Application Note

Design Considerations of Using In-Package Hall-Effect Current Sensors in Solar Systems

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ABSTRACT

In recent years, there has been a new trend in solar system applications to use in-package Hall-effect current sensors to replace the traditional through-hole sensors, that benefits system performance, power efficiency and reliability. *Summary of Solar Application Scenarios Using In-Package Hall-Effect Current Sensors* discusses where in-package Hall-effect current sensors can be used, basic requirements of current sensing in solar systems and how current sensors are used accordingly. This application note continues to further discuss design considerations of using in-package Hall-effect current sensors in solar systems, including current ratings and thermal, accuracy, bandwidth, response time and propagation delay, lightning and surge, isolation and reliability.

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1 Introduction

The solar system includes a lot of end equipment, such as string inverters, hybrid inverters, PCS, and so on. Current sensing is a critical function to the solar system because the measurement accuracy and reliability determines the control accuracy of the power stage and further affects the energy harvest efficiency.

Traditionally, open-loop through-hole board mount Hall-effect current sensors are widely used because the sensors have intrinsic isolation nature, and the non-intrusive measurement also provides wiring and installation convenience. However, open-loop through-hole hall-effect current sensors usually cannot achieve high accuracy over both lifetime and temperature. Meanwhile, failing is simple during the installation and transportation processes due to the brittle magnetic core damage, which reduces the system reliability.

The new trend in the solar system is to use in-package hall-effect current sensors to replace the traditional thorough-hole one. TI's in-package hall-effect current sensor, such as TMCS112x, TMCS113x and TMCS114x can provide high accuracy combined with low drift, enabling accurate current measurements over both lifetime and temperature. Additionally, the in-package design also provides a compact design without sacrificing isolation performance and without adding system complexity or cost.

There are some key points that must be considered when using in-package Hall-effect current sensors in solar systems. Topics of current ratings and thermals, accuracy, bandwidth, response time and propagation delay, lightning and surge, isolation and reliability are discussed in detail in this application note.

2 Current Ratings and Thermal

Due to the specific device construction, careful considerations about the thermal design of the in-package Hall-effect current sensor must be taken. High side current flows into the IC inside through the leadframe which typically has sub-milliohm level resistance, and as a result, heat is generated in the IC. In the TMCS family datasheet, there are several current ratings which correlate with different real working conditions.

2.1 Current Ratings

Continuous current capability is most frequently referred current rating, 80ARMS and 125ARMS for TMCS112x and TMCS114x, respectively. RMS (Root Mean Square) value is a statistical measure used to represent the equivalent DC value of an AC signal RMS according to thermals. So, 80ARMS and 125ARMS can be applied to DC current. This continuous current specification is determined on Evaluation Module (EVM) board's safe operating area (SOA) curve at 25°C. The impedance of input leadframe plays an important role in continuous current capability. The typical input conductor resistance for TMCS112X is 0.67mΩ, and for TMCS114X it is 0.27mΩ, which contributes higher current boundary. As shown in Figure 2-1 and Figure 2-2, lower input conductor resistance greatly reduces top case temperature.

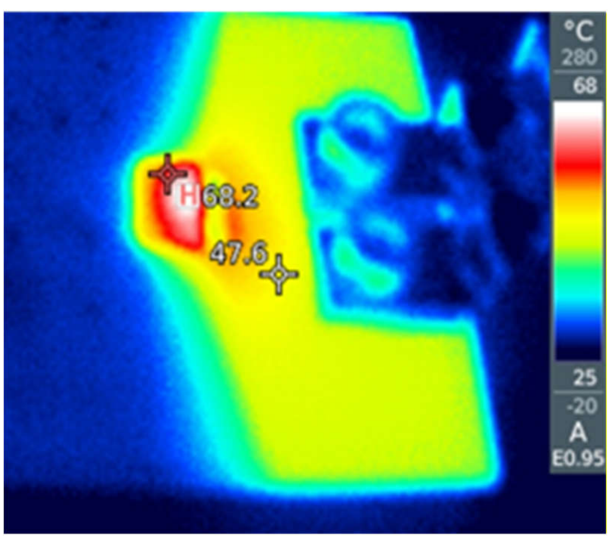

Figure 2-1. TMCS112X-50A Input, 1-minute Duration, 68.2°C Top Case

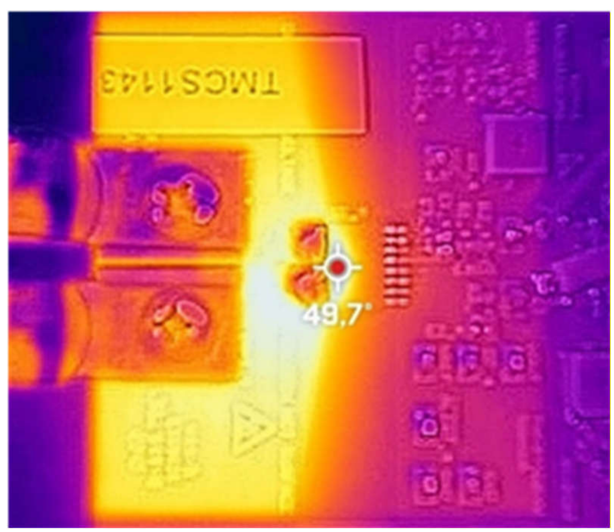

Figure 2-2. TMCS114X-50A Input, 1-minute Duration, 49.7°C Top Case

The real continuous current capability in the system is strongly influenced by the operating ambient temperature, as well as the PCB layout, cable gauge, air flow, heat sink structure and so on. Note that solar system does not usually have as excellent thermal design as the EVM and the operating ambient temperature is usually around 85℃. The continuous current capability of the current sensor can be derated in a real solar system application. As shown in Figure 2-3 and Figure 2-4, TMCS112X device is tested under 25°C and 85°C, there has great difference on top case temperature.

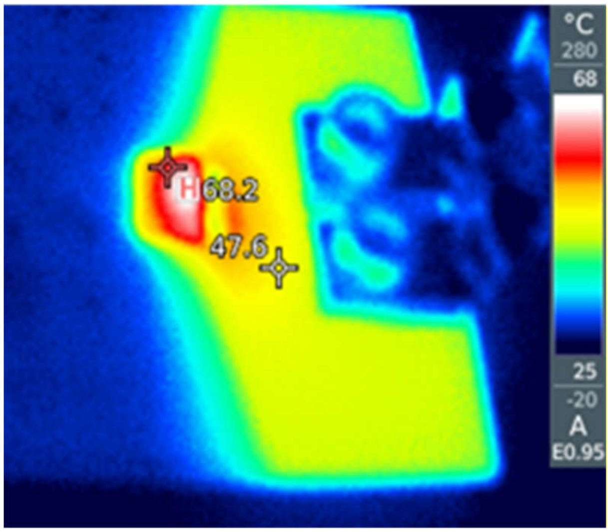

Figure 2-3. 25°C Ambient Temperature, 50A Input, 1-minute Duration, 68.2°C Top Case

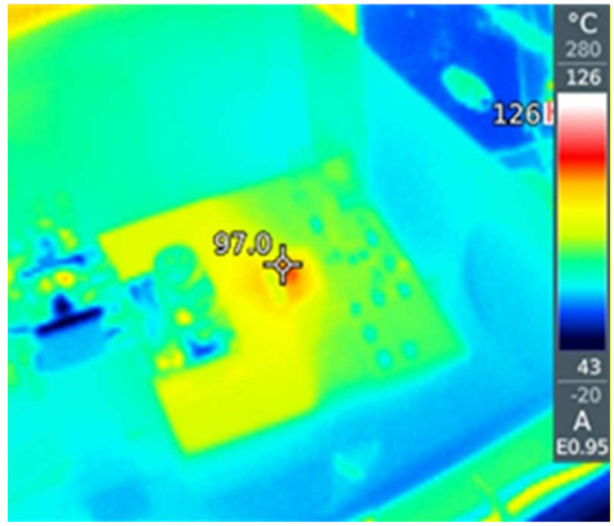

Figure 2-4. 85°C Ambient Temperature, 45A Input, 1-minute Duration, 97°C Top Case

A real case was conducted by using TMCS112x to test MPPT current in a string inverter. The test conditions were 85℃ ambient temperature, 34ARMS continuous current and lasted 1h20mins. 115℃ was detected on TMCS1126 top case while top case temperature kept rising.

The continuous-current capability of in-package Hall-effect current sensor has a strong dependence upon the operating ambient temperature range expected in operation. The maximum continuous current-handling capability of TMCS112x when mounted on the TMCS1126xEVM is approximately 80ARMS. Current capability falls off at higher ambient temperatures because of the reduced thermal transfer from junction-to-ambient and increased power dissipation in the leadframe.

TMCS devices cannot verify electrical performance while operating in over 125℃ free-air temperature. Though by improving the thermal design of an application, the SOA can be extended to higher currents at elevated temperatures, and using larger and heavier copper power planes provides air flow over the board. Adding heat sinking structures to the area of the device can also improve thermal performance. TMCS112x devices with 0.67mohm level input conductor resistance are recommended to be used in string current sampling or MPPT current sampling with single string; TMCS114X devices with 0.27mohm level input conductor resistance could be used in MPPT current sampling with 2 or more strings tied together. See SDAA234 to estimate junction temperature of in package hall sensor.

Take 50kW 3-phase hybrid inverter, shown in Figure 2-5, as an example, there are multiple current sensing places shown in Figure 2-5. See *Summary of Solar Application Scenarios Using In-Package Hall-Effect Current Sensors* for more details.

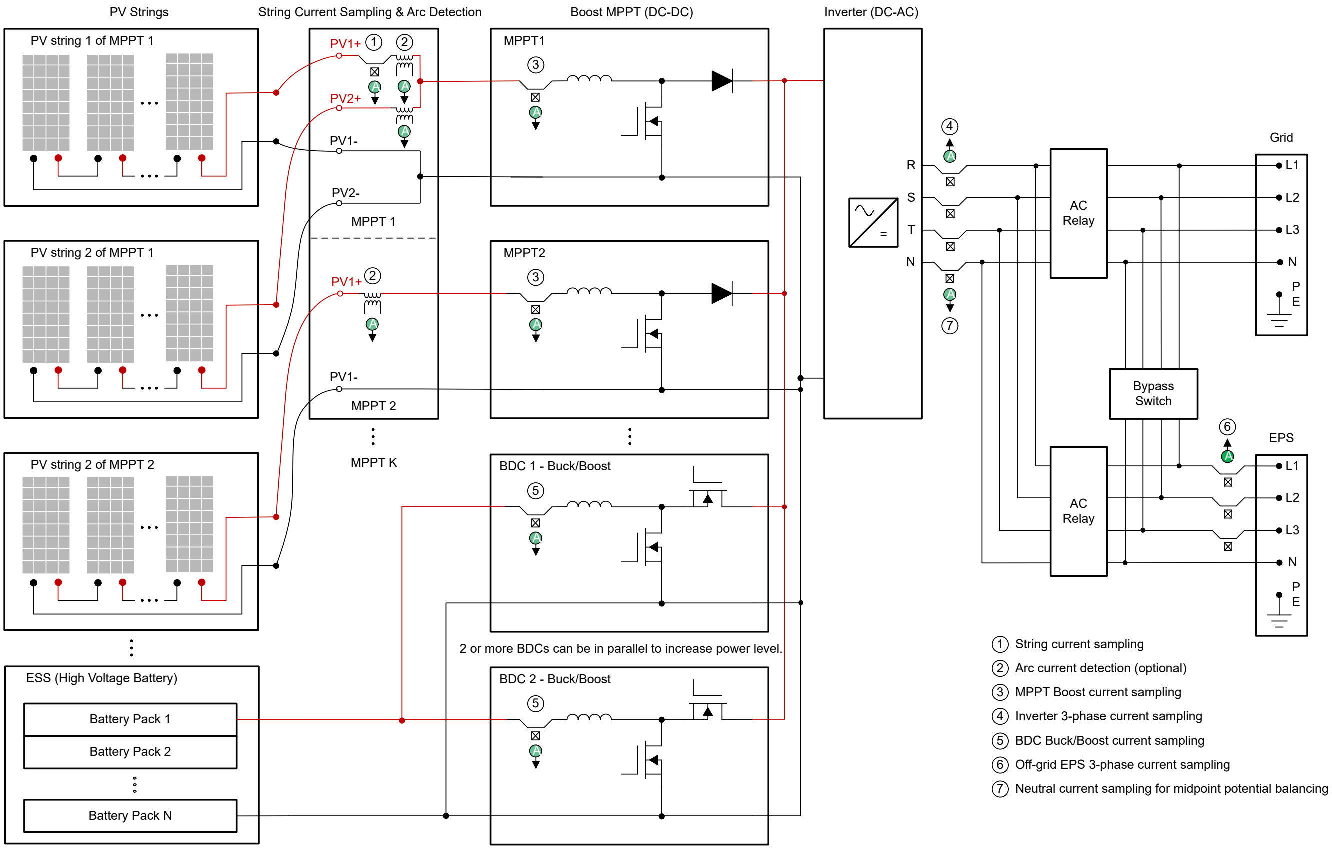

Figure 2-5. An 50kW 3-Phase Hybrid Inverter Example

Table 2-1. 50kW Hybrid Inverter Typical Current Ratings

Current Sampling Places	Current Ratings
String current	0-20A RMS
MPPT Boost current	0-40A RMS
Inverter phase current	0-76A RMS
Neutral current	0-20A RMS
BDC current	0-31A RMS

- **String Current Sampling** (location 1). Common PV panels support continuous current less than 20A. While some PV panels supporting 22A have gradually emerged with technological evolution in recent years.
- **MPPT Boost Current Sampling** (location 3). Continuous current range depends on how many PV strings are tied together per MPPT. Usually, it’s 1 ~ 8 strings per MPPT based on different power levels and inverter types. For single phase residential or hybrid inverter within 10kW power level, each MPPT has 1 string. For 3-phase residential or hybrid inverter within 50kW power level, each MPPT has 1 or 2 strings. With more than 50kW power level, each MPPT has 2 or 4 strings or even more. For those MPPT followed by over #2 PV strings, the real current flowing through MPPT Boost is usually limited to no more than 40A by software. In the solar inverter field application, full power yield of every string doesn’t happen all the time even during daytime because of light intensity changes, shadow and dust shielding, and so on. So, customers usually add more strings into MPPT as redundancy to verify solar inverters can generate full power most of the time. MPPT Boost has overcurrent protection and over current point is usually set at 1.5 times the rated current. But the real protection point is approximately two times the rated current due to control loop delay. Therefore, the linear current range must be selected to be about 2.5 times the rated current.
- **Inverter Phase Current Sampling** (location 4). This current rating depends on AC power rating and grid voltage level. Take 50kW 3-phase hybrid inverter as an example. Current rating is calculated as 50kW/380V/sqrt (3) = 76A. Some string inverters and hybrid inverters demand two times the overload capacity for 10s or longer. The linear current range and thermal should be carefully considered.

- **Neutral Current Sampling** (location 5). For a 3-phase unbalanced hybrid inverter, the neutral current usually does not exceed 20A. This current can also be calculated by software and not directly sampled for lower cost.
- **Bi-directional Converter (BDC) Current Sampling** (location 7). This current rating depends on power rating, battery voltage and interleaved phase quantity. Take 50kW 3-ph hybrid inverter as an example. Current rating is calculated as 50kw/400V/2ph=62A. Overcurrent point is typically set to approximately 1.5 times the rated current.
- **Off-grid Emergency Power Supply (EPS) Current Sampling** (location 6). Depending on various EPS function definitions, this current rating is equal or higher than rated AC current. For those higher than rated AC current scenarios, bypass switches current flow capacity plays an important role in current rating.

2.2 Effects of PCB and Layout

Thermal gradients are generated when current passes through the leadframe. A good PCB layout helps reduce thermals from the package and dissipate the layout into the environment, as a result, keeping the IC operating within optimal accuracy and long lifetime reliability. Fortunately, engineers can select copper thickness and size to achieve a balance of cost and thermal dissipation performance. Below is a short summary about thermal analysis of in-package Hall-effect current sensors. See *Thermal Analysis for the TMCS1123 Hall-Effect Current* for more details.

- Thicker copper allows larger current ratings. A doubling of copper results in the same magnitude improvement, while beyond 4oz, the current capability return begins diminishing.
- Polygon sizing can slightly improve the current rating. For thermal performance improvement, polygon sizing contributes much less than copper thickness. Engineers could put higher priority on copper thickness in case of limited PCB size.

3 Accuracy

Current measurement accuracy is critical to the solar inverter system, because it determines the control accuracy of the power stage and further affects the energy harvest efficiency. SBOA624 discusses common solar application scenarios with different current measurement accuracy requirements in different current sampling places.

Table 3-1 summarizes the typical design target of current measurement accuracy in solar inverters.

Table 3-1. Summary of Typical Design Target of Current Measurement Accuracy in Solar Inverters

Current Sampling Places	Typical Accuracy Design Target
String current	3%
MPPT Boost current	2%
Inverter phase current	1%
Neutral current	1%
BDC current	1%
Off-grid EPS current	3%

Generally, string current sampling is mandatory for string current monitoring and display. Additionally, string current sampling is also widely used for I-V curve scanning and diagnosis for smart maintaining work, especially for high power string inverters or central inverters deployed for grid or commercial-industrial application scenarios. For monitoring and display purposes, usually there are not strict accuracy requirements, 3% is enough. However, for I-V curves scanning and for diagnosis, the accuracy of string current is one of the key factors to determine the final failure diagnosis accuracy and indirectly determine the power generation efficiency. This is very important to a commercial-industrial PV plant and utility PV plant which cares a lot about output efficiency.

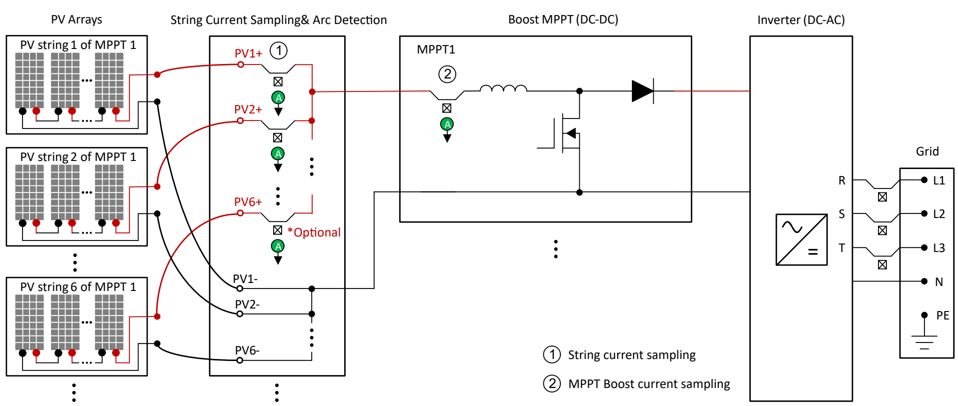

Figure 3-1. An 320kW String Inverter Example With 6 Strings per MPPT

Usually, a PV array consists of 2 or more PV strings connected in parallel to one MPPT. While there is a trend that more strings are tied together to one MPPT to cost down in high power string inverters. Figure 3-1. shows a 320kW string inverter example with 6 strings per MPPT. Note that the current sampling for string 6 is optional, because it can be calculated from MPPT boost average current subtracting other string currents. So, with more than 2 strings tied to one MPPT and using this subtraction method, the error of the last string current can be very large if errors of other string current deviate in the same positive or negative direction. That's why the last string current sampling is optional to add.

For MPPT boost current sampling, average inductor current is usually sampled and MPPT control frequency is much lower than the switching frequency. The accuracy of MPPT boost current sampling is also critical because this determines the MPPT accuracy which ultimately affects the power generation efficiency.

For inverter 3-phase current sampling, this includes AC current and the corresponding DC component. For grid-connected inverters, theoretically, only AC current is allowed to be injected into the grid. But in fact, inverter output current inevitably contains some DC component which does harm to the grid, grid load and grid equipment. Therefore, it is impractical to completely remove the DC componentof the inverter but it does need to be controlled under a certain low range. Standards such as IEEE 1547-2018 have defined the limit for DC component in the grid-side AC current. For example, below 0.5% of the rated output current.

So, the accuracy of phase current sampling is important for inverter power stage control, power generation statistics and DC component suppression. Especially for DC component excess issue, using hall-effect current sensor with high accuracy and low drift can help to solve the issue at the beginning.

Another issue regarding the accuracy of current sensors is reactive power generation. For active power generation, the reference of current loop is generated by the voltage loop. The error of current sensor is greatly alleviated by the current controller, in this case, the accuracy of DC bus voltage sensing is important. But for reactive power generation, the reference of reactive current is generated directly by the MCU. So, if the current sensor is not accurate, the output current of the inverter is not the set value. Using a high accurate TI Hall-effect current sensor helps with this problem.

For neutral current sampling in hybrid inverter, the fourth leg (neutral) current sampling is used to actively control the midpoint voltage that allows the inverter to support unbalanced output. Though the neutral current is not large as the phase current, the same current sensor is usually selected from a simple design perspective.

For BDC current sampling, it's not only used for control and protection purposes. In some designs, it's also used for battery power statistics to align with BMS (Battery Management System) data. A 1% accuracy target is required.

For EPS (Emergency Power Supply) 3-phase current sampling, this is different from inverter 3-phase current sampling. Theoretically, EPS 3-phase current sampling is not used for power stage control, and current sampling does not need to consider DC component suppression because this is for the backup loads and doesn't do harm to the grid, grid load and grid equipment even out of range. Typically, 3% accuracy is sufficient. However, if this is also used for backup loads power statistics, using Hall-effect current sensors with high accuracy and low drift benefits the metering accuracy and reliability.

4 Bandwidth, Response Time and Propagation Delay

Not only is accuracy important for the hall sensor, but also the bandwidth, response time and propagation delay, which contribute a lot to measure a correct current signal. In this section, these three parameters are discussed to show the relationship with correct current measurement.

4.1 Bandwidth

Bandwidth is defined as the cutoff frequency at -3dB gain, as shown in Figure 4-1. For example, TMCS1123 has -3dB gain at 250kHz. When measuring peak or valley current values, a high enough bandwidth is needed, because a triangular current waveform can be decomposed into a superposition of many sine waves of different frequencies. In this case, it is important to make sure high frequency harmonics are not attenuated, so that the real value and measured peak or valley current has minimal error.

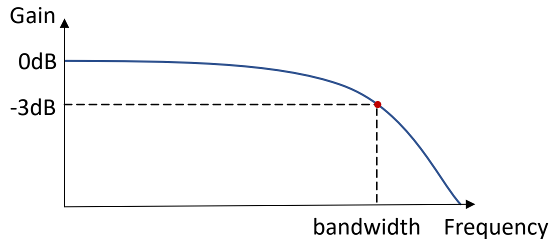

Figure 4-1. Analog Signal Bandwidth

In digital controlled switch mode converters, normally, the control loop bandwidth is < $0.2 \times f_{sw}$ (for simple analysis, considering $f_{sample} = f_{sw}$), because of the requirement for an accurate state-space average model and low phase delay within the control loop bandwidth.

The sensing stage of a current sensor can be modeled as a first-order low-pass filter. The transfer function is shown in equation (1), BW is the bandwidth of the current sensor. So, a lower bandwidth brings a bigger phase lag and amplitude attenuation at high frequency.

$$G_{lpf} = \frac{1}{\tau s + 1}, \tau = \frac{1}{2\pi \times BW} \quad (1)$$

The three scenarios discussed below are discussed regarding the bandwidth topic. Control loop bandwidth is the digital control bandwidth of the system, not the Hall sensor's bandwidth.

For solar inverters or PCS, the switching frequency is normally below 50kHz (for simple analysis, considering $f_{sample}=f_{sw}$), so the control loop bandwidth is normally below 10kHz. According to Equation 1 , a 250kHz bandwidth current sensor at 10kHz brings approximately a 2° phase delay in the control loop, which is almost negligible.

For module level power electronics (MLPE), in which the third-generation power semiconductor devices, such as gallium nitride (GaN), are becoming increasingly popular. The switching frequency can be up to 400kHz. Depending on the sampling frequency and control loop execution frequency, the bandwidth of the control loop can also be very high. The phase delay for a 250kHz current sensor TMCS1123 at 50kHz can be approximately 11°, so a higher bandwidth current sensor such as TMCS1126, TMCS1133 can be used to reduce the phase delay.

Normally, it is required that the bandwidth of hall sensors must be 5 to 10 times higher than the switching frequency to achieve accurate current sensing.

For over-current protection (OCP), the overcurrent condition can be regarded as a step input. If the bandwidth is too low, high frequency components in the step input are attenuated. So, the amplitude of current sensor output can be lower than that of the original input at the beginning of over-current event, causing obvious OCP delay which is dangerous for the protection of the power device. Of course, response time (T_r) and propagation delay (T_{pd}) also play an important role in OCP event, which is discussed in following sections.

4.2 Response Time

The definition of response time (T_r) of hall sensor is the period between the input current reaching 90% of the final value and the output voltage reaching 90% of the final value, for an input current step sufficient to cause a 1V change in the output voltage, as shown in Figure 4-2.

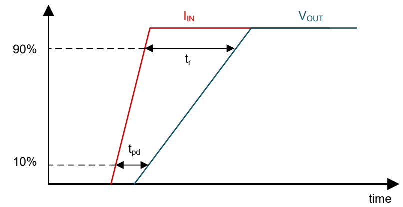

Figure 4-2. Transient Step Response

In severe short circuit conditions, the slew rate of the current can be very high, so the response time for the current sensor is critical to trigger the short circuit current protection value.

TI's in-package hall-effect current sensor offers the advantage of implementing over-current protection is the dedicated /OC pin which can be used to trigger short circuit protection with only 100ns (typical) delay.

4.3 Propagation Delay

The definition of propagation delay (T_{pd}) is the period between the input current reaching 10% of the final value and the output voltage reaching 10% of the final value, for an input current step sufficient to cause a 1V change in the output voltage, as shown in Figure 4-2.

Propagation delay is an important parameter during normal operation. For solar applications, average current sampling control is usually used. A large propagation delay can cause the sampling signal to have a big error compared with the real value. As shown in Figure 4-3, the yellow curve is the original input current, red curve is the hall sensor's signal chain output. Although the leading competitor has a higher bandwidth, due to high propagation delay, at the triggering point of ADC sampling, the output of the hall sensor experiences a 1.1us delay compared to the input current. This 1.1us delay causes a large additional offset error when sampling the average value of a triangular current in DC/DC converter. As shown in Figure 4-4, due to a much lower propagation delay, when sampling the average current, this helps minimize the additional offset error, makes the sampling signal chain more accurate.

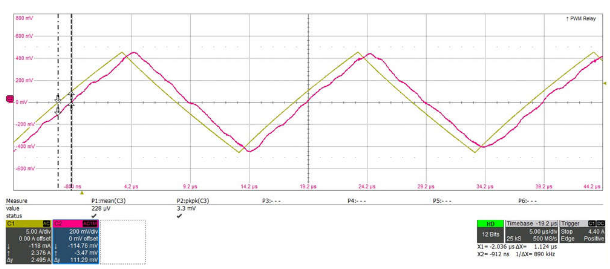

Figure 4-3. Propagation Delay Comparison of Triangular Current Measurement: Leading Competitor: BW Approximately 400kHz, Tprop Approximately 1.1µs

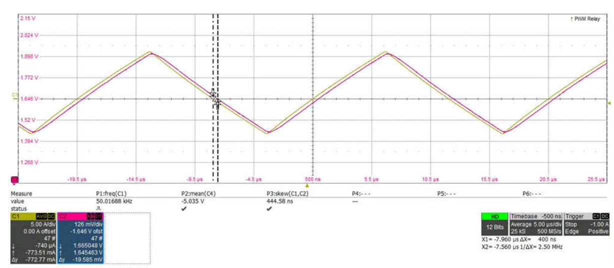

Figure 4-4. Propagation Delay Comparison of Triangular Current Measurement: TMCS1123: BW Approximately 250kHz, Tprop Approximately 0.4µs

As shown in Figure 4-5, at AC current sampling side, due to the time-varying characteristic of grid voltage (in red curve), the voltage applied to the boost inductor is also changing (in green curve). According to L*di/dt=ΔV, the slew rate of inductor current, di/dt, is time-varying. This varying slew rate causes the additional offset error also be time-varying, as shown in Figure 4-5.

For example, to see the time varying offset error more obviously, in the peak of grid voltage, the slew rate of inductor current is 0.156A/µs, so a 3.2µs total signal chain delay can bring a 0.5A offset to the AC current sensing at the grid voltage peak. But in the middle of grid voltage, the slew rate of inductor current is 0.466A/µs, so a 3.2 µs total delay can bring a 1.5A offset to the AC current sampling result. Figure 4-5 shows a high signal chain delay that brings a big time-varying error to the current loop in AC current sampling.

A time-varying offset error is hard to compensate for, which makes AC output current have worse total harmonic distortion (THD). TI's in-package Hall sensor has a very low propagation delay, which minimizes this time-varying error.

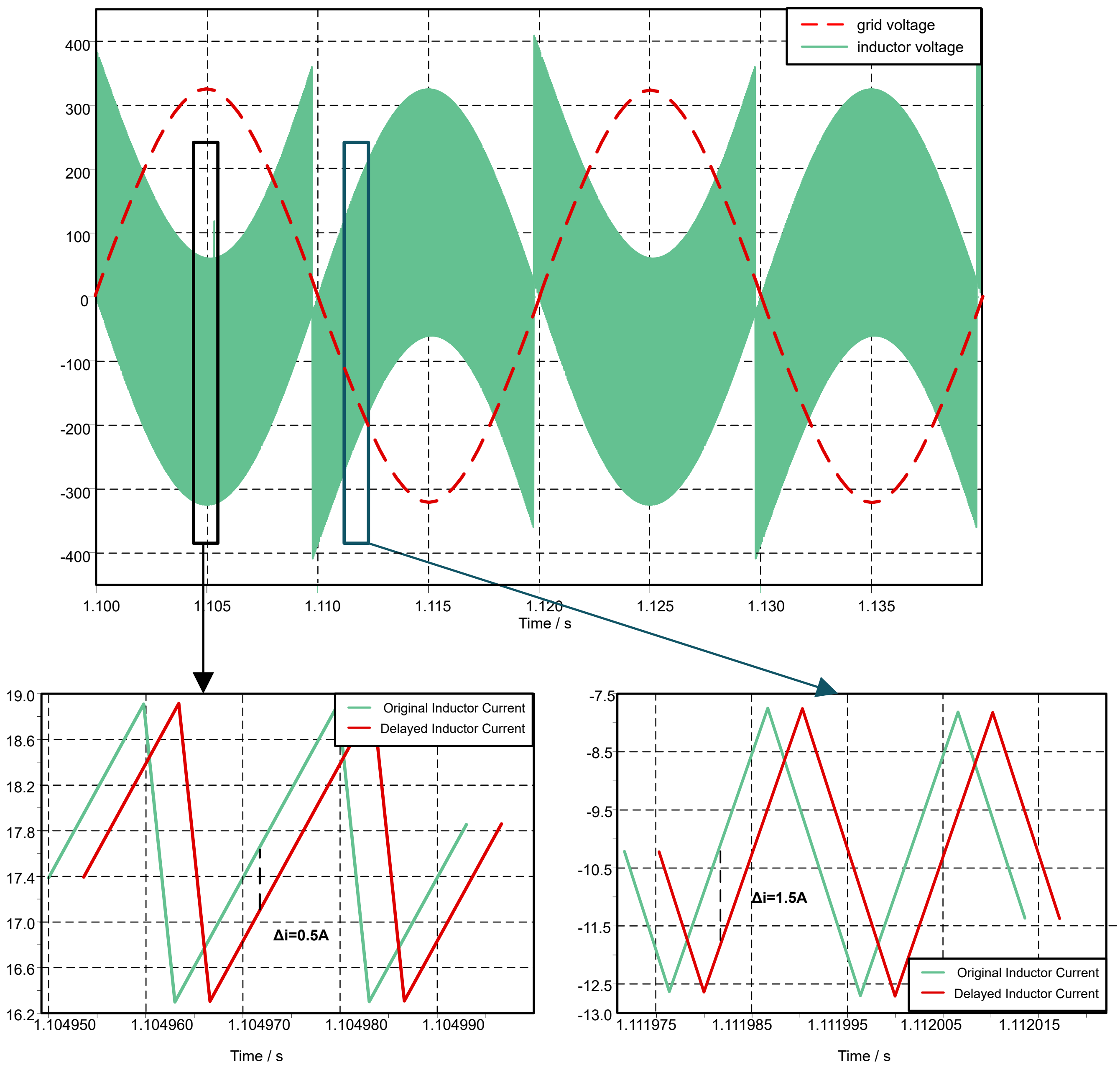

Figure 4-5. Time Varying Offset Error with Respect to Slew Rate

To more intuitively reflect the impact of the time varying offset error, the simulation is done by adding two different T_{pd} to the feedback of inductor current while keeping other parts of the control loop the same. The current control is a normal PI controller. As shown in Figure 4-6, the inductor current is filtered with a 10kHz low pass filter to lower down the switching frequency ripple and see the current waveform more clearly.

In this example, red curve is with 1us T_{pd}, inductor current THD(iTHD) is 4.36%. The green curve is with 3us T_{pd}, iTHD is 4.73%, 0.37% higher than 1us T_{pd} delay example. It's obvious that a lower propagation delay can decrease the time varying offset error and improve the output current THD. Another point can be observed in the right part of Figure 4-6, is the third harmonic component is 80% lower with a 2us lower T_{pd}, this helps the converter have a 2% more accurate amplitude in current (0.7A).

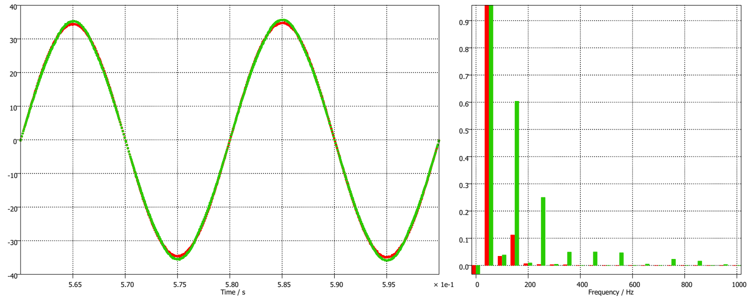

Figure 4-6. Inductor current with Different Propagation Delays

5 Lightning and Surge

Solar equipment is usually typically outdoors which needs to withstand lighting strikes. It's important to understand what's the surge current and voltage requirements and design considerations are to use in-package hall-effect current sensors in solar system applications.

5.1 Knowing Lighting and SPD in Solar

When lightning strikes the PV system, it causes induced transient current and voltage within the PV system wire loops. These transients appear at the equipment terminals and can likely cause insulation and dielectric failures within the solar PV electrical and electronics components (such as PV panels, inverter, combiner box, control and communications equipment, and so on).

Surge Protective Devices (SPD, also called surge arresters and suppressors), are designed to protect electrical installations and equipment against transient current and voltage. The protection usually shall be based on system level, not merely targeted at specific devices. Without proper surge protection, sensitive electronic equipment can easily be damaged and even create fire hazards.

The SPD are connected in parallel with the equipment; the equipment has a high impedance. Once a transient overvoltage appears in the system, the impedance of the SPD decreases so surge current is driven through the SPD, bypassing the sensitive equipment.

Figure 5-1shows an example of a solar inverter surge protection scheme. SPDs are installed on the AC side, DC side, and communication interfaces of the inverter.

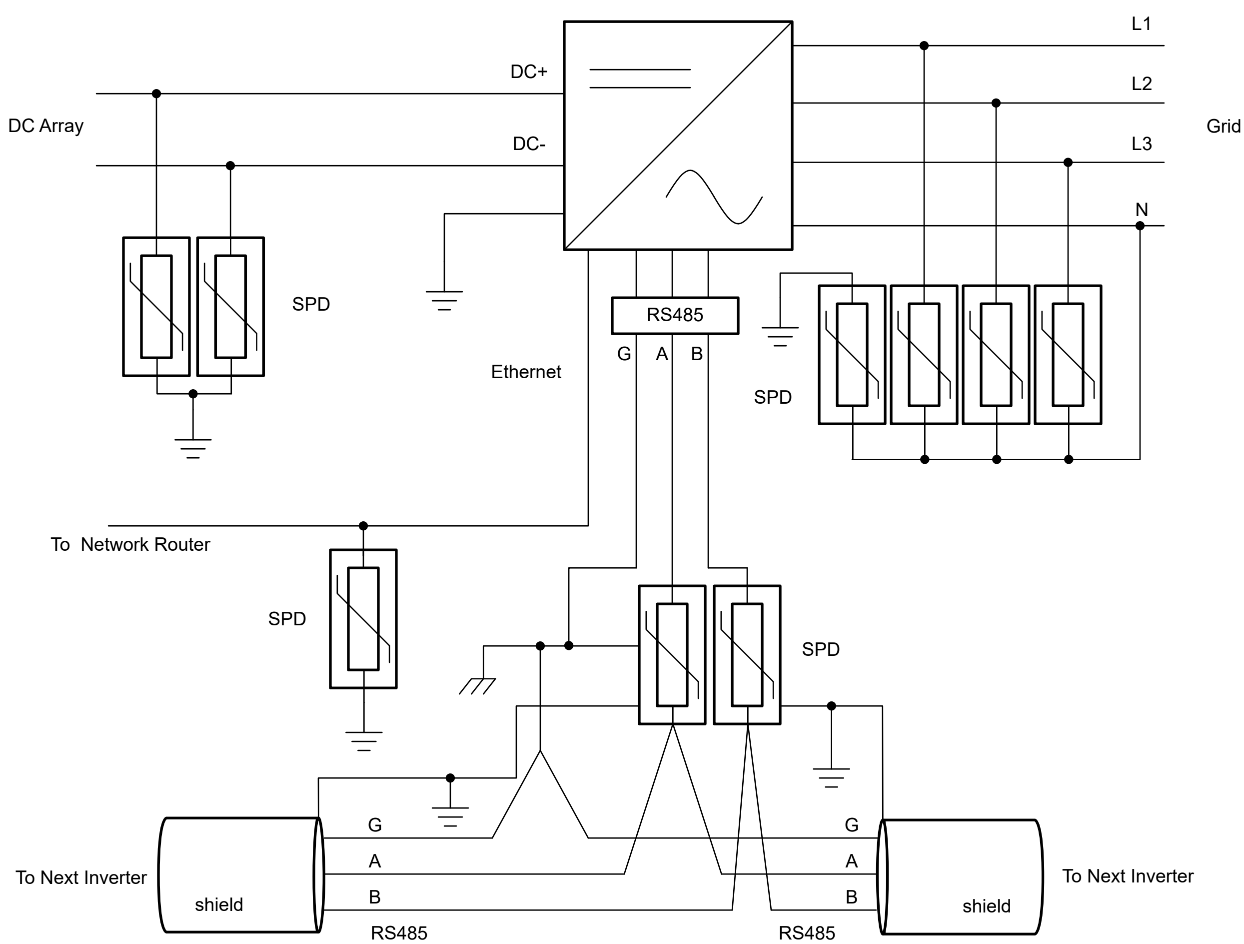

Figure 5-1. Example of Solar Inverter Surge Protection Scheme

5.2 Understanding IEC 61643-32

IEC 61643-32 (Low-voltage surge protective devices - Part 32: Surge protective devices connected to the DC side of photovoltaic installations - Selection and application principles) describes the principles for selection, installation and coordination of SPDs intended for use in Photovoltaic (PV) systems up to 1500 VDC and for the AC side of the PV system rated up to 1000 Vrms 50/60 Hz.

There are mainly three types of PV and corresponding SPD installation. Figure 5-2 shows one example of the installation of SPDs in the case of a building without external LPS (Lightning Protection System). Table 5-1 summarizes requirements for the three different installations from IEC 61643-32.

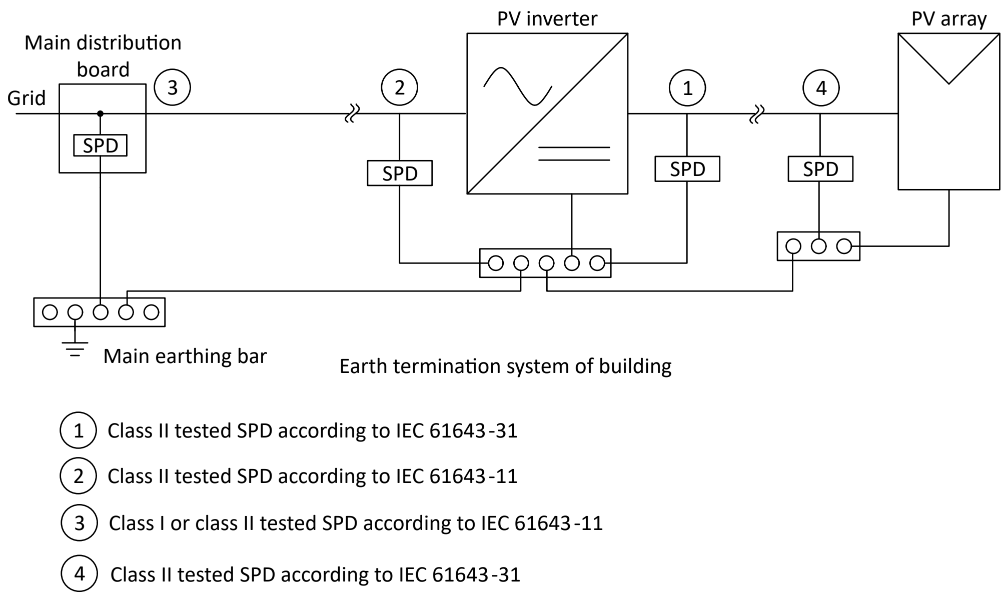

Figure 5-2. Installation of SPDs in the Case of a Building without External LPS

Table 5-1. Summary from IEC 61643-32:2017 to Select the Right SPD Class

Installation Location	Main Distribution	AC Side of Inverter (Cable Length to Main Distribution ≥10 m)	DC Side of Inverter (Cable Length to PV Panels ≥10 m)	Near PV Panels or Entrance to the Building
PV installation without external LPS	Class I or II SPD	Class II SPD	Class II SPD	Class II SPD
PV installation with external LPS, separation distance is kept	Class I SPD	Class II SPD	Class II SPD	Class II SPD
PV installation with external LPS, separation distance is not kept	Class I SPD	Class I SPD	Class I SPD	Class I SPD

5.3 Understanding IEC 61643-11

IEC 61643-11 (Low-voltage surge protective devices - Part 11: Surge protective devices connected to AC low-voltage power systems - Requirements and test methods) specifies performance and safety requirements, tests and ratings of devices for surge protection against indirect and direct effects of lightning or other transient overvoltage.

2 classes of SPD are shown in Table 5-2. In fact, there are 3 classes of SPD, Class I SPD, Class II SPD, Class III SPD, according to IEC 61643-11.

The Class I SPD is usually installed at the service entrance, such as a building. The Class I SPD can protect electrical installations and loads against direct lightning surge. The test waveform of Class I SPD is 10/350 μs current wave.

The Class II SPD is usually installed in the distribution panels. Class II SPD can protect electrical installations and loads against indirect or induced lightning surges. The test waveform of Class II SPD is 8/20 μs current wave.

The Class III SPD is usually mandatorily installed in the vicinity of sensitive loads, such as RS-485, CAN and PLC communication interface and so on as a supplemental protection to Class II SPD. Class III SPD can protect devices inside the electrical machine against residual surges or internal surges. The test waveform of Class III SPD is combination of 8/20µs current wave and 1.2/50µs voltage waveforms.

Table 5-2. Summary of 3 Classes of SPD

Feature	Class I SPD	Class II SPD	Class III SPD
Primary Protection Against	Direct lightning surges	indirect/induced lightning surges	Residual surges, internal surges
Surge Current Capacity	Largest	Medium	Smallest
Test Waveform	10/350µs	8/20µs	8/20µs + 1.2/50us
Typical Cost	Highest	Moderate	Lowest
Size	Largest	Medium	Smallest
Requires Upstream Protection	No	Yes (Class I)	Yes (Class I or II)
Typical Applications	Service entrances	Distribution panels	Outlets, Equipment connections
Solar Example	Main Distribution	Inverter AC and DC side, PV array	Comm. interface (RS-485, CAN, PLC)

In the lightning surge test, there are 2 types of current waveform to test protection devices' performance at specific current, shown in Figure 5-3. 10/350µs current wave and 8/20µs current wave models are designed to simulate the status of direct lighting surges and indirect and induced lighting surges, respectively.

In fact, the two current waveforms are different in form and energy. The time duration of the transient determines the power or amount of energy in the transient. 8/20µs waveform has much shorter time than the 10/350µs waveform. As Joule's law (E = I2Rt), Class I SPD can discharge much more energy than a Class II SPD at the same current level.

According to IEC 61643-11, Class I SPD is tested by 10/350µs waveform for direct lighting surge protection and Class II SPD is tested by 8/20µs waveform for induced lighting surge protection.

The surge immunity requirements, test methods, and range of recommended test levels for equipment with regard to unidirectional surges caused by over-voltages from switching and lightning transients. See IEC 61000-4-5 for more information, (Electromagnetic compatibility - Part 4-5: Testing and measurement techniques - Surge immunity test) which is widely adopted in semiconductor tests.

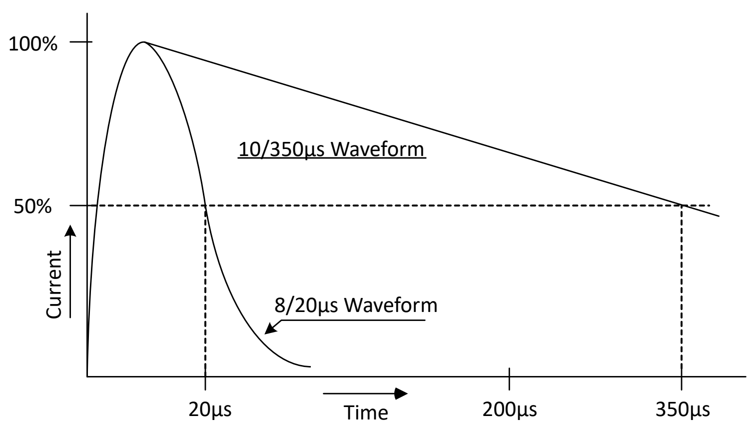

Figure 5-3. Two Types of Current Waveform in the Lightning Surge Test

5.4 Surge Requirements in Solar Systems

In fact, there are no mandatory surge requirements or standards in solar systems. Surge specs and performance are mainly decided by the vendors based on inverter's deployment scenarios and lifetime quality guarantees. However, there are some technical codes that can be used as references. For example, surge requirement and lighting protection design can refer to China local standard DL/T 1364:2014 (Technical code for protection of photovoltaic power station against lighting), which are widely adopted in the industry

Table 5-3 shows nominal discharge current (8/20us) of DC SPD which is translated from DL/T 1364:2014. It requires ≥ 10KA surge current capability for terminals in front of inverter, which means PV strings. Note that *inverter* here can include string inverter, residential inverter and hybrid inverter, and so on, which have PV strings in front of the inverter. Note that the surge requirements are more reasonable to base on system level, but not device level.

Table 5-3. Nominal Discharge Current (8/20us) of DC SPD

SPD Specs, Nominal discharge current (8/20us), Class II		
Combiner Box	**Terminals in front of Inverter**	**Other Sensitive Device Terminals**
≥ 20kA	≥ 10kA	≥ 3kA

5.5 Challenges and Designs for In-Package Hall Sensor

Figure 5-4 shows the typical block diagram of string inverter with current sensing and SPDs. The legends are:

1. Surge applies on PV+ and PV-
2. PV string current sampling
3. DC side SPD
4. MPPT Boost current sampling
5. 3-phase current sampling
6. AC side SPD

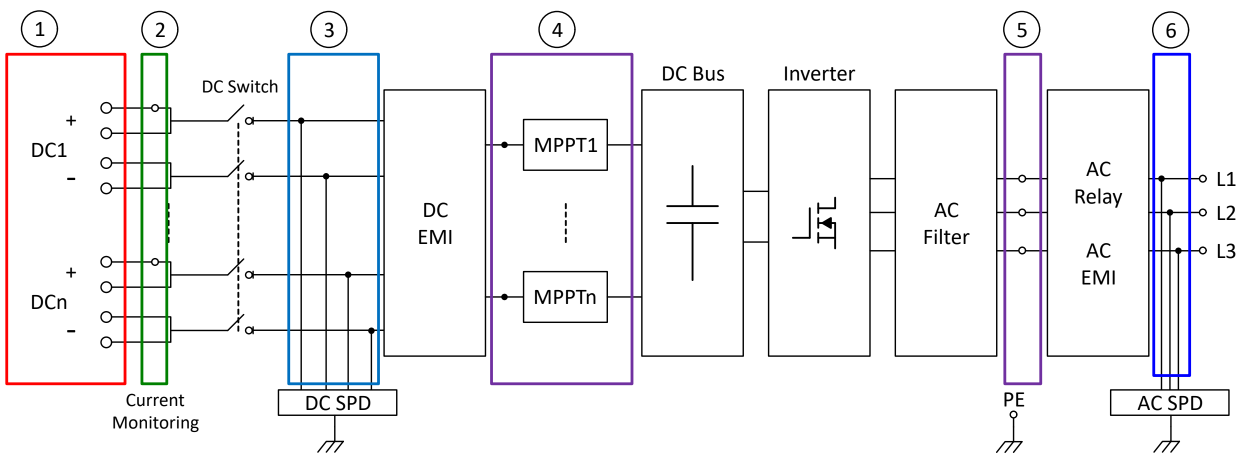

Figure 5-4. Typical Block Diagram of String Inverter with Current Sensing and SPDs

Surface Mount Device (SMD) in-package Hall-effect sensing designs can meet the surge current capability challenges in solar inverter systems even compared to through-hole mounted current sensing designs. The latter naturally has a high surge current capability because their construction allows for a very large insulation distance, while the former depends on the limited insulation performance between the leadframe and the die.

Comparing the difference between 2) PV string current sampling, 4) MPPT Boost current sampling and 5) 3-phase current sampling, AC side has SPD between AC current sampling and grid; MPPT is inside the inverter and is not directly affected by lighting surge. The DC side SPD is after PV string current sampling and there has no protection for PV string current sensors, which is very challenging for the in-package Hall-effect current sensors.

The PV string current sensing is directly exposed to the foremost position of the inverter. When DC switches are turned ON (PV strings are connected to the inverter), DC SPD can protect the PV string current sampling sensors. However, when DC switches are turned OFF in some situations (such as shutdown at night, during maintaining work and so on), meaning that DC SPD is not connected to the PV string current sampling circuit and cannot provide protection. Lighting can directly destroy the in-package Hall-effect current sensor if it doesn't have enough surge current and insulation capabilities.

Apart from selecting the in-package Hall-effect current sensor with high surge current capability (≥ 10kA) and doing lightning test in the whole system to verify reliability, there is another way to use in-package hall-effect current sensor if it doesn't have enough surge current capability.

Figure 5-5 shows the comparison between traditional inverter system architecture and new proposed architecture to allow < 10kA lower surge current capability. The main difference is the location of SPDs. For traditional architecture, the SPD circuits are placed after DC switch and on the main power board. So, when DC Switch turns OFF, SPD circuits do not function. For new architecture, SPD circuits move to the string current sampling board and before the DC switch. Therefore, SPD circuits always work in either DC switch turn OFF or turn ON.

This design works in an inverter with one PV string to one MPPT, such as low power (≤ 25KW) residential inverter or hybrid inverter. For string inverter with 2-string or multi-string per MPPT, the traditional architecture has a 2-string or multi-string connected in parallel with one SPD deployed. The new design requires an SPD installed in each corresponding string.

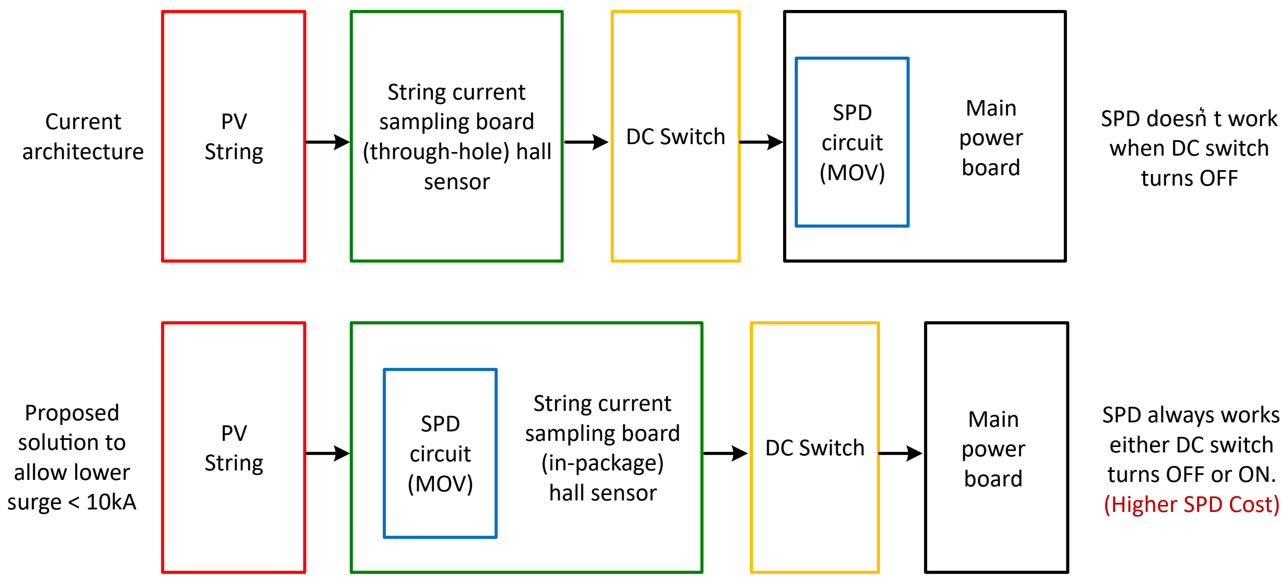

Figure 5-5. Inverter System Architectures Comparison

6 Isolation and Reliability

Figure 6-1 shows a typical isolation design of a string inverter. Usually, a 2-stage basic insulation architecture (one stage in HV side and one stage in external interface side) is used, because it can be regarded as double insulation, which is equivalent to reinforced insulation.

So, when using in-package hall-effect current sensors in solar system, firstly make sure that the key insulation specifications, such as clearance, creepage and V_{IOWM} (Maximum basic or reinforced isolation working voltage) and so on can satisfy the application related safety standards and acquire the certificates. See SDAA213 to understand more about safety requirements and isolation needs for high-voltage applications.

Taking a 1500V solar inverter as an example, it requires at least 1061VRMS and 1500VDC V_{IOWM} per VDE0884-17 or IEC 60747-17 for basic isolation working voltage. It requires at least 7.1mm clearance and 7.6mm creepage at the condition of OVC I, CTI-I, pollution degree 2 and 4000m working altitude, per IEC 62477-1:2022. The minimum clearance and creepage increase to 8.15mm for both if working altitude increase to 5000m.

Texas Instruments has a wide Hall-effect current sensors portfolio, such as TMCS112x, TMCS113x and TMCS114x that can satisfy the safety and isolation requirements and have related certificates available.

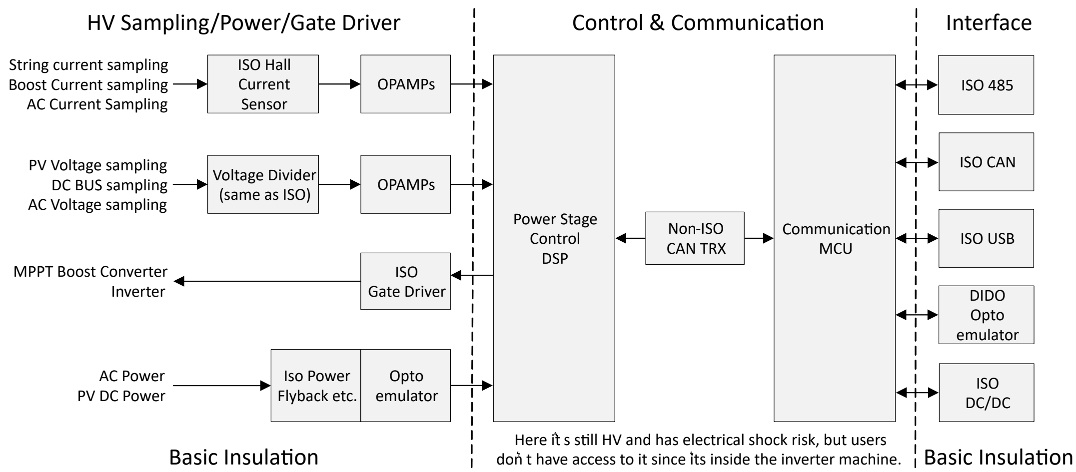

Figure 6-1. Typical Isolation Design of String Inverter

Another important consideration to use in-package hall-effect current sensors in solar system is long lifetime reliability. Solar inverters usually require more than 25 years of quality guarantee, which means there are strict reliability requirements on device isolation performance. For TI's Hall sensor products, the separation between the input conductor and the Hall sensor die due to the TMCS1126 construction provides inherent galvanic isolation between package pins on the high-voltage input side, and package pins on the low-voltage output side. In addition, TI uses special insulation materials to form the insulator.

7 Summary

With the increasing adoption of in-package Hall-effect current sensors in solar systems, it is essential to discuss the technical requirements and design considerations for their implementation. This application note addresses several key aspects critical to designing a high-performance and robust in-package Hall-effect current sensor-based current sampling circuit for solar systems. Special attention must be given to thermal capabilities, surge protection, and isolation to prevent sensor failure. Additionally, accuracy, bandwidth and delays are crucial parameters for achieving a high-performance current sampling system.

8 References

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