

Inverting Application for the LMZM23601 and LMZM23600

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Power Modules Applications

ABSTRACT

The LMZM23601 is a $3.8 \times 3 \text{ mm}^2$ 1-A rated synchronous step-down power module that features a wide operating input range from 4 V to 36 V with adjustable output voltage range from 2.5V to 15 V. The LMZM23601 can be configured in an inverting buck-boost (IBB) topology with the output voltage inverted or negative with respect to input voltage. This application report shows how the conventional non-inverting evaluation board for the LMZM23601 can be configured for an inverting application. This application note also provides the additional level-shifter circuitry for EN and PGOOD pin if the feature is required. The LMZM23600 is rated for 500 mA, is pin-to-pin compatible with the LMZM23601, and can be used if lower output current is required.

Contents

1	Inverting Buck-Boost Topology	2
2	Design Considerations	4
3	External Components	6
4	Typical Performance	7
5	Digital Pin Configurations	8
6	Conclusion	12
7	References	12

List of Figures

1	Converting From Buck to Inverting Buck Boost Topology.....	2
2	Recommended Maximum Output Current for LMZM23601	3
3	Recommended Maximum Output Current for LMZM23600	4
4	LMZM23601 Inverting Buck-Boost Schematic With Schottky Diode	5
5	SW Node Voltage During Start-Up	5
6	Efficiency vs Load Current at $V_{IN} = 24 \text{ V}$	7
7	Load Regulation at $V_{IN} = 24 \text{ V}$	7
8	Start-up on $V_{IN} = 24 \text{ V}$, $V_{OUT} = -12 \text{ V}$ With 600-mA Load.....	7
9	Shutdown on $V_{IN} = 24 \text{ V}$, $V_{OUT} = -12 \text{ V}$ With 600-mA Load	7
10	Load Transient Response, 0 mA to 600 mA With $V_{IN} = 24 \text{ V}$, $V_{OUT} = -12 \text{ V}$	7
11	Output Voltage Ripple, $V_{IN} = 24 \text{ V}$, $V_{OUT} = -12 \text{ V}$, $I_{OUT} = 600 \text{ mA}$	7
12	EN Pin Level Shifter	8
13	EN Pin Level Shifter on Start-Up	9
14	EN Pin Level Shifter on Shutdown	9
15	PG Pin Level Shifter	10
16	PG Pin Level Shifter on Start-Up.....	11
17	PG Pin Level Shifter on Shutdown.....	11

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1 Inverting Buck-Boost Topology

1.1 Concept

In a standard buck configuration the positive connection (V_{OUT}) is connected to the internal inductor, and the return connection is connected to the device ground.

In the IBB configuration, SYS_GND is connected to device V_{OUT} and the device return is now the negative output voltage (nV_{out}). This shift in topology allows the output voltage to be inverted with respect to the input voltage.

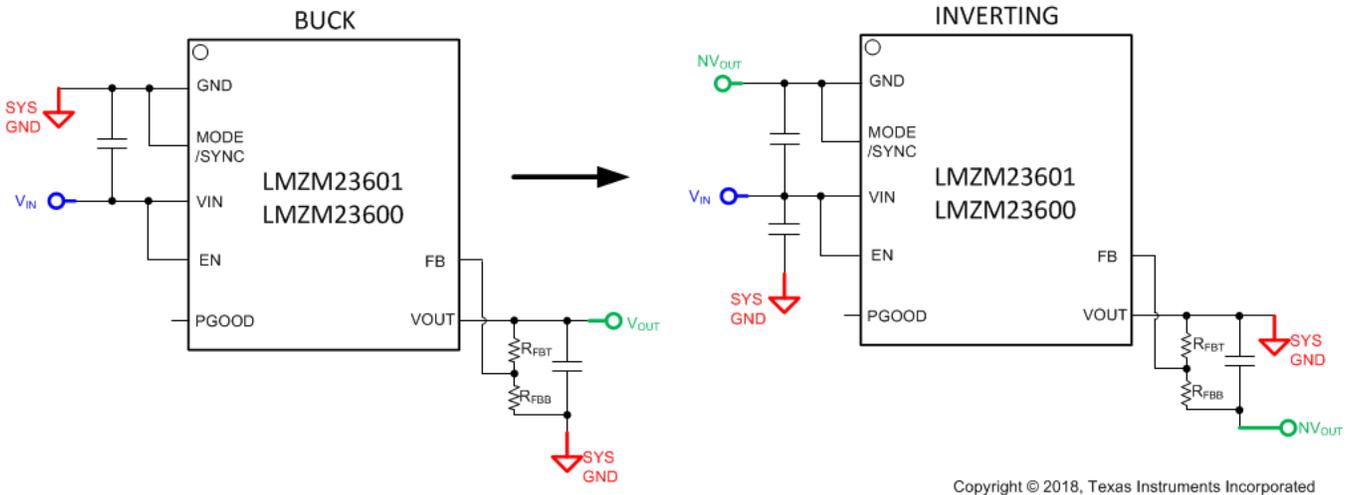


Figure 1. Converting From Buck to Inverting Buck Boost Topology

1.2 Output Current Calculations

By changing the buck configuration into an IBB configuration, the average inductor current is affected. The output current capability in the IBB topology is less than the buck configuration. The maximum achievable current is calculated by the following:

$$I_{OUT} (IBB) = I_{L,max} \times (1 - D)$$

- $I_{L,max}$ is the maximum rated inductor current
- D is the operating duty cycle

(1)

The operating duty cycle for an inverting buck-boost converter can be found with [Equation 2](#):

$$D = \frac{V_{out}}{V_{out} - V_{in} * \eta}$$
(2)

NOTE: V_{OUT} in [Equation 2](#) is represented with a negative value.

The efficiency term in [Equation 2](#) adjusts the equations in this section for power conversion losses and yields a more accurate maximum output current result. Given that the IBB configuration yields an efficiency range of 70% to 85%, the conservative value of 70% is used for calculating the duty cycle. Use [Equation 1](#) and [Equation 2](#) to calculate the recommended maximum output current. For example a 24-V input voltage, -12-V output voltage system, the duty cycle is:

$$D = \frac{-12}{-12V - 24 * 0.7} = 0.4166$$
(3)

The result of Equation 3 is then used to calculate the maximum achievable output current:

$$I_{OUT} (IBB) = 1 \times (1 - 0.4166) = 0.58 \text{ A} \quad (4)$$

Table 1 and Table 2 provides a general idea of the maximum output current allowed from the modified LMZM23601 and LMZM23600.

Table 1. Maximum Output Current Calculation for LMZM23601

V _{OUT} (V)	V _{IN} (V)	I _{L_max} (A)	η	D	I _{OUT} (A)
-2.5	24	1	0.7	0.135	0.87
-3.3	24	1	0.7	0.173	0.83
-5	24	1	0.7	0.246	0.77
-12	24	1	0.7	0.476	0.58

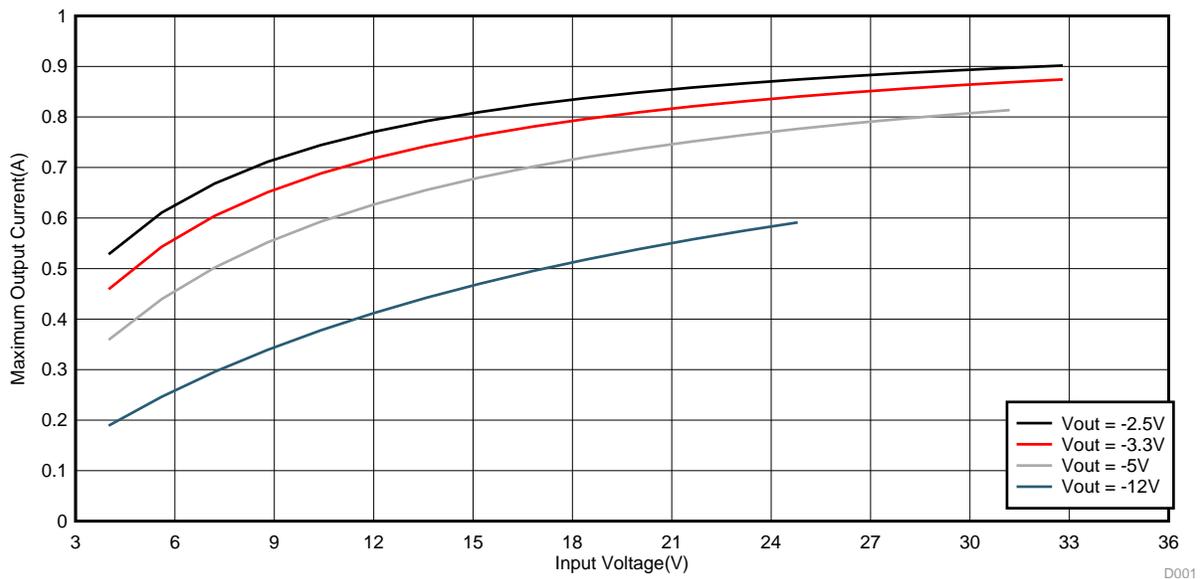


Figure 2. Recommended Maximum Output Current for LMZM23601

Table 2. Maximum Output Current Calculation for LMZM23600

V _{OUT} (V)	V _{IN} (V)	I _{L_max} (A)	η	D	I _{OUT} (A)
-2.5	24	0.5	0.70	0.135	0.43
-3.3	24	0.5	0.70	0.173	0.41
-5	24	0.5	0.70	0.246	0.38
-12	24	0.5	0.70	0.549	0.29

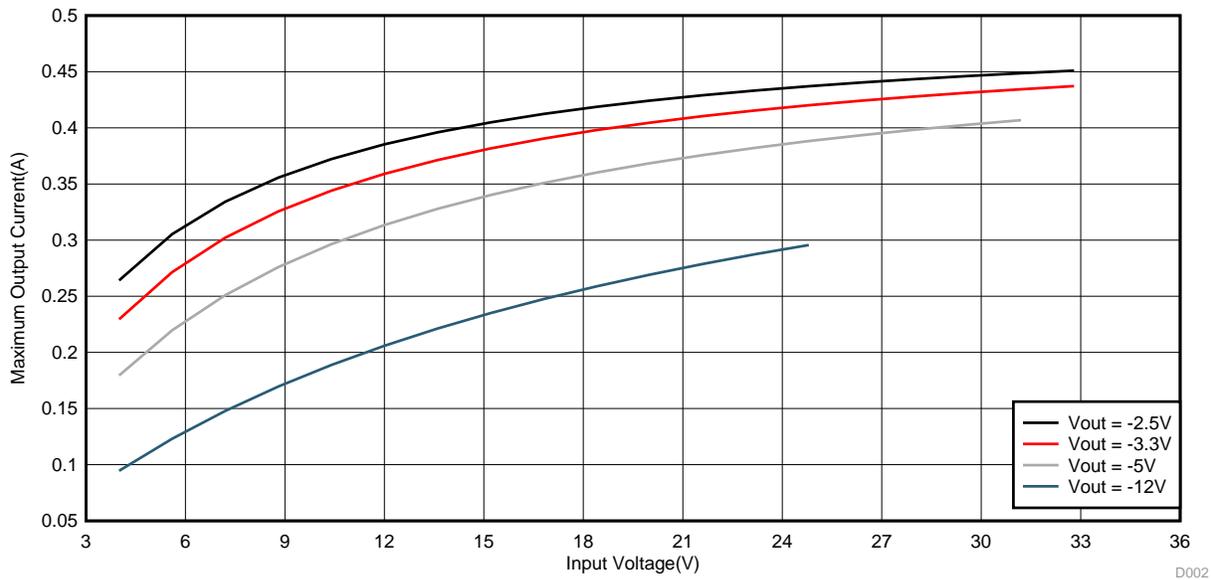


Figure 3. Recommended Maximum Output Current for LMZM23600

1.3 V_{IN} and V_{OUT} Range In Inverting Configuration

When configured in an IBB topology, the input voltage across the module is V_{IN} to V_{OUT} effectively limiting the input voltage range. The LMZM23601 has an input voltage range from 4 V to $36 + V_{OUT}$, where V_{OUT} is a negative value. For example, for an output voltage of -12 V the maximum input voltage is 24 V. A minimum input voltage of 4 V is required to ensure the device is above UVLO threshold. The output voltage range in this topology is -2.5 V to -15 V.

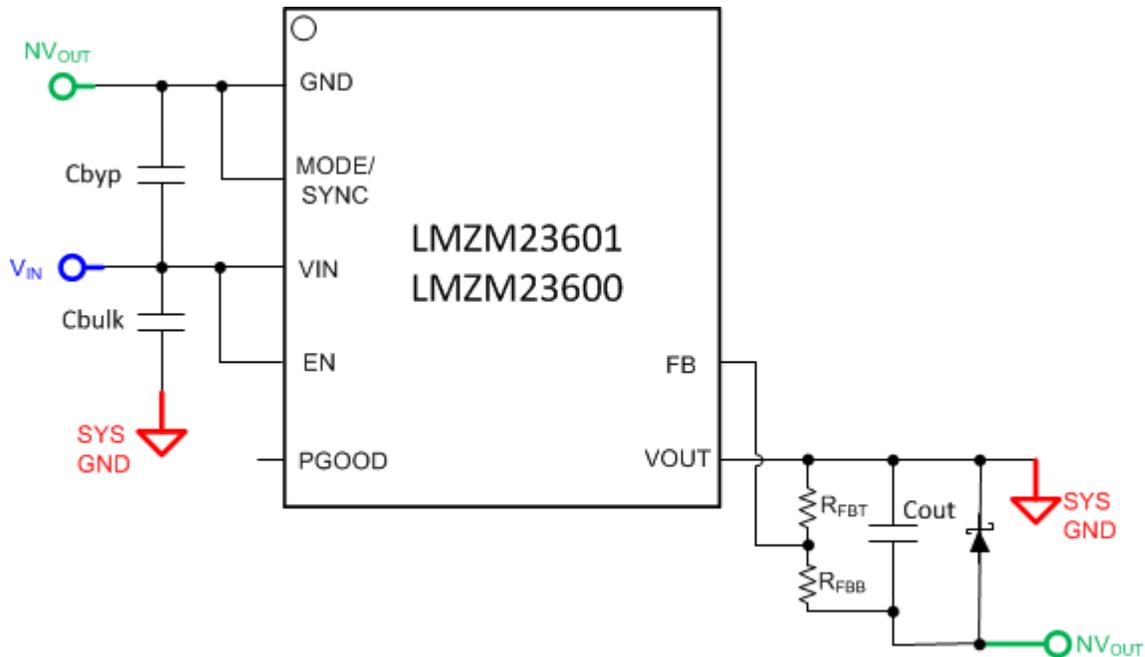
2 Design Considerations

2.1 Additional Bypass Capacitor and Schottky Diode

Use a ceramic bypass capacitor, C_{BYP} , with a minimum capacitance of 10 μ F. The voltage rating must be taken into consideration because this capacitor will experience stress equal to the full voltage range between V_{IN} and V_{OUT} .

Consider that the inclusion of the C_{BYP} capacitor introduces an AC path from V_{IN} to V_{OUT} and might worsen the transient response. When V_{IN} is applied to the circuit, this dV/dt across the bypass capacitor creates a current that must return to ground to complete the loop. This current might flow through the internal low-side body diode of the MOSFET and the inductor to return to ground. For this case, TI recommends having a Schottky diode between V_{OUT} and GND. If large line transients are expected, increase the output capacitance to keep the output voltage within acceptable levels.

Also note that in order for the system to be stable, there must be an input power supply capacitor to help dampen the high-frequency noise that can couple onto the circuit. An electrolytic capacitor with moderate ESR helps dampen any input supply ringing caused by long power leads. When using the LMZM23601EVM, C_{BULK} capacitor should be added across V_{IN} and SYS_GND.



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Figure 4. LMZM23601 Inverting Buck-Boost Schematic With Schottky Diode

2.2 Start-up Behavior and Switching Node Consideration

The voltage on the SW pin switches from V_{IN} to V_{OUT} in an inverting topology instead of from V_{IN} to GND in a buck topology. When the high-side MOSFET turns on, the SW node sees the input voltage. When the low-side MOSFET turns on, the SW node detects the device return, which is the output voltage. During start-up, V_{IN} rises to achieve the desired input voltage. V_{OUT} starts ramping down after the EN pin voltage exceeds its threshold level and V_{IN} exceeds its UVLO threshold. As V_{OUT} continues to ramp down, the SW node low level follows it down. Figure 5 shows the resulting normal and smooth start-up of the output voltage.

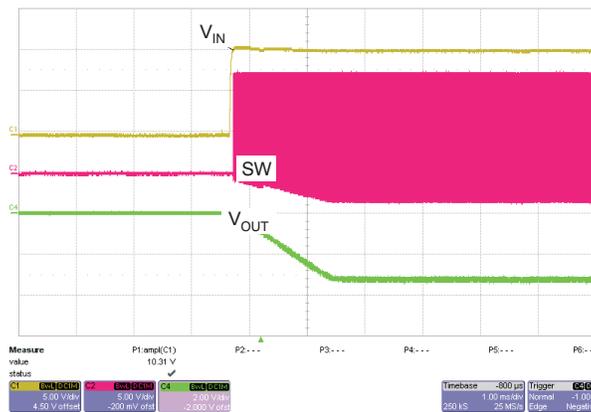


Figure 5. SW Node Voltage During Start-Up

3 External Components

The LMZM23601 power module integrates power MOSFETs and shielded inductor. As a result, this application only requires as few as four external components. Performing a load-transient test and frequency sweep is recommended to evaluate stability.

3.1 Capacitor Selection

Ceramic capacitors with low equivalent series resistance (ESR) are recommended to achieve low output voltage ripple. X5R- or X7R-type dielectrics are recommended for the stable capacitance versus temperature characteristics and DC bias. The higher the DC voltage applied to the capacitor, the less the effective capacitance. Use a minimum of 10- μ F capacitance for both C_{BYP} and C_{IN} . Making this capacitor value too large can prevent proper start-up operations. Refer to [Table 4](#) for minimum and maximum output capacitance. Evaluating the Bode plot of the circuit under normal operation can provide insight on the stability of the system.

3.2 System Loop Stability

Stability is an important factor in the system when adding more output capacitance. The general rule of thumb for a stable design is a desired phase margin (PM) of at least 45°. In extreme conditions too much output capacitance added to the system result in a lowered bandwidth and PM least than 45°. The table below shows the PM for each output voltage selection measured from the original BOM ($C_{OUT} = 22 \mu\text{F} + 47 \mu\text{F}$) of the LMZM23601. For the LMZM23600 design, TI recommends running a Bode plot with all ceramic capacitors to ensure stability.

Table 3. Phase Margin of IBB LMZM23601

V_{IN} (V)	V_{OUT} (V)	I_{OUT} (A)	$F_{crossover}$ (kHz)	PM (°)
24	-2.5	0.86	44.34	56.8
24	-3.3	0.84	36.1	59.7
24	-5	0.78	29.02	58.3
24	-12	0.550	20.9	55.8

Additionally too much output capacitance can falsely trigger hiccup mode in the LMZM23601. After start-up hiccup mode is a feature in the LMZM23601 that protects the device against output short circuit conditions. In this mode the high-side and low-side MOSFETs power off and wait for a fixed hiccup time interval before restarting the device operation. Larger output capacitance results in longer charge time of the capacitors to the desired output voltage. The device can see this as a false short circuit condition and trigger hiccup mode. [Table 4](#) shows the maximum output capacitance recommended for the LMZM23601 in IBB topology. Note that the output capacitance listed takes DC bias effects into account for each output voltage.

Table 4. Recommended Output Capacitance for Stability and Startup

V_{IN} (V)	V_{OUT} (V)	I_{OUT} (A)	C_{OUT_MIN} (μ F)	C_{OUT_MAX} (μ F)
24	-2.5	0.86	22	350
24	-3.3	0.84	16	235
24	-5	0.78	10	150
24	-12	0.6	10	50

4 Typical Performance

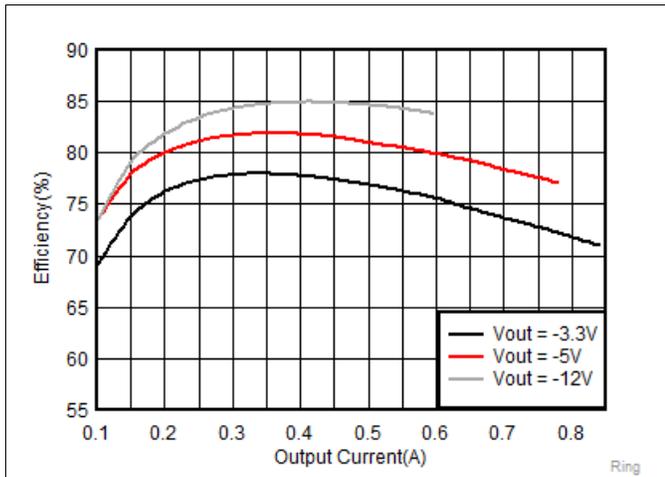


Figure 6. Efficiency vs Load Current at $V_{IN} = 24\text{ V}$

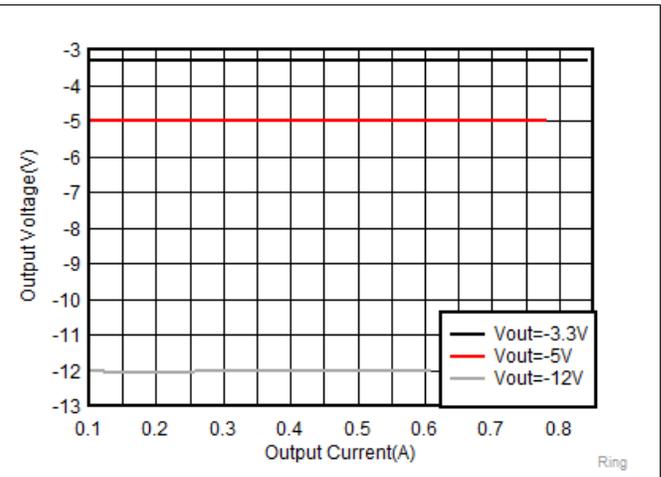


Figure 7. Load Regulation at $V_{IN} = 24\text{ V}$

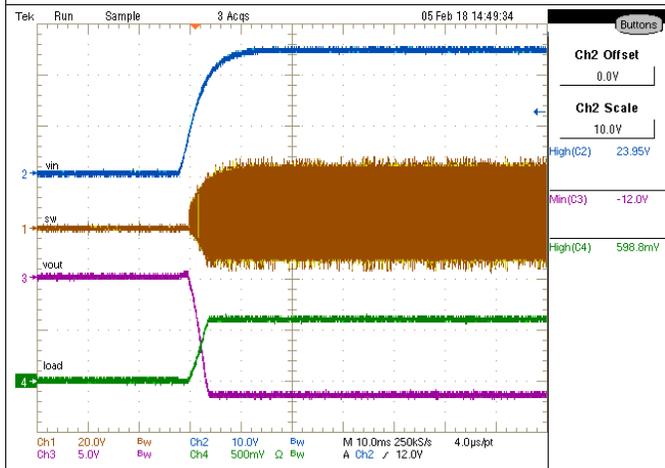


Figure 8. Start-up on $V_{IN} = 24\text{ V}$, $V_{OUT} = -12\text{ V}$ With 600-mA Load

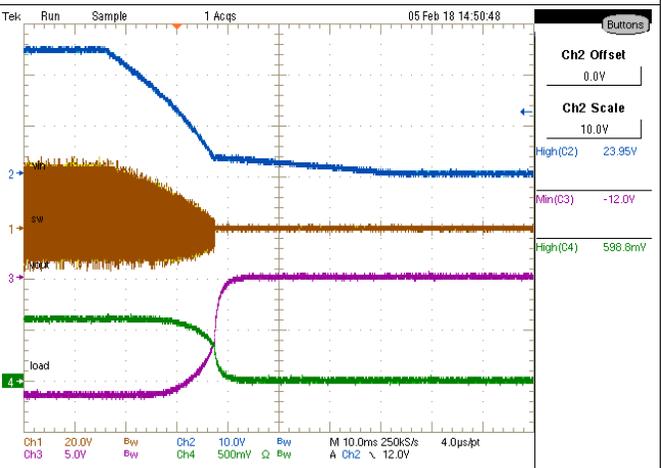


Figure 9. Shutdown on $V_{IN} = 24\text{ V}$, $V_{OUT} = -12\text{ V}$ With 600-mA Load

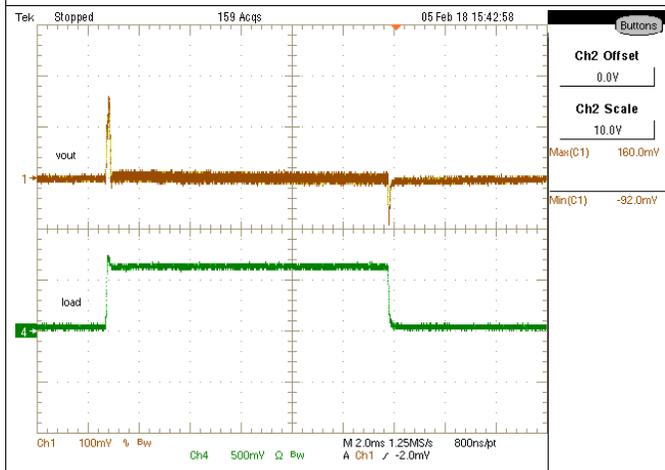


Figure 10. Load Transient Response, 0 mA to 600 mA With $V_{IN} = 24\text{ V}$, $V_{OUT} = -12\text{ V}$

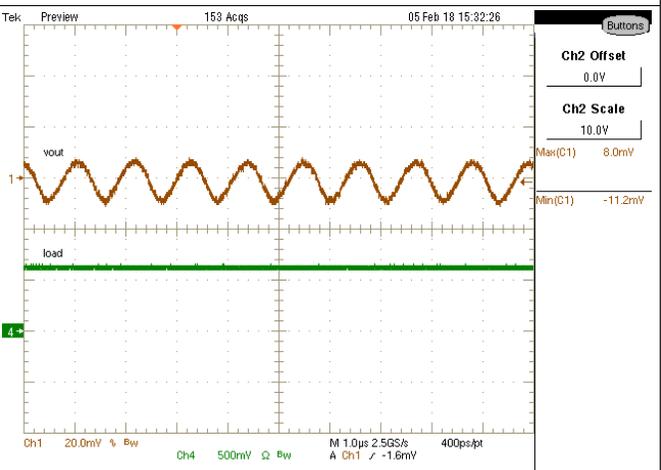


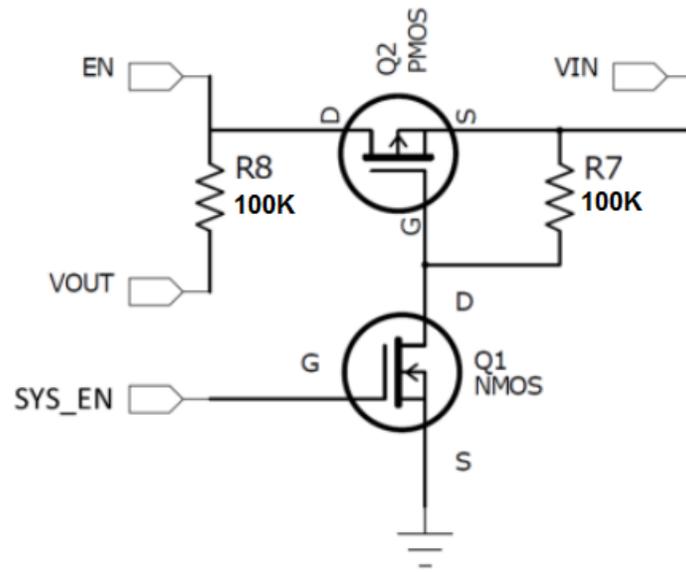
Figure 11. Output Voltage Ripple, $V_{IN} = 24\text{ V}$, $V_{OUT} = -12\text{ V}$, $I_{OUT} = 600\text{ mA}$

5 Digital Pin Configurations

5.1 Digital Input Pin (EN)

Because the EN pin is referenced to V_{OUT} instead of 0 V, the EN voltage that turns the module on is affected. In a buck configuration, the specified typical threshold voltage for the EN pin with respect to IC return to be considered high is 1.9 V and 1.15 V is considered low. In the inverting buck-boost configuration, however, the V_{OUT} voltage is the reference; therefore, the high threshold is $1.9\text{ V} + V_{OUT}$, and the low threshold is $1.15\text{ V} + V_{OUT}$. For example, if $V_{OUT} = -12\text{ V}$, V_{EN} is considered a high for voltages above -10.1 V and a low for voltages below -10.85 V when V_{OUT} is up and running.

This behavior can cause difficulties enabling or disabling the part, because in some applications the IC providing the EN signal may not be able to produce negative voltages. The level shifter alleviates any problems associated with the offset EN threshold voltages by eliminating the need for negative EN signals.



VOUT is the negative output voltage of the inverting buck-boost converter

Figure 12. EN Pin Level Shifter

The positive signal (SYS_EN) that originally drove EN is instead tied to the gate of Q1 (SYS_EN). When Q1 is off (SYS_EN grounded), Q2 detects 0 V across its V_{GS} and also remains off. In this state, the EN pin detects V_{OUT} , which is below the low level threshold and disables the device.

When SYS_EN provides enough positive voltage to turn Q1 on (minimum V_{GS} as specified in the data sheet of the MOSFET), the gate of Q2 is pulled low through Q1. This drives the V_{GS} of Q2 negative and turns Q2 on. As a consequence, V_{IN} ties to EN through Q2, and the pin is above the high level threshold, causing the device to turn on. Ensure that the V_{GD} of Q2 remains within the ratings of the MOSFET ratings during both enabled and disabled states. Also ensure that V_{GS} and V_{DS} ratings are not exceeded. Failing to adhere to these constraint can result in damaged MOSFETs.

The SYS_EN signal activates the enable circuit, and the G/D NODE signal represents the shared node between Q1 and Q2. The EN signal is the output of the circuit and goes from VIN to $-V_{OUT}$ properly enabling and disabling the device.

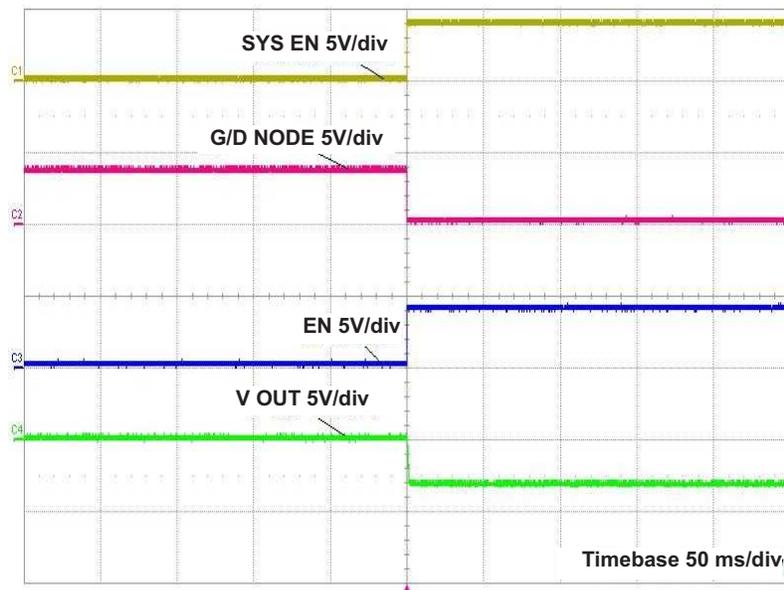


Figure 13. EN Pin Level Shifter on Start-Up

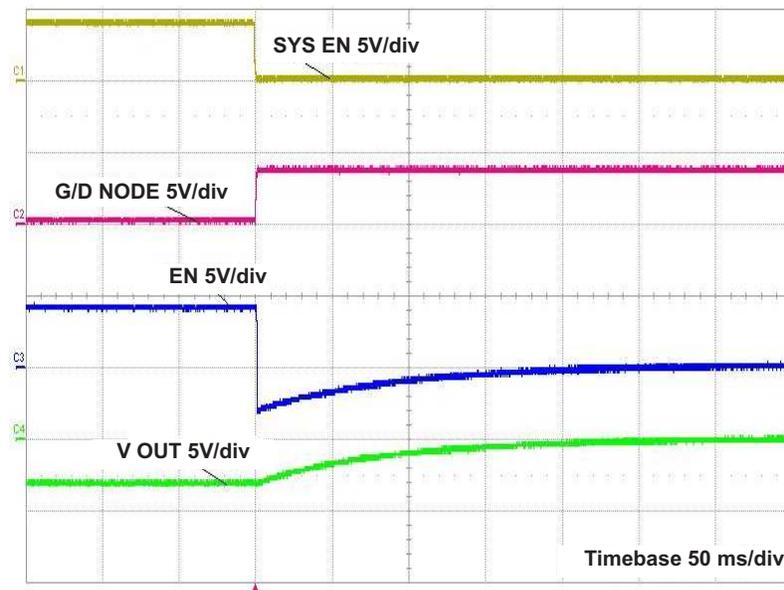


Figure 14. EN Pin Level Shifter on Shutdown

5.2 Power-Good Pin

The LMZM23601 has a built-in power-good (PG) function to indicate whether the output voltage has reached its appropriate level or not. The PG pin is an open-drain output that requires a pullup resistor. Because V_{OUT} is the IC return in this configuration, the PG pin is referenced to V_{OUT} instead of ground, which means that the device pulls PG to V_{OUT} when it is low.

This behavior can cause difficulties in reading the state of the PG pin, because in some applications the IC detecting the polarity of the PG pin may not be able to withstand negative voltages. The level shifter circuit alleviates any difficulties associated with the offset PG pin voltages by eliminating the negative output signals of the PG pin. If the PG pin functionality is not needed, it may be left floating or connected to V_{OUT} without this circuit. Note that to avoid violating its absolute maximum rating, the PG pin must not be driven more than 12 V above the negative output voltage (IC return).

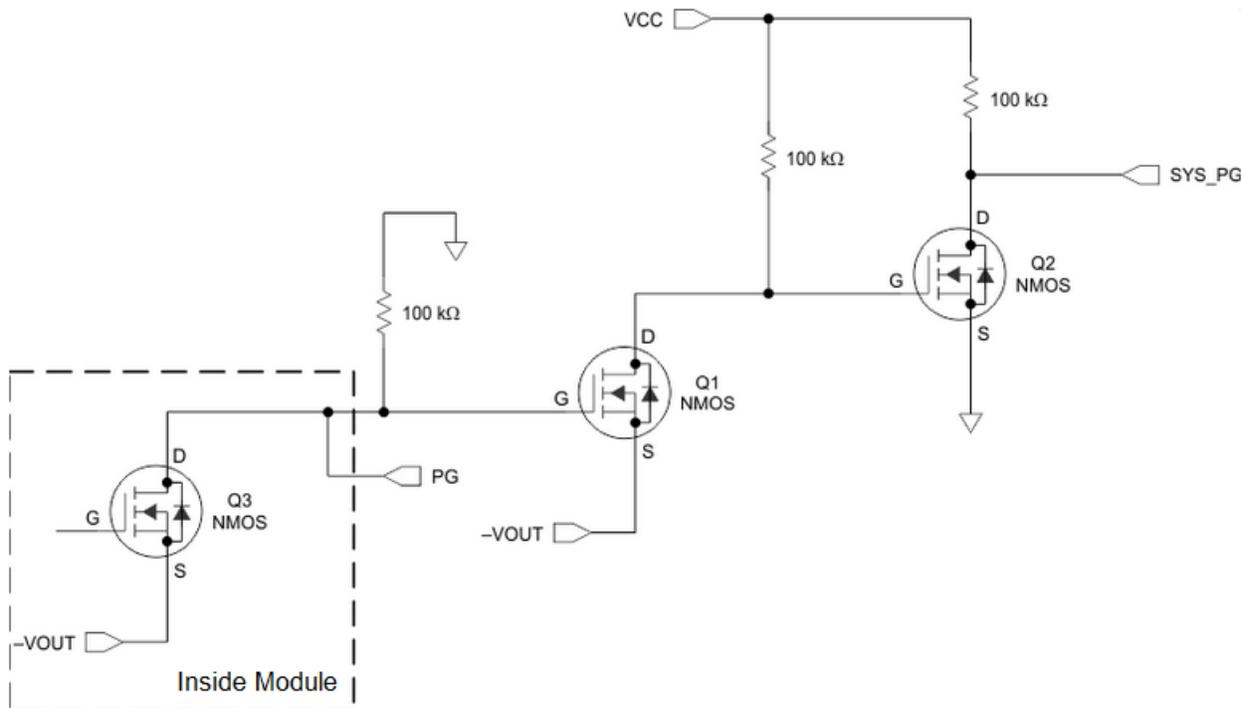
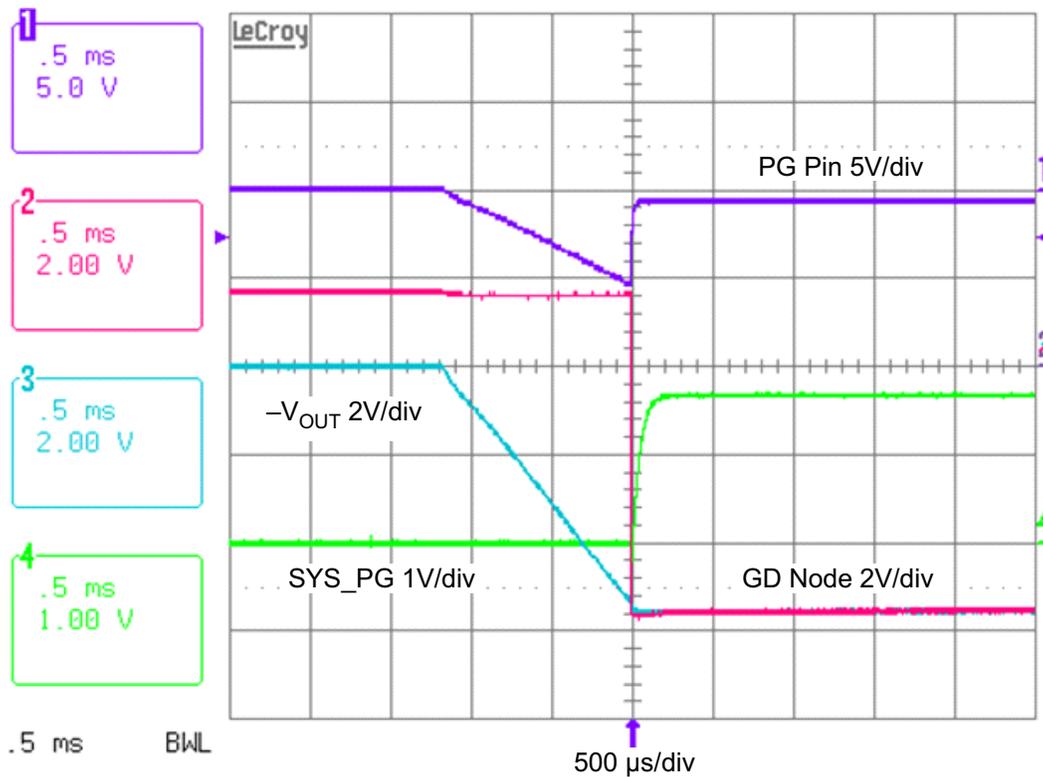


Figure 15. PG Pin Level Shifter

Inside these devices, the PG pin is connected to an N-channel MOSFET (Q3). By tying the PG pin to the gate of Q1, when the PG pin is pulled low, Q1 is off and Q2 is on because its V_{GS} detects V_{CC} . SYS_PG is then pulled to ground.

When Q3 turns off, the gate of Q1 is pulled to ground potential turning it on. This pulls the gate of Q2 below ground, turning it off. SYS_PG is then pulled up to the V_{CC} voltage. Note that the V_{CC} voltage must be at an appropriate logic level for the circuitry connected to the SYS_PG net.

This PG pin level shifter sequence is illustrated in [Figure 16](#) and [Figure 17](#). The PG signal activates the PG pin level shifter circuit, and the GD Node signal represents the shared node between Q1 and Q2. This circuit was tested with a V_{CC} of 1.8 V and FemtoFET CSD15830F3. The SYS_PG net is the output of the circuit that transitions between ground and 1.8 V and is easily read by a separate device.



Note that the PG pin is with respect to system return.

Figure 16. PG Pin Level Shifter on Start-Up

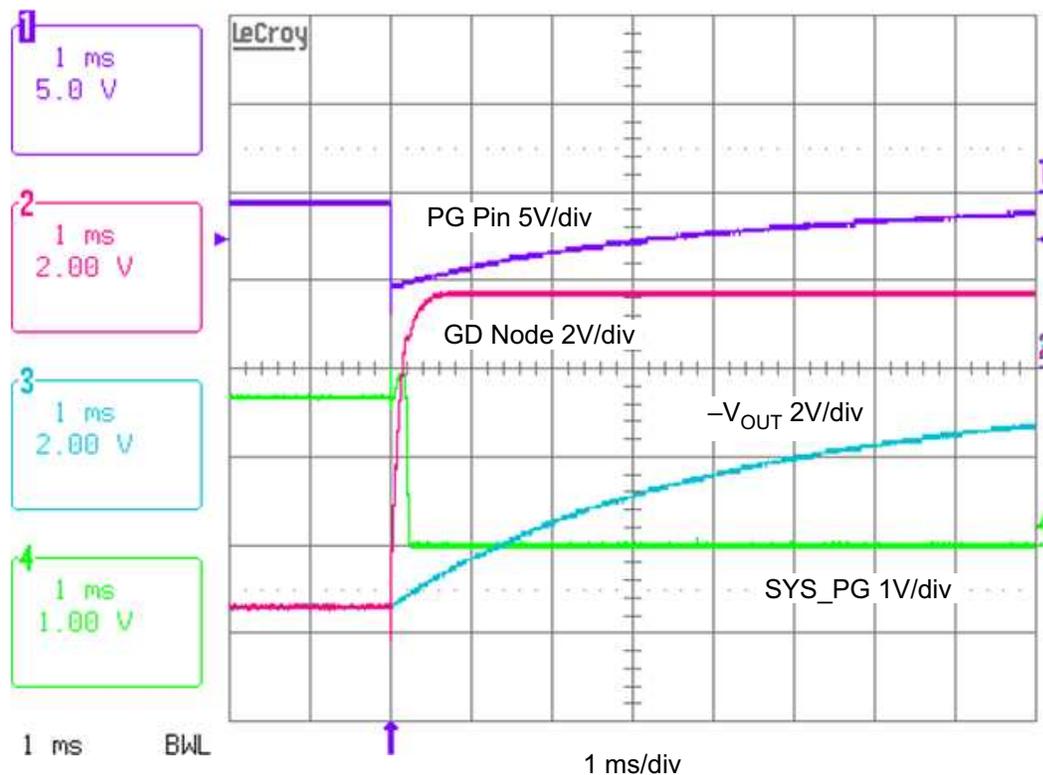


Figure 17. PG Pin Level Shifter on Shutdown

6 Conclusion

The LMZM23601 step-down power module can be configured in an IBB topology to generate a negative output voltage by switching the output and ground connection. The input voltage range is lowered because the device now has a reference point set to the negative output voltage rather than ground. Additionally, the inductor peak current is much higher effectively lowering the recommended maximum output current operating range. Converting an original buck topology into an IBB topology will result in a lowered input voltage range and maximum output current. This application report explains the IBB topology and how to select the proper external components to keep the system stable. Data from the test circuit are measured and provided.

7 References

The following documents are available for download from the [TI web site](#):

1. [Create an Inverting Power Supply From a Step-Down Regulator](#) .
2. [LMZM23601 36-V, 1-A Step-Down DC-DC Nano Module](#)
3. [Using a buck converter in an inverting buck-boost topology](#)
4. [Using the TPS5430 as an Inverting Buck-Boost Converter](#)
5. [Inverting Application for the LMZM33602 and LMZM33603](#)

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (February 2018) to A Revision	Page
• Updated duty cycle equation.....	2
• Updated duty cycle calculation	2
• Updated Table 1	3
• Updated Table 2.....	3

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