designfeature *By Robert Bell, National Semiconductor Corp*

VARIOUS ISOLATED DESIGN APPROACHES HAVE THEIR OPTIONS, DIFFICULTIES, AND TRADE-OFFS. AN IMPORTANT DESIGN DECISION IS WHETHER TO USE THE PRIMARY-SIDE GROUND OR THE SECONDARY-SIDE GROUND AS THE CONTROLLER'S REFERENCE.

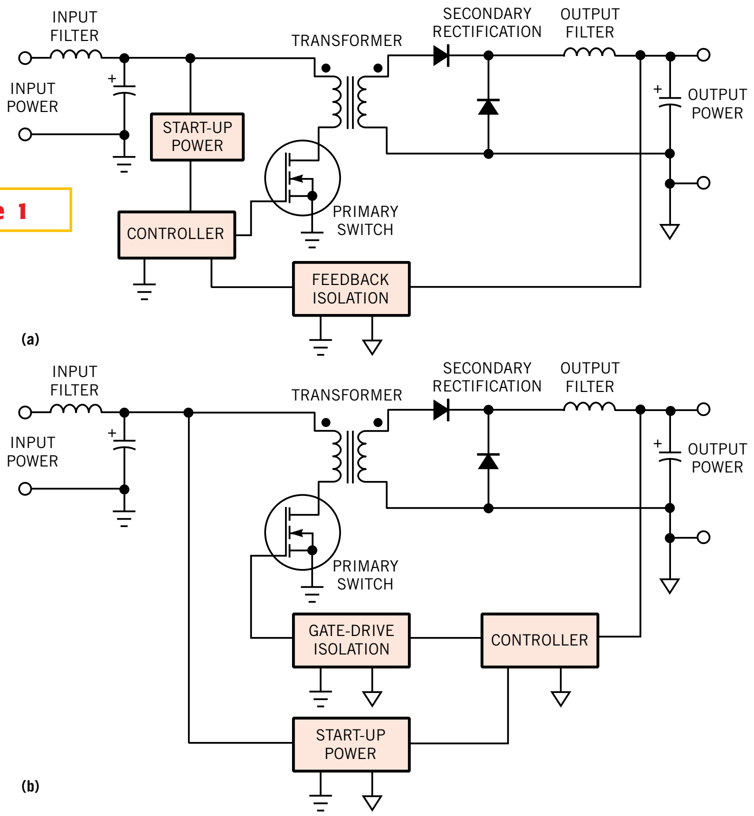
Crossing the boundary: strategies for feedback across an isolation barrier

Designers often categorize power converters into two basic types: isolated and nonisolated. These categories refer to the relationship between the input power ground and the output power ground. Many applications require isolation between the two grounds. The isolation requirement often stems from various safety agencies, and the main purpose of isolation is to protect personnel from exposure to dangerous voltage levels. In some cases, the grounds must have sufficient isolation so that applying a potential of 1500V or more between them shows no indication of breakdown. The specification that quantifies this isolation requirement is a small leakage current. An isolated power-converter design imposes several extra design challenges on a power-supply designer. Transmitting power or feedback information from one ground reference to the other is often referred to as "crossing the boundary."

Given that there are two separate grounds, the first design task is to assign the input- or output-ground reference to particular circuits. All switching power converters include an input filter, an output filter, a transformer, a primary-side switching element, a secondary-side rectification element, and a controller circuit. The center of the converter is some type of controller. The reference for the controller can be either the primary- or the secondary-side ground (**Figure 1**). This decision determines most of the basic configuration.

Of the two types, the primary-side-referenced controller configuration is less complex and the

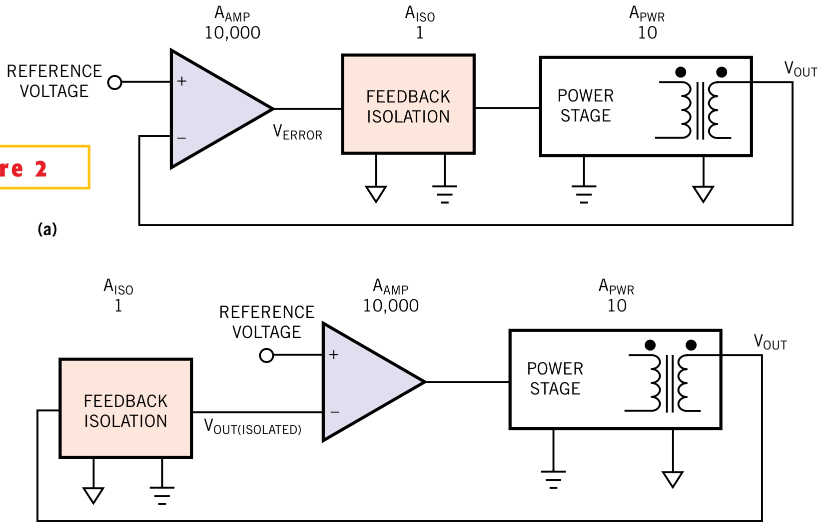
Figure 1



The reference for the controller can be the primary-side ground (a) or the secondary-side ground (b).

most common configuration. Both configurations generally use a scheme that derives bias power for the controller from a start-up circuit and then derives a more efficient bias power from an auxiliary winding during normal operation. The efficiency is high because the auxiliary winding steps down the bias power from the transformer.

Figure 2

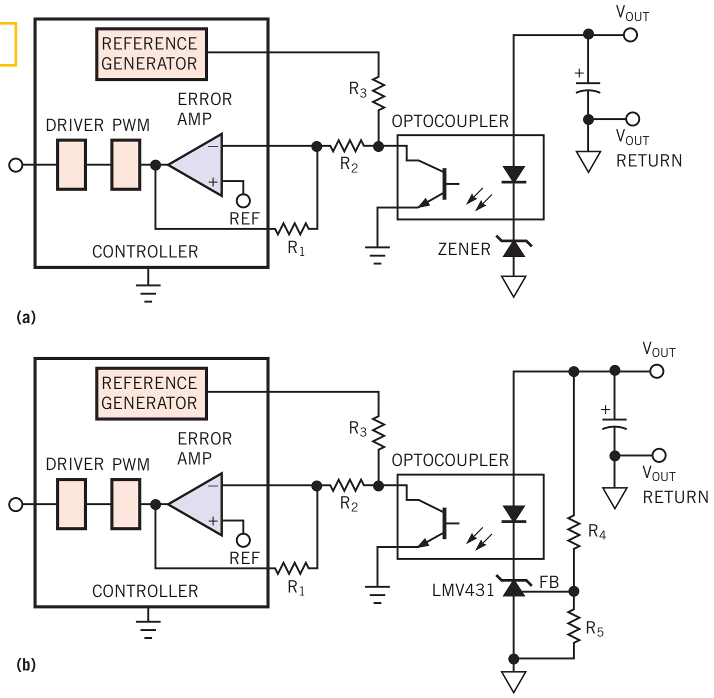


For a power converter with the error amplifier on the secondary side, the static error of the output voltage, assuming an ideal reference and no offsets, is simply equal to $1/(A_{AMP} \times A_{ISO} \times A_{PWR})$ (a). For a power converter with the error amplifier and reference on the primary side and an isolated copy of the output voltage crossing the boundary, the isolation amplifier is part of the feedback network and not part of the forward gain (b).

PRIMARY-SIDE CONTROL

The problem with the secondary-side-referenced controller is that the circuit must derive bias power from the primary-side power—the opposite ground in this case—on initial power-up. You can overcome this problem in one of two ways. You can add a separate isolated bias power supply to supply the few hundred milliwatts necessary for the secondary-side controller. This bias supply can run all the time because it is more efficient than a linear start-up regulator. The separate-bias-supply approach adds complexity but ensures an orderly start-up under all starting conditions. The second approach to derive bias power for the secondary controller is to design a scheme that causes the main primary-side switching FET to start switching immediately at power-up in a somewhat-controlled manner. As the switching commences, the auxiliary winding starts to provide the required bias power to the controller, which then takes control of the main switching FET. This approach of blindly starting the main switching FET can have problems with overshoots, short circuits, and excessive loading conditions.

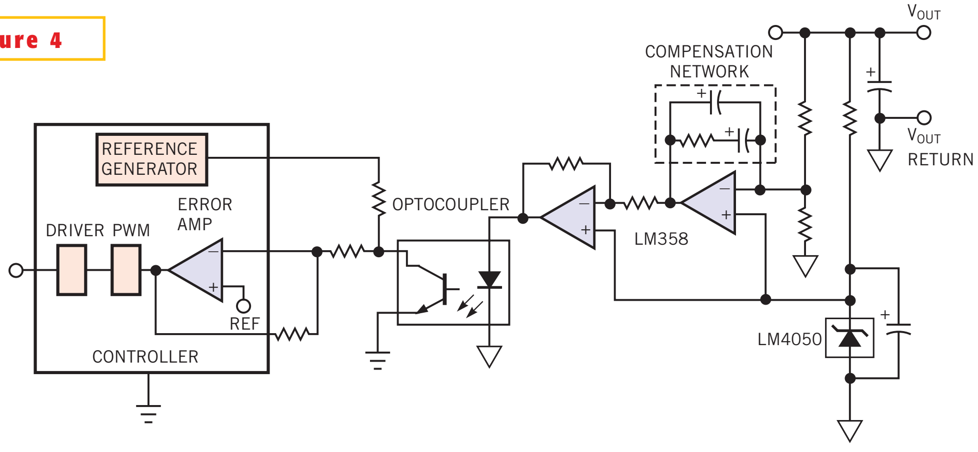
Figure 3



A simple approach to deriving the error signal uses a zener diode and an optocoupler (a). Replacing the zener diode with an LMV431 shunt regulator improves accuracy (b).

You might well ask, then, why a designer would ever want to configure a converter with a secondary-side-referenced controller. In **Figure 1a**, an isolated feedback signal must cross from the primary ground to the secondary ground. This feedback uses few components but always suffers from some quantity of phase delay. This delay limits the achievable bandwidth and ultimately the transient response of the converter. Removing the need for the optocoupler that isolates the feedback signal ultimately increases the converter reliability; the characteristics of these devices tend to shift with age and temperature. Many converters today use FETs instead of diodes as a means of secondary rectification, known as synchronous rectification. These synchronous FETs require a control-gate drive. With the controller on the secondary-side ground, the controller can now directly drive the synchronous FETs. This situation can lead to optimized control timing, because the controller can adapt the timing due to operating conditions and directly control the FET gates. Thus, a secondary-side-controller scheme is more complex but can perform better than can a primary-side-referenced controller.

Figure 4



A dual op amp optimizes the loop compensation and ensures the proper polarity of the feedback signal.

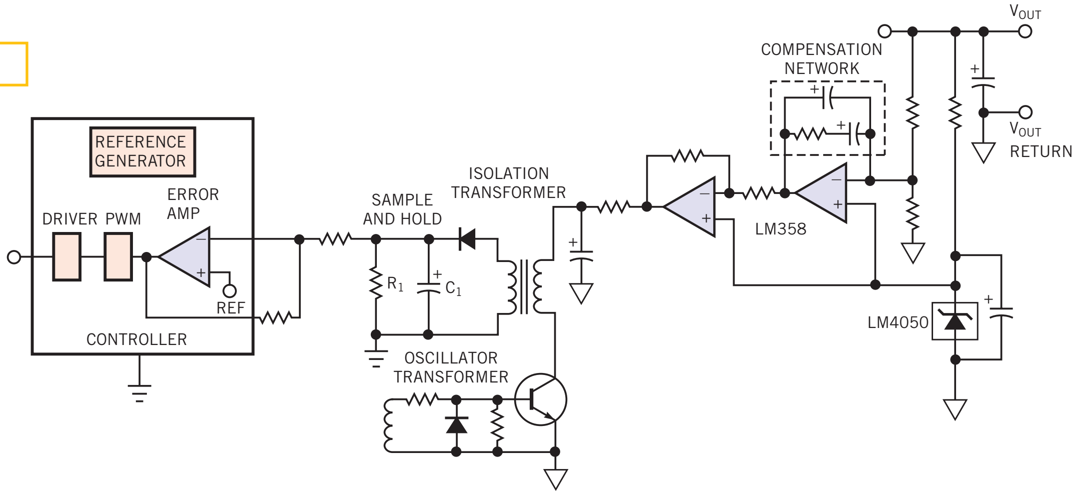
If the performance requirements are less stringent, then using a primary-side-referenced controller can make the converter simpler and less expensive. In this configuration, the main transformer transmits power across the boundary, and an optocoupler or magnetic pulse transformer provides feedback from the output back across the boundary to the primary side. An optocoupler is the most common approach due to its lower cost and complexity. The feedback signal is generally not a signal proportional to the output voltage. Rather, the feedback signal represents the difference between the output voltage and a fixed, precision reference voltage. If you attempt to bring the output voltage directly across the boundary, any inaccuracy that the isolation circuit causes will directly affect the regulation. Most optocouplers have wide gain tolerances and large variations over temperature and time. Alternatively, if the circuit compares the output voltage with a fixed reference and then multiplies the result by a large gain, the resulting signal will be just an error signal. When the circuit transmits this error signal across the isolation boundary, the error signal can tie directly into the pulse-width modulator.

Figure 2 shows two feedback approaches with typical assigned gains for each block. A_{ISO} represents the gain of the isolation stage, A_{AMP} represents the gain of the error amp, and A_{PWR} represents the gain of the pulse-width modulator and the remainder of the power stage. The only difference between the two approaches is that the error amplifier and the isolation stage are transposed. **Figure 2a** represents a power converter with the error amplifier on the secondary side. The static error of the output voltage, assuming an ideal reference and no offsets, is simply equal to $1/(A_{AMP} \times A_{ISO} \times A_{PWR})$. In this example, the error is 0.001%.

If the gain of the isolation stage, A_{ISO}, decreases by a factor of two, the overall error increases to only 0.002%. **Figure 2b** represents a power converter with the error amplifier and reference on the primary side and an isolated copy of the output voltage, $V_{OUT(ISOLATED)}$, crossing the boundary. The high gain of the error amplifier and the power stage continuously keep $V_{OUT(ISOLATED)}$ at the same potential as the reference voltage. The isolation amplifier in this case is part of the feedback network and not just part of the forward gain. In this case, the initial error with ideal components is also 0.001%. However, if the isolation-stage gain decreases by a factor of two, the system error increases to 100%.

Consider an example for which the reference voltage and the output voltage are initially 3.3V. The reference voltage and $V_{OUT(ISOLATED)}$ remain locked together even with an isolation-stage-gain de-

Figure 5



A winding from the main power transformer drives a switching (oscillator) transistor that periodically applies the error signal to the isolation transformer.

crease of a factor of two. However, at that time, the secondary-side output voltage will be 6.6V.

DERIVE AN ERROR SIGNAL

Several configurations are possible for deriving an error signal on the secondary side and bringing that signal across the isolation boundary. The simplest approach is to use a zener diode and an optocoupler (**Figure 3a**). An increasing output voltage increases the current in the optocoupler diode, which leads to a reduced output signal of the primary controller's error amplifier. This simple, low-cost configuration is inaccurate due to the zener-diode and optocoupler-diode tolerances.

A more accurate and more popular configuration for medium-performance applications uses the same basic idea in **Figure 3a** but replaces the zener diode with an LMV431 shunt regulator (**Figure 3b**). The LMV431 shunts current through the device's cathode until the voltage present at the feedback pin is 1.24V. Using this device, you set up a voltage divider with R_4 and R_5 such that $V_{OUT}=1.24((R_4+R_5)/R_5)$. This configuration is more accurate than a zener-diode configuration because the initial tolerance of the shunt regulator is as low as 0.5%. Also, the voltage drop across the optocoupler diode is no longer part of the feedback divider. You can connect loop compensation between the cathode and the feedback pins of the LMV431.

Some loop compensation is necessary for all of these configurations. In some applications using the LMV431 configuration, optimizing the compensation can be difficult. Power-supply-rejection issues can arise because this configuration applies disturbances on the V_{OUT} line to the cathode. Also, the amount of voltage feedback at the cathode pin is limited because the output of the LMV431 is a current. Adding a dual op amp provides all of the benefits of **Figure 3b** with the ability to optimize the loop compensation (**Figure 4**). This error-amplifier configuration provides high gain, high accuracy, and the ability to compensate the loop. This circuit also includes a separate temperature-compensated reference, the LM4050.

For all of these configurations, you have to think through what happens in start-up mode. When you initially apply input power, neither output voltage nor voltage exists to bias any secondary-side circuits. In this situation, the feedback error signal must be the right polarity so that the circuit requests full power. The dual op amp in **Figure 4** ensures the correct polarity. Another consideration during start-up is soft start. You can slow the rate at which the output voltage rises by increasing the capacitor across the reference device.

MAGNETIC SIGNAL TRANSFORMERS

Optocouplers are not the only devices available to provide signal isolation. Many military applications prohibit the use of optocouplers due to age-degeneration effects. Another way to provide the required isolation is by using a magnetic signal transformer. Many methods use a signal transformer to cross the boundary. Each method requires a circuit that applies the signal to the transformer only periodically because transformers do not accommodate dc signals. One method is basically a form of amplitude modulation (**Figure 5**). This approach uses a winding from the main power transformer to drive a switching transistor that periodically applies the error signal to the isolation transformer. A sample-and-hold circuit connects to the signal transformer's output winding. In this design, you need to pay particular attention to the sample-and-hold circuit's effect on the system bandwidth (R_1, C_1), the duty-cycle range of the chopper signal, and capacitor-loading effects on the error amplifier.

Ultimately, the best design approach to crossing the isolation boundary varies with each application. Performance, complexity, and cost are important considerations. Evaluation of the isolation circuit against the system objectives is necessary throughout each stage of the design. Careful test and measurement is necessary over all operating conditions, including fault conditions, such as short circuits and overloads.□

AUTHOR'S BIOGRAPHY

Robert Bell is a principal applications engineer at National Semiconductor Corp (www.nsc.com). He has helped to define several high-performance PWM controllers and associated application circuits. He holds a BSEE from Fairleigh Dickinson University (Teaneck, NJ) and enjoys hiking, camping, and tennis.