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SiC for Industrial Power Supplies

SiC Based Totem Pole PFC for Industrial Power Supplies

For industrial power supplies, energy efficiency is a key product feature since any energy, which is not delivered to the load but is converted to waste heat, is a direct cost factor in system operation. In addition, any waste heat from inefficient energy conversion results in additional demands on the air conditioning system.

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One particular area that is characterised by high energy demands and a need for high efficiency power supplies are data centres. To minimise the cost and the ecological footprint of the higher and higher demand for computing infrastructure power very efficient energy conversion systems are of essence here. The SiC based Totem Pole PFC discussed in this article can play a role in addressing this challenge.

Introduction

Electric power transmission in the power grid uses alternating current (AC) to supply energy from the power generators to the loads. However, many modern electronic loads such as computer processors require direct current (DC) to operate. Therefore, a power supply unit (PSU) at the input of most modern electronic loads converts the available AC to DC. Additionally, such a PSU converts the voltage to a level suitable for distribution in the system to drive the final loads. In many cases, the DC-to-DC conversion stage also implements galvanic isolation to provide protection. If the power required by the system is low (typically no more than 3.6 kW) the input is single phase AC with a voltage of between 85 and 265 V and a frequency of 50 or 60 Hz depending on the region in the world. The general structure of a single-phase power supply unit is illustrated in Figure 1.

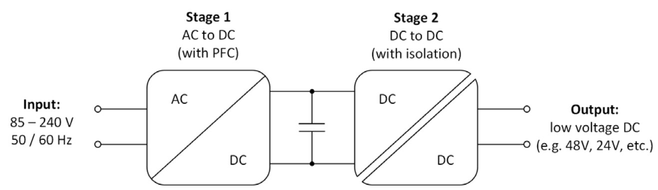


Figure 1:
General high-level structure of a single-phase power supply unit

To achieve the highest efficiency level certification of 80 Plus Titanium a redundant power supply needs to reach at least 96% efficiency at 50% of its nominal load with 230V input voltage. Additionally, targets for 10%, 20% and 100% load as well as 115V input voltage also have to be met. If an efficiency of 98% is assumed for the DC-to-DC stage of the PSU, as can be expected if a soft-switching converter is implemented, the AC-to-DC stage also needs to achieve at least 98% at half load to reach the overall target of 96% for 80 Plus Titanium.

Topologies for AC to DC conversion with power factor correction

In this article, the focus is on the AC-to-DC stage with power factor correction. Multiple circuit topologies exist for this part of the power supply unit. Some of the common options are shown in Figure 2. The classical and probably simplest topology for realising a single-phase PFC stage is the Boost PFC topology. Here a low frequency diode rectifier is combined with a standard boost converter usually comprised of a SJ MOSFET and a SiC SBD. The gate-driving of the SJ MOSFET is controlled in order to draw a sinusoidal current from the AC supply. For larger power (e.g. 3.6 kW) a common approach is to realise the booster in an interleaved version consisting of two inductors, two SiC SBDs and two SJ MOSFETs. In this way, a high efficiency and suitable output powers can be realised. One limitation of this topology is the conduction loss of the low-frequency rectifier bridge. This limits the achievable maximum efficiency of the classical boost PFC.

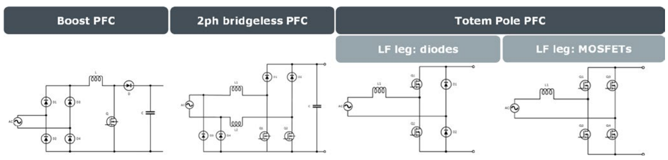


Figure 2: common topologies for single-phase PFC

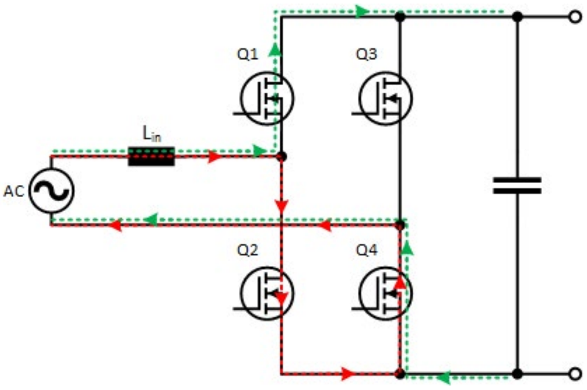
Alternative topologies such as the two phase bridgeless PFC and the Totem Pole PFC avoid the low frequency input rectifier and thus can reach higher efficiencies. While good performance can be achieved with the two phase bridgeless PFC topology, the main disadvantage is that either bridge-leg is only utilised during half of the grid period. This results in a high cycling load and poor utilisation of the components.

The two variants of the Totem Pole PFC shown in Figure 2 are an alternative that gains more and more appeal with the availability of wide-band-gap devices such as SiC MOSFETs. While the topology is already widely described in literature its practical use was limited to low power using SJ MOSFETS because the body-diode performance of these devices did not permit operation in continuous-current-mode (CCM). To avoid the hard commutation of the high loss body-diodes in SJ MOSFETs this circuit needs to be operated in discontinuous-current-mode (DCM) which results in large ripple current.

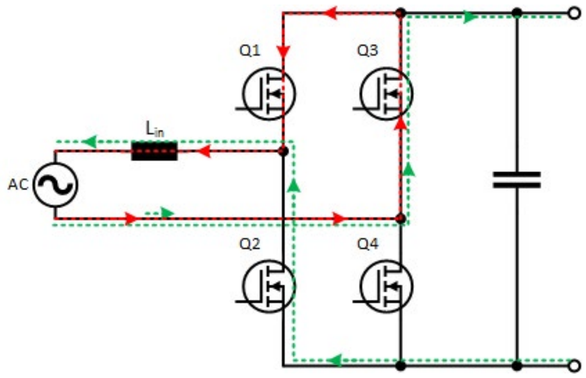
Modern wide-bandgap power semiconductors such as SiC MOSFETs as well as GaN HEMTs now enable the Totem Pole PFC to be operated with low ripple currents in CCM. This is possible, because the body-diodes of the SiC MOSFETs are suitable for hard commutation and only have low reverse recovers losses.

Details of Totem Pole PFC operation

To operate a Totem Pole PFC in continuous-current-mode (CCM) two high-frequency power semiconductor switches with high performance body-diodes are required. These are denoted Q1 and Q2 in Figure 3. SiC MOSFETs can be used for Q1 and Q2 very effectively. For the two switches operated at grid frequency (Q3 and Q4 in Figure 3) no high-performance body-diode is required and Si SJ MOSFETs can be used here. For a more cost-optimised design with slightly lower performance, it is possible to replace Q3 and Q4 with diodes.



a) Positive half-wave



a) Negative half-wave

Figure 3: Current paths in Totem Pole PFC. Red: Current path to charge inductor, Green: freewheeling path

In this topology, the Si SJ MOSFETs are switched with grid frequency. In the positive half-wave Q4 is permanently on, as indicated in Figure 3 a). While the primary boost-switch Q2 is on the current rises in the input inductor L_{in}. In this phase, the load is supplied from the DC link capacitor. At turn-off of Q2 the current commutates to the body-diode of Q1. After a short dead-time the gate of Q1 is turned on and the channel of the SiC MOSFET takes over the current (synchronous rectification). The idealised currents, along with the gate signals, for Q1 and Q2 during the positive half-wave are illustrated in Figure 4.

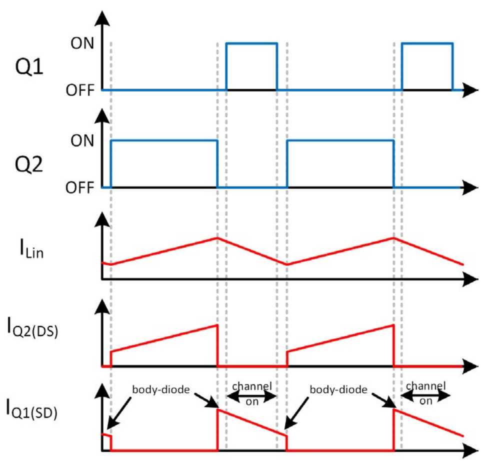


Figure 4: Idealised currents and gate signals for Q1 and Q2

In the negative half-wave of the input voltage the switches Q1 and Q2 interchange their function as primary switch and synchronous rectifier. Additionally, the current flows through Q3 in this half-wave while Q4 remains off. The current paths in the negative half-wave are shown in Figure 3 b).

The operation description shows that the body-diodes of the SiC MOSFETs are hard commutating. However, this is not problematic in SiC MOSFETs as the body diode reverse recovery loss is very low.

Demonstrator for 3.6 kW Totem Pole PFC

In order to illustrate the performance of a Totem Pole PFC based on SiC MOSFETs a demonstrator for the following specification was designed.

Input voltage	85 to 265 V, 50 Hz
Output voltage	400 V
Maximum output power	3600 W at V_{in} = 230 V
Switching frequency	100 kHz

Figure 5 contains a photo of a demonstrator designed to these specifications. Size and compactness were no key design targets for this set-up, as the main objective was accessibility to key components of the converter for easy testing. In the test set-up 650V 60mΩ SiC Trench MOSFETs (SCT3060AR) in a TO-247-4L package are used as the high-frequency switches (Q1 / Q2 in Figure 3) alongside 600V 60mΩ Si SJ MOSFETs (R6047ENZ4) for the leg which operates at grid frequency. With the 60mΩ SiC MOSFET a good compromise between switching and conduction loss is reached for the selected switching frequency and the specified maximum output power. Further efficiency gains could be reached by replacing the line-frequency operated SJ MOSFETs with lower $R_{DS(on)}$ types, as switching loss for these components is not relevant.

For gate-driving of the SiC MOSFETs the isolated gate-driver BM61S41RFV is used for both high-side and low-side to take full advantage of the driving-sense pin of the TO-247-4L. For driving the Si SJ MOSFETs a 2 channel gate-driver IC (BM60212FV-C) is used and boot-strap supply of the high-side is realised.

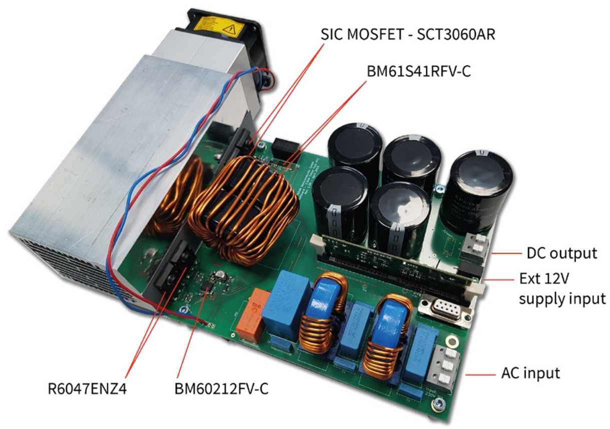


Figure 5: Demonstrator for 3.6 kW Totem Pole PFC

Experimental Results for SiC based Totem Pole PFC

Using the mentioned demonstrator measurements were performed at up to 3.6 kW output power. The measured efficiency across the output power range for low-line (V_{in} = 110 V) and high-line (V_{in} = 230 V) is shown in Figure 6. At high-line input, a peak efficiency of 98.5% was reached and between ca. 500 W and full load the efficiency remains above 98%.

During testing the case temperature of the power devices was monitored using infrared thermography. The result in Figure 7 shows that upon reaching full output power the case temperature of the devices reached approximately 100°C at an ambient temperature of 25°C. Loss reduction measures and improvements in the cooling path can help to ensure thermal stability also at increase ambient temperature.

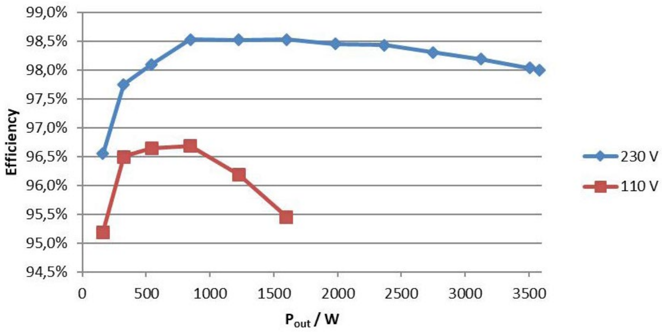


Figure 6: Measured efficiency for Totem Pole PFC Demonstrator (V_{out} = 400 V, f_{SW} = 100 kHz, SCT3060AR, R6047ENZ4)

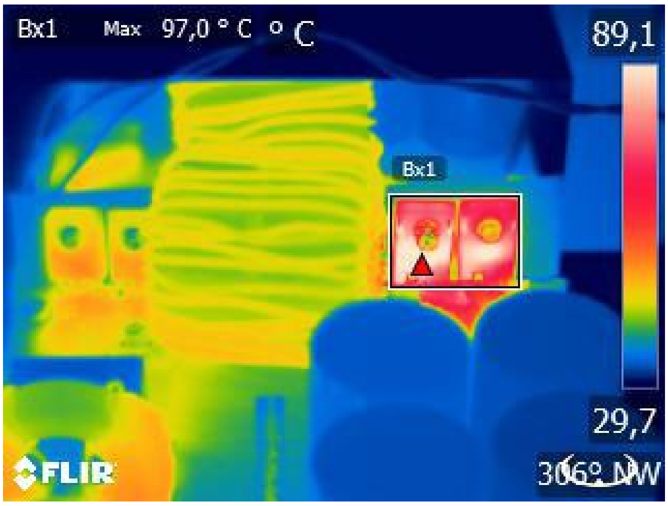


Figure 7: Thermal measurement of semiconductor case temperatures (V_{in} = 230V, V_{out}=400V, f_{SW} = 100 kHz)

As can be seen from the measurement results a Totem Pole PFC using SiC MOSFETs and Si SJ MOSFETs can be a performant solution for a 3.6 kW AC-to-DC stage of a power supply unit. The achieved efficiency is sufficient, even at 100 kHz switching frequency, in order to achieve 80 Plus Titanium certification for a power supply provided a DC-to-DC stage of an efficiency in the region upwards of 98% is also used.

Summary

For many kinds of power supplies, a high efficiency is a key requirement. Especially for power supplies for computer systems, clear requirements need to be met to obtain certain energy efficiency labels. The limitation of traditional AC to DC conversion topologies is the diode bridge rectifier at the input. The conduction loss in these diodes can limit the achievable overall efficiency. The Totem Pole PFC shown here is a very promising alternative topology to overcome this limitation. It was shown that efficiencies of significantly above 98% can be reached using commercially available SiC MOSFETs and Si SJ MOSFETs from ROHM Semiconductor.

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