Reference design: An isolated bidirectional DC-DC power supply

Using SiC MOSFETs to improve the efficiency of power supply systems

Introduction

Solving environmental and energy problems is an important global issue. While the demand for electric power continues to escalate, the call for energy conservation and the need for highly efficient and compact electric power conversion systems increases rapidly.

For example, in recent years, there has been a series of initiatives worldwide to regulate the use of gasoline vehicles, in a bid to reduce global warming gas emissions. These initiatives occur in both developed and emerging countries such as China and India and have become a global trend. The adoption of electric vehicles (EVs) is one of the key responses supporting the trend to reduce our dependence on gasoline. However, there are some challenges to be solved, and the development of charging infrastructures is possibly the most critical one.

The same trend is seeing increased demand for solar power generation systems worldwide. Solar power generation systems are built around highly efficient power conversion circuits that manage the battery storage system and the supply of energy to the power grid, with minimal waste. Emerging countries face increased challenges in the development of their EV charging infrastructure, as they are looking to develop high performance systems and solar power generation systems in the same, short period. This results in a strong demand for technical support and development resources coming from engineering teams, to enable their smooth and quick transition from development to commercialization.

This is just one example in a growing number of cases, where engineering teams are now using reference designs as an efficient development design approach. It is especially apparent in the industrial sector, as commoditization and standardization progress. These highly versatile reference designs, based on device manufacturers' relevant and practical application information, are now attracting increased attention.

Toshiba Electronic Device & Storage's reference design

Toshiba Electronic Devices & Storage Corporation provides various device-based reference designs for facilitating system development and prototyping. The complete set of reference designs can be downloaded from the Reference Design Center. Please use the "Further Information" at the end for the reference designs introduced here and links to related information. Please note that the reference designs have terms of use, so please check them as well.

This article introduces a reference design for an "isolated bidirectional DC-DC power supply" that can be used as the basis for high-power conversion applications, including EV charging stations and inverters in solar power generators.

5kW Isolated Bidirectional DC-DC Converter (Reference Design: RD167)

This reference design is an isolated bidirectional DC-DC converter that uses the dual active bridge (DAB) method, which is one of the most popular methods for high power conversion applications. The DAB method has full bridges on both sides, and by adjusting the phase difference between the left and right bridge circuits, the direction and amount of power transmission is controlled. This reference design has the following features:

(1) Bidirectional high-power conversion by DAB method
Although there are several power topologies via which to configure a bidirectional DC-DC converter, in this 5kW

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reference design the DAB method has been chosen in order to put greater emphasis on efficiency. As the DAB method has a full-bridge configuration on both the high- and low- voltage sides, it supports higher power than the half-bridge method. In addition, soft switching is possible, because of phase-shift power transfer. This results in higher conversion efficiencies. Employment of insulated gate bipolar transistors (IGBTs) as switching elements cannot achieve the desired improvements in efficiency, due to relatively large switching losses. However, the use of silicon carbide (SiC) MOSFETs enables both high power conversion and high efficiency figures to be attained.

(2) High power conversion efficiency using SiC MOSFETs on the high voltage side (TW070J120B)
If a three-phase 400VAC input power factor corrected input is supplied, then the high-voltage side should support a voltage of 750VDC. Normally IGBTs would be specified when working with these voltages. However, switching loss is notably larger in IGBTs than MOSFETs (structurally and characteristically), which places limitations on efficiency levels. In contrast, because of their rapid switching capabilities, SiC MOSFETs have lower switching losses than IGBTs and enable operation at the higher switching frequencies too. In general, when switching frequencies become higher, the switching losses witnessed will tend to increase. However, the use of SiC MOSFETs keeps the overall losses smaller than for IGBTs. In addition, shifting to higher switching frequencies allows the use of small inductors, leading to potential for the downsizing of power units.

(3) Total solution including low voltage side MOSFET (TK49N65W5) and gate driver (TLP5214A)
This reference design uses silicon (Si) MOSFETs based on the assumption of 400V input-output on the low-voltage side. The TK49N65W5 Si MOSFET features a high-speed parasitic diode. This, along with the super junction structure utilized, helps to reduce switching losses and ensure high efficiency levels. The TLP5214A gate driver IC has a 4A sink and source current capability that can adequately drive gate charge and discharge current to support MOSFET and SiC MOSFET switching, even at elevated voltages. With its overcurrent protection (OVP) function and under-voltage lock-out (UVLO) function, the TLP5214A also safeguards the circuit from abnormal conditions.

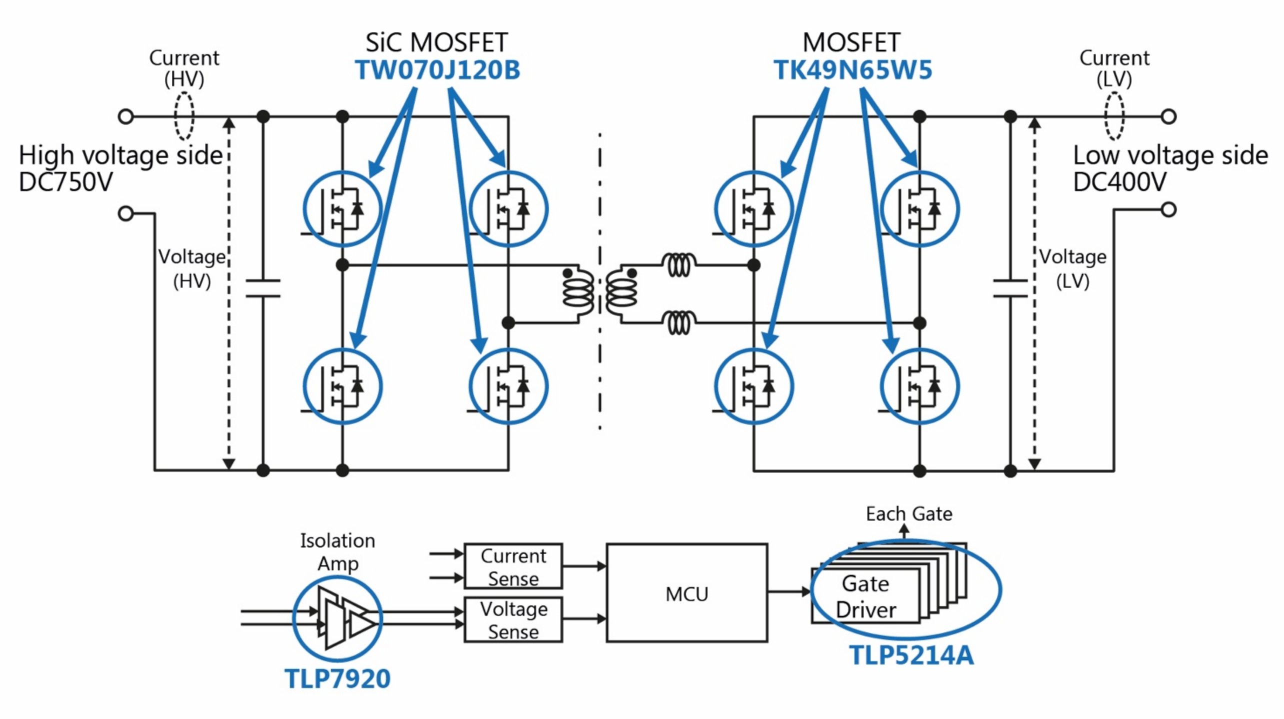

Figure 1: Functional block diagram of 5kW isolated bidirectional DC-DC converter

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The main specifications are as follows.

- High-side voltage: 750VDC (voltage range: 732V to 768V)
- Low-side voltage: 400VDC (voltage range: 396V to 404V)
- Power rating: 5kW
- Power conversion efficiency: 97% or more at 100% step-up load, 97% or more at 100% step-down load
- Switching frequency: 50kHz
- Control method: Constant voltage output control
- Isolation voltage: 2500V (main circuit - control circuit)
- Protection (S/W): High-side overvoltage protection, Low-side overvoltage protection

This reference circuit's high conversion efficiency is achieved through the combined benefits of the DAB bidirectional DC-DC conversion method, and using SiC MOSFETs as the switching elements. A key figure of merit here is the higher switching frequency of SiC MOSFETs in comparison with IGBTs. This means SiC power devices have a lot of potential to improve the performance and efficiency of power conversion circuits, which has seen their use increase in a wide range of related applications.

Example applications based on the DAB/SiC MOSFET DC-DC Converter reference design

Example 1: EV charging system

The diagram in Figure 2 shows a system that combines two reference designs available from Toshiba. The 5kW isolated bidirectional DC-DC converter reference design (introduced previously) is matched with a high-efficiency three-phase 400VAC input PFC power supply. The two reference designs can be used together for quick and easy system development and are both available from Toshiba..

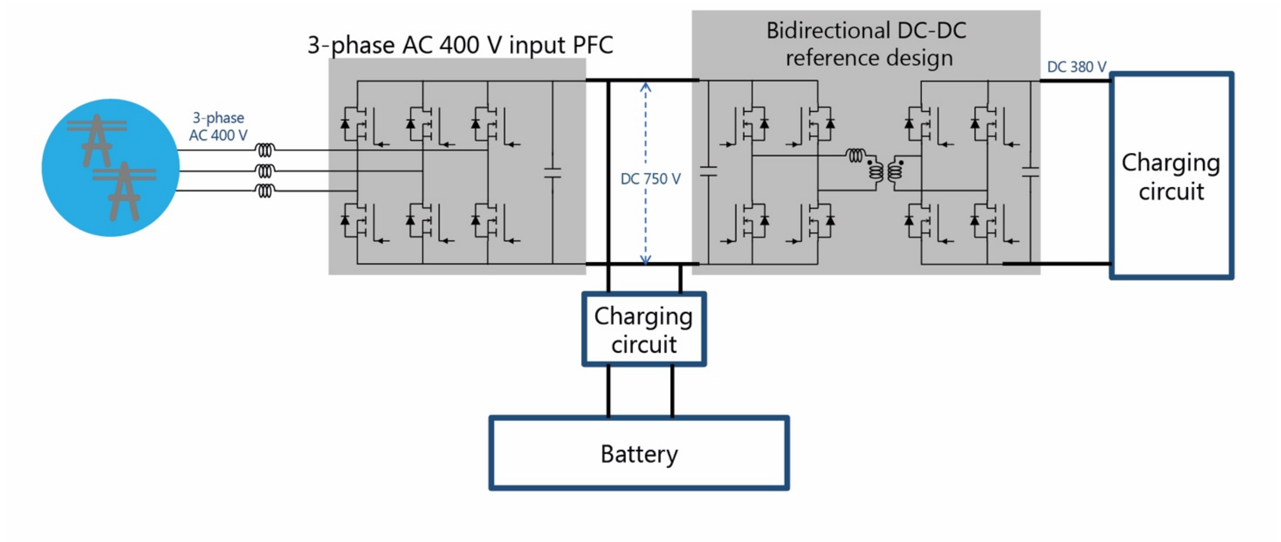

Figure 2: Image of an EV charging system using the 5kW isolated bidirectional DC-DC converter reference design. The 3-Phase AC 400V PFC reference design is also available.

Extending driving distance and accelerating charging rates will be pivotal in encouraging more widespread proliferation of EVs in the future.

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Although increasing the battery capacity is one approach via which longer driving distances can be achieved, the capacity of batteries that may be installed within vehicles will be subject to size and weight constraints. Therefore, one possible way to lengthen the driving distance is to ensure that the battery has adequate capacity, but then increase the charging frequency. Increased charging frequency will mean a shorter charging time is needed per charge, but higher voltages will consequently be required.

To deal with this issue, infrastructure is being developed for high-speed battery charging, and there are already three-phase 400VAC EV charging stations starting to see deployment. Though the use of a three-phase 400VAC input source achieves the high-power levels mandated for EV charging, there are other issues to consider. As the number of charging stations increases, the overall power losses cannot be ignored. Highly efficient power conversion is therefore essential.

The use of three-phase 400VAC as input power requires a power factor corrected (PFC) power source for AC-DC conversion plus a highly efficient insulated DC-DC conversion mechanism for supplying power to the EV battery charging circuit from the DC output of PFC with minimal losses. Furthermore, if there needs to be scope for the EV battery to potentially be used as a power source for other tasks, then bidirectional DC-DC converters will clearly prove useful.

This application example intends to promote the widespread use of high-speed, low loss EV charging stations. It does this through the combination of PFC power supplies, for efficient AC-DC conversion of high power from three-phase 400VAC, plus insulated DC-DC converters that ensure both elevated efficiency and bidirectional operation.

Example 2: A photovoltaic inverter

Inverters for photovoltaic power generation (hereinafter referred to as PV inverters) require highly efficient bidirectional DC-DC converters with low loss. They are used to adjust the DC voltage level supplied by the solar panels and transfer it to the inverter and storage battery charging circuit.

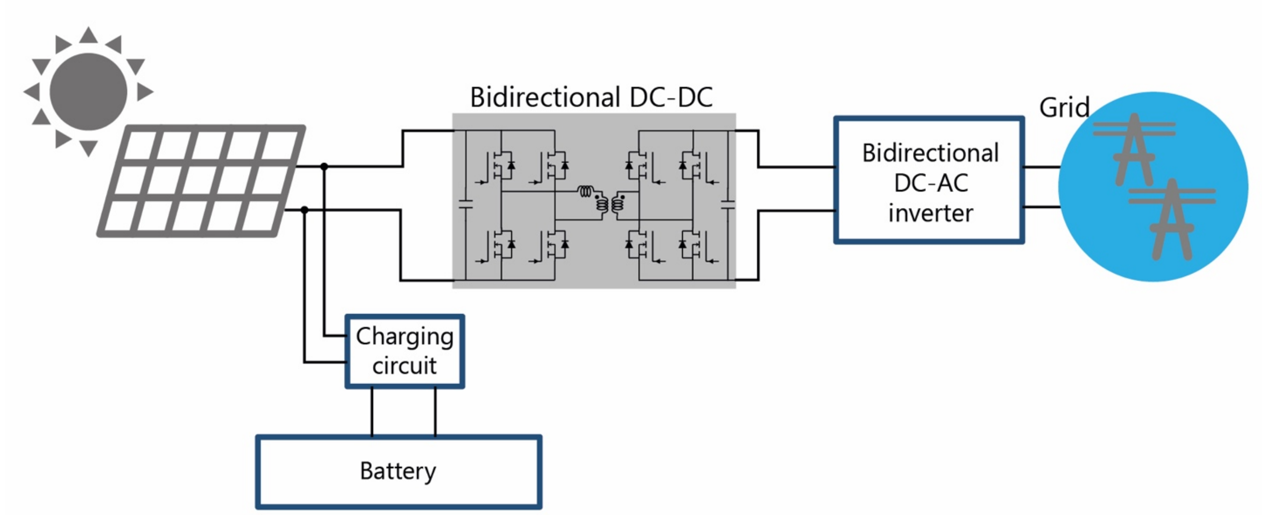

Figure 3: Image of a PV inverter system using an isolated bidirectional DC-DC power supply reference design.

PV inverters are used to convert DC voltages generated by PV panels into commercial AC voltages for use in houses and factories, or to feed them to the power system (Grid) (reverse power flow). However, the power generation capacity of solar panels depends on the time of day and the weather, and it is impossible for the PV panel to supply enough power at night or during cloudy weather. By adding a battery that stores surplus power during favourable weather, we can build a system that can provide a stable supply of electricity whenever it’s needed.

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Bidirectional DC-DC converters are indispensable in providing power from storage batteries to the power system, and vice versa, providing power from the power system to the storage battery. Highly efficient and bidirectional operation uses isolated DC-DC converters to create a PV-inverter system that utilizes limited power with low-loss performance.

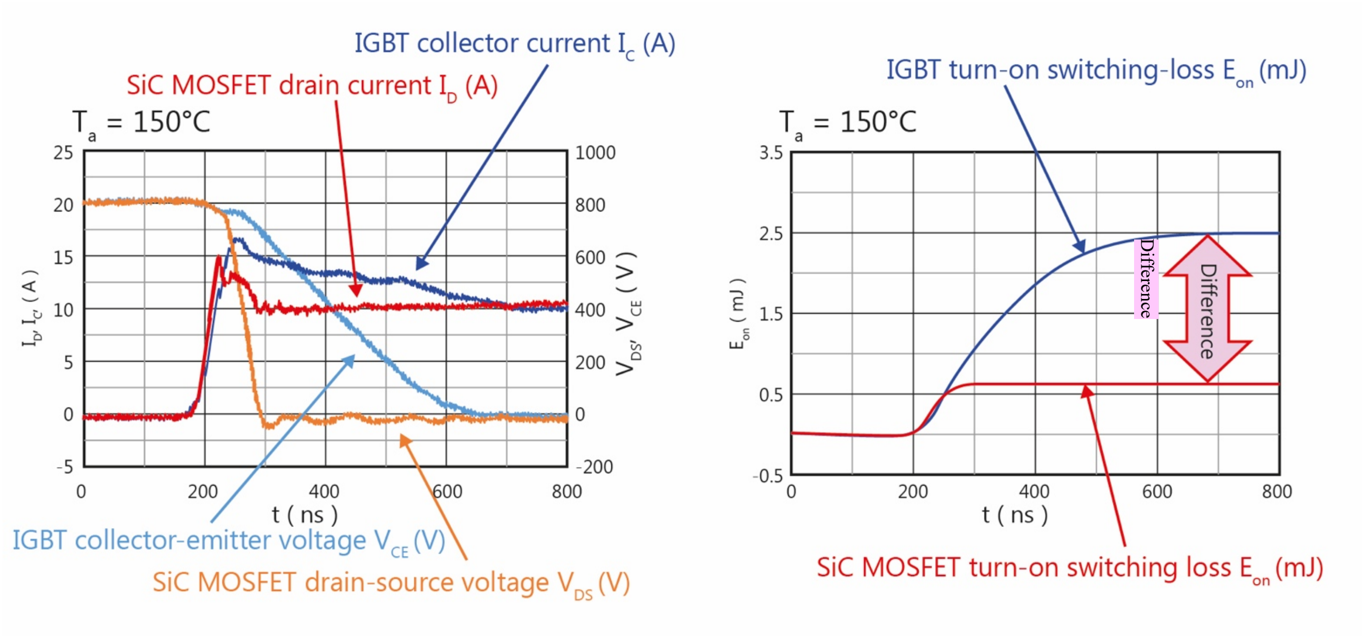
Features of a SiC MOSFET

The power switching devices used significantly influence the efficiency of power conversion systems. The main aim is to reduce the switching losses. In addition to conventional Si devices, there are a growing number of power devices that are based on wide bandgap (WBG) semiconductor materials, most notably SiC and gallium nitride (GaN).

In the reference design highlighted above, the conversion efficiency is improved by adopting a SiC MOSFET as indicated. The following shows a comparative loss example of IGBT and SiC MOSFETs.

Comparison of losses between SiC MOSFET and IGBT

The switching transistor's loss is the sum of the switching losses, the conduction loss due to the on-resistance, and the forward voltage loss of the internal diode. Among them, the switching loss accounts for nearly 90% of the total. Figure 4 is a comparative example of switching waveforms and loss E_{on} during turn-on of the SiC MOSFET and IGBT. The SiC MOSFET used for comparison is Toshiba's TW070J120B as used in this reference design, while the IGBT is a high-speed switching type made by another company.



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●SiC MOSFET test conditions

V_{DD} = 800 V, I_D = 10 A, T_a = 150 ℃, V_{GS} = 20 V / -5 V, Dielectric load: L = 1 mH, External gate resistance R_G = 150Ω
Source-drain diode is used as freewheeling diode (FWD) in parallel with inductive load

●IGBT test conditions

V_{CC} = 800 V, I_C = 10 A, T_a = 150 ℃, V_{GE} = 20 V / -5V, Dielectric load: L = 1 mH, External gate resistance R_G = 47Ω
Emitter-collector diode is used as FWD in parallel with inductive load

* Test conditions set to match the inclination dID(IC)/dt of the ID and IC at turn-on

Figure 4: Comparative example of switching waveform and loss E_{on} at turn-on of SiC MOSFET and IGBT

This example in Figure 4 shows that the turn-on loss of the IGBT is 2.5 mJ and that of the SiC MOSFET is 0.6 mJ, so the turn-on loss can be reduced by 76% when replacing an IGBT switching transistor with a SiC MOSFET. This difference in loss is mainly due to the difference in switching characteristics (speed) between VDS and VCE in the switching waveform diagram. The SiC MOSFET turns fully on almost instantly, allowing I_D to flow accordingly. The IGBT takes time to turn on completely, and the delay accounts for the losses.

Also, Figure 5 is a comparative example of the sum of the turn-on and turn-off switching losses, the conduction loss due to the on-resistance, and the loss due to the forward voltage of the internal diode SiC MOSFET and IGBT by simulation. The conditions are V_{CC} = 400 V, I_O = 7.0 Arms, power factor = 1, 3-phase modulation, T_j = 150 °C. From this result, it can be seen that the SiC MOSFET loss is approximately 28 W lower than the IGBT losses. This reduction in losses contributes to the efficiency improvement of the equipment.

In this way, even in existing general-purpose power conversion applications, it is possible to significantly reduce losses by replacing an IGBT with a SiC MOSFET. By reducing the loss, it is also possible to reduce the size of the circuit for the same power, thanks to the higher power density offered by SiC technology. This also means that a power supply of the same size can handle more power.

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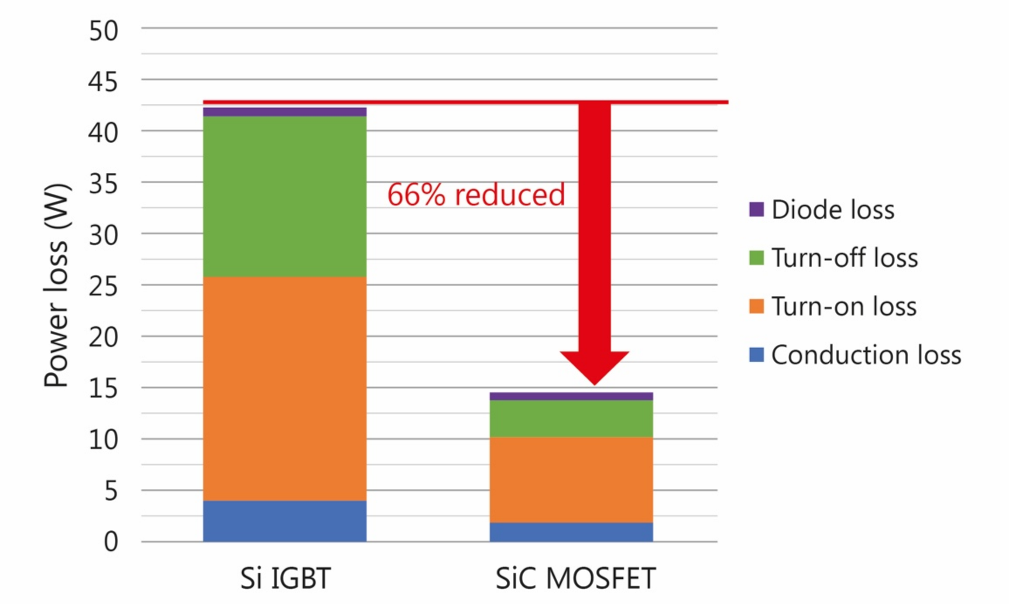
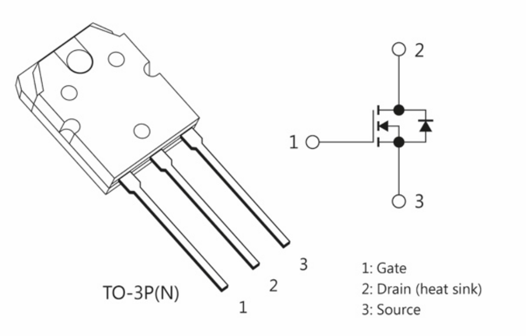


Figure 5: Comparative example of SiC MOSFET and IGBT losses

SiC MOSFET: TW070J120B

The TW070J120B used on the high-voltage side of this reference circuit is an N-channel SiC MOSFET with a built-in SiC Schottky barrier diode (SiC SBD), designed using Toshiba's 2nd generation technology. The main specifications are shown below.

- Built-in SiC Schottky barrier diode
- Low built-in diode forward voltage: V_{DSF} = -1.35 V (typ)
- High withstand voltage: V_{DSS} = 1200 V
- Wide gate-source voltage: V_{GSS} = + 25 V to -10 V
- Low on-resistance: $R_{DS(ON)}$ = 70 mΩ (typ)
- High gate threshold: V_{th} = 4.2 V to 5.8 V



The built-in SiC Schottky barrier diode realizes a lower V_{DSF} than the MOSFET body (parasitic) diode and reduces the diode's conduction loss. Also, because it incorporates a diode with a high I_{FSM} (peak forward surge current), it has very strong surge current withstand capabilities. From the viewpoint of reliability, the built-in diode reduces the component count, which can also help reduce the final circuit failure rate.

The gate-source voltage rating V_{GSS} has a broader range than competing products. The wide tolerance of V_{GSS} helps simplify circuit design. In addition, the gate threshold voltage specified is generally higher than competing products. This makes it less prone to damage caused by fluctuations in the gate voltage and noise. These features and its low loss and robustness make designing highly efficient power solutions easier with the TW070J120B SiC MOSFET.

Gate drivers for SiC MOSFETs

The gate driver for a SiC MOSFET must take into consideration the physical characteristics and the high-speed switching characteristics of SiC. Below is a summary of the main points to consider when using the TW070J120B. For full details, please refer to the related application notes.

Key points to consider for SiC MOSFET gate control
(1) Strictly adhere to the absolute maximum rating of -10 V to 25 V for the gate-source voltage.
(2) Set the gate voltage at turn-on to 18 V to 20 V.
(3) Set the gate voltage at turn-off to 0 to -5 V.

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(4) It is necessary to fully charge the gate-source capacitance (C_{GS}) with the gate charge.

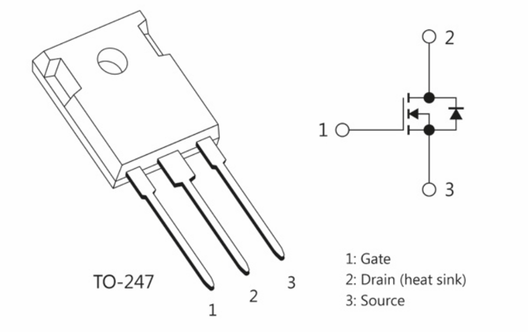
To apply the gate voltage and turn it on, the gate-source capacitance must be charged to the gate charge. The standard gate charge when V_{GS} is 0 to 20 V is 70 nC (V_{DD} = 800 V, V_{GS} = 20 V, I_D = 36 A). It is necessary to present a current at the selected switching frequency that is sufficient to deliver this charge.

The design engineer should also note that standard conditions are set for the gate drive circuit in the reference design introduced earlier. It is possible to optimize these by checking and evaluating the circuit's operation.

Super Junction MOSFET: TK49N65W5

For the low-voltage side of the reference circuit, an TK49N65W5 N-channel Si MOSFET is used. This has low on-resistance value ($R_{DS(ON)}$), due to its DTMOS super junction topology and fast reverse recovery time (t_{rr}). In addition, the gate switching speed is optimized. The main specifications are shown below.

- $R_{DS(ON)}$: 0.051Ω (typical)
- t_{rr}: 145ns (typical)
- Drain-source voltage (V_{DSS}): 650V (rated)
- Gate-source voltage (V_{GSS}): ±30V (rated)
- Drain DC current (I_D): 49.2A (rated)
- Drain pulse current (I_{DP}): 196A (rated)



Isolation amplifier: TLP7920

In order to generate the PWM signals controlling the SiCs it is necessary to continuously measure the input and output currents and voltages of the PFC, which are then the inputs of an appropriate algorithm running on the MCU. The isolation amplifier TLP7920, with an isolation voltage of 5000 Vrms is ideally suited to this task. When using an appropriate voltage divider to guarantee the allowed input voltage range of ±300 mV shown in Figure 5 its fixed gain of 8.2 ensures with a second amplification stage a flexible full scale signal preparation for the ADC of a 3.3V or 5V MCU system.

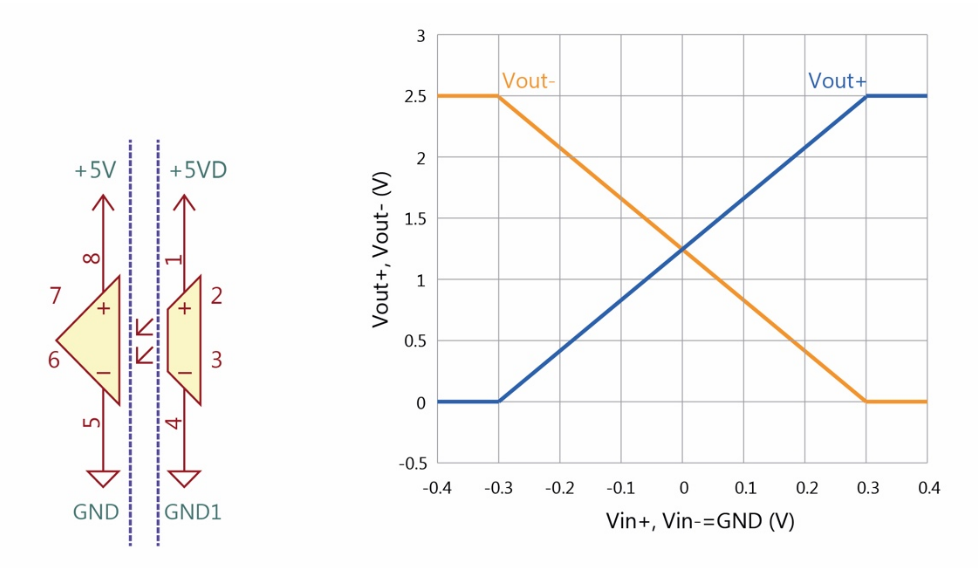


Figure 5: Basic symbol of TLP7920 and its input-output characteristic

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The available bandwidth of 230 kHz (-3 dB) of the TLP7920 in combination with a fast ADC in the MCU allows the sampling of suitable inputs for the algorithm.

Summary

In recent years, the demand for shortening the time to market of products has increased, and engineers involved in the development and design of equipment are required to make it production-ready in the shortest time possible. Manufacturer-supplied reference designs significantly aid the design and prototyping process.

The reference design of 5kW isolated bidirectional DC-DC converter introduced here can help engineering teams develop high efficiency power conversion applications with high power density. The key to reducing losses and achieving higher efficiency was to replace the power switch on the step-down side from a conventional IGBT to a SiC MOSFET. In addition, the use of super junction MOSFETs with low $R_{DS(ON)}$ and fast t_{rr} on the low voltage side also contributes to the loss reductions.

It is now widely known that SiC power devices offer advantages in high power applications, but to take advantage of their excellent properties, it is necessary to understand the characteristics of SiC power devices. In this respect, the reference design presented here provides a standard approach that can help accelerate development and design.

From an application perspective, the growing adoption of EVs is in response to an urgent need worldwide to reduce global warming gas emissions. Development teams can use this reference design for infrastructure designs - such as EV charging stations and solar power generation systems, which are key to the widespread use of EVs and to the emergence of a low-carbon society. The reference designs presented here can be particularly beneficial for development teams working in emerging countries.

Toshiba plans to increase the number of reference designs it provides in the future, ramping up the development of designs that incorporate SiC power devices for high-power conversion applications. At the same time, we are developing a new generation of SiC power devices and are planning to announce a third-generation product in addition to the current second-generation product shortly.

Further Information

- 5kW isolated bidirectional DC-DC converter reference design
- PFC circuit for 3-phase 400V AC input reference design
- Reference Design Center

Contact us to discuss incorporating our products and solutions into your design:
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