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TWO DESIGNS WITH THE PWM CONTROL ON THE SECONDARY SIDE HIGHLIGHT THE BENEFITS OF SECONDARY-SIDE CONTROL AND POINT THE WAY TOWARD MORE OPTIMUM ARCHITECTURES FOR FUTURE CONVERTER DESIGNS.

Isolated power conversion: making the case for secondary-side control

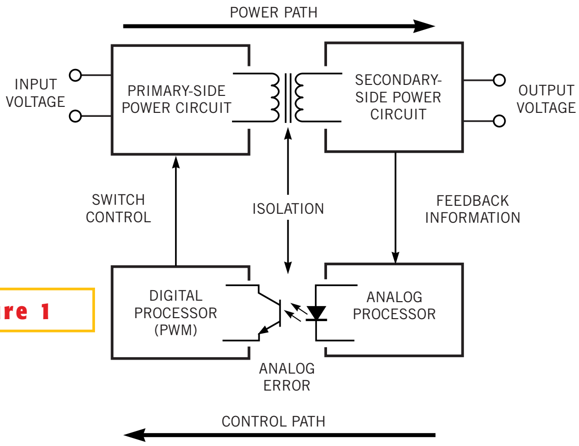
All regulated power supplies require a feedback link from the output to control the power stage. When isolation is necessary, designers traditionally use an optocoupler to transmit an error signal from the secondary side to a PWM controller located on the primary side of the isolation boundary. Although inexpensive and adequate in the past, this system fails to accommodate the needs of newer systems that require lower output voltages and faster dynamic responses. Moving the PWM control to the secondary side offers many benefits and requires some new technologies.

The need for isolation in a power supply is primarily an issue of safety, requiring that there is no direct conductive path between the power supply's input source and its output terminals or load. The input-voltage level usually defines the actual specification, and this voltage level can range from 3500V for a universal line-voltage capability to 500V for some telecomm applications for which the maximum input voltage might be only approximately 80V. In addition to safety, other driving forces for isolation can be grounding or noise issues, but, in all cases, isolation means that there is some form of ac coupling—specifically, a power transformer—in series with the power flow from input to output.

Because a power supply is typically also a voltage regulator, however, some means of control from the output back to the input circuitry is also necessary, which means that another signal must cross the isolation boundary. In a common switching-power-supply architecture, the power path includes the power switches—as well as rectifiers and input filters if necessary—on the primary, or input, side of the isolation barrier, with the output rectifiers and filters on the secondary side (**Figure 1**). Between these blocks, the power transformer provides, among other things, the required isolation between input and output. The control loop measures the output voltage, compares it with a reference value, and generates a PWM command to drive the power switches on the primary side with appropriate commands to regulate the output voltage.

You can isolate the control loop in many ways, but by far the most popular is to divide the total control into two sections, as in **Figure 1**. A secondary-side circuit consists of the error amplifier and reference and generates an analog-error signal. The primary-side PWM controller uses this analog information to develop time-based turn-on and turn-off commands to the power switches. And in between sits an optocoupler that uses light coupling to transmit an analog voltage across an isolation barrier. Experienced designers will recognize this as "primary-side-control," named for the position of the PWM con-

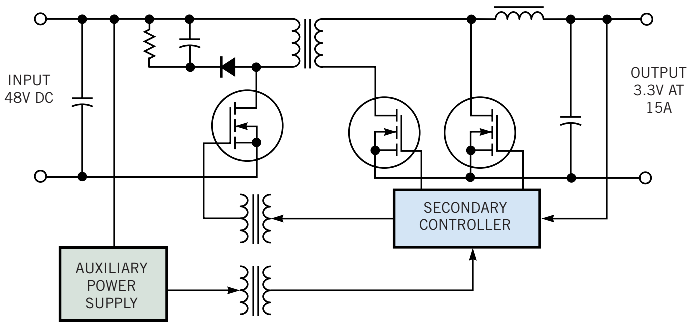
Figure 1



Primary-side control uses an optocoupler to isolate the feedback loop.

troller. Designers have successfully and inexpensively implemented this approach for many years with many low-cost devices, such as a TL431 on the secondary side, a UC3842 on the primary side, and a 4N25 between them.

Figure 2



Secondary-side control allows direct drive to the synchronous rectifiers and the use of a pulse transformer for primary-side power-switch commands.

PRIMARY-SIDE CONTROL HAS LIMITATIONS

Despite the popularity of this architecture, it has two primary limitations. The first limitation is the use of an optocoupler as an isolated analog transmitter. These devices characteristically have limited bandwidth, poor accuracy, and suffer from degradation over time and temperature. Although improved models are available, they come at significantly increased cost. In particular, a bandwidth-limiting component in the analog-feedback loop can make it difficult to achieve compliance with more recent demands for fast, dynamic load response.

The second difficulty with primary-side control is that every output-related function that must communicate with the PWM controller must also cross the isolation barrier. Modern-day power systems are becoming ever more complex, and you can now list many functions, in addition to voltage regulation, which might require this communication link, including:

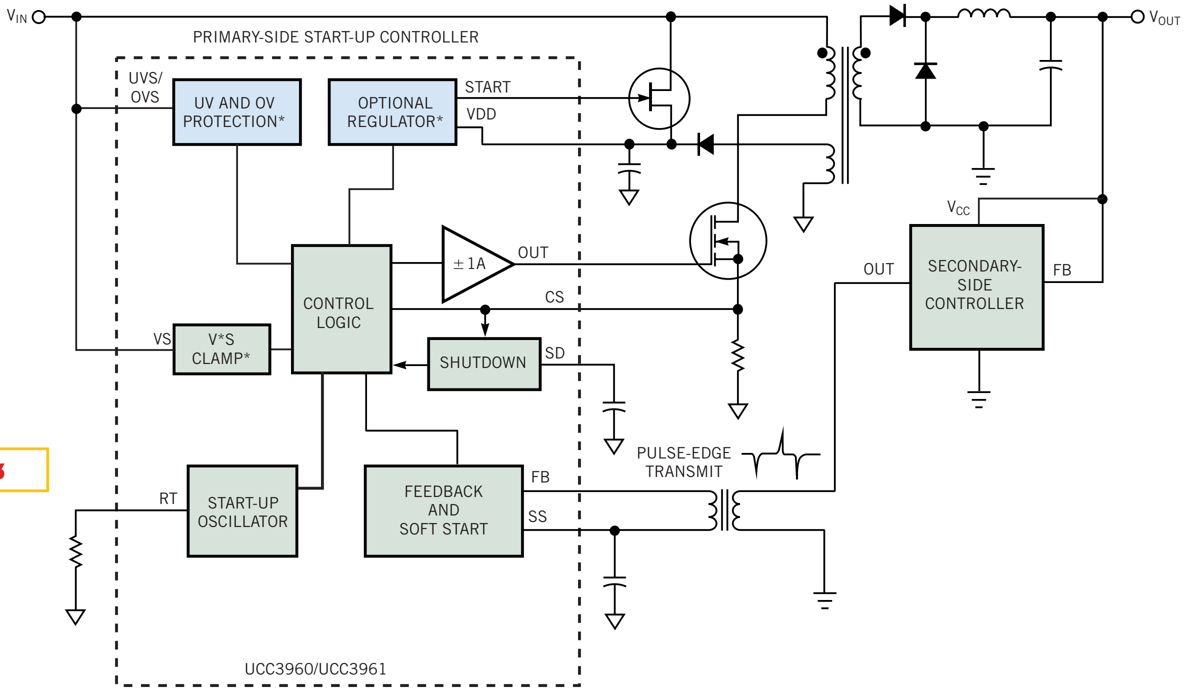
- overvoltage protection,
- frequency synchronization with load clocks,
- power sequencing among multiple supplies,
- load sharing for parallel-output operation,
- average current-mode control of output current,
- load-current limiting, and
- driving synchronous rectifiers.

IMPLEMENT SECONDARY-SIDE CONTROL

An alternative topology, which has in the past been more complex and, therefore, more costly, is an architecture that places the PWM controller on the secondary side of the isolation for direct contact with both the analog-control section and the system load. In this case, a digital PWM signal, which essentially comprises the turn-on and turn-off commands to the primary-side power switches, crosses the isolation boundary. Because the information is now time-dependent, rather than amplitude-dependent, alternative coupling techniques are possible.

One of the reasons for increasing interest in secondary-side control is that the industry is experiencing a transition away from the stand-alone power supply

Figure 3



NOTE: *UCC3961 ONLY.

The UCC3960 primary-side start-up IC allows a secondary output voltage to provide power for the secondary-side controller.

to considering the power supply together with its load as a system-level element. This approach imposes the need for a higher degree of interface between the supply and the load that it powers, a task that is easier when they share a common ground.

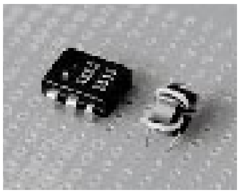


Figure 4

You can build a pulse-edge transformer, or PET, with four-turn windings on a 0.22-in.-diameter core.

SYNCHRONOUS RECTIFIERS

A second and relatively recent development that is encouraging heightened interest in secondary-side control is the issue of driving synchronous rectifiers in the output circuitry. It is well known that with reduced levels of load voltage, the inefficiencies of conventional—and even Schottky—rectifiers are becoming much more difficult to accept. Coupled with significant improvements in high-current FET technology, synchronous rectifiers are becoming common for designs that require voltage levels of 3.3V and less.

Most power topologies require drive commands for a synchronous-rectifier FET. And because the design must accurately time these drive commands with the power switch or switches, a secondary-side controller is a more optimal configuration for all topologies that require one PWM command on the primary side (**Figure 2**). The PWM controller now has three outputs: two that you can directly couple to the output synchronous rectifiers and one that must still cross the isolation barrier to drive the primary switch. This primary-side signal, however, is now a pulse, which allows the use of a high-speed, low-cost pulse transformer as an isolation medium. Timing considerations are important with synchronous rectifiers because incorrect delays can result in either FET body-diode conduction, with losses even worse than a simple rectifier, or high-shoot-through-current transients. But the design issues are easier to manage with one controller generating all three signals.

Moving the PWM controller has created a new problem, however. With the controller on the primary side, start-up of the power supply is not an issue, because the input voltage is always present. But on the secondary side, no power exists until after start-up, causing designers to choose between two alternatives, neither of which is a slam-dunk.

The simplest option, from an architecture standpoint, is to use a separate housekeeping, or auxiliary power supply, as **Figure 2** indicates. Working off the input voltage, this supply needs an isolated, low-power output to supply the PWM controller, which, of course, adds another crossing of the isolation boundary. This housekeeping supply is usually either a simple flyback switcher or a 50- to 60-Hz step-down transformer. Either way, the added cost is the main drawback, relegating the use of housekeeping supplies to high-power systems for which this cost is a small addition to the total overhead budget.

The alternative approach is to devise a way to "kick-start" the power supply to develop a preliminary output voltage and then use that output as the power source for the secondary-side controller. Depending on the voltage levels and timing, this source can either be the supply's main output or a special one developed from an additional winding on the main power transformer. Although this approach has the potential to be low-cost, choices for simple implementations have been limited in the past.

PRIMARY-SIDE START-UP CIRCUITS

To meet the growing need for a dedicated IC controller to perform this primary-side start-up function, new products have become available, such as the UCC3960 and the UCC3961 (**Figure 3**). The functions of these devices include initial start-up, secondary-side communication, and primary-side protection. This controller uses the same high-voltage-start and bootstrap-winding supply common to all primary-side PWM controllers and contains an output driver capable of providing a high-current gate drive to the main power switch. A free-running oscillator that delivers the initial PWM signal to the power switch implements the start-up function. The drive signal has a programmable slow ramp up in pulse width but with a maximum duty-cycle clamp to prevent transformer saturation. Current-limit protection also protects the power switch.

Although a dedicated primary-side start-up circuit is not a new idea, previous designs typically shut down the start functions after establishing secondary-side control. A unique feature of the UCC3960 is that the start-up timing remains active, serving as a "watchdog" monitor to override any feedback signal that might command a pulse width beyond the established duty-cycle limit.

The secondary-side communication function accepts start and stop pulses from an isolating PET (pulse-edge transformer), which is very small because it transmits only very narrow pulses. **Figure 4** shows a hand-wound version of this transformer comparing its size with a standard optocoupler. Two transformer manufacturers now offer this PET in surface-mount packaging and with a range of isolation voltage specifications for as little as 30 cents.

The IC derives feedback-control information

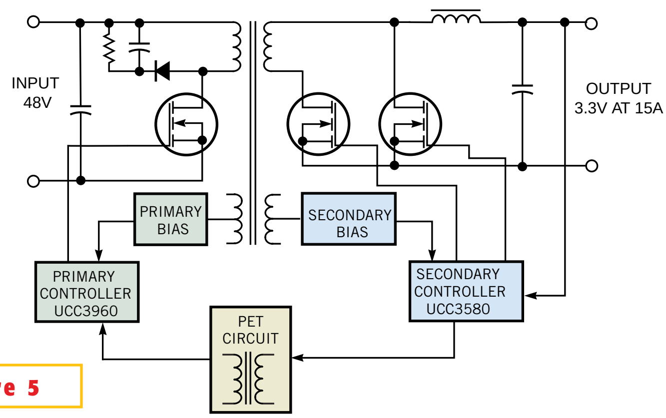
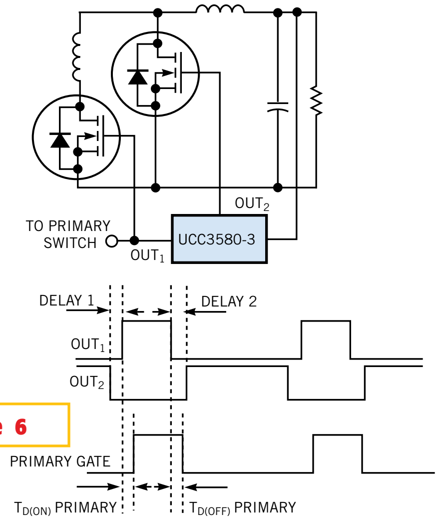


Figure 5

Using the UCC3580 on the secondary side provides PWM control for both synchronous rectifiers as well for the primary switch by way of the UCC3960.

by differentiating the rectangular PWM signal that the secondary-side controller generates. This differentiation yields a positive pulse from the leading edge of the PWM command and a negative pulse from its trailing edge. The IC on the primary side then uses these positive and negative pulses to override and take command away from the open-loop start-up oscillator and reconstruct the required PWM waveform, which now becomes the gate drive for the power switch. The advantages of this design are first, that there are no special requirements on the secondary-side controller—you can use any controller with a PWM output—and second, that a component with no cost or size penalties delivers the important timing information across the isolation boundary.

Figure 6

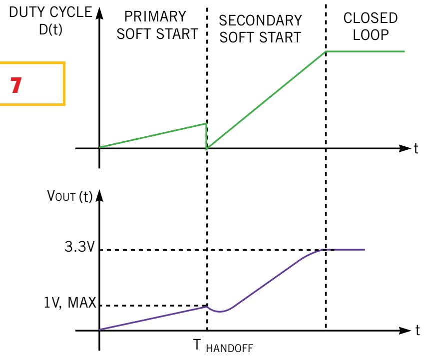


The UCC3580's complementary outputs drive both synchronous rectifiers and control the power switch on the primary side.

The third function of this start-up circuit is primary-side protection. In the eight-pin UCC3960, the protective features include soft-start, duty-cycle clamping, current limiting, and undervoltage lockout. The 14-pin UCC3961 adds overvoltage stop, input volt-second clamping, multimode overcurrent shutdown, and an independent fault latch to the list of protective functions. The UCC3961 also includes an optional lower power start circuit implemented with an external depletion-mode FET.

A demonstration dc/dc converter illustrates the advantages of secondary-side control in a low-cost, low-power module. This design uses a single-ended forward topology and runs at 200 kHz, delivering 3.3V at 50W from an input range of 36 to 72V (**Figure 5**). More design details are available as a technical reprint at http://power.ti.com. This application uses a UCC3580 as the secondary-side controller, primarily because this device has both PWM and $\overline{\text{PWM}}$ outputs with a programmable deadband between them. The waveform timing shows that in addition to ensuring no overlap in the synchronous-rectifier drive signals, the deadband also allows an accommodation of the finite delay that occurs as the signal from OUT_1 traverses the path through the primary-side circuitry and back to the secondary (**Figure 6**).

Figure 7



With soft start in both the primary and secondary circuits, the control hand-off from primary to secondary must occur well before the output reaches its final value.

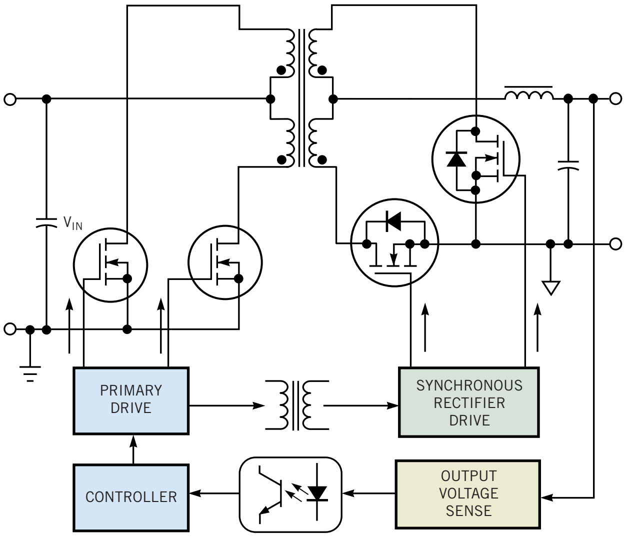
Another important design issue is that when the controller for a secondary-side-control application gets its power from the same output voltage that it intends to control, a race condition may exist at start-up. The design must ensure that the controller gets enough voltage to become intelligent before the actual output to the load rises too high under open-loop conditions. This problem is even more challenging when both primary and secondary circuits each have finite start-up characteristics (**Figure 7**). When using an auxiliary winding on the power transformer, you can readily solve this problem by considering the time constants associated with the main power output when setting the auxiliary control supply's voltage level. Although the output could momentarily droop when control transfers from the start-up circuit to the secondary-side controller, the proper voltage setting can force this droop to occur acceptably early in the output's rise time.

NO ISOLATED FEEDBACK

Thus far, this article has discussed the positioning of the PWM controller with respect to closing the feedback-control loop from the output back across an isolation boundary. However, an innovative new architecture gets around this issue by taking a lead from the SSPR (secondary-side post regulator) concept of a two-stage converter with localized control of the second stage.

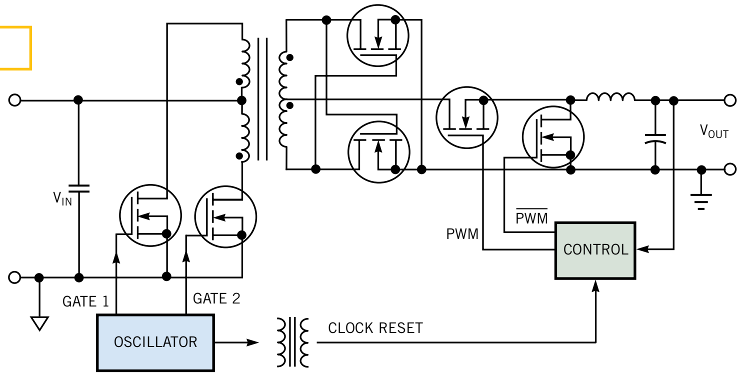
The starting point for this development is the conventional push-pull topology with synchronous rectifiers in the secondary circuit (**Figure 8**). This approach uses primary-side control and requires three crossings of the isolation boundary: the power transformer, gate drives for the synchronous rectifiers, and the analog feedback-control loop. Although the push-pull power stage is an optimized design for driving the power transformer, this configuration can have difficulties with switching losses caused by leakage inductance and the higher induced voltage on the primary power FETs. And, of course, you have the added difficulty of getting the drive signals to the output FETs.

Figure 8



A conventional push-pull dc/dc converter has primary-side control and synchronous rectifiers in the secondary.

Figure 9



A two-stage topology allows for closed-loop control without isolation on the secondary side of an isolated open-loop primary winding.

A new patented topology might at first appear to have an economic disadvantage because the circuitry includes two additional FETs (**Figure 9**). However, a description of the operation illustrates significant advantages.

To understand the operation of this circuit, start with a free-running, square-wave push-pull primary stage. This stage contains no pulse-width modulation. Each primary-side power switch alternates with successive switching periods, on for just slightly less than the full period. The oscillator drives the switches at a fixed frequency and also programs a defined deadtime between periods during which both switches are off. The deadtime setting allows the leakage inductance in the primary windings to resonate with the parasitic drain capacitance such that the circuit forces the drain voltage on each FET in the off state to zero before it turns on. This ZVS (zero-voltage switching) on the primary side greatly reduces the potential for switching losses, even with frequencies into the hundreds of kilohertz.

The power transformer in this stage serves two functions. The first, of course, is to provide isolation in the power-flow path. Note that with this stage running open loop, no feedback has to cross the isolation boundary. Secondly, the transformer turns ratio converts the input voltage down to a much lower value, albeit with the same variation, because no feedback means no regulation. This turns ratio might typically convert 48V to 6V. The synchronous rectifiers operating on the secondary of this transformer can now be self-driven because there is a turn-on voltage available whenever there is secondary current flowing. Moreover, these devices also operate with zero-voltage turn-on for minimum switching losses.

The key to this design's significant advantage lies with the second stage, which now is just a nonisolated, synchronous buck regulator but with several unique characteristics. First, because this stage is operating from the stepped-down input voltage, the PWM duty-cycle is larger, enhancing the stage's conversion efficiency. Secondly, there is no interstage filtering. This buck regulator operates from the interim rectified square wave with leading-edge modulation to control the pulse width to the output filter, a technique well developed with older SSPR and mag-amp technology. And finally, a local nonisolated feedback loop determines the output regulation, which provides both high accuracy and maximum bandwidth. The only additional crossing of the isolation barrier is merely for frequency synchronization between the two stages. This synchronization is necessary to enable the use of leading-edge modulation, but isolation is easy to accomplish with a simple pulse transformer.

This example shows once again that secondary-side control provides significant benefits, in this case for a two-stage conversion topology for which isolation and voltage step-down occur in the first stage, allowing the second stage to achieve low-cost, high-performance regulation with a closed-loop nonisolated configuration. And there is the additional bonus of ZVS operation for both the primary-side power switches and the synchronous rectifiers.□

Author's biography

Bob Mammano holds the title of Fellow in Texas Instruments' Power Management Products Division, where he has worked for two years. He is involved in new product definition, technical marketing, and education programs. Mammano holds a degree in physics from the University of Colorado (Boulder).