Application Note

Using Ideal Diode Controller LM746x0-Q1 to Achieve Bypass Function in Solar MLPE Applications

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ABSTRACT

Module-level Power Electronics (MLPE) are devices that can be incorporated into solar photovoltaic (PV) systems to improve power yield performance in certain conditions, especially where shade is present, and achieve some other system benefits. MLPE are once costly specialty products, but have made great strides in the last decade and been becoming one of the fastest growing market segments in the solar industry. A solar power optimizer is one kind of MLPE that optimizes power output and increases efficiency, which requires the MLPE to have high-power conversion efficiency and low self-heating.

The conventional solar power optimizer commonly uses P-N junction diode or Schottky diode for the bypass circuit. When high current flows through the diode, this can have high power dissipation and bring severe thermal issue because of diode's relatively high forward voltage drop. The improved method uses MOSFET with lower voltage drop than diode to overcome the high power loss drawback of diode. However, MOSFET needs extra control to turn ON or OFF and the control circuit has control failure probability. This increases the circuit complexity and reduces module reliability. This application note provides a new bypass circuit design using TI's ideal diode controller LM746x0-Q1 to solve these challenges. In addition, a remarkable idea using depletion MOSFET to extend the reverse voltage range of LM746x0-Q1 to support PV panel with wider output voltage, is also discussed in detail. In addition, this bypass circuit design can be also used in rapid Shut Down (RSD), also regarded as one kind of MLPE, and PV junction box, where traditionally uses diode.

Table of Contents

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1 Introduction

The output characteristics of solar Photovoltaic (PV) cells vary greatly depending on the light radiation intensity and ambient temperature. One basic requirement of PV system is making PV cells to always deliver the maximum power to use solar energy more efficiently. Hence, Maximum Power Point Tracking (MPPT) circuits and algorithms are used for solar power optimization to dynamically keep the output voltage and output current of the PV panel at this expected maximum power point when the PV panel environment changes.

The conventional widely used method for solar power optimization is performed at the PV string level. In fact, each PV string usually consists of multiple PV modules (also called PV panels, each PV module consist of multiple PV cells) in series. Solar power optimization performed at the PV string level only achieves global string MPPT but not module level MPPT. Also, each PV module possibly does not work in the MPP and still has energy loss, even the PV string works in the MPP. To solve this issue, Module-level Power Electronics (MLPE) technology was raised and commercialized for years.

1.1 What is MLPE

MLPE are devices that can be incorporated into solar PV system to improve power yield performance in certain conditions, especially where shade is present, and achieve some other system benefits.

MLPE were once costly specialty products, but have made great strides in the last decade and have become one of the fastest growing market segments in the solar industry.

MLPE includes Micro-Inverter and Solar Power Optimizer. The Micro-Inverter and Solar Power Optimizer perform some of the same functions (such as MPPT) as a string inverter or central inverter, but are typically coupled to just one (or a few) PV panels rather than many (PV String), and offer additional features.

For example, MLPE is an extra layer of MPPT at the per-panel level. This is in contrast to MPPT in string inverter that is connected per string of multiple panels.

1.2 Why, When, Where Needs MLPE

Figure 1-1 through Figure 1-4 shows I-V curves of PV cell comparing shade and no shade conditions. If no shade, the overall string characteristic curve can be regarded as the sum of each cell's curve, as well as the MPP. If shade on Cell 1 (red), the maximum allowed current going through this rapidly decreases and the same for the string current because cells are in series with the same current. The overall string characteristic curve is pulled down by the shady cell, as well as the MPP.

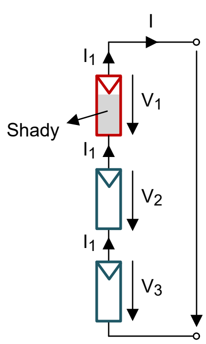


Figure 1-1. Circuit Shade

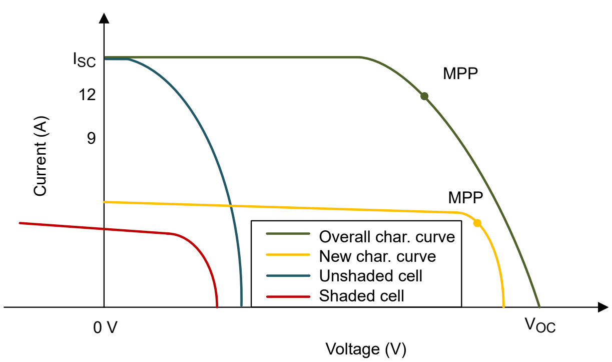


Figure 1-2. Graph Shade

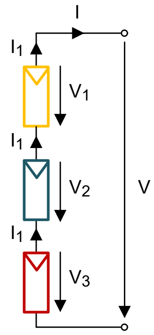


Figure 1-3. Circuit No Shade

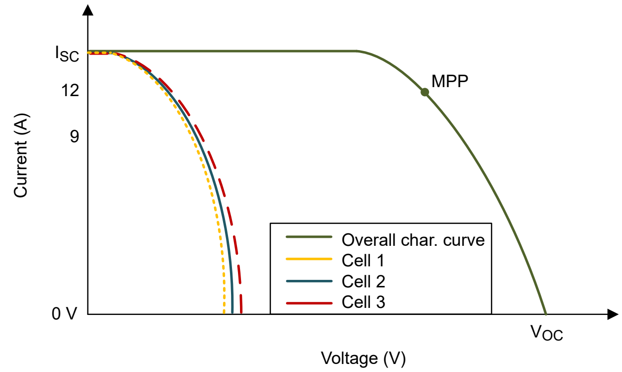


Figure 1-4. Graph No Shade

Figure 1-5 shows a rooftop PV application scenario example. There are some PV panels in different shady conditions, from no shade to almost in full shade. This means the panels corresponding I-V Curves also vary from each other, as well as the MPP. This can be seen that as the shade gradually aggravates, the power generation capability of the PV panel also gradually decreases.

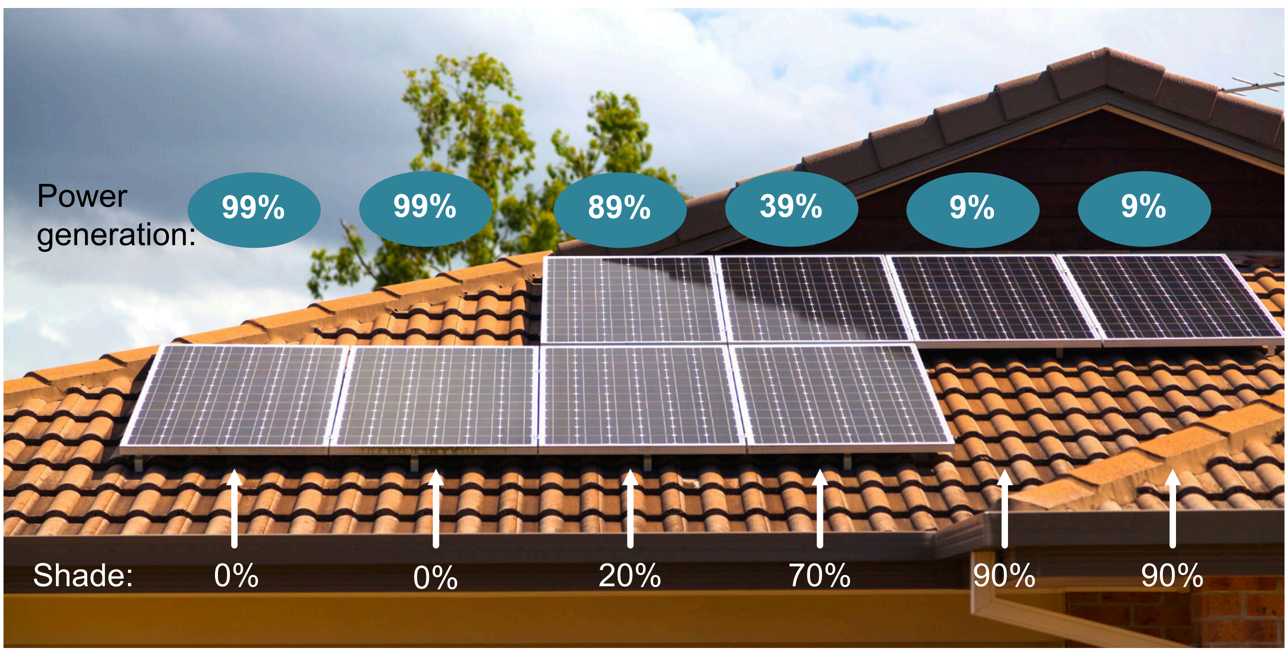


Figure 1-5. Rooftop PV Application Scenario Example

However, for the string inverter, since PV panels are connected in series to form a string with the same string current, the power generation capability of the all PV panels are limited by the poorest one. Also, all PV panels are forced to have the same current as the poorest one having, that is known as buckets effect.

Figure 1-6 through Figure 1-9 shows the power generation effect demo of PV system in with or without shady condition.

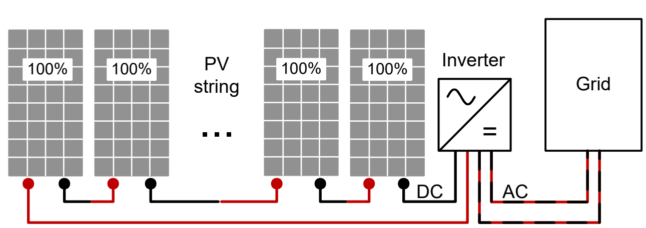


Figure 1-6. PV System without MLPE in Non-Shady Condition

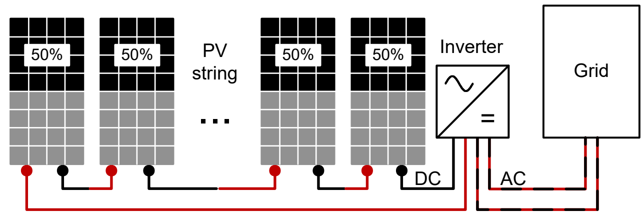


Figure 1-7. PV System without MLPE in Shady Condition

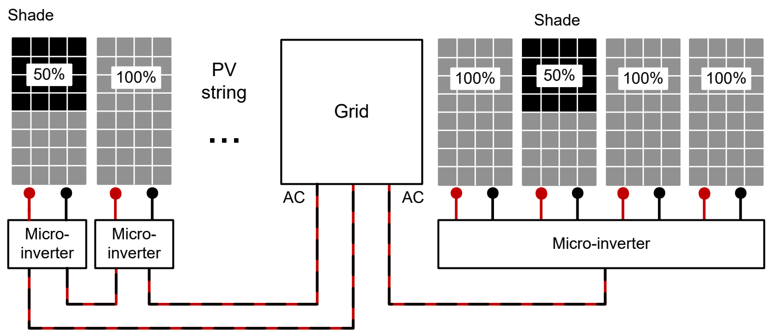


Figure 1-8. PV System with Micro-Inverter in Shady Condition

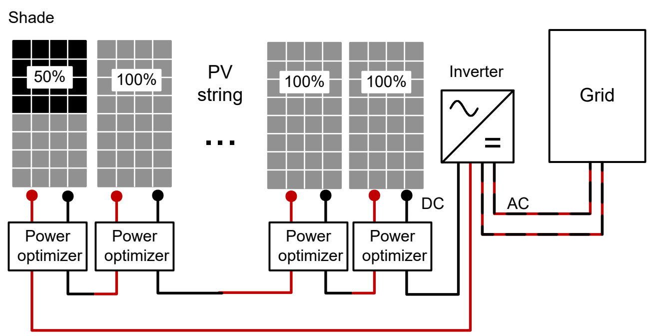


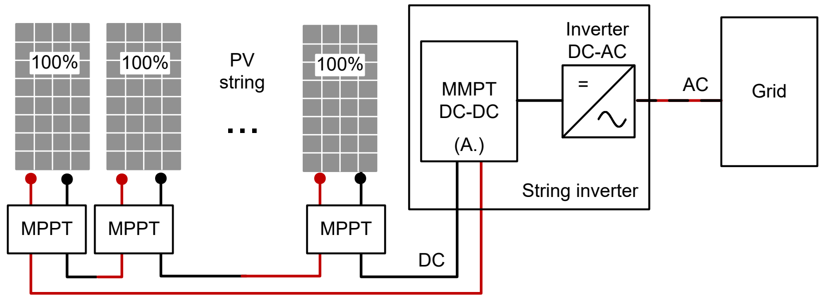
Figure 1-9. PV System with Solar Power Optimizer in Shady Condition

The summarize, the power yield efficiency of traditional string inverter PV system is affected by some factors such as shady (surrounding buildings, trees, clouds, fallen leaves and bird droppings, and so on), PV module mismatch losses, and PV panel orientation mismatch losses (PV panels deployed on roofs with different orientation).

The reason MLPE needed is, because String inverter only achieves global MPPT, MLPE can achieve module level MPPT to improve energy production. In addition, MLPE naturally can provide compliance with module-level rapid shutdown (RSD) requirements under the National Electrical Code (NEC) and module-level monitoring and diagnostic functionality. So, when the users meet situations of low power yield efficiency, or RSD being required by local law, the user needs to consider MLPE products in the PV system. Typically, this is mostly designed for residential and small-size commercial PV system. Also note that, RSD can be a product independent from Micro-Inverter and Solar Power Optimizer. Hence, sometimes RSD is also regarded as one kind of MLPE product, though this does not improve power yield performance as Micro-Inverter and Solar Power Optimizer do, only provides shutdown function.

1.3 What is Solar Power Optimizer

Figure 1-10 shows the PV system with solar power optimizer.



A. Solar power systems deploy optimizers based on actual needs. Optimizers are not always required for each PV panel.

Figure 1-10. PV System with Solar Power Optimizer

The optional solar power optimizer can be added into a solar power system based on actual needs. The optional solar power optimizer is not a type of inverter. This helps max out the solar system by module-level MPPT, making this a compatible complement with the existing string inverters (global MPPT). So, a solar power system with optimizers can have a more efficient DC output than one without. This can be considered a compromise between micro-inverter and string inverter. The solar power optimizer can be installed on individual solar panels like the micro inverter but the function has nothing to do with converting DC to AC.

1.4 Solar Power Optimizer Working Principle

Figure 1-11 through Figure 1-14 describe the solar power optimizer working principle. Suppose that the PV panel can output maximum 420 Watts (35V, 12A) when there is no shady (MPP on the blue I-V curve).

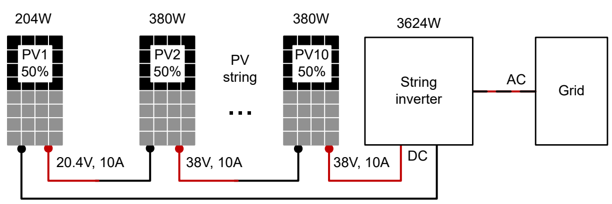


Figure 1-11. PV System Without Solar Power Optimizer

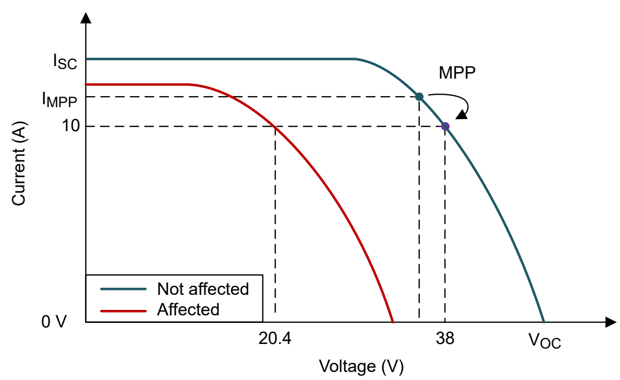


Figure 1-12. PV Curve Characterization Without Solar Power Optimizer

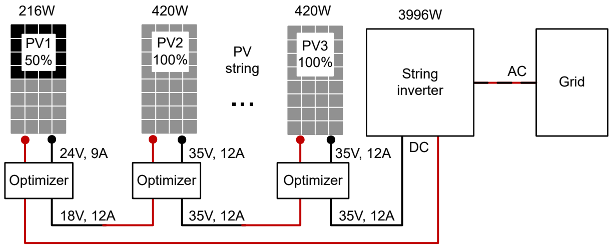


Figure 1-13. PV System With Solar Power Optimizer

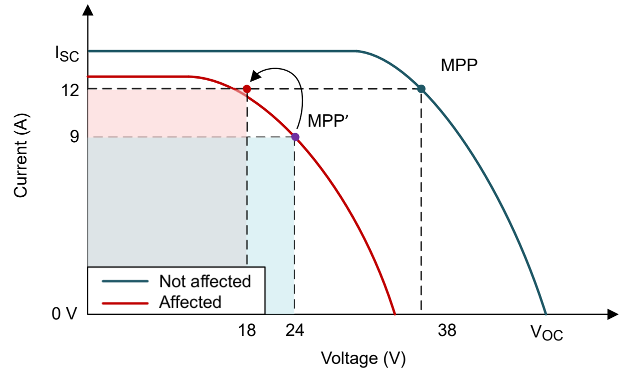


Figure 1-14. PV Curve Characterization With Solar Power Optimizer

Power equilibrium: The two shared areas are equal.

The top half part is the PV system without the optimizer. The example shows, when PV 1 is partially obscured by a leaf, the I-V curve is in green. There has no shady on PV 2 to PV 10 and the I-V curves are in light blue. Now the string inverter finds the maximum output power is in the condition of the 10A string current. This can be found that though there having no shady on PV 2 to PV 10, MPP of PV 2 to PV 10 changes from the light blue point to the purple point. The total power goes into the string inverter is 3624 Watts.

The bottom half part is the PV system with the optimizer. The example shows, when PV 1 is partially obscured by a leaf, the I-V curve is in green. There has no shady on PV 2 to PV 10 and the I-V curves are in light blue. With solar power optimizer, now the string inverter finds the maximum output power is in the condition of the 12A string current, which aligns to the MPP current of PV 2 to PV 10. So, PV 2 to PV 10 are working on the MPP. For PV 1, the MPP is at 24V 9A (dark blue point). By the simple power equilibrium principle (ideally ignore loss) of power optimizer, the output after this is changed to 18V 12A (purple point). The total power goes into the string inverter is 3996 Watts. As shown, with power optimizer, the total power goes into the string inverter increases 10.2%.

In short, power optimizer tracks the max power of each panel in real time and regulates the output voltage before sending the output to the inverter, The inverter can process much more electricity. The result is optimized power yield performance for every single panel, regardless of orientation to the sun, shady, or even damage to one or more of the panels.

1.5 Output Bypass Function of Solar Power Optimizer

Figure 1-15 shows that the optimizers are deployed parallel to the corresponding PV panels. Now the PV string is actually connected by the outputs of optimizer. Supposing that there has damage on the panel or the power stage (MPPT DC-DC) of the optimizer, how the string can still work? Figure 1-15 shows the simplified block diagram of the optimizer. There has a bypass circuit that provides another path allowing the string current around the damaged panel or the power stage of the optimizer.

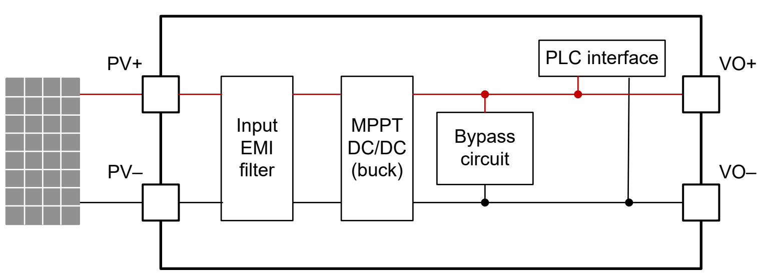


Figure 1-15. Simplified Block Diagram of Solar Power Optimizer

Figure 1-16 shows how the bypass function works. In this example, the second PV panel is broken, now the string current does not pass through this PV panel, the string current passes through the bypass circuit inside the optimizer.

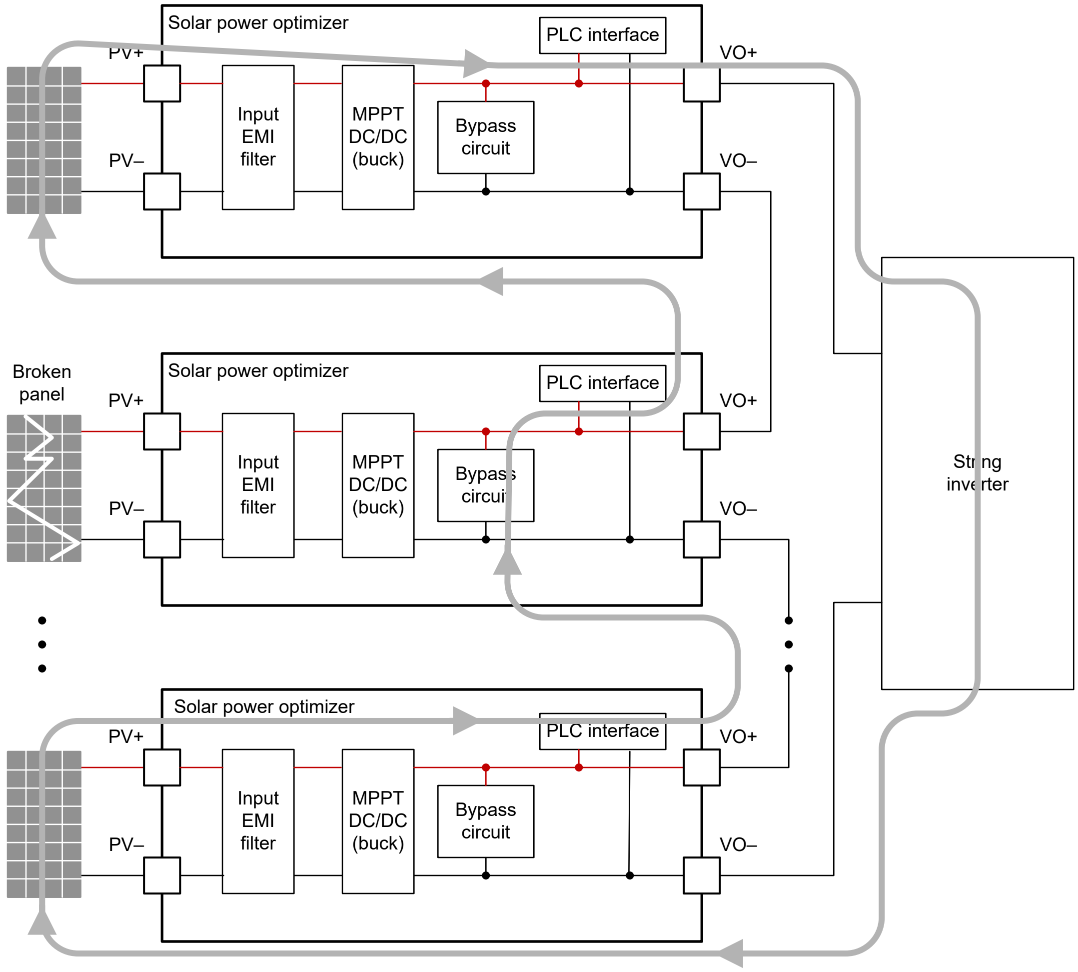


Figure 1-16. Output Bypass Function of Solar Power Optimizer

2 Traditional Designs of the Bypass Circuit

The bypass current can be up to dozens of amperes (for example 20A), there are typically two kinds of traditional designs of the bypass circuit.

2.1 Design 1 - Using P-N Junction Diode or Schottky Diode

Figure 2-1 shows the common and simplest method to achieve bypass function by using P-N junction diodes or Schottky diodes. This method is low cost, easy to use, and can achieve very high reverse voltage based on the diode selection. However, these drawbacks remain:

- High power loss (0.7V/0.4V × 20A = 8 to 14 watts losses)
- Severe thermal issue
- Lower solar power generation efficiency
- Large PCB size occupied because high current diodes needed

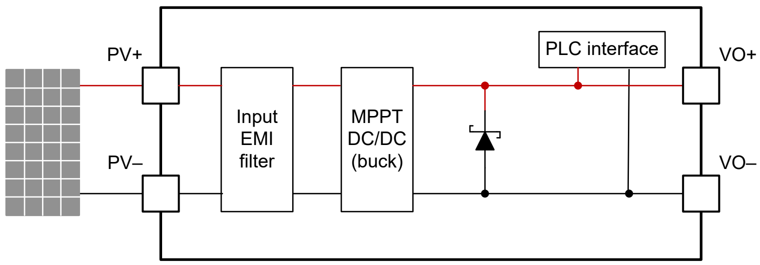


Figure 2-1. Diode Method of Bypass Circuit

Note

Bypass circuit using P-N junction diode or Schottky diode.

2.2 Design 2 - Using MOSFET

To overcome high power loss disadvantages of the diode design, as shown in Figure 2-2, using MOSFET which has much lower voltage drop or power loss (because of low Rdson) is an alternative. However, there still are some drawbacks,

- MOSFET is not a standalone design, the ON or OFF needs MCU control.
- MCU control needs power from PV panel, if PV panel is badly damaged or fully covered by shadow, then MCU is not able to work then MOSFET cannot be correctly turned ON.
- In cases that MCU does not work or is out of control, the MOSFET is not turned ON, now the bypass path is the parasitic diode. But parasitic diode cannot bear large current and can accumulate huge amounts of heat that finally has risk of causing fire.

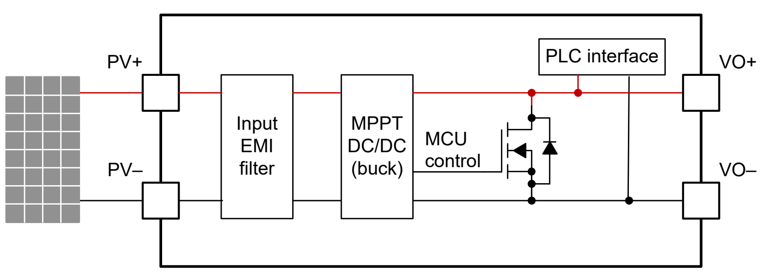


Figure 2-2. MOSFET Design of Bypass Circuit

3 New Design of the Bypass Circuit

How to solve challenges of the traditional bypass circuit designs? This session discusses a new bypass circuit design using TI's low-voltage ideal diode controller LM746x0-Q1.

3.1 Requirements on Bypass Circuit

There are three requirements on the bypass circuit to make this a better design than the traditional designs.

- **High Input Voltage**: Minimum 100V rated design to cover common single solar panel with rated input voltage up to 80V (plus 20V margin). Minimum 150V rated design to cover two solar panels in series with rated input voltage up to 125V (plus 25V margin).
- **Low Power loss**: MOSFET with lower power loss needs to be used, instead of P-N junction diodes or Schottky diodes.
- **Standalone**: Bypass circuit needs to be independent from other circuits, which means even other circuits fail, this does not affect the bypass circuit.

3.2 Using Ideal Diode Controller LM746x0-Q1

The new bypass circuit design uses ideal diode controller with floating gate drive architecture (such as LM74610-Q1) to drive an external MOSFET to emulate an ideal diode as the bypass circuit and make this circuit be independent from other circuits. The floating gate drive architecture can achieve universal input range as gate drive is not with respect to GND. In addition, a unique advantage of this scheme is that the scheme is not referenced to ground and thus has Zero Iq.

The working principle is shown in Figure 3-1 and Figure 3-2. When the PV panel or the solar equipment fails, the bypass circuit works. In cycles, Body diode of external MOSFET conducts the load current, voltage across body diode is used to build charge pump internally with duty cycle D and then turn on the FET with duty cycle 1-D. When solar panel and solar equipment operate normally, the bypass circuit does not conduct and reverse voltage (VO+ to VO-) appears across cathode to anode of the ideal diode controller.

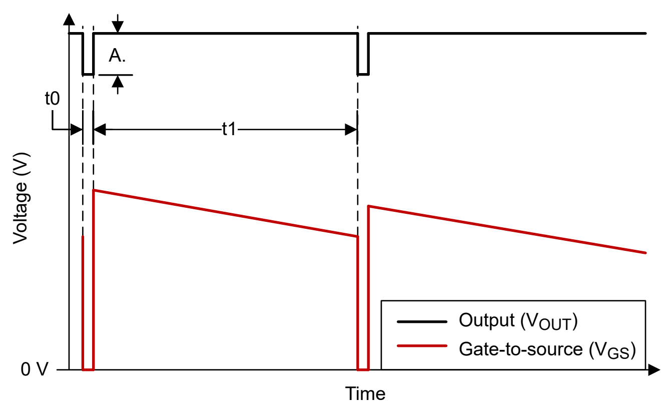


Figure 3-1. Output Voltage and VGS Operation Example of LM746x0-Q1

LM746x0-Q1	A: Body diode voltage drop
t0: FET is OFF, duty cycle = D	t1: FET is ON, duty cycle = 1-D

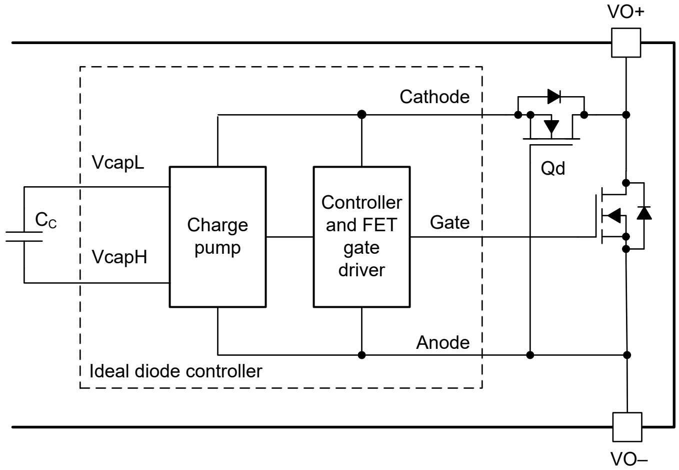


Figure 3-2. Ideal Diode Controller Design of Bypass Circuits

3.3 Challenges of Using Ideal Diode Controller

However, the reverse voltage (VO+ to VO-) across cathode to anode of the ideal diode controller can up to very high as the PV panel or string transient voltage. Especially in some cases that PV panels are used in series with very large input voltage range, which is challenging to design the max input voltage range for the bypass circuit.

The maximum reverse voltage of LM74610-Q1 is limited to 45Vmax (transient). Thus, currently available ideal diode controller devices are not designed for solar panel with rated input voltage up to 80V or 125V.

To sustain this high voltage for any range of low voltage ideal diode controller, a depletion MOSFET Q_d, as shown in Figure 3-2, is used to extent the reverse voltage range of the ideal diode controller. The drain of Q_d is connected to output VO+, source is connected to the cathode and gate is connected to the anode of the ideal diode controller. Now reverse voltage across cathode to anode is decided by the depletion MOS, while not limited by LM74610-Q1.

3.4 Working Principle of LM746x0-Q1 Reverse Voltage Range Extension

First of all, understand what is depletion MOSFET. Distinguishing from the common used enhanced MOSFET that normally turns ON with applying some voltage to the gate (i.g, $V_{GS} > V_{GS\ (th)}$ for N-channel MOSFET), a depletion mode MOSFET normally turns ON without applying any gate voltage, which means the MOSFET can turn on when $V_{GS} > 0$, $V_{GS} = 0$, or $V_{GS} < 0$. Because the depletion MOSFET is based on the enhanced MOSFET with positive ions being injected into the insulation layer of the FET. So there naturally exists a conductive channel.

For depleted N-channel MOSFET, the original positive ion field can only be offset once V_{GS} (negative value) is negatively increased further to reach the pinch-off mode at $V_{GS\ (OFF)}$, or is called $V_{GS\ (th)}$. Then the conductive channel can be closed.

Figure 3-3 shows the modes of operation with adding the depletion MOSFET Q_d to the existing ideal diode controller circuit.

When $V_{CATHODE} <= V_{ANODE}$, the normal operation that $V_{IN} >= V_{OUT}$. At this time, the bypass circuit of the solar power optimizer works. MOSFETs Q_1 and Q_d are turned ON, $V_{CATHODE} \cong V_{ANODE}$.

$V_{CATHODE} > V_{ANODE}$ during reverse polarity or reverse current protection operation that $V_{IN} < V_{OUT}$. At this time, the bypass circuit of the solar power optimizer does not operate. MOSFET Q_1 is turned off, MOSFET Q_d is in regulation mode as a source follower, maintaining $V_{CATHODE}$ above V_{ANODE}, $V_{CATHODE} = V_{IN(VANODE)}$+ Abs ($V_{GS\ (th)}$). So, voltage across $V_{CATHODE}$ to V_{ANODE} is within absolute maximum rating $V_{GS\ (th)}$ of Q_d (< 5V. typ) which is far less than the maximum reverse voltage $45V_{MAX}$ (transient) of LM74610-Q1. Now, the high reverse voltage ($V_{OUT} – V_{IN}$) is sustained by the drain-source voltage V_{DS} of Q_d.

How to choose the right depletion MOSFET mainly depends on two factors.

- Choose a V_{DS} rating of $Q_d \geq V_{IN(max)}$ (maximum peak input voltage).

- $R_{DS(on)}$ can be in the hundreds of ohms range (LM746x0-Q1 is floating gate drive architecture with large impedance of CATHODE pin to ground, $I_{CATHODE}$ of the controller is in µA range).

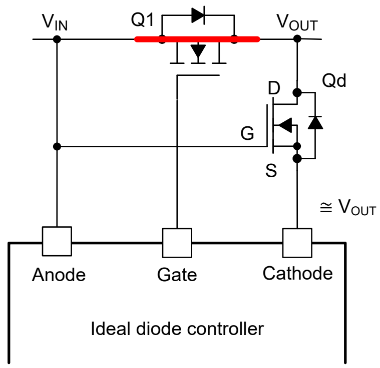


Figure 3-3. Modes of Operation With Adding Depletion MOSFET ($V_{CATHODE} \leq V_{ANODE}$)

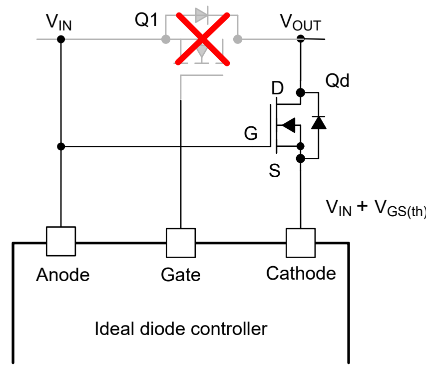


Figure 3-4. Modes of Operation With Adding Depletion MOSFET ($V_{CATHODE} > V_{ANODE}$)

Figure 3-5 and Figure 3-6 shows the simulation circuit and results of the bypass circuit with LM74610-Q1 and depletion MOSFET. From the simulation results, this can be seen that using depletion MOSFET is an effective method to extent the reverse voltage range of the current low voltage ideal diode controller, which solves the challenge of very large input voltage range of PV panel or string.

With this design, there also have system benefits to the solar power optimizer system as the following.

- Solve hot-spot issue due to very low power loss.
- Make solar equipment be safer, reduce the fire risk.
- Improve solar power generation efficiency.

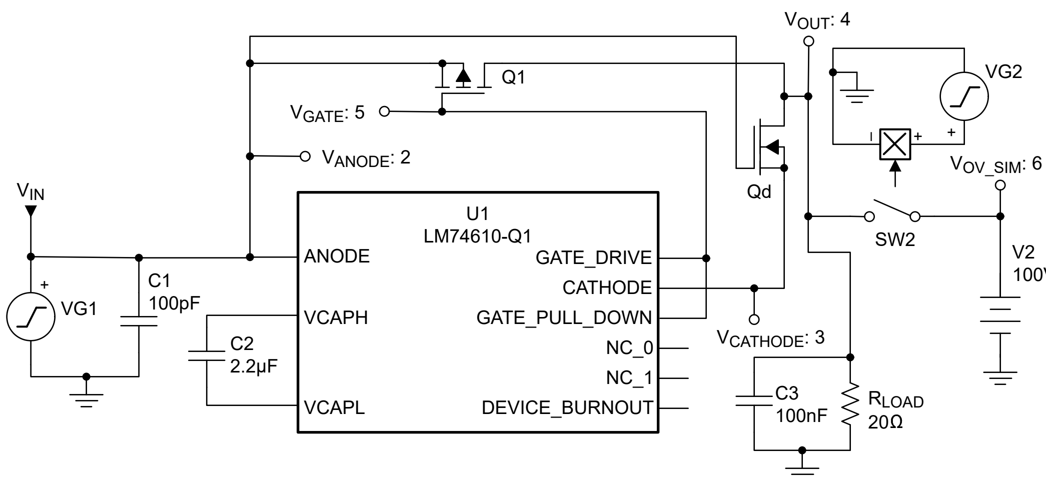


Figure 3-5. Simulation Circuit of the Bypass Circuit With LM74610-Q1 and Depletion MOSFET

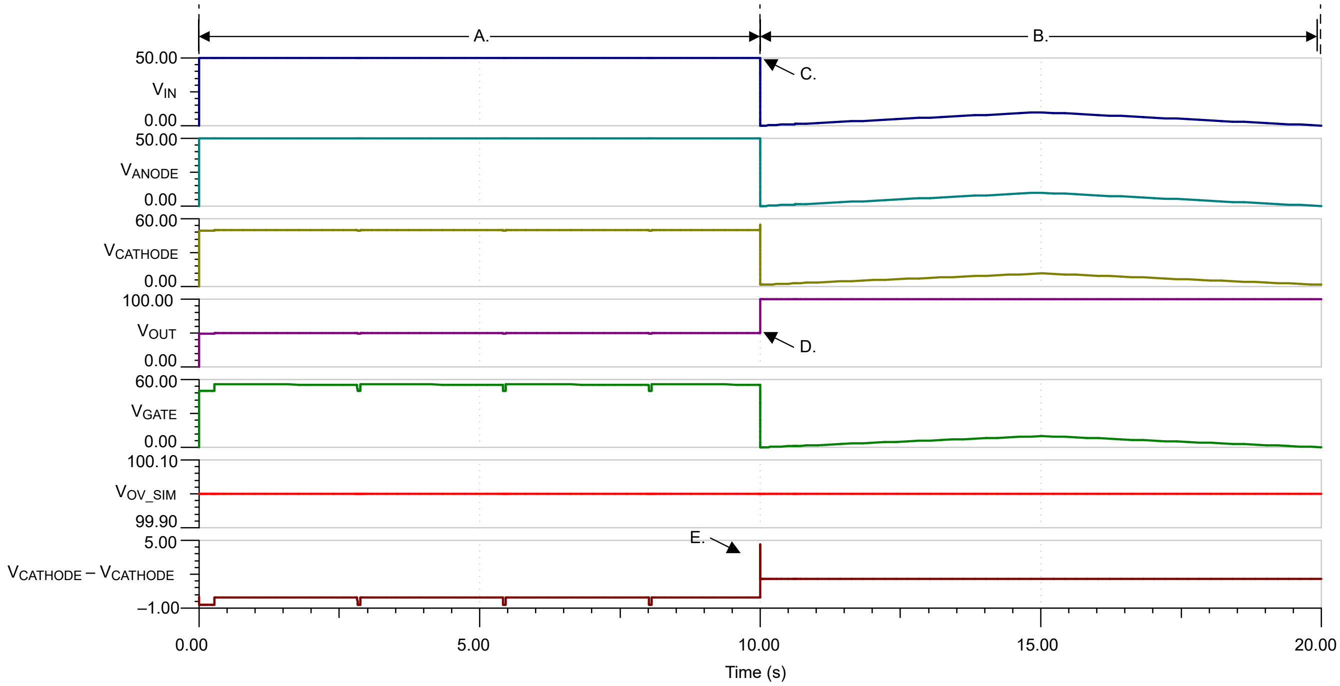


Figure 3-6. Simulation Results of the Bypass Circuit With LM74610-Q1 and Depletion MOSFET

Note

- Bypass circuit operational, $V_{IN} \geq V_{OUT}$
- Bypass circuit non-operational, $V_{IN} < V_{OUT}$
- Simulates input voltage variations
- Simulates high-transient voltage appears on V_{OUT} , generated by V_{OV_SIM} source
- Qd operates as source follower, maintaining $V_{CATHODE}–V_{ANODE} = |V_{GS(th)}| \cong 1.6V$

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4 Bench Test and Result

Figure 4-1 shows the LM74610-Q1 Bypass function application schematic with depletion MOSFET and Figure 4-2 shows the demo board top view with test modifications and setup.

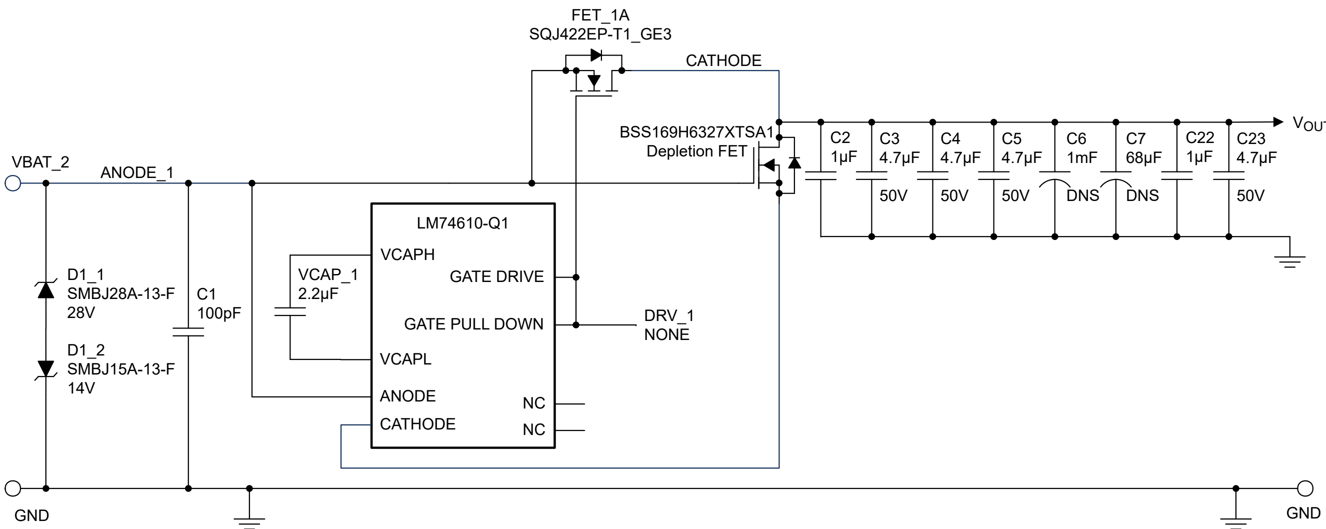

Figure 4-1. LM74610-Q1 Bypass Function Application Schematic With Depletion MOSFET

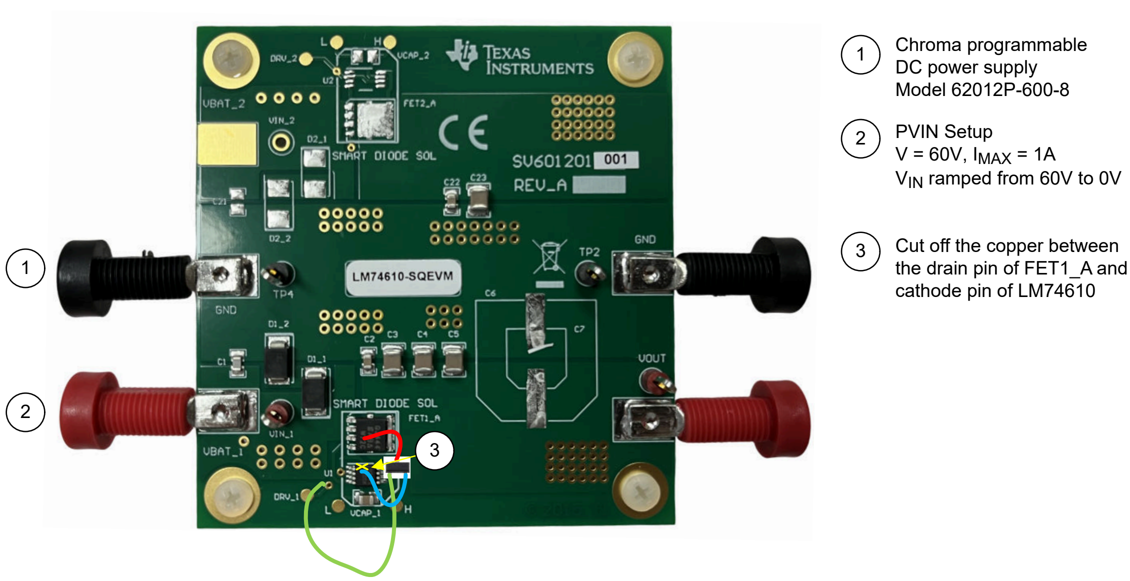

Figure 4-2. LM74610-Q1 Bypass Function Demo Board With Depletion MOSFET

Figure 4-3 shows test results for a 60V bypass switch design using the 40V LM74610-Q1 controller. With properly scaled MOSFETs (Q1 and QD), the input voltage range can extend to the VDS 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.

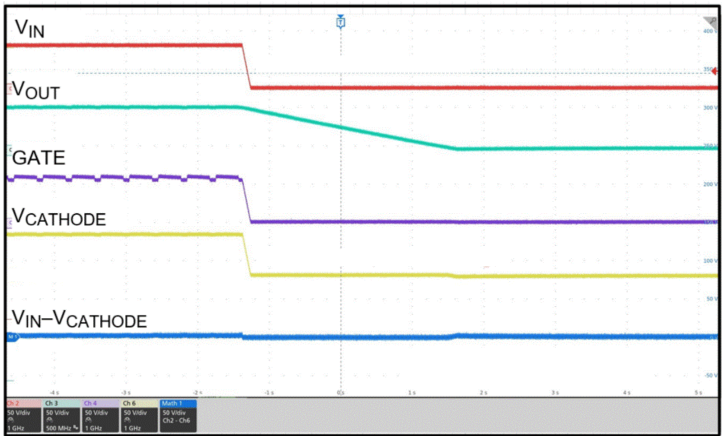

Figure 4-3. Test Result for a 60V Bypass Circuit with LM74610 and Depletion MOSFET

60V bypass

LM74610-Q1 with depletion MOSFET

V_{IN} ramped down from 60V to 0V

Device CATHODE pin follows (V_{IN} + V_{T_QD})

Effective V_{ANODE} –$V_{CATHODE}$ clamped to V_T of FET QD

5 Summary

If PV panels or solar equipment connected in a series are broken or faulty, having a design in place to avoid hot spotting and or voltage supply interruption is important. This responsibility commonly lies with the solar power optimizer or rapid shutdown. While standard rectifier diodes or Schottky diodes are the simplest design to bypass the broken panel, the diodes are not preferred given thermal inefficiency. This application note discusses a floating-gate ideal diode controller along with an N-channel MOSFET that can offer less stand-alone loss than a bypass switch design, and an additional system workaround with a depletion MOSFET that can offer a completely scalable design to address the wide input voltage range of PV panels (ranging from few volts to 150V) making this plug and play design for bypass switch application.

6 References

- Texas Instruments, *LM74610-Q1 Zero IQ Reverse Polarity Protection Smart Diode Controller*, data sheet.
- Sonoma County Permit Sonoma, *Solar Permits for Residential Rooftop Systems*
- El-Pro-Cus *What is Depletion Mode MOSFET: Working and Its Applications*

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