Design Guide: TIDA-011012

A 50kW SiC-Based Modular Solid-State Transformer for Medium-Voltage Applications Reference Design

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Description

This design implements a three-phase solid-state transformer (SST) based on a silicon carbide (SiC) power module. Using a modular architecture allows for stacking multiple converter submodules in series to meet medium-voltage grid requirements. Using fast switching SiC devices enables the DC/AC stage to switch at 10kHz and the dual active bridge (DAB) isolation stage at 100kHz, which reduces the size of the high-frequency magnetic components and increases the overall power density. Inter-module communication provide the high isolation voltage levels required in medium-voltage end equipment. The cascaded topology distributes the grid voltage evenly across submodules, allowing the use of standard lower-voltage rated SiC devices while maintaining full medium-voltage operation.

Resources

TIDA-011012	Design Folder
UCC35131-Q1	Product Folder
UCC218915-Q1	Product Folder
TMS320F28P650DK	Product Folder
AMC0306M05	Product Folder
AMC1336	Product Folder
UCC33421	Product Folder
AMC23C12	Product Folder
ISOTMP35	Product Folder
TMCS1133	Product Folder

Features

- 50kW rated reference design with modular and scalable architecture.
- Medium-voltage DC link rated at 2.2kV, low-voltage DC link at 1.5kV.
- SiC power module based H-Bridge converter on the medium-voltage side.
- Dual active bridge (DAB) for isolated DC/DC conversion stage switching at 100kHz.
- DC/AC converter switching at 10kHz in unipolar mode.
- Fiber optic communication between submodules providing the required isolation voltage.
- Bidirectional power flow capability supporting grid-to-storage and storage-to-grid operation.
- Single module dimensions: 850mm × 300mm × 80mm.

Applications

- Solid-state transformer (SST)
- Central inverter
- Power conversion system (PCS)
- Energy storage systems

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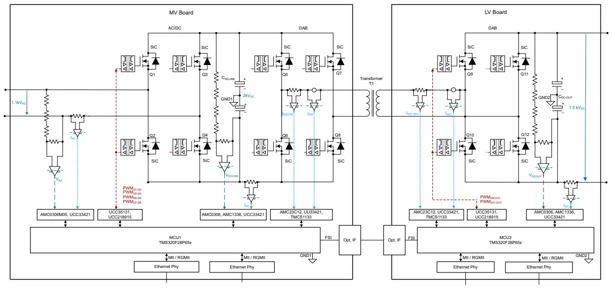

Figure 1-1. Block Diagram

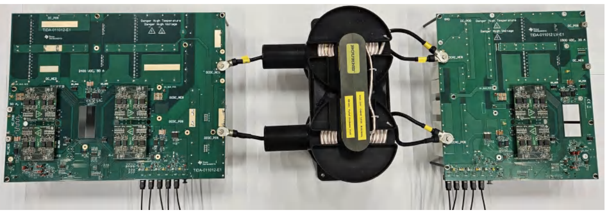

Figure 1-2. Board Setup

1 System Description

The way power is converted and distributed across industrial and commercial installations is going through a significant transformation. For decades, line-frequency transformers have been a fixture of any grid-connected system. These transformers are reliable but also bulky, heavy, and not particularly efficient when interfaced with low voltage power electronics systems. Today, applications like utility-scale photovoltaic, grid-tied battery storage, and high-density data centers demand compact and efficient installations and higher power levels. This demand for innovation puts pressure on the power electronics systems built around conventional transformer architectures.

Solid-state transformers (SSTs) have emerged as a alternative. Rather than relying on a large iron-core transformer operating at 50 or 60Hz, an SST performs the same galvanic isolation and voltage conversion using high-frequency power electronics stages switching at a frequency above 10kHz. The immediate consequence is a reduction in the size and weight of transformer. Furthermore, a direct power conversion from a medium-voltage grid to DC links is possible and improves system efficiency.

Medium-voltage grids operate from 10kV up to 30kV. The difficulty with medium-voltage operation is that standard power semiconductors cannot withstand those voltage levels. Topology selection becomes critical to address this problem. Among the various converter architectures that have been explored in the literature, the Cascaded H-Bridge (CHB) is arguably the most practical option for SST designs. Instead of exposing one set of switching devices to the full medium voltage, the voltage is split across multiple series-connected H-bridge cells. Each cell only sees a fraction of the total medium voltage because individual devices are selected from a range of commercially available, lower-voltage components. Furthermore, these components typically are faster, cheaper, and better characterized than the high-voltage counterparts.

Beyond solving the voltage problem, the modular structure of the CHB topology has other advantages. For example, the number of cells can be scaled up or down depending on the target voltage, and the architecture supports redundancy. Redundancy means that a failed cell can often be bypassed without taking the entire converter off-line.

These characteristics make SSTs a compelling building block for the power infrastructure that photovoltaic plants, battery energy storage systems, and data centers require in the future.

This design guide presents a bidirectional 50kW SST reference design built around a Cascaded H-Bridge topology, where each submodule consists of an H-Bridge converter on the medium-voltage side and a dual active bridge (DAB) for the isolated DC/DC conversion stage. The medium-voltage DC link is rated at 2.2kV, while the low-voltage DC link operates at 1.5kV. Communication between sub modules is established through fiber optic links, providing the electrical isolation level required when operating across medium-voltage potentials.

1.1 Key System Specifications

Table 1-1. Key System Specifications of the DC/AC Converter

Parameters	Specification	Details
Nominal AC Power	±50kVA	± Active ± Reactive
Nominal AC Voltage	1000 VRMS	
Nominal AC Current	50 ARMS	
Nominal DC Voltage	2200VDC	
DC Link Voltage Ripple	±200V	at 2200V
Switching Frequency	From 5kHz to 10kHz	H-Bridge Unipolar
Cooling Technology	Air Force Cooling	12V Fans
Max Ambient Temperature	60°C	
Power FETs Specs	3.3kV, 22.5mΩ	SiC FETs

Table 1-2. Key System Specifications of the DC/DC Converter

Parameters	Specification	Details
Nominal DC Power	±50kW	Bidirectional Power Flow
MV Nominal DC Voltage	2.2kV	
MV Nominal DC Current	23A	
LV Nominal DC Voltage	1.5kV	
LV Nominal DC Current	33.3A	
Switching Frequency	100kHz	
Max Ambient Temperature	60°C	
Power FETs Specs on MV	3.3kV, 22.5mΩ	SiC FETs
Power FETs Specs on LV	2.3kV, 11.5mΩ	SiC FETs

CAUTION

Do not leave the design powered when unattended.

WARNING

High voltage! *Accessible high voltages are present on the board*. Electric shock is possible. The board operates at voltages and currents that can cause shock, fire, or injury if not properly handled. Use the equipment with necessary caution and appropriate safeguards to avoid injuring yourself or damaging property. For safety, use of isolated test equipment with overvoltage and overcurrent protection is highly recommended.

TI considers the user's responsibility to confirm that the voltages and isolation requirements are identified and understood before energizing the board or simulation. *When energized, do not touch the design or components connected to the design*.

WARNING

Hot surface! Contact can cause burns. Do not touch!

Some components can reach high temperatures > 55°C when the board is powered on. Do not touch the board at any point during operation or immediately after operating, as high temperatures can be present.

WARNING

TI intends this reference design to be operated in a ***lab environment only and does not consider the design as a finished product*** for general consumer use. The design is intended to be run at ambient room temperature and is not tested for operation under other ambient temperatures.

TI intends this reference design to be used only by ***qualified engineers and technicians*** familiar with risks associated with handling high-voltage electrical and mechanical components, systems, and subsystems.

There are ***accessible high voltages present on the board*** . The board operates at voltages and currents that can cause shock, fire, or injury if not properly handled or applied. Use the equipment with necessary caution and appropriate safeguards to avoid injuring yourself or damaging property.

2 System Overview

2.1 Block Diagram

This reference design is composed of the following boards:

- Medium voltage board composed of an AC/DC and a part of DAB Converter (2 H-Bridges).
- Low voltage board composed of the second part of the DAB Converter (1 H-Bridge).
- Two control card boards (TMDSCNCD28P65X) used for the MV Board and the LV Board.
- Six gate drivers boards used to control and protect the power FETs.

Figure 2-1 shows a schematic representation of the 50kW SiC-based modular solid-state transformer.

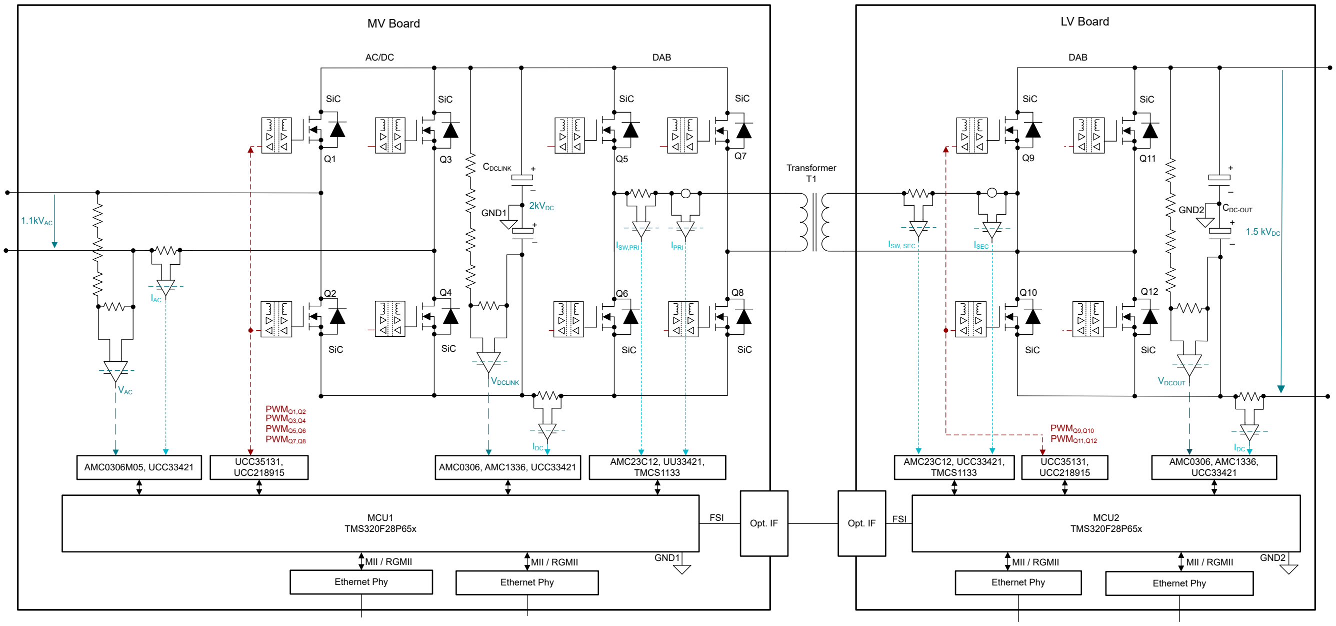

Figure 2-1. 50kW Sic-based Modular Solid-state Transformer Schematic

2.2 Design Considerations

Figure 2-2 shows the basic architecture of the SST, converting power from a three-phase medium-voltage grid to a DC output. Multiple H-Bridge submodules are connected in series on the grid side, allowing the even distribution of the medium voltage across each cell. On the output side, the DAB converters are connected in parallel, performing the step-down function and contributing together to feed the low-voltage DC link. A main controller works alongside local submodule controllers to regulate the output voltage while shaping the input currents to be in phase with the grid voltages. From a circuit isolation perspective, each medium-voltage submodule is referenced to the midpoint of the capacitor, effectively halving the voltage that the isolation components within each submodule need to withstand.

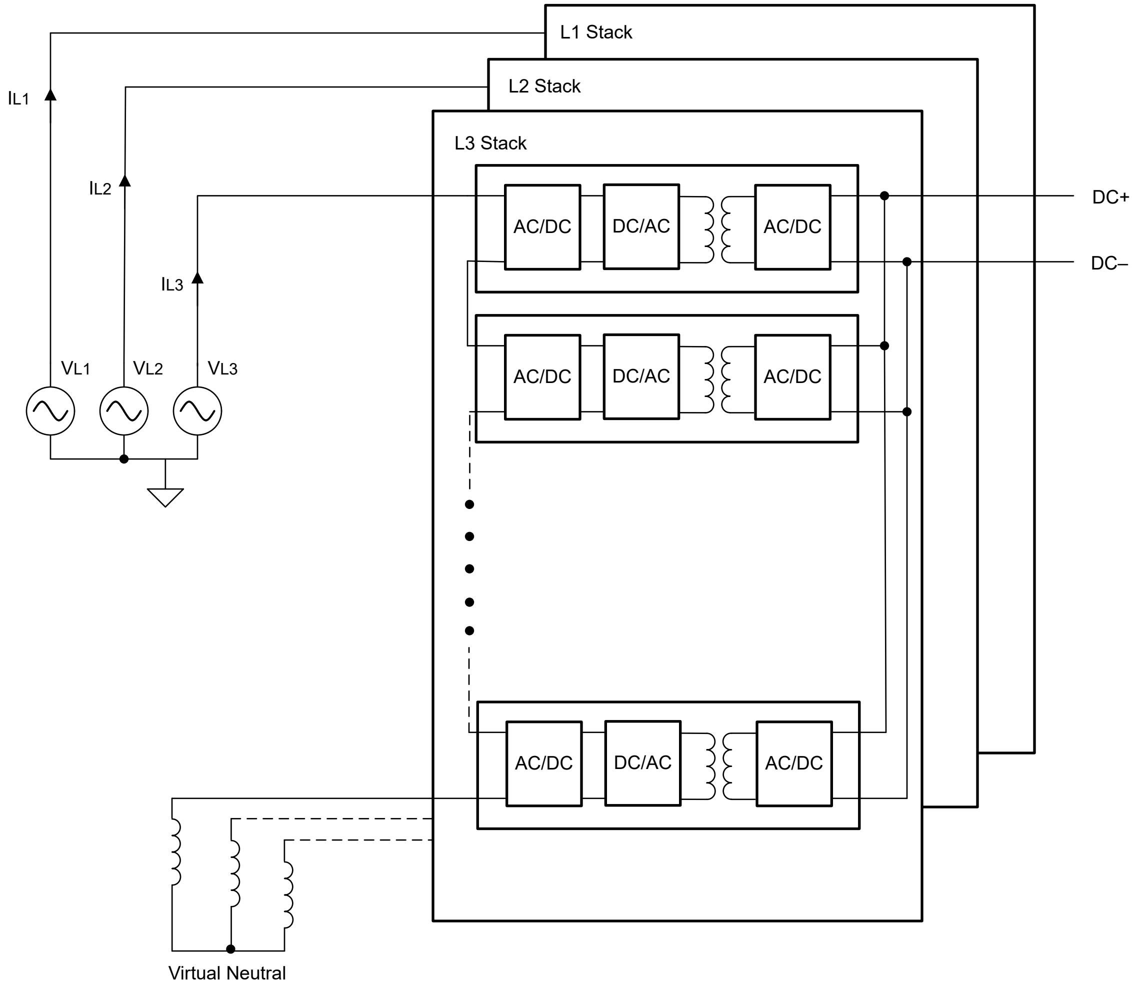

Figure 2-2. Stack Overview

2.2.1 DC/AC Converter

Several topologies are available in the literature for the medium-voltage converter stage. Among these, the H-Bridge is the most straightforward to implement because the H-Bridge does not require any additional protection circuitry or clamping components. The H-Bridge can operate in bipolar and unipolar switching modes. Unipolar switching mode effectively doubles the equivalent output switching frequency that the filter sees. When using multiple H-Bridge cells, phase-shifting the PWM carriers between cells further multiplies the equivalent switching frequency at the output. Phase-shifting significantly reduces the inductance required for the boost inductor. The DC link capacitors in this topology are sized to absorb the inherent power ripple at twice the fundamental frequency. This sizing is a deliberate design choice that avoids propagating this ripple into the DAB converter and over-complicating the design.

2.2.2 DC/DC Converter

Several isolated DC/DC converter topologies are documented in the literature. The most commonly considered for SST applications are the CLLC resonant converter and the Dual Active Bridge. Both have merits, but for this design, the DAB was selected for the bidirectional control simplicity, which aligns well with the grid-connected storage application requirements. Because the isolation transformer provides the galvanic barrier between the medium-voltage and low-voltage sides of the system, the isolation transformer within each DAB cell must be rated to withstand the full medium-voltage grid potential. If all DAB converters are running in parallel,interleaving the switching patterns can significantly reduce the high-frequency current ripple on the output DC link. Note that the DAB in this design is not sized to handle the low-frequency power ripple coming from the grid side. The DC link capacitors of the H-Bridge stage fully absorbs the power ripple, keeping the DAB design focused and well optimized.

2.3 Highlighted Products

2.3.1 UCC35131-Q1

The UCC35131-Q1 is an automotive-qualified high-isolation voltage DC/DC power module designed to provide power to IGBT, SiC, Si, and GaN isolated gate drivers and UIR sensors. The proprietary integrated transformer, flip-chip package, and advanced control architectures of the device achieve high power density and low noise. This device can deliver 2.0W typical output power at 85°C ambient temperature. The highly accurate dual-output voltages, set by resistor dividers, enable low on-resistance, fast and reliable switching for SiC, IGBT, and GaN devices. The low-latency feedback control reduces the output capacitance for fast load transient and supports dynamic voltage programming. The wide input voltage and adjustable VIN UVLO supports both wide battery voltage of electric vehicles and regulated input rails. The device is operational from 5.5V to 20V VIN, and can withstand VIN overvoltage transient up to 28V. The integrated protection features, fault-report Power Good pin, and enable function increase system robustness and save external components. The SOIC package with 8.2mm creepage and clearance distance provides high-isolation capability.

2.3.2 UCC218915-Q1

The UCC218915-Q1 is a galvanically-isolated single channel predriver designed for SiC MOSFETs and IGBTs up to 1500V DC operating voltage with advanced protection features, best-in-class dynamic performance, and robustness. The UCC218915-Q1 has dual 2.8A outputs for directly driving an external buffer NMOS/PMOS pair. The input side is isolated from the output side with SiO2 isolation technology, supporting up to 1.06kVRMS working voltage, 10kVPK surge immunity with longer than 40-years isolation barrier life, as well as providing low part-to-part skew, and >200V/ns common mode noise immunity (CMTI). The UCC218915-Q1 includes the following protection features that help optimize SiC and IGBT switching behavior and robustness:

1. Fast overcurrent and short-circuit detection
2. Controlled soft shutdown after a fault
3. Fault reporting
4. Active Miller clamp
5. Active short-circuit input on the high-voltage side
6. Input and output side power supply UVLO

2.3.3 TMDSCNCD28P55X - controlCARD Evaluation Module

TMDSCNCD28P65X is a low-cost evaluation and development board which is designed for initial evaluation and prototyping of the TI C2000™ MCU series of F28P65x devices. The device comes with a HSEC180 (180-pin High speed edge connector). The 180-pin docking station TMDSHSECDOCK is required to evaluate the TMDSCNCD28P65X. To purchase the TMDSHSECDOCK as an individual unit or as a bundled kit, see the TMDSHSECDOCK product page.

Hardware Features

- Isolated on-board XDS110 USB-to-JTAG debug probe enables real-time in-system programming and debugging
- Standard 180-pin controlCARD HSEC interface
- 2-Port EtherCAT Slave Controller
- Analog I/O, digital I/O, and JTAG signals at standard 180-pin HSEC interface
- Hardware Files are in C2000Ware at boards\controlCARDs\TMDSCNCD28P65X

Software Features

- TI Code Composer Studio IDE - integrated development environment for TI microcontrollers and embedded processors
- Software development kits (SDK)
- C2000Ware - low level device drivers and examples.
- MotorControl SDK - motor control system development for various three-phase motor control applications
- DigitalPower SDK - digital Power system development for various AC-DC, DC-DC and DC-AC power supply applications

2.3.4 AMC0306M05

The AMC0x06M05 is a precision, galvanically isolated delta-sigma (ΔΣ) modulator with a ±50mV differential input and digital output. The input is optimized for connection to low-impedance shunt resistors commonly used for current-sensing applications. The isolation barrier separates parts of the system that operate on different common-mode voltage levels. The isolation barrier is highly resistant to magnetic interference. This barrier is certified to provide reinforced isolation up to 5kVRMS (DWV package) and basic isolation up to 3kVRMS (D package) (60s). The output bitstream of the AMC0x06M05 is synchronized to an external clock. Combined with a sinc3, OSR 256 filter, the device achieves 16 effective bits of resolution or 84dB of dynamic range, at a 78kSPS sample rate. The AMC0x06M05 comes in 8-pin, wide- and narrowbody SOIC packages. The device is fully specified over the temperature range from –40°C to +125°C.

2.3.5 AMC1336

The AMC1336 is a precision, delta-sigma (ΔΣ) modulator with the output separated from the input circuitry by a capacitive double isolation barrier that is highly resistant to magnetic interference. This barrier is certified to provide reinforced isolation of up to 8000 VPEAK according to the DIN VDE V 0884-11 and UL1577 standards. Used in conjunction with isolated power supplies, this isolated modulator separates parts of the system that operate on different commonmode voltage levels and protects lower-voltage parts from damage. The unique wide, bipolar. ±1V input voltage range of the AMC1336 and the high input resistance support direct connection of the device to resistive dividers in high-voltage applications. When used with a digital filter (for instance, as integrated in the TMS320F28004x, TMS320F2807x or TMS320F2837x microcontroller families) to decimate the output bitstream, the device can achieve 16 bits of resolution with a dynamic range of 87dB at a data rate of 82 kSPS. On the high-side, the AMC1336 is supplied by a 3.3V or 5V power supply. The isolated digital interface operates from a 3.0V, 3.3V or 5V power supply. The AMC1336 performance is specified over the extended industrial temperature range of –40°C to +125°C.

2.3.6 UCC33421-Q1

The UCC33421-Q1 is an automotive qualified DC/DC power module with integrated transformer technology designed to provide 1.5W of isolated output power. The device can support an input voltage operation range from 4.5V to 5.5V and regulate 5.0V output voltage with a selectable headroom of 5.5V. The UCC33421-Q1 features a proprietary transformer architecture that achieves a 5kVRMS isolation rating, while simultaneously supporting low EMI and excellent load regulation. The UCC33421-Q1 integrates protection features for increased system robustness such as enable pin with fault reporting mechanism, short-circuit protection and thermal shutdown. The UCC33421-Q1 comes in a miniaturized, low- profile SSOP (5.85mm × 7.50mm) package with 2.65mm height and > 8.2mm clearance and creepage.

2.3.7 AMC23C12

The AMC23C12 is an isolated window comparator with a short response time. The open drain output is separated from the input circuitry by an isolation barrier that is highly resistant to magnetic interference. This barrier is certified to provide reinforced galvanic isolation of up to 5kVRMS according to VDE 0884-17 and UL1577, and supports a working voltage of up to 1kVRMS. The comparison window is centered around 0V, meaning that the comparator trips if the absolute value of the input voltage exceeds the trip threshold value. The trip threshold is adjustable from 20mV to 300mV through one external resistor and, therefore, the comparison window ranges from ±20mV to ±300mV. When the voltage on the REF pin is greater than 550mV, the negative comparator is disabled and only the positive comparator is functional. The reference voltage in this mode ranges as high as 2.7V. This mode is particularly useful for monitoring voltage supplies. The open drain output on the device supports transparent mode (LATCH input tied to GND2) where the output follows the input state, or latch mode, where the output is cleared on the falling edge of the latch input signal. The AMC23C12 is available in an 8-pin, wide-body SOIC package and is specified over the full automotive temperature range from –40°C to +125°C.

2.3.8 ISOTMP35

The ISOTMP35 combines an integrated isolation barrier, up to 3000VRMS withstand voltage, with an analog temperature sensor featuring a 10mV/°C slope from –40°C to 150°C. This integration enables the sensor to be co-located with high voltage heat sources (for example: HV FETs, IGBTs, or HV contactors) without requiring expensive isolation circuitry. The direct contact with the high-voltage heat source also provides greater accuracy and faster thermal response compared with approaches where the sensor is placed further away to meet isolation requirements. Operating from a non-isolated 2.3V to 5.5V supply, the ISOTMP35 allows easy integration into applications where sub-regulated power is not available on the high-voltage plane. The integrated isolation barrier satisfies UL 1577 requirements. The surface-mount package (7-pin SOIC) provides excellent heat flow from the heat source to the embedded thermal sensor, minimizing thermal mass and providing more accurate heat- source measurement. This reduces the need for time- consuming thermal modeling and improves system design margin by reducing mechanical variations due to manufacturing and assembly. The ISOTMP35 class-AB output driver provides a strong 500µA maximum output to drive capacitive loads up to 1000pF and is designed to directly interface with analog-to-digital converter (ADC) sample and hold inputs.

2.3.9 TMCS1133

The TMCS1133 is a galvanically isolated Hall-effect current sensor with industry leading isolation and accuracy. An output voltage proportional to the input current is provided with excellent linearity and low drift at all sensitivity options. Precision signal conditioning circuitry with built-in drift compensation is capable of less than 1.4% maximum sensitivity error, overtemperature 1.4%, and lifetime with no system-level calibration. Precision signal conditioning circuity is also capable of less than 0.9% maximum sensitivity error including lifetime and temperature drift with a one-time calibration at room temperature. AC or DC input current flows through an internal conductor generating a magnetic field measured by integrated, on-chip, Hall-effect sensors. Core-less construction eliminates the need for magnetic concentrators. Differential Hall sensors reject interference from stray external magnetic fields. Low conductor resistance increases measurable current ranges up to ±96A while minimizing power loss and easing thermal dissipation requirements. Insulation that can withstand 5kVRMS, coupled with a minimum of 8mm creepage and clearance, provides high levels of reliable lifetime reinforced working voltage. Integrated shielding enables excellent common-mode rejection and transient immunity. Fixed sensitivity allows the device to operate from one 3V to 5.5V power supply, eliminating ratiometry errors and improving supply noise rejection.

3 Design and Documentation Support

3.1 Design Files

To download the design files, see the design files at TIDA-011012 {https://www.ti.com/tool/TIDA-011012}.

3.1.1 Schematics

To download the schematics, see the design files at TIDA-011012.

3.1.2 BOM

To download the bill of materials (BOM), see the design files at TIDA-011012.

3.2 Documentation Support

1. Texas Instruments, Comparison of AC/DC Power- Conversion Topologies for Three-Phase Industrial Systems Power Supply Design Seminar.
2. Texas Instruments, Bi-directional, Dual Active Bridge Reference Design for Level 3 Electric Vehicle Charging Stations reference design.
3. Texas Instruments, A 11kW, bidirectional, three-phase ANPC based on GaN reference design
4. Texas Instruments, 11kW, bidirectional three-phase three-level (T-type) inverter and PFC reference design.
5. Texas Instruments, A 15kW to 30kW bidirectional, three-phase plus neutral flying capacitor based on GaN reference design.
6. Texas Instruments, Isolated Gate Driver Board With Isolated Bias Supply for 3.3kV SiC-FET Reference Design.

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4 About the Author

Riccardo Ruffo received his Ph.D. in Electric, Electronics and Communication Engineering from Politecnico di Torino, Turin, Italy in 2019. He is currently working at Texas Instruments Germany as System Engineer in the area of Solar Energy within the Energy Infrastructure Team. His main work includes EV charging, inductive wireless power transfer, photovoltaic, renewable energy, and energy storage applications.

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