Quasi-resonant control with XMC1000

XMC1300, XMC1400

About this document

Scope and purpose

This document introduces quasi-resonant control as a technique which enables traditional switched-mode power supplies to achieve the highest efficiency possible when compared to other conventional control methods. The document also discusses how to implement this technique using Infineon's XMC1000 microcontroller family. Code examples are given as a reference to simplify and speed up implementation.

Intended audience

This document is intended for engineers who wish to implement quasi-resonant control in their application with an XMC1000 microcontroller.

Applicable products

- XMC130x
- XMC140x
- DAVE™

References

Infineon: DAVE™, http://www.infineon.com/DAVE

Infineon: XMC™ family, http://www.infineon.com/XMC

Infineon: "Pseudo Digital-to-Analog Converter (DAC) with XMC1000", Application Note AN_201511_PL30_0011.

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1 Introduction

Switched-mode power supplies have become a crucial component in many devices we use in daily life. In the past, they were often implemented using simple circuitry. As the market demands smaller, lighter and more efficient power supplies, many control schemes have been invented to address such requirements. One of the most popular control schemes is called quasi-resonant control, also known as “valley switching”.

This application note provides hints and guidance on how a user can implement quasi-resonant control using the XMC1000 microcontroller family.

1.1 Conduction modes in power supplies

Switched-mode power supplies are rated based on the amount of the output power they can deliver to the load. Assuming a power supply has a constant output voltage, the output current is proportional to its output power. Depending on the magnitude of the output current, three distinct conduction modes can be observed in the power supply's magnetic component. Figure 1 shows a boost converter driven with a constant pulse-width modulated (PWM) signal used to illustrate these conduction modes. It is assumed that the boost converter has reached its steady-state.

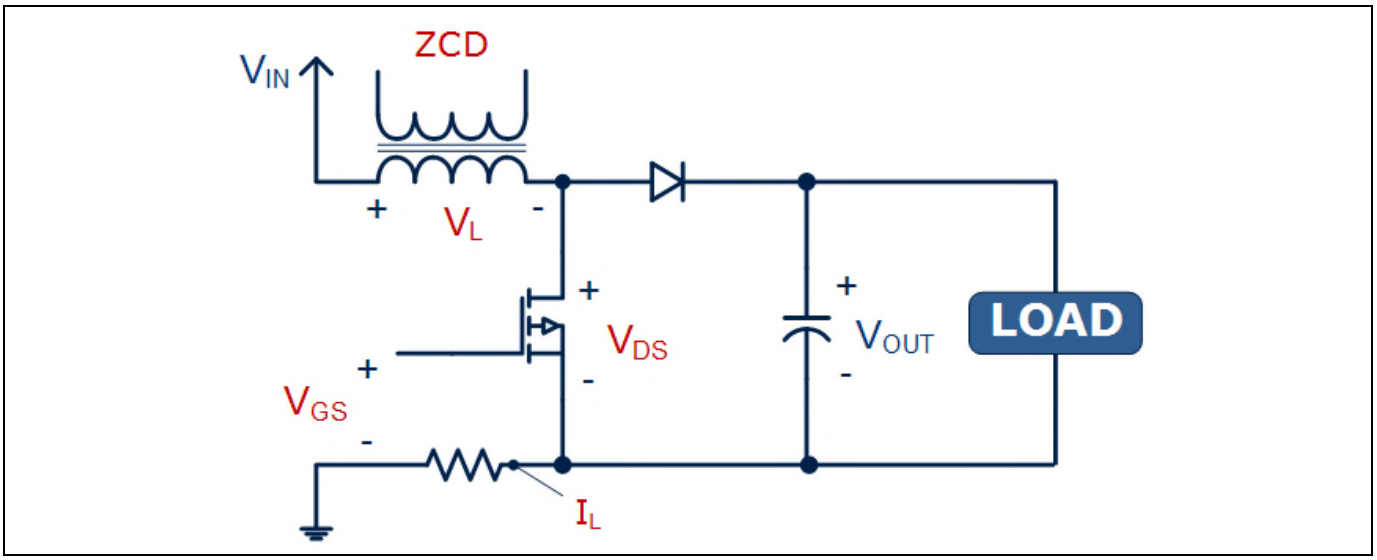

Figure 1 Standard boost converter with zero crossing detection winding

1.1.1 Continuous conduction mode

There are converters that are designed to permanently operate in continuous conduction mode (CCM). Other converters operate in a variety of conduction modes and CCM occurs when high output power is delivered to the load (high load condition), characterized by current continuously flowing through the magnetic component (typically an inductor or a transformer).

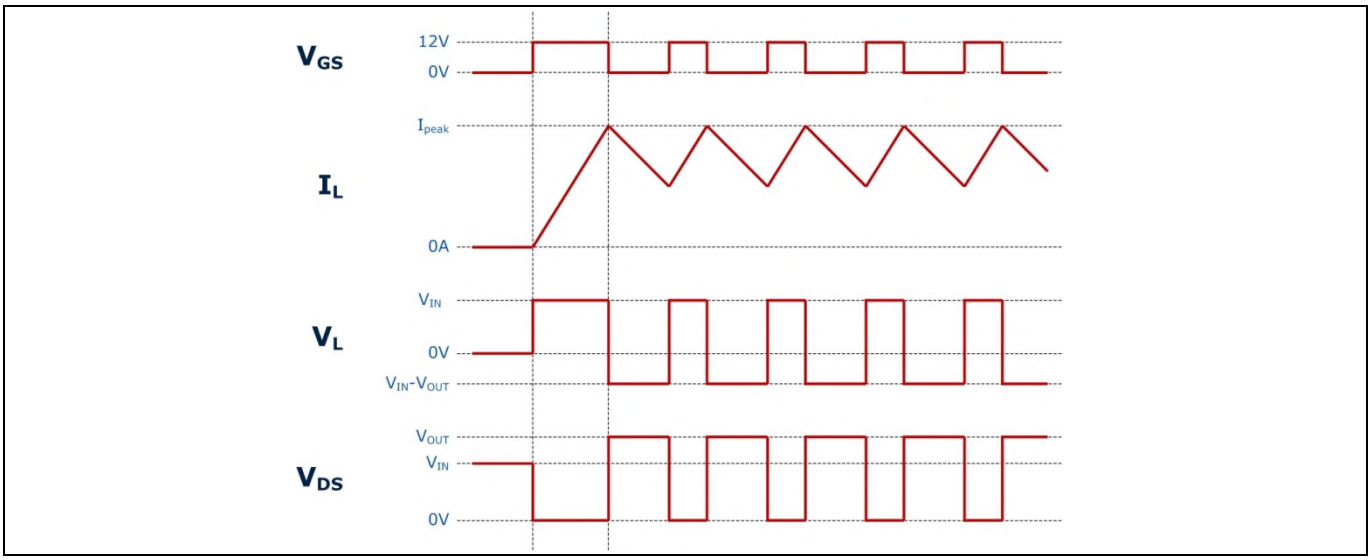

Figure 2 CCM waveform

This conduction mode results in relatively low efficiency due to high losses during hard switching of the MOSFET. This simulation shows the behavior of a boost converter operated in CCM.

1.1.2 Critical Conduction Mode (CrCM)

Critical Conduction Mode (CrCM), also known as transition or boundary mode, occurs when the inductor current reaches zero before the next switching cycle begins. CrCM is often used when medium power is delivered to the load. However, there are converters which are designed to constantly operate in CrCM, across a wide range of loads.

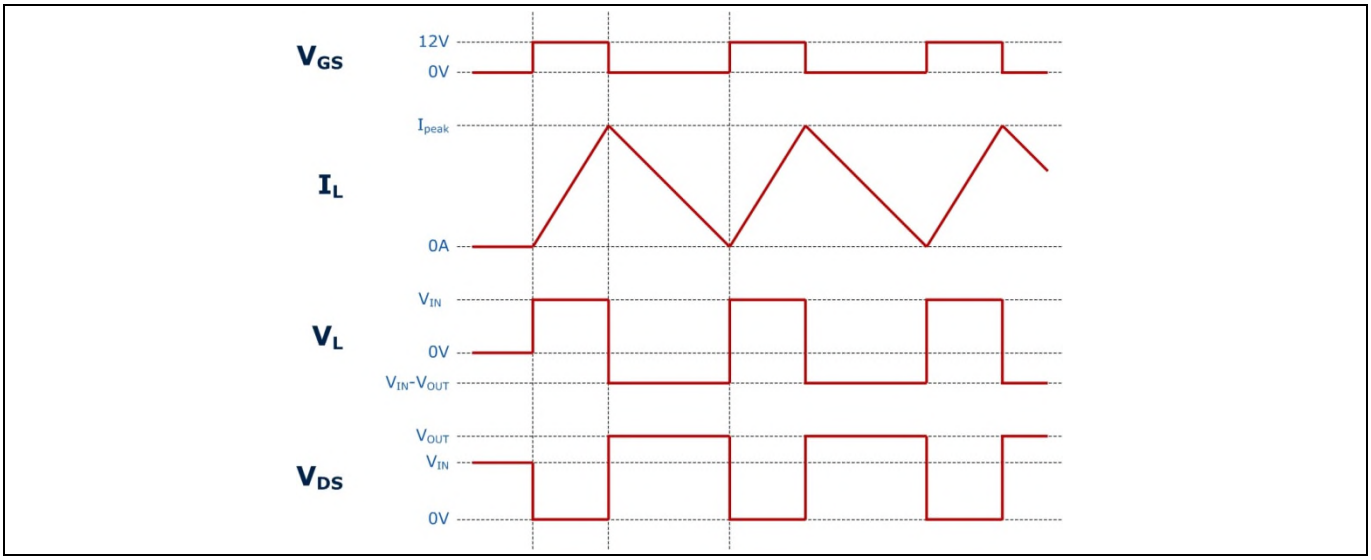

Figure 3 CrCM waveform

This conduction mode results in relatively high efficiency due to reduced turn-on losses in the MOSFET. This simulation shows the behavior of a boost converter operated in critical conduction mode.

CrCM is very popular in power factor correction applications because it is easy to implement. Typically a zero-current detection (ZCD) circuit is added to enable this mode of operation, as shown in Figure 1. The ZCD circuit detects the zero crossing of the inductor current and is used to trigger the next switching cycle. In a boost PFC,

constant ON-time switching is used at every switching cycle in order to force the inductor current to be in the same phase and shape as input voltage.

1.1.3 Discontinuous Conduction Mode (DCM)

Discontinuous Conduction Mode (DCM) occurs when output power delivered to the load is very low (i.e. low load condition), characterized by a discontinuous flow of current through the magnetic component. There are some converters designed to permanently operate in DCM, especially low power and cost-sensitive converters, as it is easy to control and offers good transient behavior.

DCM is characterized by the inductor current staying at zero for a period before the next switching cycle begins. DCM is typically implemented with constant frequency switching and a short duty cycle and usually, the next switching cycle is not synchronized in any way to the oscillations of the drain-source voltage (V_{DS}).

In a boost converter, the output diode becomes reversed biased when the inductor current reaches zero. This prevents the current from flowing in the reverse direction as the output voltage is higher than the input voltage. At this point, V_{DS} returns to its steady state, the input voltage. Due to parasitic capacitance within the MOSFET and the inductance from the magnetic components, V_{DS} exhibits underdamped oscillation behavior before reaching the steady state.

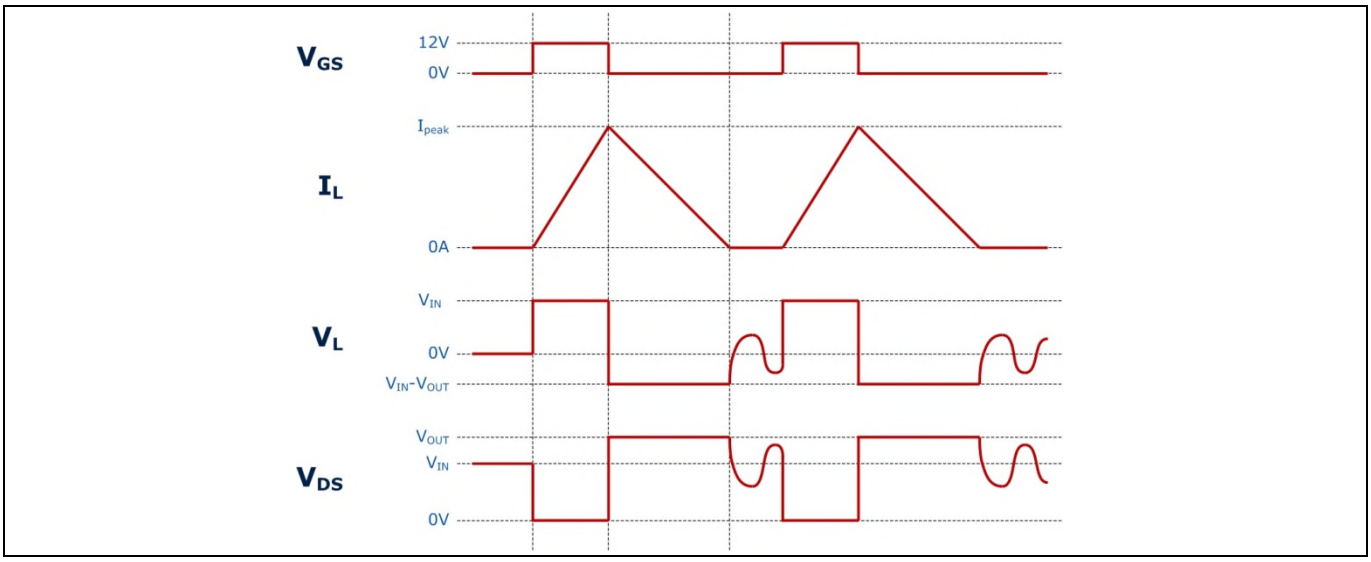

Figure 4 DCM waveform

Similar to CrCM, this conduction mode results in relatively high efficiency due to reduced turn-on losses in the MOSFET. This simulation shows the behavior of a boost converter operated in critical conduction mode.

1.1.3.1 One-time switching

The underdamped oscillation behavior of MOSFET V_{DS} can be observed clearly when the MOSFET is turned on momentarily, as illustrated in the following figure.

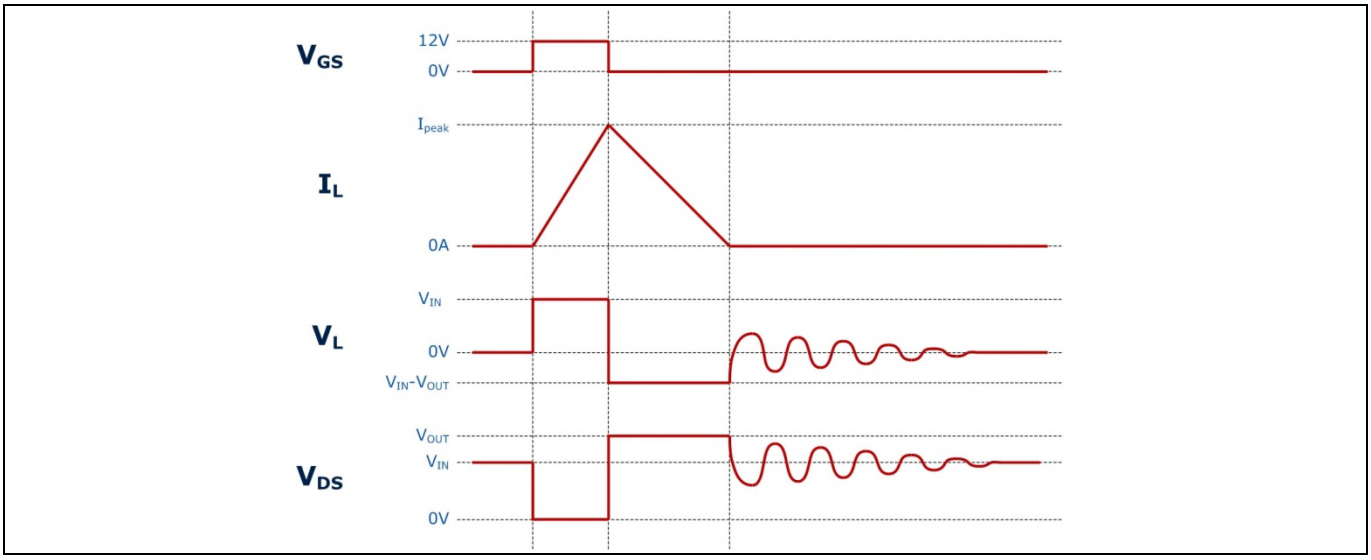

Figure 5 One-time switching

The underdamped oscillation consists of “valleys” and “peaks” gradually subsiding over time until V_{DS} reaches steady state equilibrium. In the case of a boost converter, the steady state equilibrium is the input voltage V_{IN}. This simulation shows the waveforms in a boost converter.

1.2 Hard switching vs soft switching

Section 1.1 details various types of conduction modes in power supplies - all of which are assumed to be ideal. This section considers the non-ideal behavior of the components during switching, which are largely influenced by parasitic capacitances and inductances; and how the switching loss is generated due to such non-ideal behavior.

1.2.1 Hard switching

When a MOSFET is used as a switching element in a clamped inductive load (e.g. boost converter) and is operating in CCM, its turn-on and turn-off switching is not instantaneous. There is a brief moment where its V_{DS} and I_D are overlapping. This is the main source of switching loss and it is heavily influenced by the MOSFET parasitic capacitance.

This phenomenon is also known as “hard switching” and always occurs when the power supplies operate in CCM, due to the fact that the next switching cycle begins before the inductor current reaches zero. Figure 6 shows the waveforms. The overlapped area between V_{DS} and I_D representing the switching loss ($P_{LOSS} = V_{DS} * I_D$) is highlighted.

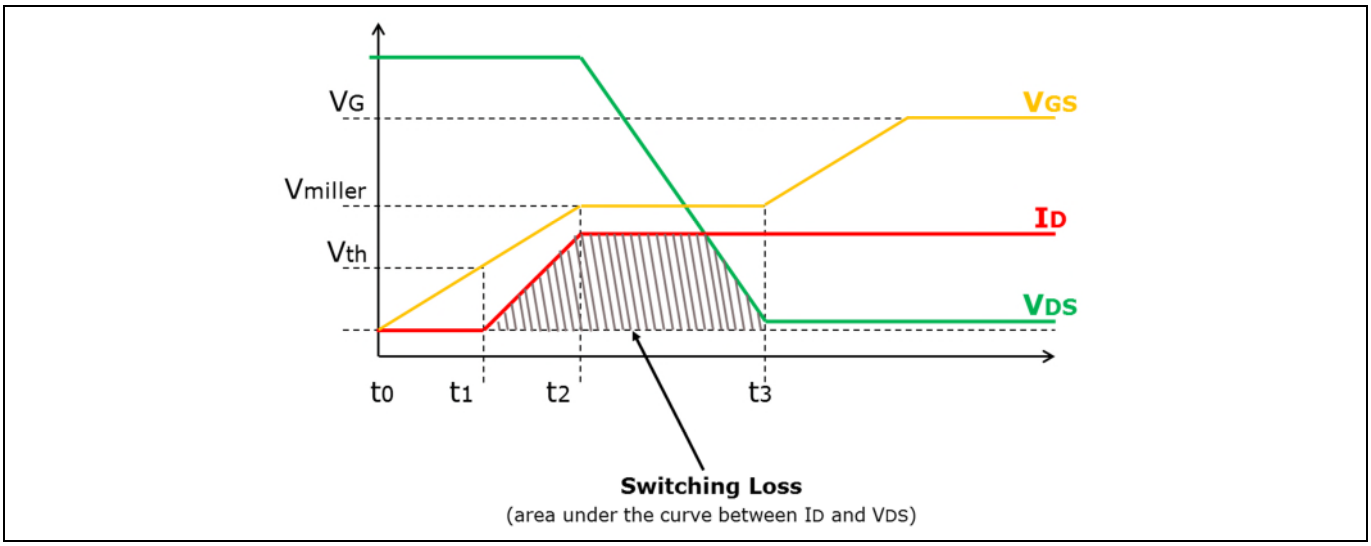

Figure 6 Hard switching

1.2.2 Soft switching

1.2.2.1 Zero-Voltage Switching (ZVS)

Having understood how the switching loss is produced, it is logical to think that it can be completely eliminated by triggering the next switching cycle when MOSFET V_{DS} goes to zero. Such a method is known as Zero-Voltage Switching (ZVS), as shown in the following figure.

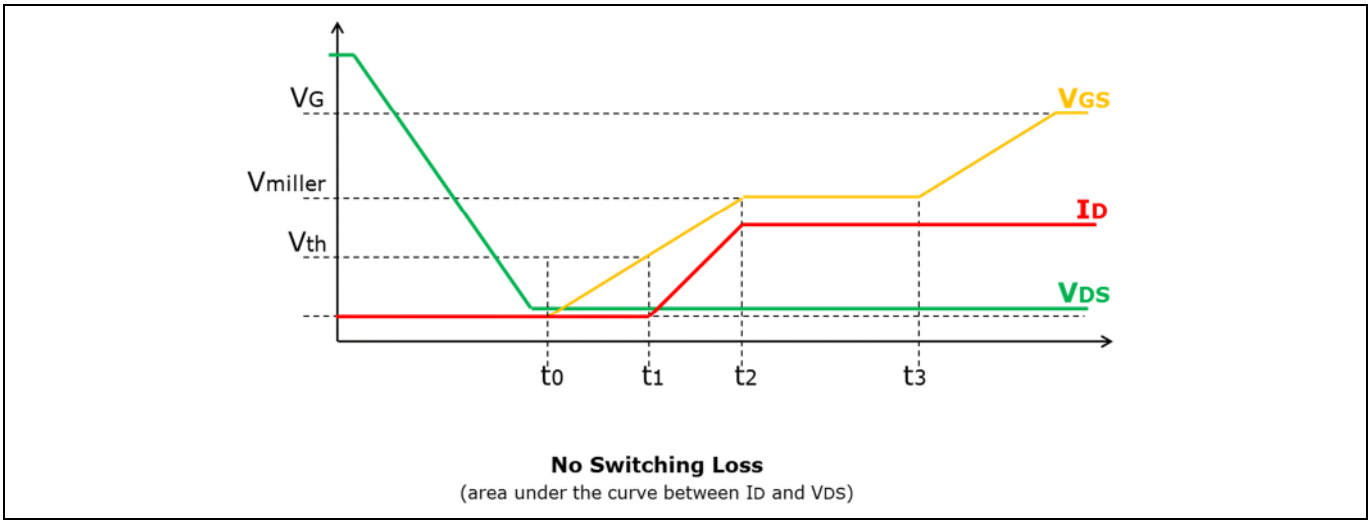

Figure 7 Zero-Voltage Switching (ZVS)

However, none of the standard power topologies such as boost converter, buck converter or flyback converter are able to achieve ZVS because their V_{DS} converges to the input voltage. This method requires a specialized “resonant topology” with a resonant circuit such as LLC or LCC in order to enable ZVS.

1.2.2.2 Zero-Current Switching (ZCS)

In power converters which are designed to operate in CrCM or DCM, the magnetic current reaches zero before the next switching cycle begins. This is known as Zero-Current Switching (ZCS), which minimizes the overlapped area between V_{DS} and I_D therefore reduces the switching loss, albeit not completely.

In contrast to CCM hard switching, both ZVS and ZCS are also known as “Soft Switching”.

1.3 Quasi-resonant switching

As mentioned in Section 1.2.2, in all standard power topologies (boost, buck and flyback) V_{DS} converges to the input voltage after every switching cycle. As a result, the MOSFET’s drain-source parasitic capacitance (C_{DS}) stores some charge that is released through the MOSFET at the next switching cycle. This materializes as additional transient drain current (I_D) in the MOSFET.

In the case of power converters switching in DCM with a constant frequency, the switching loss varies significantly because the next switching cycle may start at any valley or peak. More switching loss is generated when the next switching cycle starts at the peak and the reverse is true; less switching loss is generated when the next switching cycle starts at the valley.

By triggering the next switching cycle in the middle of any of the valleys, V_{DS} is kept to its lowest possible level. Assuming the same amount of drain current I_D is flowing through the MOSFET, the relative amount of turn-on loss ($P_{LOSS} = V_{DS} * I_D$) has been significantly reduced when compared to the conventional hard switching. Figure 8 illustrates this behavior and the reduced turn-on loss is represented by the reduced overlapped area under the curve.

In some cases when there is a large difference between output voltage and input voltage, V_{DS} may reach zero when the next switching cycle begins. In this condition, turn-on loss is completely eliminated and therefore mimics ZVS operation. For this reason, this method is known as “quasi-resonant switching” or “valley switching”.

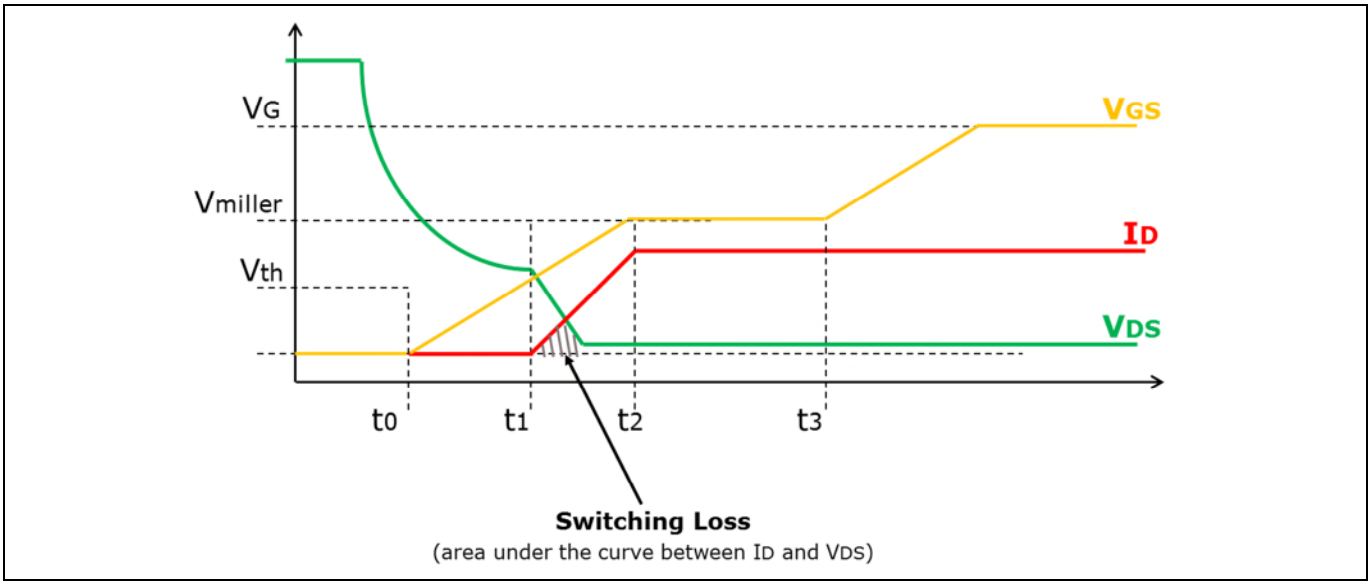

Figure 8 Quasi-resonant switching or “valley switching”

Quasi-resonant switching always operates in DCM and requires a ZCD circuit in order to force the next switching cycle to begin at the lowest level of V_{DS} (i.e. in a valley).

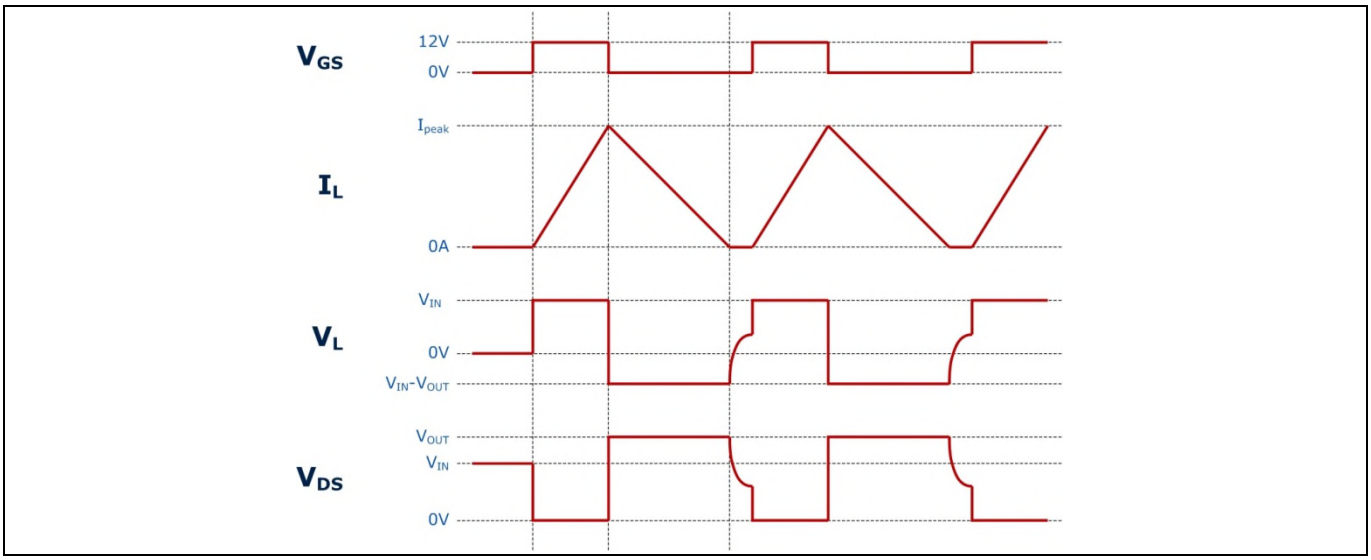

Figure 9 Quasi-resonant on 1st valley

Quasi-resonant conduction mode results in the highest achievable efficiency due to minimized turn-on losses in the MOSFET. This simulation shows the behavior of a boost converter operated in quasi-resonant conduction mode.

1.3.1 Valley skipping

In AC/DC power factor correction applications with a boost or flyback converter, it is possible to implement quasi-resonant switching with a constant ON-time. Such a method has the same effect with CrCM implementation.

As the PFC load gets lower, the ON-time gets shorter in order to maintain constant output voltage. As a result, the average switching frequency of the PFC increases. Although switching loss has been greatly reduced by using a quasi-resonant mode, it will increase again as the switching frequency increases. In addition, the electromagnetic interference (EMI) will also increase.

In order to mitigate this problem, the switching frequency can be reduced by triggering the next switching cycle at the subsequent valleys. This technique is known as “valley skipping”, which reduces switching losses at low load and also maintains EMI at acceptable levels.

The following figure shows valley skipping with MOSFET turn on performed in the second valley.

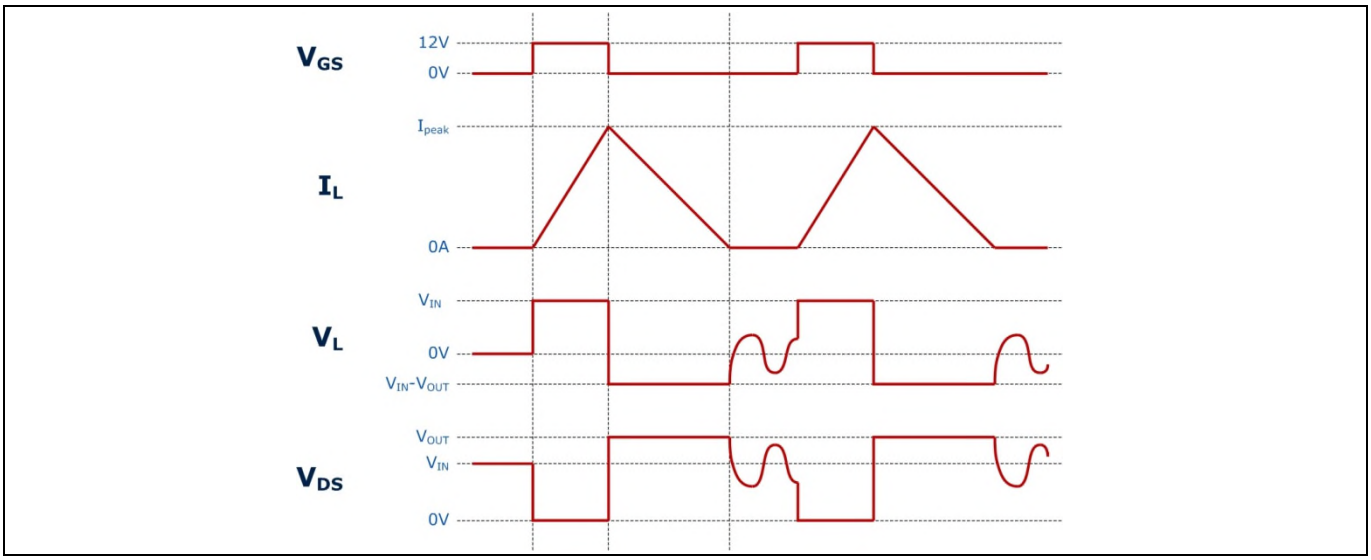

Figure 10 Quasi-resonant on 2nd valley

Valley skipping decreases the switching frequency without reducing efficiency. This simulation shows the behavior of a boost converter operated in quasi-resonant conduction mode, turning the MOSFET on in every second valley.

2 Simulation with Infineon Designer

Infineon Designer is a digital prototyping engine that makes it easy for engineers to simulate, modify and evaluate circuits and Infineon products. It is a powerful online SPICE and digital simulator with a sophisticated circuit and waveform viewer to help you quickly fine-tune designs with simulation.

The various conduction modes explained in Chapter 1 have been simulated in this environment.

Table 1 Example circuits in Infineon Designer

Mode	Efficiency	Switching frequency	Link to simulation
CCM	92.7%	455 kHz	power_optimos_24V_boost_2_CCM.tsc
CrCM	97.6%	132 kHz	power_optimos_24V_boost_3_CrCM.tsc
QR-1st	97.9%	120 kHz	power_optimos_24V_boost_4_QR_1v.tsc
QR-2nd	97.9%	102 kHz	power_optimos_24V_boost_4_QR_2v.tsc
DCM	97.5%	108 kHz	power_optimos_24V_boost_5_DCM.tsc
One-time	NA	56 kHz	power_optimos_24V_boost_1_onetime.tsc

3 Implementation with XMC1000

XMC1000 is a 32-bit microcontroller product family from Infineon, based on an ARM Cortex™-M0. It contains various peripherals that are designed and optimized for digital power conversion, including quasi-resonant control. Capture Compare Unit 4 (CCU4) and CCU8 are timer blocks used for generating a modulation signal. The CCUs have flexible interconnects between slices to enable triggering and signaling.

Quasi-resonant control can be easily implemented in the XMC1000 microcontroller family by making use of CCU4/8 features such as Load, Clear, Flush, etc. as well as the interconnects. As a result, quasi-resonant control is largely dependent on the hardware and requires very little computation during run-time.

There are two types of quasi-resonant control methods that have been implemented in XMC1000, Constant ON-Time Control (QR_CON) and Peak-Current Mode Control (QR_PCC).

3.1 Constant ON-time control (QR_CON)

In constant ON-time control, the MOSFET is turned on for a fixed time to achieve the desired current, followed by valley switching. This implementation is very suitable for AC/DC power factor correction applications.

QR_CON can be implemented on the XMC1300 is shown in Figure 11.

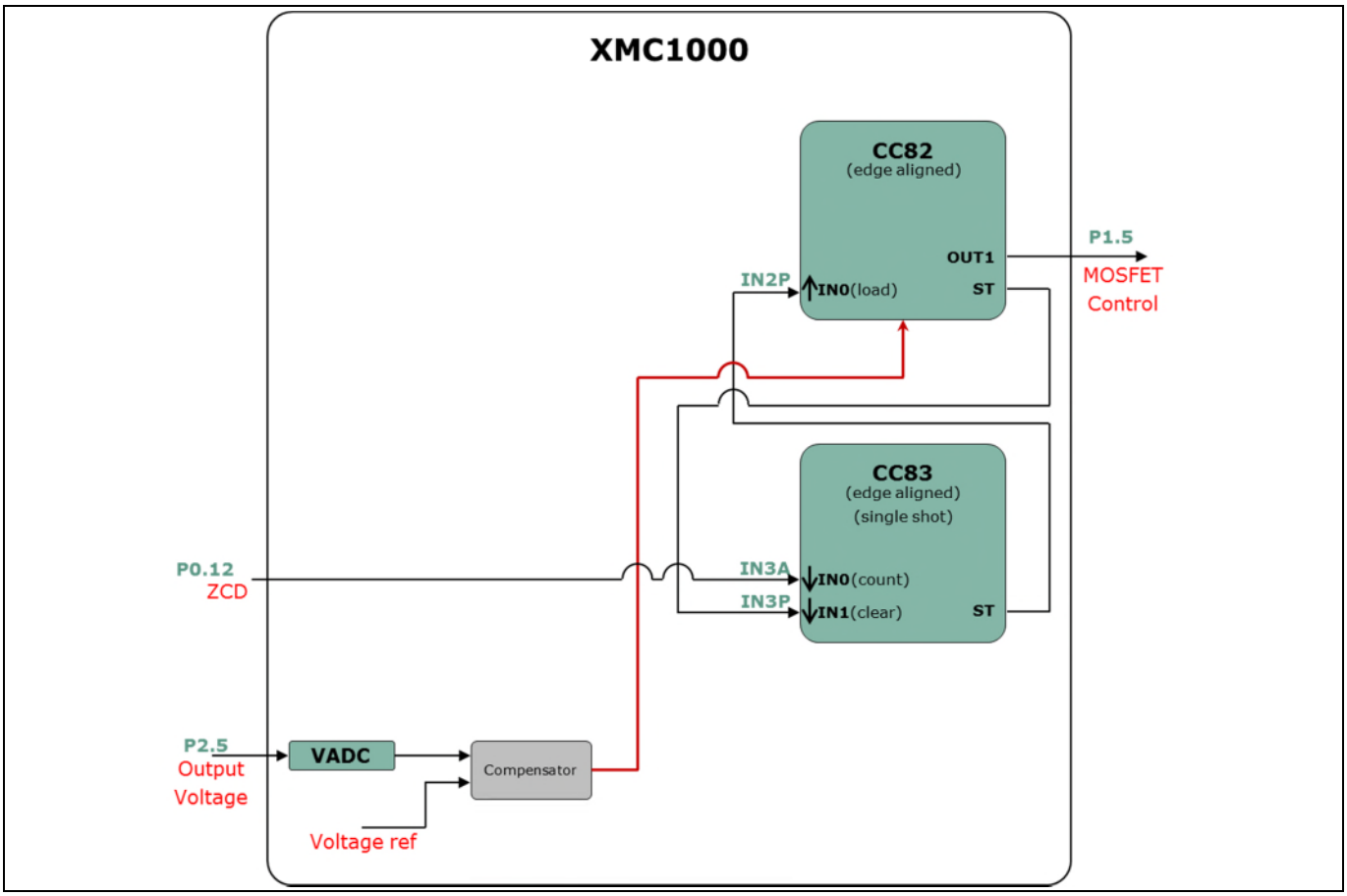

Figure 11 QR_CON with CCU8

Two slices of CCU8 can be used to implement QR_CON. In this example, CC82 and CC83 are used.

CC82 is configured as an edge-aligned timer to generate the fixed ON-time signal and its output is connected to the MOSFET gate. CC83 serves as the zero-current detector. It is configured as a single-shot counter on falling edge to count the number of valleys allowing the valley skipping feature to be realized.

The peripheral timing diagrams with related waveforms are shown in Figure 12, demonstrating QR_CON switching at 3rd valley.

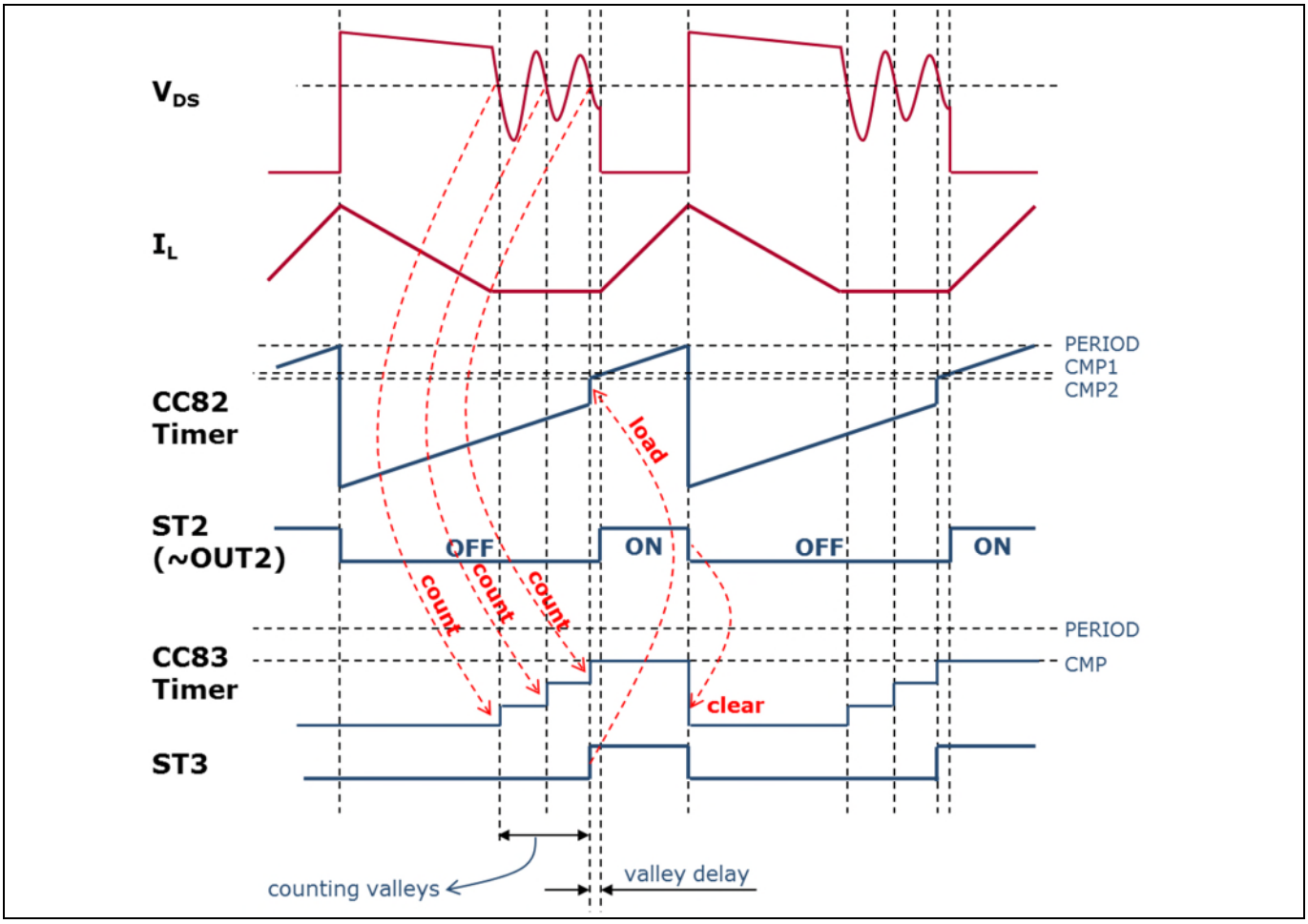

Figure 12 QR_CON waveforms and CCU8 timing diagram

When a zero crossing (falling edge signal) is detected at the CC83.IN3A input, the CC83 counter increments its count value. When the desired valley (CMP) is reached, the CC83 status signal (ST3) changes status to high. This signal is used as a load event to CC82 via the CC82.IN2P input signal, forcing the CC82 timer value to “jump” or “load” itself with a predefined value in CMP2. CC82 continues to run until it reaches CMP1, changing its status signal (ST2) to high. This is the signal that generates the ON-time for PFC modulation. The timer continues to run until it reaches the PERIOD, resetting the status signal ST2 back to low. When it happens, CC82 restarts itself, the MOSFET is switched off and the CC83 counter is cleared to zero via CC83.IN3P.

In summary:

- ON time = CC82.PERIOD – CC82.CMP1
- Valley delay = CC82.CMP1 – CC82.CMP2
- Valley count = CC83.CMP

3.2 Peak-current control (QR_PCC)

Peak-current control limits the maximum current that flows out of the power converter to the load. In the past, peak-current control was often implemented with a comparator and a constant frequency PWM with slope compensation for eliminating subharmonic oscillation. In addition, a leading edge blanking is required to prevent the comparator from mistriggering due to the current spike at the beginning of every switching cycle. Since it is operating with a constant frequency, it tends to operate in CCM mode.

Quasi-resonant switching can be integrated with peak-current control for better efficiency and simplicity. By implementing quasi-resonant switching, peak-current control is no longer operating in constant frequency and therefore, the slope compensation circuit can be completely eliminated. Implementation with an XMC1300 is shown in Figure 13.

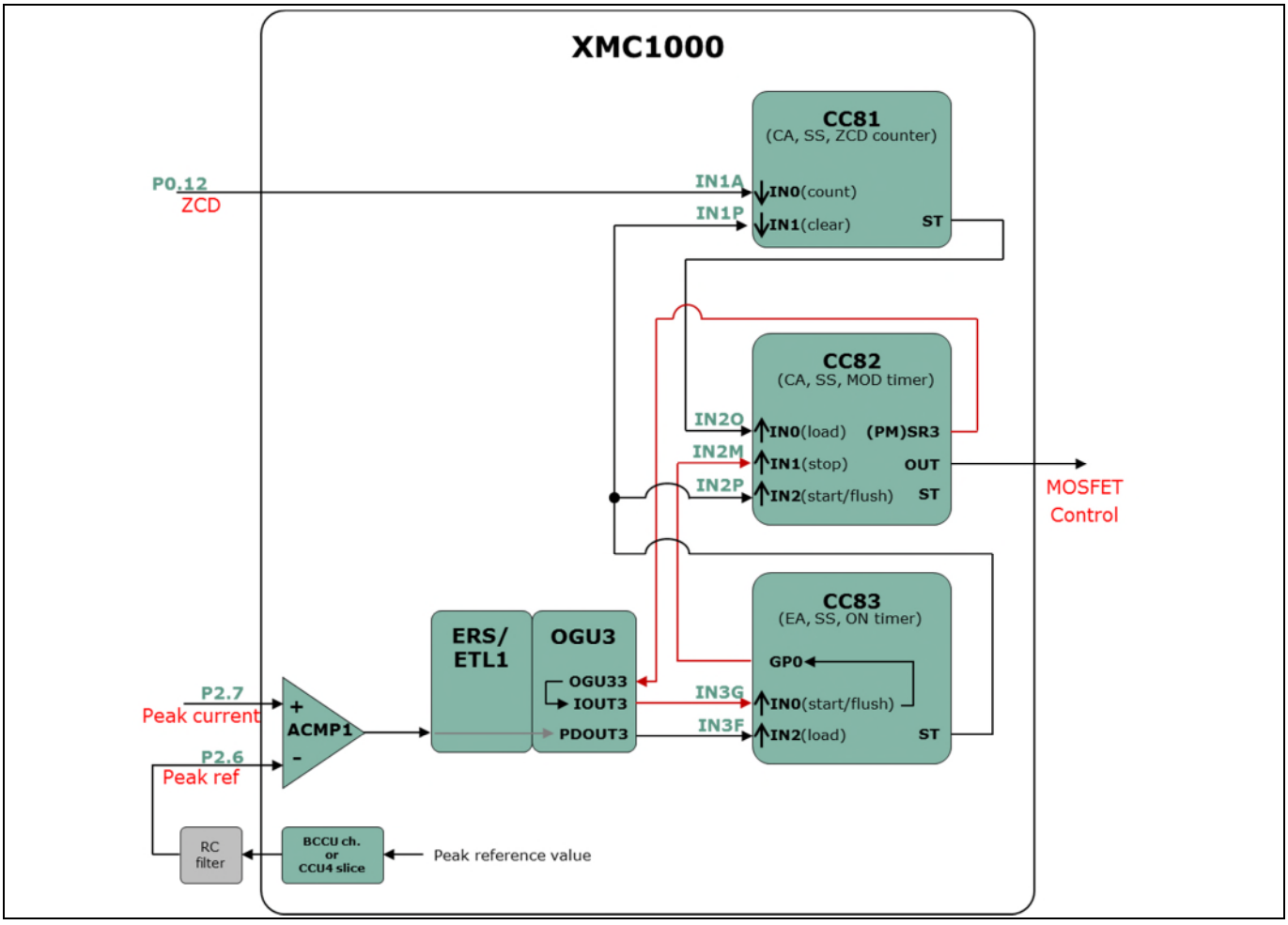

Figure 13 QR_PCC with CCU8

The following peripherals are required to implement peak-current control with Quasi-Resonant (QR) switching:

- 3x Capture Compare Unit 8 (CCU8) slices, namely CC81, CC82 and CC83 for ZCD detection and valley skipping, modulation signal generator and leading edge blanking generation.
- 1x Analog Comparator (ACMP) for peak current limit
- 1x Brightness Color Control Unit (BCCU) for peak current reference generation. More information can be found in AN_201511_PL30_0011 for implementing Pseudo-DAC functionality in XMC1000.
- 1x ERU for interconnecting CC82 and CC83.

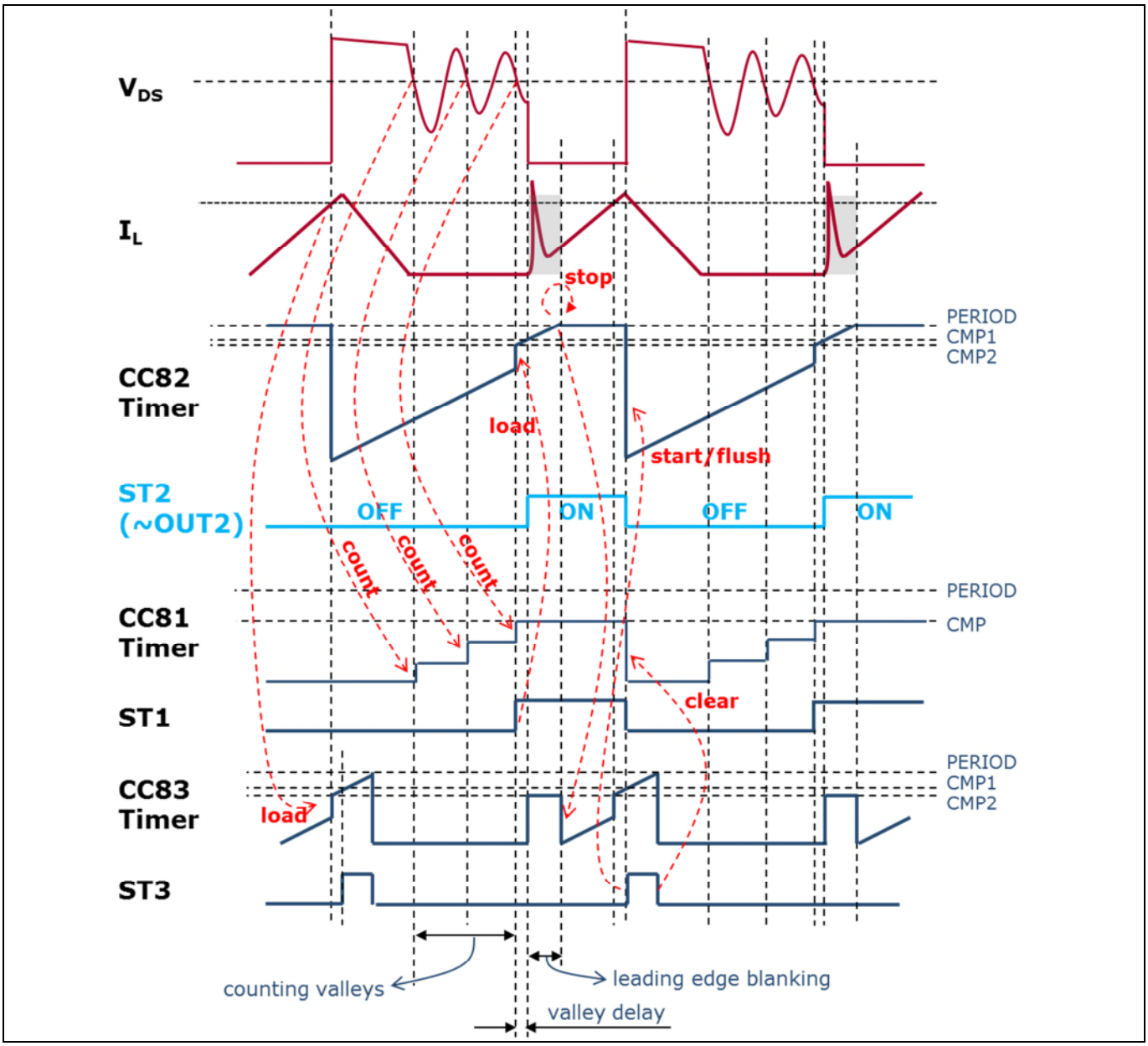

Figure 14 QR_PCC waveforms and CCU8 timing diagram

Similar to QR_CON, QR_PCC can be achieved by configuring CCU8 slices and their interconnection accordingly.

In summary:

- Peak current ref = BCCU compare value or CCU4 compare value (12-bit).
- Leading edge blanking time = CC82.PERIOD – CC82.CMP1
- Valley delay = CC82.CMP1 – CC82.CMP2
- Valley count = CC81.CMP

4 Summary

This document introduces various conduction modes that can be found in switched-mode power supplies. Conventional switching techniques operate the power supplies in a hard switching condition, resulting in a high switching loss. By using a different switching scheme such as quasi-resonant control, switching losses can be significantly reduced.

Quasi-resonant control intentionally triggers the next switching cycle in the middle of MOSFET's V_{DS} valley, i.e. at its lowest possible level that reduces the overlapping area between its V_{DS} and I_D. In some operating conditions where the MOSFET V_{DS} valley reaches zero voltage, switching loss is eliminated completely. Quasi-resonant control, therefore, enables traditional switched-mode power supplies to achieve the highest efficiency possible when compared to other conventional control methods.

Quasi-resonant control can be implemented on an AC-DC stage using constant ON-time control for power factor correction and on a DC-DC stage using peak-current mode control. In addition, quasi-resonant control can be easily implemented in the XMC1000 product family by making use of its timer peripherals (CCU4/CCU8) and their interconnection. This application note shows how constant ON-time control and peak-current control are implemented using CCU8. Since these implementations are hardware dependent, very minimum CPU load is required during run-time. Users have the flexibility to integrate their proprietary codes or other features such as communication, by utilizing USIC (Universal Serial Interface Communication). Implementing quasi-resonant control in XMC1000 microcontrollers, therefore, is ideal for LED drivers and any other applications with a low power requirement (typically less than 300 W).

Example codes are given as a reference to simplify and speed up implementation.

This example project can be downloaded from the same Infineon web page where this Application Note is located or from the example repository: http://www.infineon.com/cms/en/product/promopages/aim-mc/dave_downloads.html

To filter for this example use the key word: Quasi-Resonant Control

Revision history

Major changes since the last revision

Page or reference	Description of change

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