Reference design: 5kW Isolated Bidirectional DC-DC Converter

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.

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 "Related Information" at the end for the reference designs introduced here (URL TBA) 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 bi-directional 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 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
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 are maintained. The TLP5214A gate driver IC has a 4A sink and source current capability that can adequately drive gate charge and discharge current to support 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.
The main specifications are as follows.

- **High-side voltage**: 750VDC (voltage range at input: 732V to 768V)
- **Low-side voltage**: 400VDC (Input 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 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.

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

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 bi-directional 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.

![Image of a PV inverter system using the 5kW isolated bidirectional DC-DC converter reference design.](image)

**Figure 3:** Image of a PV inverter system using the 5kW isolated bidirectional DC-DC converter 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 favorable weather, we can build a system that can provide a stable supply of electricity whenever it’s needed.

Bi-directional 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.

![Comparative example of switching waveform and loss $E_{on}$ at turn-on of SiC MOSFET and IGBT](image)

*Test conditions set to match the inclination $dI_d/dt$ of the ID and IC at turn-on*
This example 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 $V_{DS}$ and $V_{CE}$ 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, $I_O = 7.0$ A$_{rms}$, 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.

![Figure 5: Comparative example of SiC MOSFET and IGBT losses](image)
SiC MOSFET: **TW070J120B**

The TW070J120B used in the high-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: $V_{DSF} = -1.35 \text{ V (typ)}$
- High withstand voltage: $V_{DSS} = 1200 \text{ V}$
- Wide gate-source voltage: $V_{GSS} = +25 \text{ V to } -10 \text{ V}$
- Low on-resistance: $R_{DS(ON)} = 70 \text{ m}\Omega \text{ (typ)}$
- High gate threshold: $V_{th} = 4.2 \text{ V to } 5.8 \text{ V}$

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 $I_{FSM}$, 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.
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 ($V_{DD} = 800 \text{ V}, V_{GS} = 20 \text{ V}, I_{O} = 36 \text{ A}$). 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.
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)

**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 the 5kW isolated bidirectional DC-DC converter reference design 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.
Information Link

- 5kW isolated bidirectional DC-DC converter (reference design: RD167)
- PFC circuit for 3-phase 400V AC input (reference design: RD044)
- Reference Design Center
- SiC MOSFET Product Page
- SiC MOSFET: TW070J120B
- Super Junction MOSFET: TK49N65W5

Toshiba Electronic Devices & Storage Corporation

https://toshiba.semicon-storage.com/ad/contact.html
RESTRICTIONS ON PRODUCT USE

Toshiba Corporation and its subsidiaries and affiliates are collectively referred to as “TOSHIBA”.

Hardware, software and systems described in this document are collectively referred to as “Product”.

- TOSHIBA reserves the right to make changes to the information in this document and related Product without notice.
- This document and any information herein may not be reproduced without prior written permission from TOSHIBA. Even with TOSHIBA's written permission, reproduction is permissible only if reproduction is without alteration/omission.
- Though TOSHIBA works continually to improve Product’s quality and reliability, Product can malfunction or fail. Customers are responsible for complying with safety standards and for providing adequate designs and safeguards for their hardware, software and systems which minimize risk and avoid situations in which a malfunction or failure of Product could cause loss of human life, bodily injury or damage to property, including data loss or corruption. Before customers use the Product, create designs including the Product, or incorporate the Product into their own applications, customers must also refer to and comply with (a) the latest versions of all relevant TOSHIBA information, including without limitation, this document, the specifications, the data sheets and application notes for Product and the precautions and conditions set forth in the "TOSHIBA Semiconductor Reliability Handbook" and (b) the instructions for the application with which the Product will be used with or for. Customers are solely responsible for all aspects of their own product design or applications, including but not limited to (a) determining the appropriateness of the use of this Product in such design or applications; (b) evaluating and determining the applicability of any information contained in this document, or in charts, diagrams, programs, algorithms, sample application circuits, or any other referenced documents; and (c) validating all operating parameters for such designs and applications. TOSHIBA ASSUMES NO LIABILITY FOR CUSTOMERS’ PRODUCT DESIGN OR APPLICATIONS.

- PRODUCT IS NEITHER INTENDED NOR WARRANTED FOR USE IN EQUIPMENTS OR SYSTEMS THAT REQUIRE EXTRAORDINARILY HIGH LEVELS OF QUALITY AND/OR RELIABILITY, AND/OR A MALFUNCTION OR FAILURE OF WHICH MAY CAUSE LOSS OF HUMAN LIFE, BODILY INJURY, SERIOUS PROPERTY DAMAGE AND/OR SERIOUS PUBLIC IMPACT (“UNINTENDED USE”). Except for specific applications as expressly stated in this document, Unintended Use includes, without limitation, equipment used in nuclear facilities, equipment used in the aerospace industry, lifesaving and/or life supporting medical equipment, equipment used for automobiles, trains, ships and other transportation, traffic signaling equipment, equipment used to control combustions or explosions, safety devices, elevators and escalators, and devices related to power plant. IF YOU USE PRODUCT FOR UNINTENDED USE, TOSHIBA ASSUMES NO LIABILITY FOR PRODUCT. For details, please contact your TOSHIBA sales representative or contact us via our website.

- Do not disassemble, analyze, reverse-engineer, alter, modify, translate or copy Product, whether in whole or in part.
- Product shall not be used for or incorporated into any products or systems whose manufacture, use, or sale is prohibited under any applicable laws or regulations.
- The information contained herein is presented only as guidance for Product use. No responsibility is
assumed by TOSHIBA for any infringement of patents or any other intellectual property rights of third parties that may result from the use of Product. No license to any intellectual property right is granted by this document, whether express or implied, by estoppel or otherwise.

- ABSENT A WRITTEN SIGNED AGREEMENT, EXCEPT AS PROVIDED IN THE RELEVANT TERMS AND CONDITIONS OF SALE FOR PRODUCT, AND TO THE MAXIMUM EXTENT ALLOWABLE BY LAW, TOSHIBA (1) ASSUMES NO LIABILITY WHATSOEVER, INCLUDING WITHOUT LIMITATION, INDIRECT, CONSEQUENTIAL, SPECIAL, OR INCIDENTAL DAMAGES OR LOSS, INCLUDING WITHOUT LIMITATION, LOSS OF PROFITS, LOSS OF OPPORTUNITIES, BUSINESS INTERRUPTION AND LOSS OF DATA, AND (2) DISCLAIMS ANY AND ALL EXPRESS OR IMPLIED WARRANTIES AND CONDITIONS RELATED TO SALE, USE OF PRODUCT, OR INFORMATION, INCLUDING WARRANTIES OR CONDITIONS OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, ACCURACY OF INFORMATION, OR NONINFRINGEMENT.

- Product may include products using GaAs (Gallium Arsenide). GaAs is harmful to humans if consumed or absorbed, whether in the form of dust or vapor. Handle with care and do not break, cut, crush, grind, dissolve chemically or otherwise expose GaAs in Product.

- Do not use or otherwise make available Product or related software or technology for any military purposes, including without limitation, for the design, development, use, stockpiling or manufacturing of nuclear, chemical, or biological weapons or missile technology products (mass destruction weapons). Product and related software and technology may be controlled under the applicable export laws and regulations including, without limitation, the Japanese Foreign Exchange and Foreign Trade Law and the U.S. Export Administration Regulations. Export and re-export of Product or related software or technology are strictly prohibited except in compliance with all applicable export laws and regulations.

- Product is subject to foreign exchange and foreign trade control laws.

- Please contact your TOSHIBA sales representative for details as to environmental matters such as the RoHS compatibility of Product. Please use Product in compliance with all applicable laws and regulations that regulate the inclusion or use of controlled substances, including without limitation, the EU RoHS Directive. TOSHIBA assumes no liability for damages or losses occurring as a result of noncompliance with applicable laws and regulations.