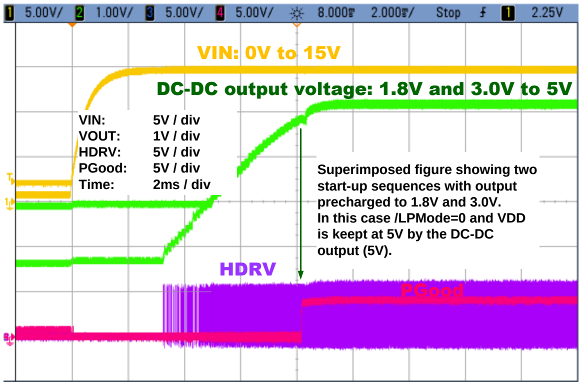

Figure 8. Superimposed image showing two different start-ip sequences with output precharged to 1.8V and 3.0V. /LPMode=0 with DC-DC output (5V) fed back to VOUT of the XTR30011. Rload=100 Ohm.

The following figures show several performance parameters of the XTR30011. In these figures it is shown the evolution over temperature of several major DC parameters of the XTR30011, for two different input voltages (6V and 50V). Some figures show curves for several typical product samples, showing the normal spread of parameters.

Figure 9 and Figure 10 show a very interesting result, which is the impressive reduction of the current drawn from the input voltage when the XTR30011 is supplied by the output (5V) of the DC-DC converter. This greatly improves efficiency when this feature is used.

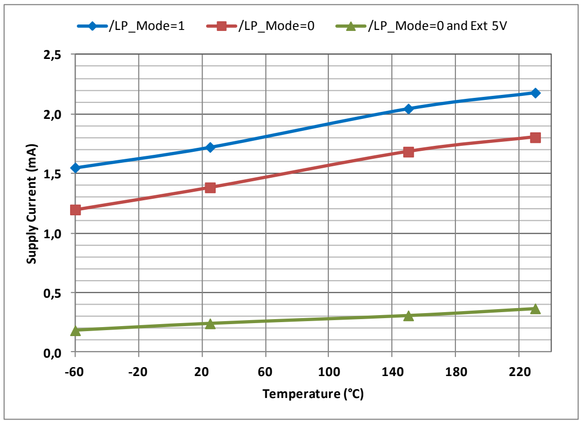

Figure 9. Current through Vin for standard mode (/LPMode=1), low-power mode (/LPMode=0) and low-power mode (/LPMode=0) with DC-DC output fed back to VOUT of XTR30011. Vin=6V and oscillation frequency 520kHz.

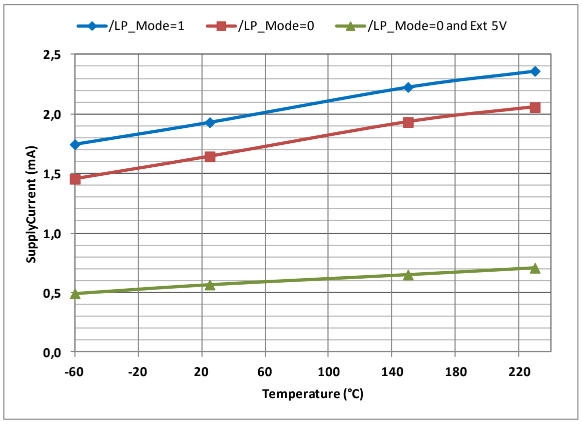

Figure 10. Current through Vin for standard mode (/LPMode=1), low-power mode (/LPMode=0) and low-power mode (/LPMode=0) with DC-DC output fed back to VOUT of XTR30011. Vin=50V and oscillation frequency 520kHz.

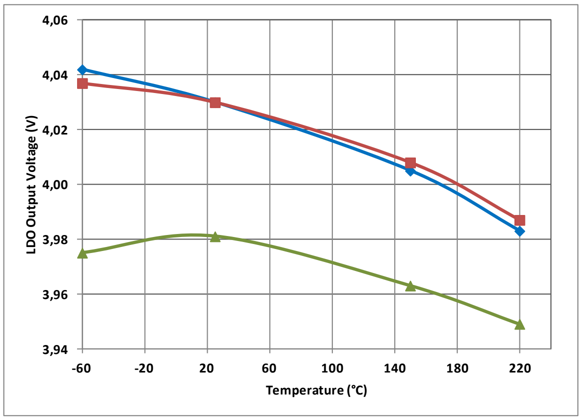

Figure 11. LDO output voltage in low-power mode (/LPMode=0) for three typical samples. Vin=6V.

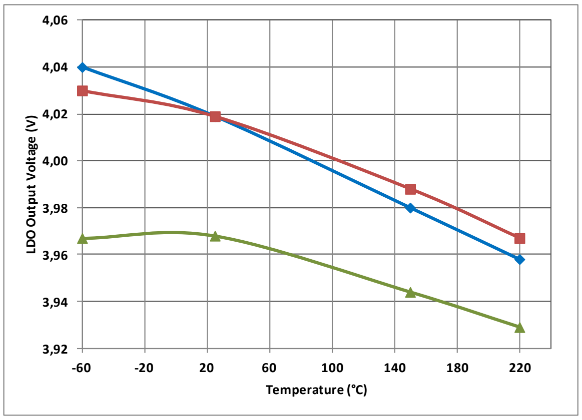

Figure 12. LDO output voltage in low-power mode (/LPMode=0) for three typical samples. Vin=50V.

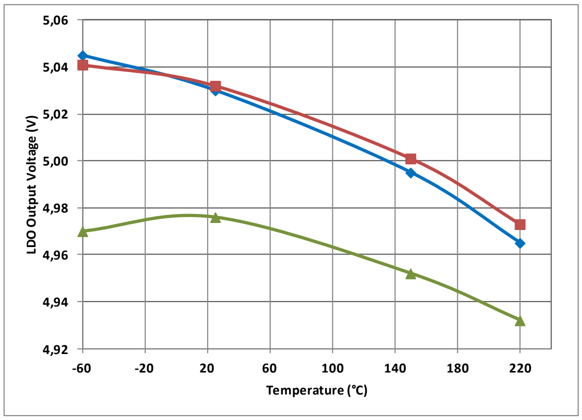

Figure 13. LDO output voltage in standard mode (/LPMode=1) for three typical samples. Vin=6V.

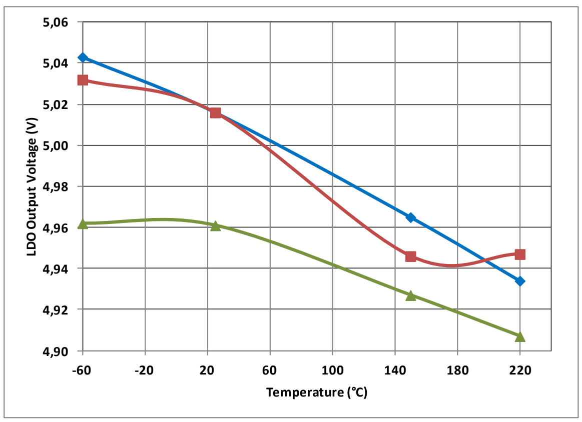

Figure 14. LDO output voltage in standard mode (/LPMode=1) for three typical samples. Vin=50V.

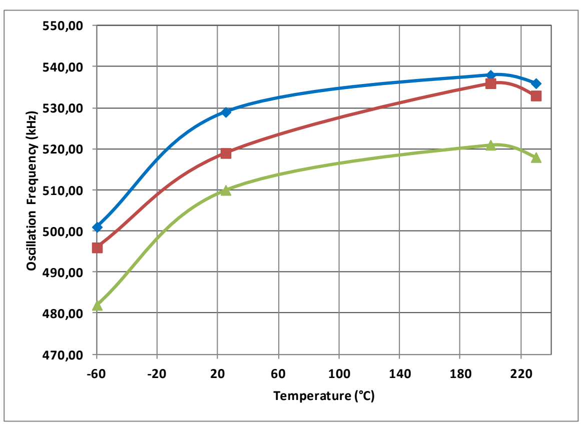

Figure 15. Free running oscillation frequency for three typical samples.

Efficiency Measurements

In this section we present efficiency measurements carried out using several different configurations on the X-REL Semiconductor demo board XTDB30010.

In Table 1 are described the different configurations used for the measurements of the efficiency. VOUT indicates the dedicated input on the XTR30011 to feed back the output of the DC-DC converter (5V). Cells under PSkipTh indicate whether this input has been left open or if a 220kOhm resistor has been connected between this input and VDD (output of the internal LDO). When PSkipTh is left open, the voltage on PSkipTh is about 230mV. When an external resistor of 220kOhm is connected between PSkipTh and VDD, the voltage on PSkipTh is about 660mV. Cells under AsyncEn and PSkipEn indicate the status of these control inputs enabling or not operation in asynchronous and pulse-skipping mode.

Table 1. Description of test configuration.

Config	/LPMode	VOUT	PSkipTh	AsyncEn	PSkipEn
1	1	open	open	0	0
2	1	open	open	1	0
3	1	open	open	1	1
4	1	open	220kOhm	1	1
5	0	5V	220kOhm	1	1
6	0	open	220kOhm	1	1

In Figure 16 through Figure 21 it is presented the efficiency measured using the different configurations for several input voltages and for ambient temperatures of -60°C and +230°C. These figures show that the best configuration in terms of efficiency at moderate and light loads is configuration #5. This trend, though slightly noticeable for Vin=7V, is valid for all output voltages and temperature. A knee is observed in Figure 17 and Figure 18 at load currents about 300mA for configurations allowing operation in asynchronous mode. This is due to the fact that the low-side switch is inactive under this threshold current, increasing the conduction losses. This knee can be moved to lower loads by appropriate trimming of the resistor connected to PSkipTh. Indeed, the voltage on PSkipTh allows setting the current at which the XTR3011 starts operating in pulse-skipping mode. At maximum load current, configuration #5 also provides the maximum efficiency due to the fact that at these currents the XTR30011 still operates in CCM and synchronous mode (minimum conduction losses) and that the DC-DC output supplies the XTR30011 itself. The pure synchronous mode (configuration #1) results to be the worst solution in nearly all cases, but for low input voltages and high load currents.

Configuration	/LPMode	VOUT PWM	PSkipTh	AsyncEnbl	PSkipEnbl
1	1	open	open	0	0
2	1	open	open	1	0
3	1	open	open	1	1
4	1	open	220kOhm	1	1
5	0	5V	220kOhm	1	1
6	0	open	220kOhm	1	1

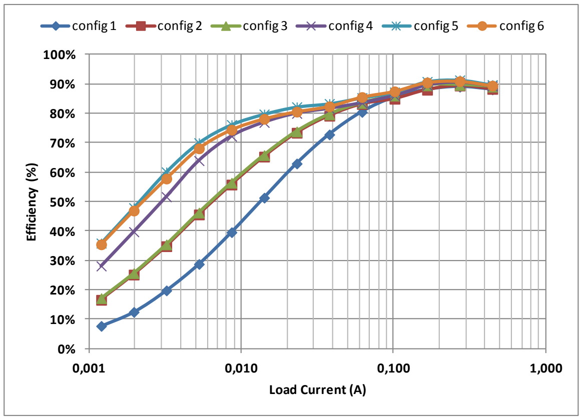

Figure 16. Efficiency for the different configurations. Vin=7V, Tamb=-60°C.

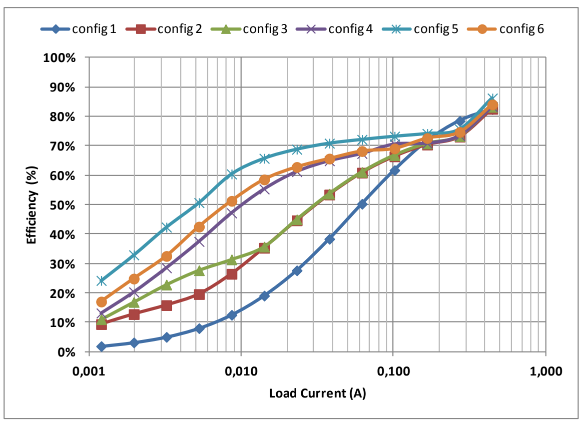

Figure 17. Efficiency for the different configurations. Vin=20V, Tamb=-60°C.

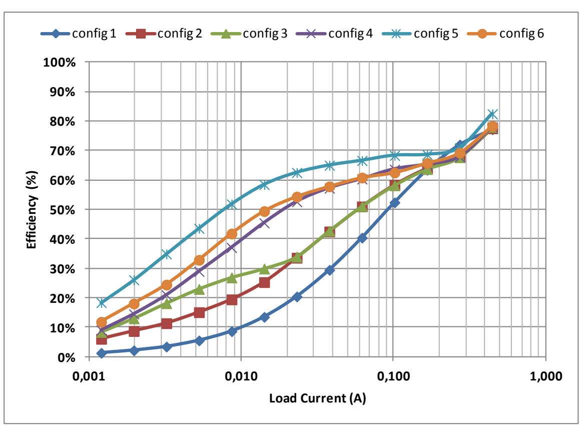

Figure 18. Efficiency for the different configurations. Vin=30V, Tamb=-60°C.

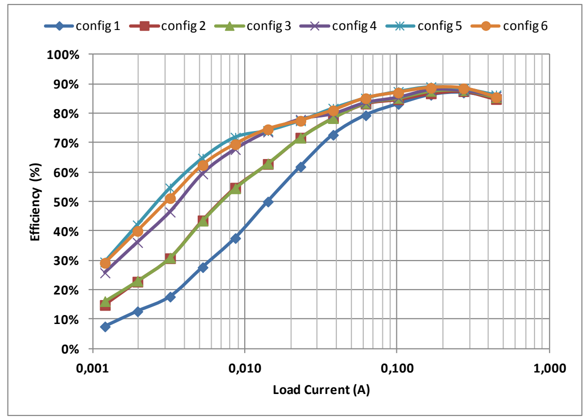

Figure 19. Efficiency for the different configurations. Vin=7V, Tamb=230°C.

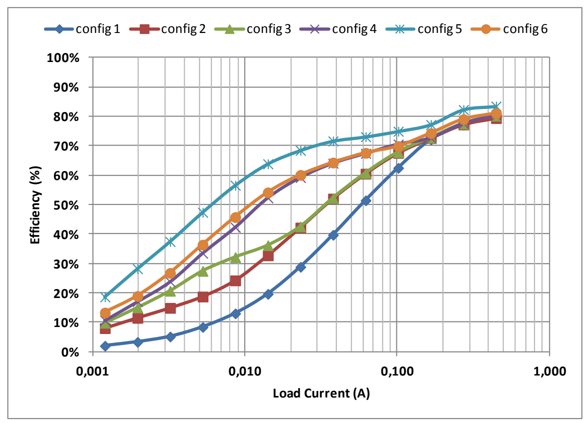

Figure 20. Efficiency for the different configurations. Vin=20V, Tamb=230°C.

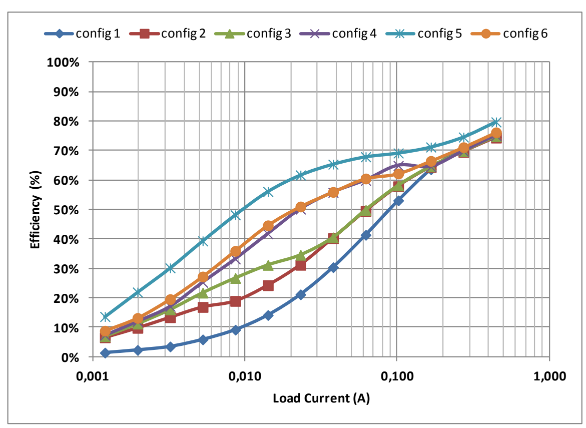

Figure 21. Efficiency for the different configurations. Vin=30V, Tamb=230°C.

Figure 22 and Figure 23 show the efficiency for the best (#5) and worst (#1) configurations for Vin=20V and several temperatures.

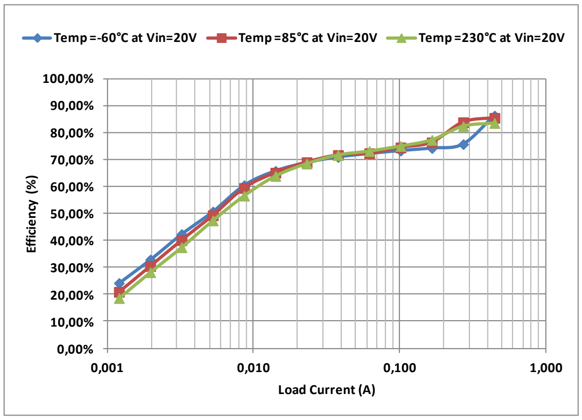

Figure 22. Efficiency for different temperatures. Config5 (best), Vin=20V.

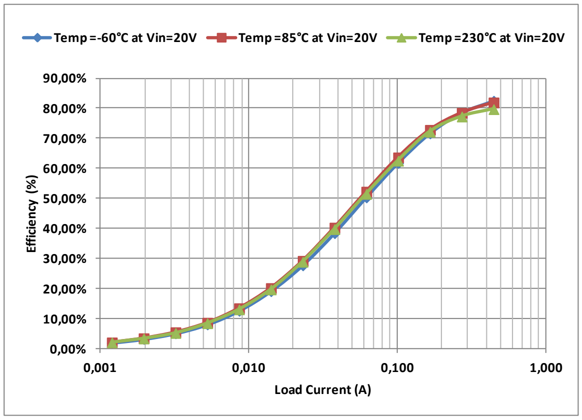

Figure 23. Efficiency for different temperatures. Config1 (worst), Vin=20V.

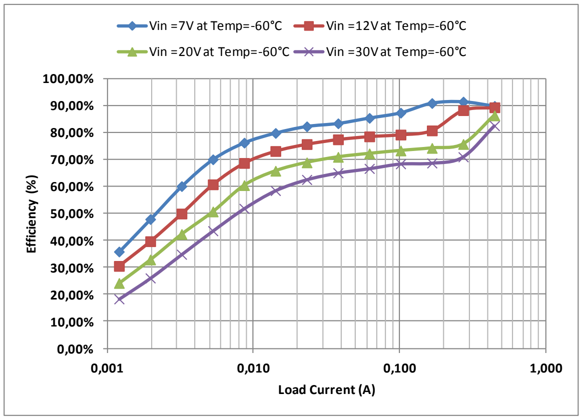

Figure 24. Efficiency for different input voltages. Config5 (best), Tamb=-60°C.

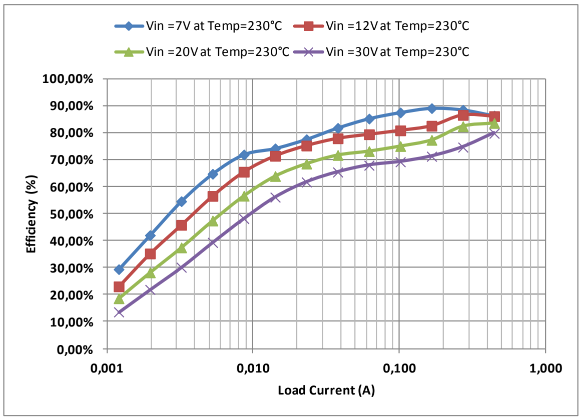

Figure 25. Efficiency for different input voltages. Config5 (best), Tamb=230°C.

Figure 24 and Figure 25 show the efficiency for the best (#5) configuration for ambient temperatures of -60°C and +230°C respectively, for several input voltages. It can be seen that even at an input voltage of 30V, the efficiency remains at very fair values above 60% at load currents of some tens of mili amps.

Conclusions

This work demonstrates the viability of efficiency improvement in DC-DC converters operating at extreme temperatures by taking profit of advanced features in the XTR30010 PWM controllers family.

Thanks to the flexibility and to its low power intrinsic consumption of these PWM controllers, the final user can optimize its architecture in order to improve efficiency at nearly no trade-off.

The possibility of feeding back the DC-DC output to supply the PWM, provided it is 5V, contributes to reaching excellent efficiency values at moderate and light loads.

Extremely low variability with temperature of functional parameters as well as efficiency has been shown.

References

[1] M. K. Kazimierczuk, “Pulse-width Modulated DC-DC Power converters, Wiley, Dayton, Ohio, Chapter 2, pp 37-46, 2008.
[2] www.x-relsemi.com