How to use an ideal diode controller as a scalable input bypass switch in solar applications

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Introduction

In solar photovoltaic (PV) systems, module-level power electronics (MLPE) improve power-yield performance under certain conditions, especially in shade. Once considered a costly specialty category, MLPE is now one of the fastest-growing market segments in the solar industry. A solar power optimizer is one type of MLPE that optimizes the power output of the PV panel and increases efficiency.

Conventional solar power optimizers use a P-N junction diode or a Schottky diode for the bypass circuit. When high current flows through the diode, the high-power dissipation can cause severe thermal issues because of the diode's relatively high forward voltage drop. An improved method uses a metal-oxide semiconductor field-effect transistor (MOSFET) with a lower voltage drop than diodes to overcome the high-power loss.

Additionally, solar optimizers can now support higher input voltages – up to 150V transient with two PV panels in series – thanks to the efficiency improvements gained by lower conduction losses for a given power level, and lower system costs. In this article, we'll discuss a scalable bypass circuit solution using a floating-gate ideal diode controller. This circuit addresses challenges related to bypass switches with wide voltage support in solar power applications such as solar power optimizers, rapid shutdown and PV junction boxes.

What is a solar power optimizer?

Figure 1 illustrates a PV system with a solar power optimizer installed on an individual PV panel.

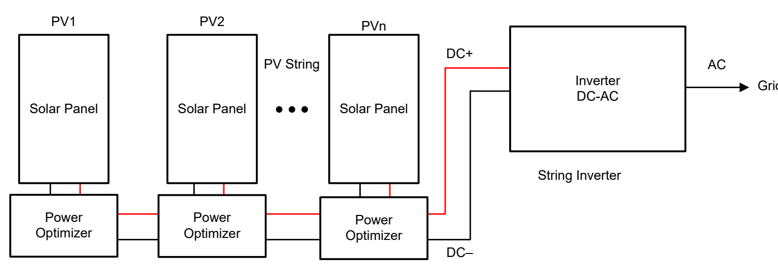

Figure 1. *PV system with a solar power optimizer.*

Think of a power optimizer as a compromise between a microinverter and a string inverter. It is installed on individual solar panels like a microinverter, but its function has nothing to do with converting DC to AC electricity. A power optimizer tracks the maximum power of each solar panel in real time and regulates the output voltage before sending it to the inverter. Therefore, the inverter can process much more electricity. The result is optimized power-yield performance for every single solar panel, regardless of orientation to the sun, shade or even damage to one or more panels. Solar systems with power optimizers installed at each PV panel can be 20% to 30% higher in efficiency compared to one without an individual panel-level optimizer.

Output bypass function of a solar power optimizer

For high-power solar inverters, connecting multiple PV panels in series achieves a high DC input voltage going into the inverter input. Deploying the optimizers to the corresponding PV panels obtains the highest efficiency, as shown in **Figure 2**. The PV string is actually connected by the outputs of the optimizer. If any one of the solar panels fails, then the PV string voltage can collapse, as all of the PV panels are connected in series. An output bypass circuit provides a parallel path to the string current around the damaged optimizer. **Figure 2** shows how the bypass function works when one of the PV panels breaks.

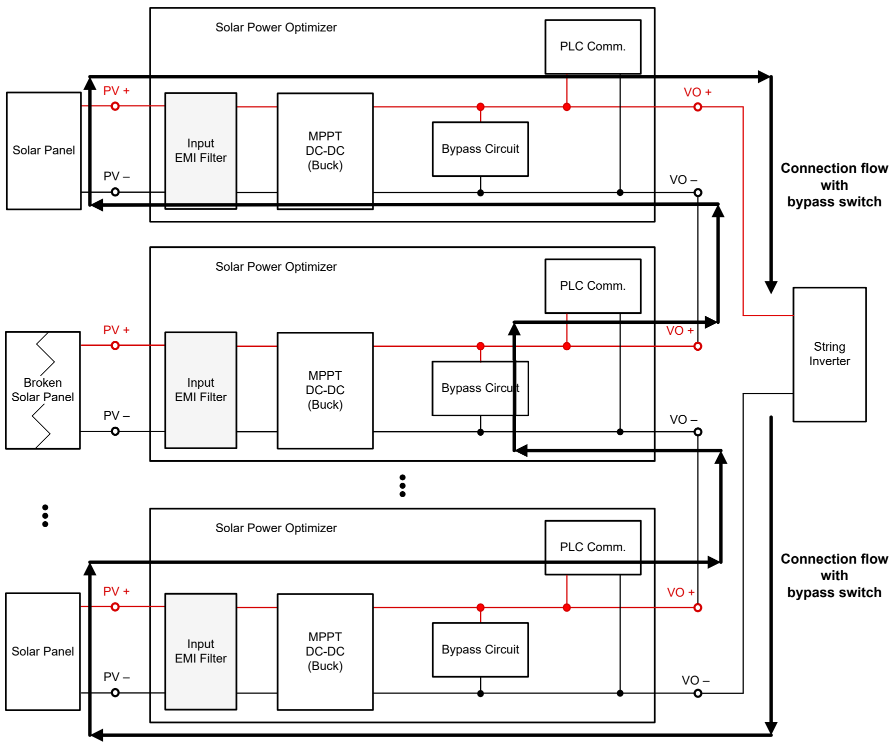

Figure 2. *Output bypass junction of a solar power optimizer.*

Output bypass circuit solutions

There are typically two kinds of solutions for the bypass circuit. The common way to achieve bypass functionality to use P-N junction diodes or Schottky diodes, as shown in **Figure 3**. It's low cost, easy to use and can achieve a very high reverse voltage based on the diode selected. There are drawbacks, however, such as a high forward voltage drop (0.5V to 1V), which causes higher power dissipation and larger printed circuit board requirements. In order to overcome the disadvantages of the bypass diode solution, using an N-channel MOSFET, which has a much lower voltage drop and lower power losses (because of low $R_{DS(on)}$), is an alternative. There are still some drawbacks, however:

- The MOSFET is not a stand-alone solution – it requires a control circuit to operate it as a switch, usually a microcontroller (MCU) with discrete MOSFET driver circuit.
- The MCU needs power from the PV panel. So if the PV panel is badly damaged or fully covered by

shadows or shade, then the MCU will not work and the MOSFET cannot turn on,

- In cases when the MCU fails, the MOSFET cannot be turned on, and the bypass path is through body diode of the MOSFET. But body diode of the MOSFET cannot withstand large currents and will accumulate high degrees of heat that can risk fire.

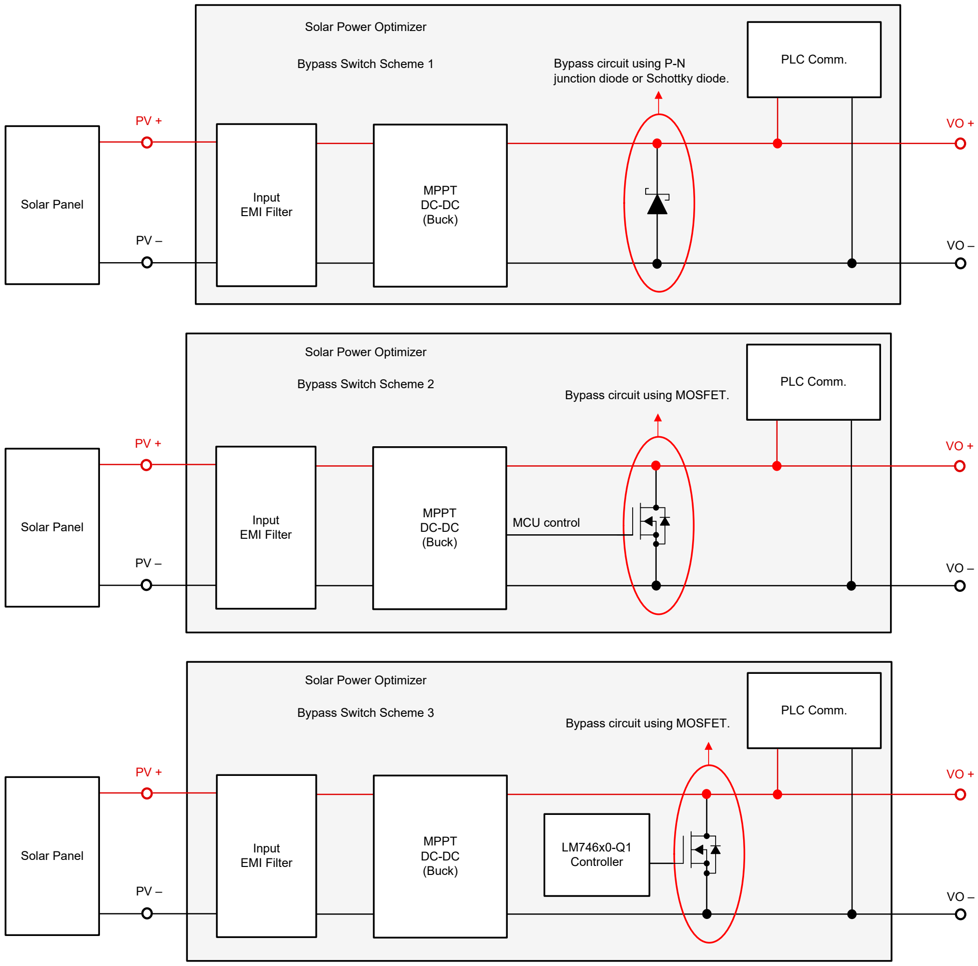

Figure 3. *Typical solutions when using a bypass switch in solar optimizers.*

An intelligent way to address the drawbacks of an MCU-based on or off control scheme is to use a stand-alone MOSFET controller that can work autonomously without any external intervention. The **LM74610-Q1** family of floating-gate ideal diode controllers from Texas Instruments provides a stand-alone, low-loss bypass switch solution by controlling the external N-channel MOSFET to emulate series diode behavior. These controllers have a floating gate-drive architecture that can operate with an input voltage as low as the MOSFET's body diode forward drop (approximately 0.5V).

However, as solar inverter power levels increase, and the adoption of higher-voltage PV panels increases, the bypass circuit has a few requirements to make it a better solution than traditional ones. It needs to work with a PV panel voltage ranging from 20V to 150V to make it scalable across multiple platforms, and it should be independent from other circuits.

A scalable bypass switch solution using a low-voltage ideal diode controller

The bypass circuit solution uses an ideal diode controller with a floating gate-drive architecture (such as the **LM74610-Q1**) to drive an external MOSFET and emulate an ideal diode as the bypass circuit so that it is independent from other circuits. Its floating gate-drive architecture can achieve a universal input range, as the gate drive does not respect to ground. In addition, a unusual advantage of this scheme is that it is not referenced to ground and thus has zero quiescent current.

When solar panels and solar equipment operate normally, the bypass MOSFET is off, and the reverse voltage equal to the maximum panel voltage appears from the cathode to the anode pins of the ideal diode controller. However, the reverse voltage (PV+ to PV–) from the cathode to the anode pins of the ideal diode controller can be very high as the PV panel and string transient voltage. In cases where the PV panels are used in series with a very large input voltage range, it can be challenging to design the maximum input voltage range for the bypass circuit. The maximum reverse voltage of the **LM74610-Q1** is limited to 45V transient. Thus, currently available ideal diode controller devices are not suitable for solar panels with a rated input voltage of 80V or 125V.

Adding a depletion MOSFET Q_D in the sense path to extend the reverse voltage range of the ideal diode controller sustains this voltage level for any range, as shown in **Figure 4**. The drain of Q_D connects to output PV+. The source connects to the cathode and the gate connects to the anode of the ideal diode controller.

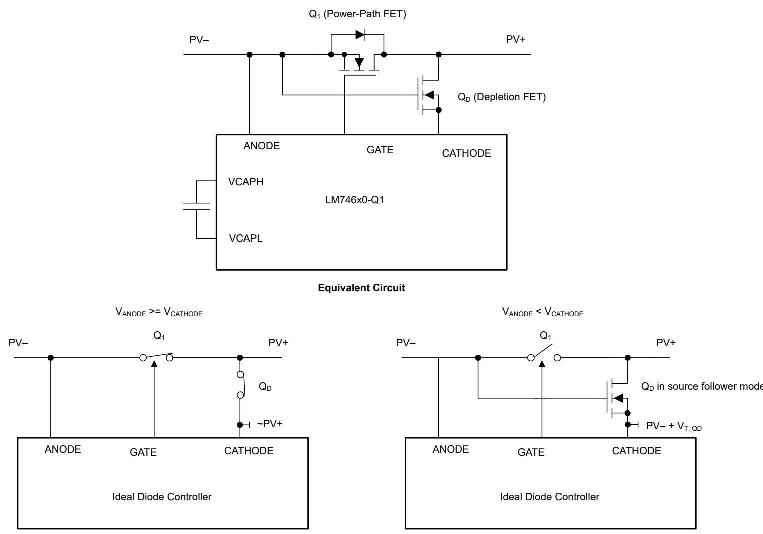

Figure 4. *Scalable bypass switch solution.*

Working principle of LM74610-Q1 reverse-voltage range extension

Depletion-mode MOSFETs are by default on when MOSFET V_{GS} is 0V, unlike enhanced-mode MOSFETs that require V_{GS} to be greater than the threshold voltage of the MOSFET. In order to turn off the depletion MOSFET, V_{GS} needs to be <0V (typical ranges are from –1V to –4V). To analyze the effect of the depletion-mode MOSFET in an ideal diode-sense path, let's look at device operation under these conditions:

- When V_{PV-} V_{PV+}: The ideal diode controller is in forward-condition mode, keeping both the power MOSFET Q_1 and depletion FET Q_D on. With these operating conditions, you can calculate the output voltage as $V_{OUT} = V_{IN} - (I_{D\_Q1}\ R_{DS(on)\_Q1})$, approximated to V_{PV+}.
- When $V_{PV-} < V_{PV+}$: The ideal diode controller is in the reverse current blocking condition, with MOSFET Q1 turned off. MOSFET Q_D is in regulation mode as a source follower, maintaining $V_{CATHODE}$ above V_{ANODE}, $V_{CATHODE} = V_{IN}(V_{ANODE})+ (V_{GSMAX})$. So the voltage across $V_{CATHODE}$ to V_{ANODE} is within the absolute maximum rating V_{GSMAX} of Q_D (usually <5V), which is far less than the maximum reverse voltage of 45V transient of the LM74610-Q1. The high reverse

voltage ($V_{OUT} – V_{IN}$) is sustained by the drain-to-source voltage (V_{DS}) of Q_D and Q_1.

Selecting the correct depletion MOSFET and power MOSFET depends on these points:

- Choose a V_{DS} rating of Q_1 and Q_D greater than the maximum peak input voltage.
- Select $R_{DS(on)}$ such that dissipation across the power-path MOSFET is lowest. The drain current (I_D) of the FET should be higher than the maximum peak current demanded by the output load. Selecting a depletion MOSFET with a drop of 50mV to 100mV across the power MOSFET at the full load current is a good starting point.
- $R_{DS(on)}$ can be in the hundreds of ohms range (the **LM74610-Q1**'s floating gate-drive architecture has a large impedance of cathode pin to ground, and the $I_{CATHODE}$ of the controller is in the microamperes range).

Figure 5 shows test results for a 60V bypass switch solution using the 40V **LM74610-Q1** controller.

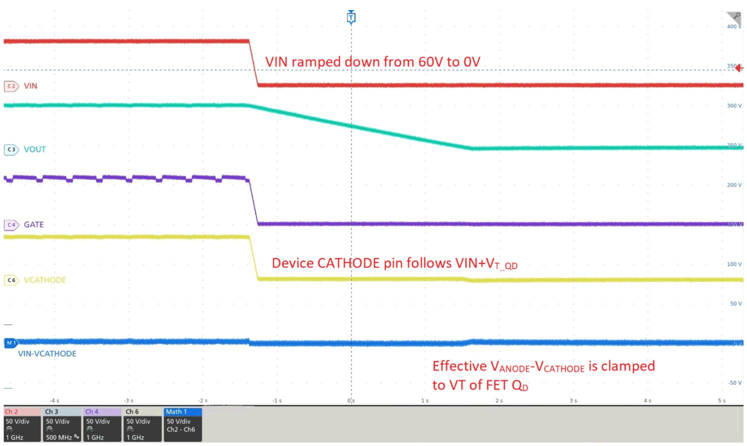

Figure 5. *Test results for a 60V bypass circuit with the LM74610-Q1 and depletion MOSFET.*

With properly scaled MOSFETs (Q1 and Q_D), the input voltage range can extend to the V_{DS} rating of the FETs.

This enables high-voltage designs using the same low-voltage controller. Also, extending the input voltage range can also be useful in enterprise, communication, power tool and high-voltage battery-management applications.

Conclusion

If PV panels or solar equipment connected in a series are broen or faulty, it is important to have a design in place to avoid hot spotting and/or voltage supply interruption. This responsibility commonly lies with the solar power optimizer or rapid shutdown. While standard rectifier diodes or Schottky diodes are the simplest solution to bypass the broken panel, they aren't preferred given thermal inefficiency. A floating-gate ideal diode controller along with an N-channel MOSFET offers less stand-alone loss than a bypass switch solution, and an additional system workaround with a depletion MOSFET offers a completely scalable solution to address the wide input voltage range of PV panels.

Additional resources

- **LM74610-Q1 Zero IQ Reverse Polarity Protection Smart Diode Controller Data Sheet**

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