Understanding isolated DC/DC converter voltage regulation

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Isolated DC/DC converters are required in a broad range of applications including power metering, industrial programmable logic controllers (PLCs), insulated-gate bipolar transistor (IGBT) driver power supplies, industrial fieldbus, and industrial automation. These converters often are used to provide galvanic isolation, improve safety, and enhance noise immunity. Moreover, they can be used to generate multiple output voltage rails including dual-polarity rails.

In terms of output voltage regulation accuracy, isolated DC/DC converters usually fall into three categories: regulated, unregulated, and semi-regulated. This article discusses various regulating schemes and the corresponding topologies. Factors affecting regulation accuracy are examined in detail. This leads to some design tips to improve regulation accuracy in practical designs. Additionally, the pros and cons of each scheme are presented to provide a guideline for choosing an appropriate solution for a specific application need.

Feedback and control of isolated DC/DC converters

Isolated DC/DC converters typically use a transformer to electrically isolate the output from the input of the power stage (**Figure 1**).

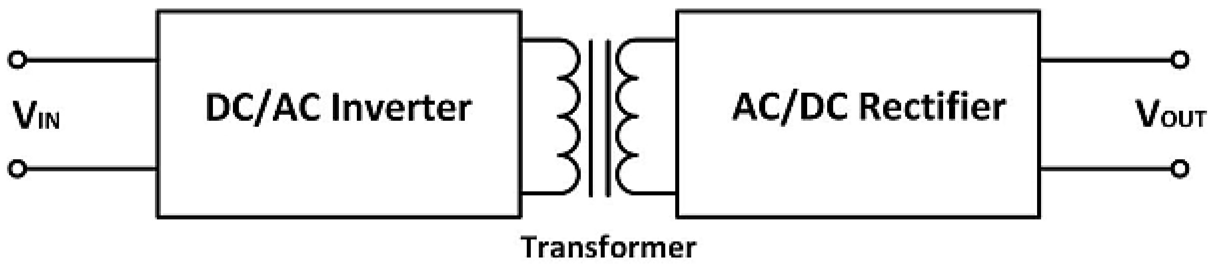

Figure 1. Block diagram of an isolated DC/DC converter power stage

In a closed-loop isolated DC/DC converter (**Figure 2**), the feedback circuitry senses the output voltage and generates an error by comparing the sensed voltage with its target (feedback voltage reference). The error is then used to adjust the control variable (duty cycle in this example) to compensate the output deviation. Galvanic isolation between control circuitry on primary side and secondary side is also essential. Such isolation can be achieved by utilizing either a transformer or an optocoupler. Assuming the reference voltage V_{REF} is precise and stable over temperature, regulation accuracy mainly depends on output voltage sensing accuracy (in other words, how well V_{SENSE} resembles V_{OUT}).

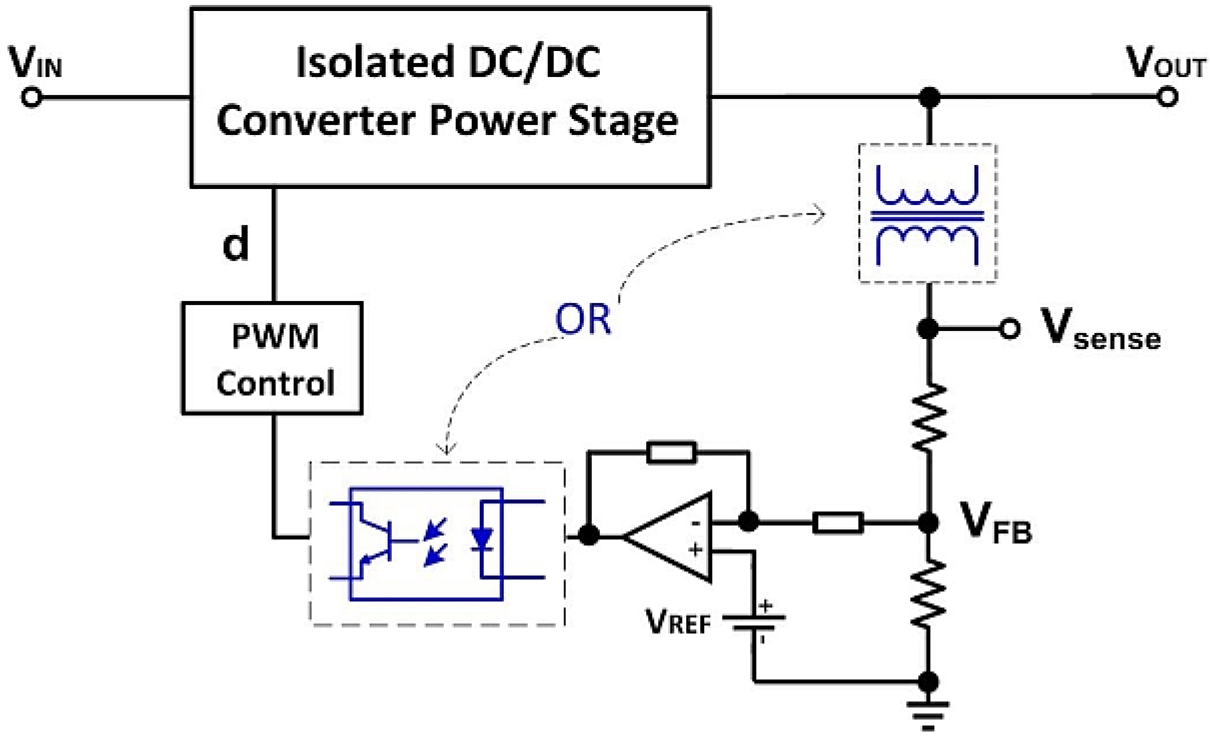

Figure 2. Feedback and control of a closed-loop isolated DC/DC converter

Unregulated isolated DC/DC converters

Unregulated isolated DC/DC converters, also known as open-loop isolated DC/DC converters, are widely used in applications that don’t require precise output voltage. A typical example is the push-pull converter with fixed 50% duty cycle (**Figure 3**). The control circuitry consists of only an oscillator along with two gate drivers, which generates two complimentary fixed 50% duty cycle gate signals to drive Q1 and Q2. The transformer turns ratio is selected to deliver the desired output voltage. Neither a feedback circuitry nor a signal isolator is required, which reduces cost and solution size.

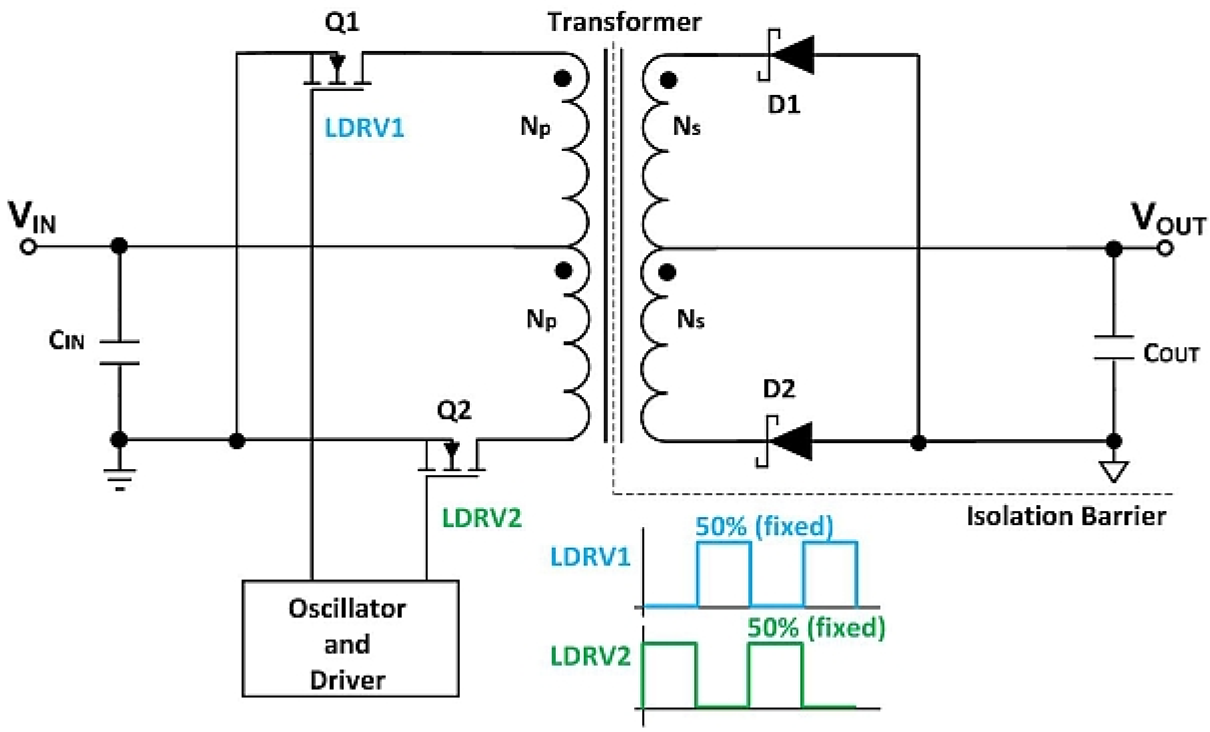

Figure 3. Unregulated push-pull converter with fixed 50% duty cycle

A push-pull converter is essentially a forward-derived topology. When it operates with a fixed 50% duty cycle, the output voltage regulation can be elaborated using the equivalent circuit in **Figure 4**. *R* is the equivalent resistance of secondary transformer winding and trace. The output voltage can be expressed by (1):

$$V_{OUT} = (Ns/Np)V_{IN} - V_R - V_F \tag{1}$$

where V_R is the voltage drop across resistor *R* and V_F is diode forward voltage drop, which are both load- current-dependent. Moreover, V_R and V_F also vary with the ambient temperature, and so does V_{OUT}. Equation 1 indicates V_{IN}, in addition to load current and ambient temperature, is also a factor of V_{OUT}. These factors are not compensated at all which could result in significant output voltage variation. That is why such converters are called *unregulated*.

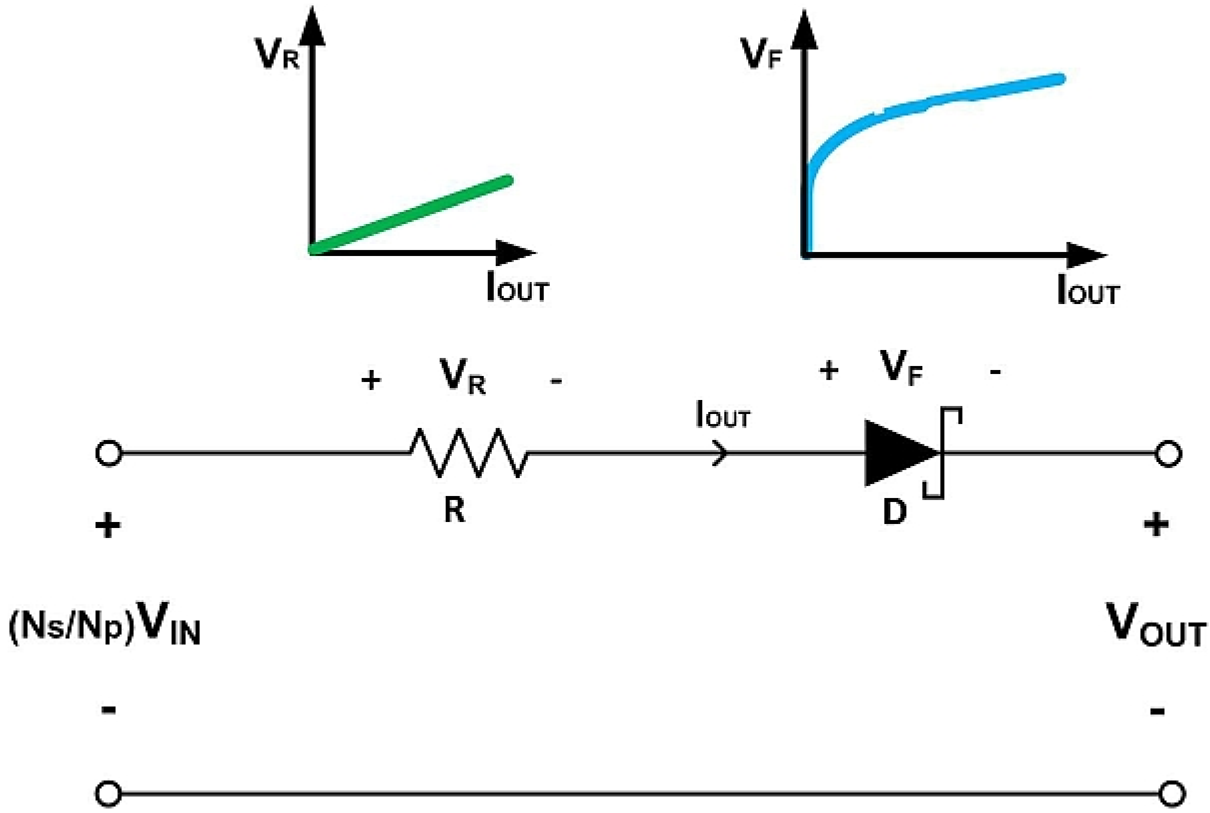

Figure 4. The equivalent circuit of unregulated push-pull converter

Similar to a push-pull converter, other topologies commonly used for unregulated isolated DC/DC converters are half-bridge and full-bridge (H-Bridge) converters. Due to the low cost and circuitry simplicity, these unregulated isolated DC/DC converters are commonly used as DC transformers to provide galvanic isolation. A low-dropout (LDO) regulator is often used as the post regulator to provide low noise and low ripple power supply.

Regulated isolated DC/DC converters

Regulated isolated DC/DC converters

Input voltage, load current, and ambient temperature all have an impact on the output voltage accuracy in an unregulated isolated DC/DC converter. This is not acceptable to applications where a precise output voltage and tight regulation are critical, and a regulated isolated DC/DC converter should be adopted. A flyback converter in **Figure 5** is taken as an example to elaborate how the tight regulation is achieved. Compared with the unregulated push-pull converter (**Figure 3**), the regulated flyback converter has an additional feedback circuitry. Also an optocoupler is used to transfer the control signal from the secondary side to the primary side while achieving galvanic isolation.

The advantage of using an optocoupler is that the feedback circuitry can be placed on the secondary side. As such, the output voltage can be directly sensed and regulated (that is V_{SENSE}=V_{OUT}), which in turn compensates all the effects of input voltage, load current and temperature on output voltage regulation. As a result, a tight regulation in the range of ±1% to ±3% usually can be expected over all operating input voltage, load current, and temperature conditions.

There are several disadvantages to use an optocoupler. First of all, an optocoupler introduces an extra pole in the control loop, which reduces the converter's bandwidth. Second, an optocoupler has large unit-to-unit variation and temperature and lifetime degradation in the current transfer ratio (CTR), which imposes constraints on the control loop design.

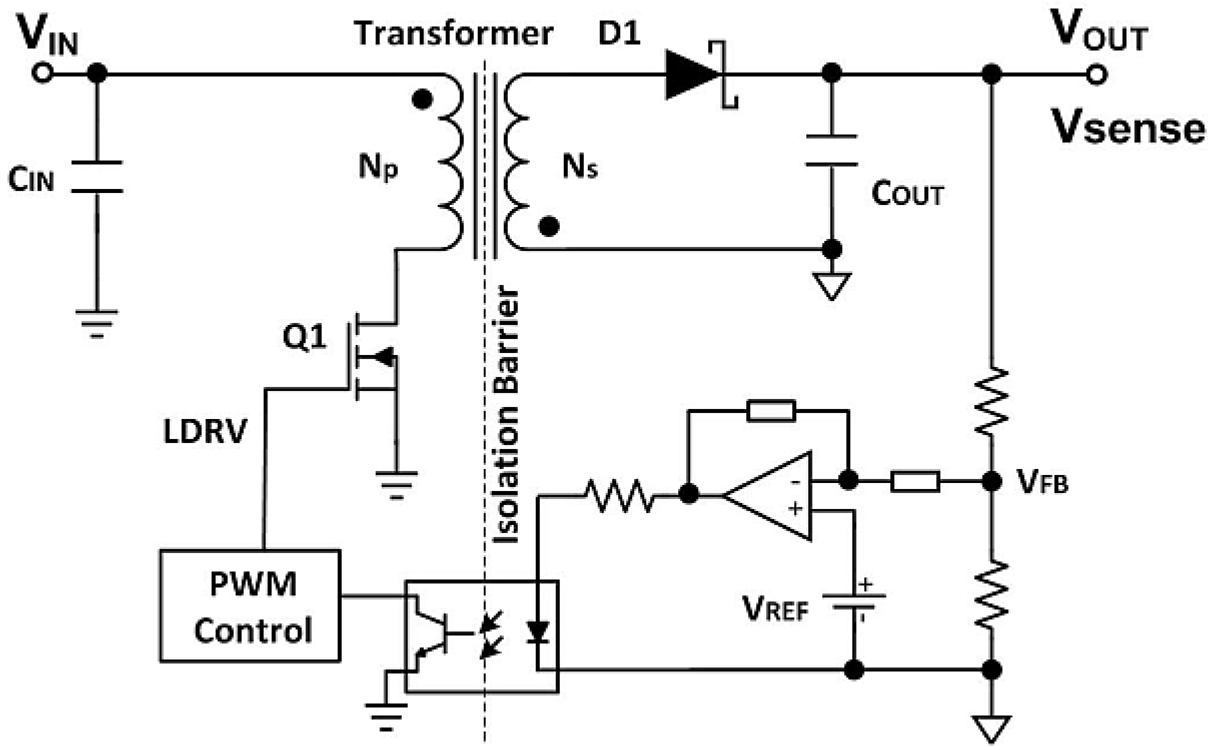

Figure 5. Regulated flyback converter using an optocoupler

Semi-regulated isolated DC/DC converters

Unregulated isolated DC/DC converters do not require any optocoupler, but fail to provide any regulation. Conversely, regulated isolated DC/DC converters provide tight output voltage regulation, but require an optocoupler. There are many applications where the customer may not want an optocoupler, but require the output voltage to be regulated to some extent. The so-called semi-regulated isolated DC/DC converter will be the appropriate solution.

From an output voltage regulation perspective, the semi-regulated isolated DC/DC converter is something between the unregulated and regulated isolated DC/DC converters. Like a regulated isolated DC/DC converter, the semi-regulated isolated DC/DC converter also has a feedback circuit. However, it does not sense and regulate the output directly. Instead, it just senses a voltage, which resembles the output voltage on secondary side but is commonly referenced with the primary input voltage. These techniques might not be able to achieve as accurate an output voltage, but they eliminate the optocoupler while achieving decent output voltage regulation. Three examples discussed in this article are Fly-Buck converter, flyback converter with cross-regulated output, and the primary side regulation (PSR) flyback converter.

Fly-Buck converter

A fly-buck converter (**Figure 6**) is basically a synchronous buck converter with an additional winding coupled to its inductor to generate an isolated output (V_{OUT}). In addition to the isolated output on secondary side, Fly-Buck converters provide a regulated output (V_P) on the primary side. The primary side output is regulated in the same way as a standalone synchronous buck converter (2):

$$V_P = DV_{IN} \tag{2}$$

where D is the duty cycle of the buck switch Q1 in **Figure 6**. When the low-side synchronous switch Q2 conducts, V_P is reflected to secondary and rectified as V_{OUT}. The equivalent circuit is shown in **Figure 7**. V_{OUT} can be calculated by (3):

$$V_{OUT} = (Ns/Np)V_P - V_R - V_F \tag{3}$$

Like the unregulated push-pull converter described by equation 1 and **Figure 4**, the isolated output of the Fly-Buck is a function of V_R and V_F, which are both load-current and temperature-dependent. However, V_P is a constant voltage regulated by a feedback circuit, which makes V_P and, thus, V_{OUT} independent of V_{IN}. To the isolated output of a Fly-Buck converter, the effect of V_{IN} is compensated, but the effects of load current and temperature are not compensated. So the Fly-Buck™ converter falls into the semi-regulated isolated DC/DC converter category.

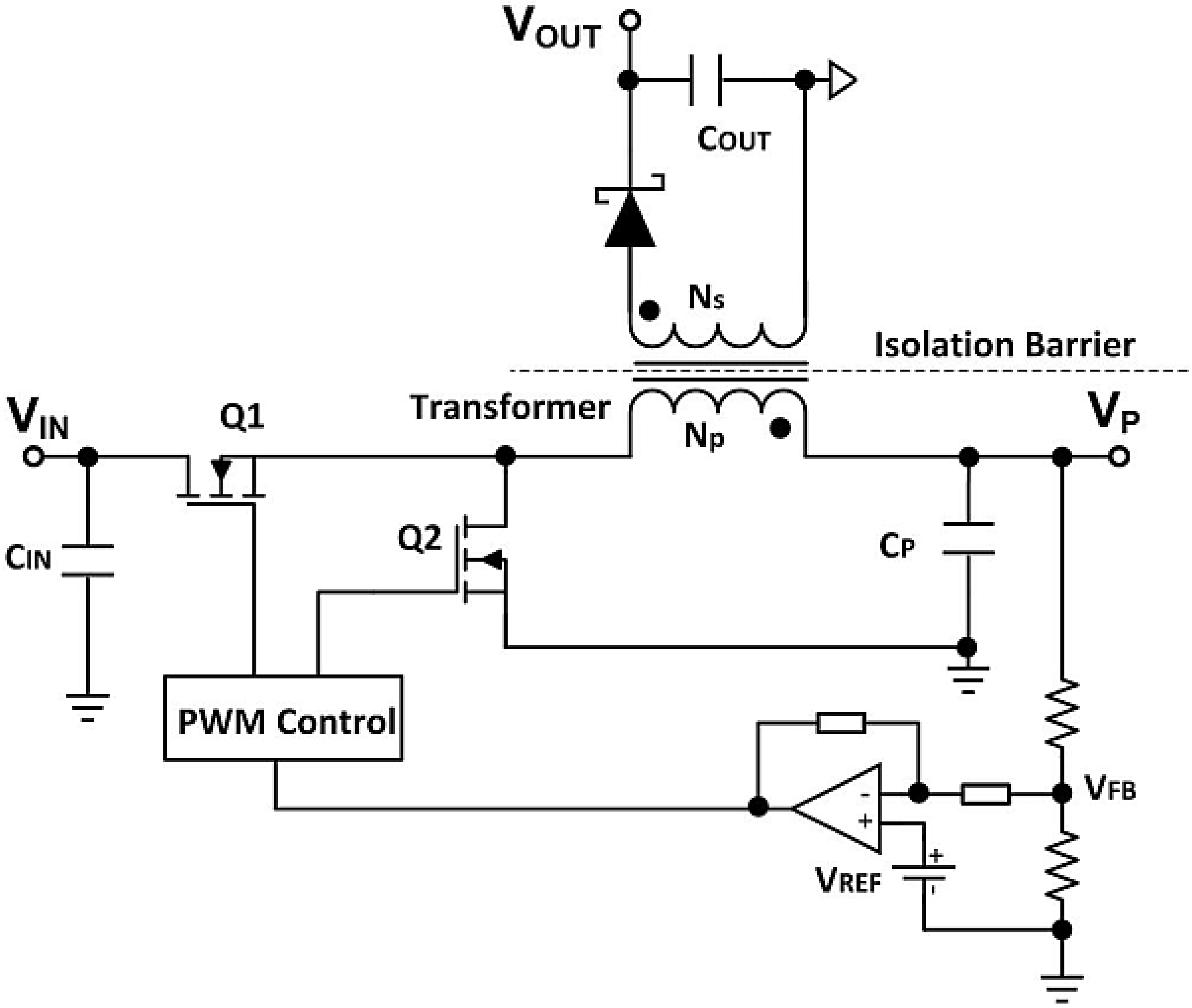

Figure 6. Fly-Buck converter

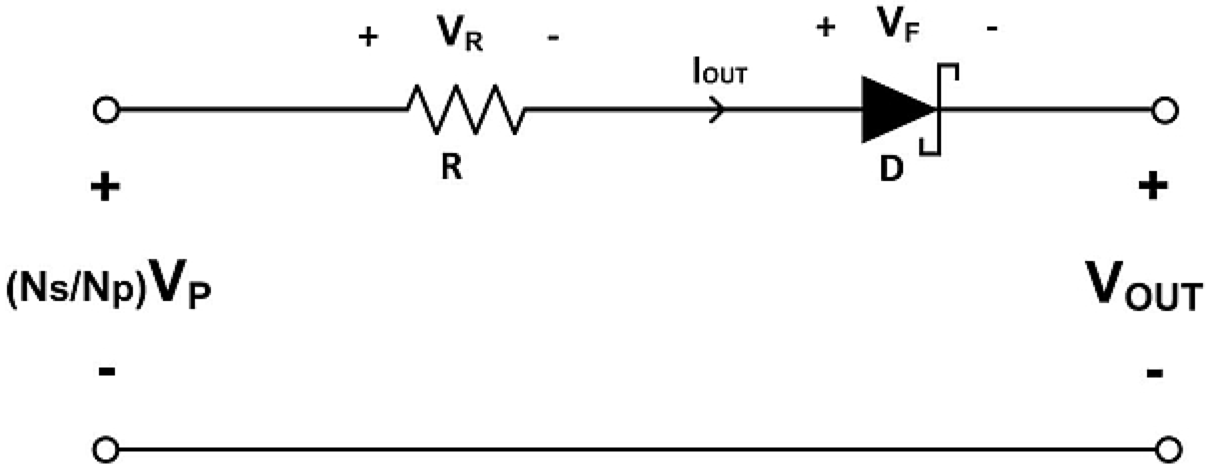

Figure 7. The equivalent circuit of a Fly-Buck converter

When Q1 is on, the output capacitor C_{OUT} is discharged, supplying the load current. When Q2 is on, the output capacitor charge is replenished to maintain regulation. In practice, the transformer has more or less leakage inductance, which determines ramp rate of the current in the secondary winding to charge the output capacitor. The leakage inductance along with duty cycle impacts on the output voltage regulation. The leakage inductance should be minimized and the maximum operating duty cycle should be chosen carefully to mitigate their impacts on the regulation. By proper design, roughly a ±5 to ±10 percent output voltage regulation could be achieved, depending on the load current range.

Flyback converter with cross-regulated output

Flyback converter with cross-regulated output

A flyback converter can easily generate multiple outputs without any additional output filter inductor which is usually required by other DC/DC converter topologies. In the multiple outputs configuration (**Figure 8**), only one output (Vaux) is directly regulated while others (V_{OUT}) rely on cross regulation. By referring the regulated output (Vaux) commonly with the input (V_{IN}) on primary side (**Figure 8**), the optocoupler of the regulated flyback converter in **Figure 5** can be eliminated. The isolated output (V_{OUT}) on secondary side can be given by (4):

$$V_{OUT} = (Ns/Na)(V_{aux} + V_{Ra} + V_{FD2}) - V_{Rs} - V_{FD1} \qquad (4)$$

where V_{Rs} and V_{Ra} are equivalent resistance voltage drop of secondary winding and auxiliary winding, respectively. V_{Rs}, V_{Ra}, V_{FD1}, and V_{FD2} are all functions of its own current. The currents flowing in secondary winding and auxiliary winding are not even, which results in a mismatch in the load regulation between V_{OUT} and V_{AUX}. Consequently, the load regulation of V_{OUT} is not as good as V_{AUX}. The isolated output is independent of V_{IN}, which suggests good line regulation. Usually ±5 to ±10 percent output voltage regulation could be achieved as the cross-regulated output depends on the load current range.

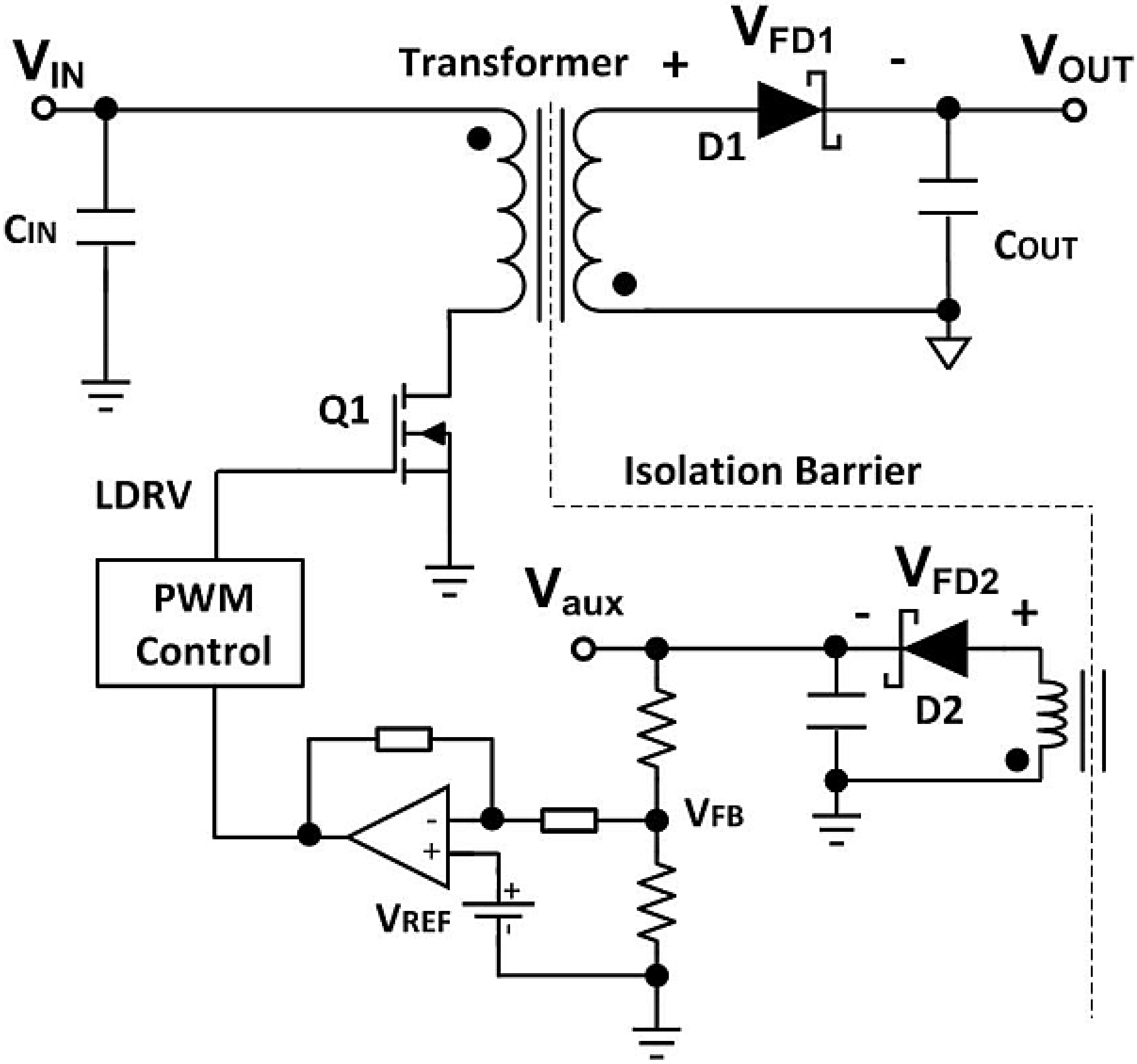

Figure 8. Flyback converter with cross-regulated output

PSR flyback converter

Both Fly-Buck and flyback that rely on cross-regulation fail to compensate the load current impact on the output voltage regulation, although the line regulation is good. Hence, the output voltage accuracy depends on the load current. The PSR flyback converter (**Figure 9**) is intended to minimize this dependence by sensing the output voltage more accurately.

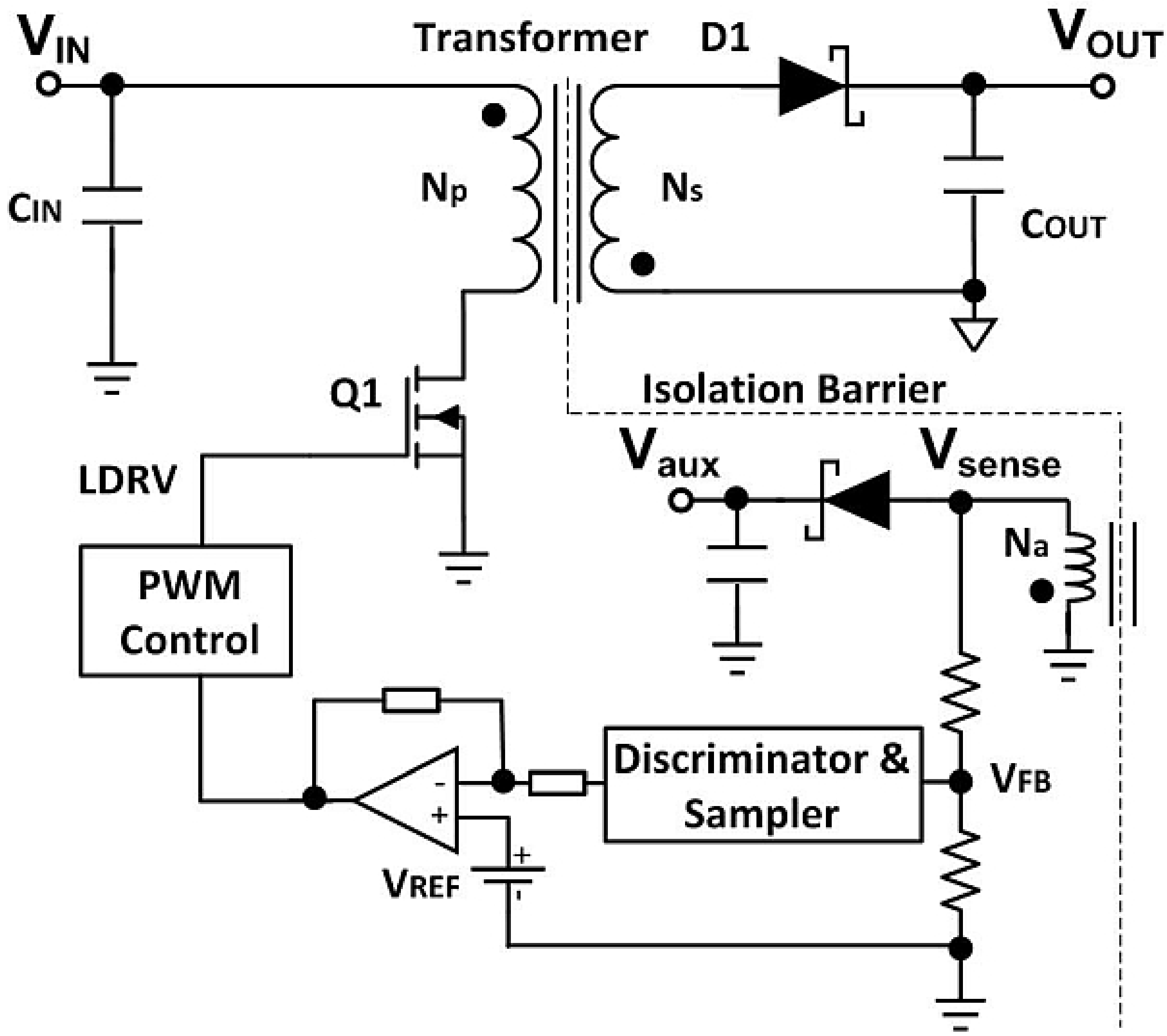

Figure 9. PSR flyback converter

By operating in discontinuous conduction mode (DCM) or boundary conduction mode (BCM), the secondary current returns to zero in every switching cycle. **Figure 10** shows the auxiliary winding voltage profile in DCM. The PSR flyback converter senses the auxiliary winding voltage (V_{SENSE}) at the knee when the secondary current is approximately zero via a dedicated discriminator and sampler circuitry. At the sampling point, there is no resistance voltage drop across winding and trace since secondary current is zero. Also, the diode forward voltage drop at the sampling point becomes a constant (V_{OFFSET}), regardless of the actual load current. Thus, the sensed voltage becomes (5):

$$V_{sense} = (Na/Ns) \times \left(V_{OUT} + V_{offset}\right) \quad (5)$$

As such, no matter the load current, V_{SENSE} well represents the output voltage with only a fixed voltage, which could be offset by tuning the voltage feedback resistor divider. In this way, the load current's impact on output voltage regulation is minimized, and a good load regulation can be expected. Since a PSR flyback converter compensates both line and load variation, a better than ±5 percent overall regulation can be achieved.

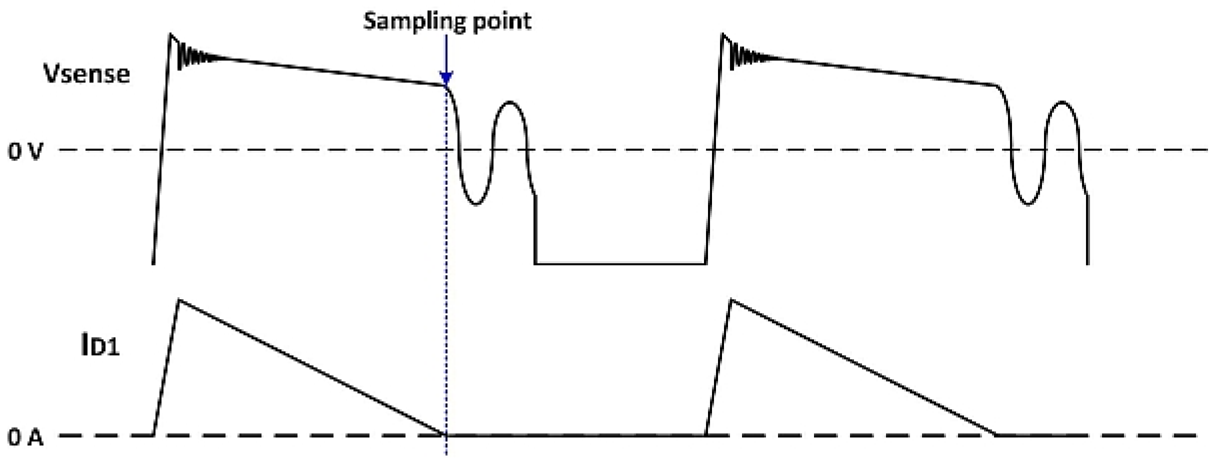

Figure 10. Voltage sensing scheme of PSR flyback converter

Conclusion

To achieve galvanic isolation, safety, and enhanced noise immunity, the secondary side is electrically isolated from the primary side in isolated DC/DC converters. This isolation applies to both power stage and control circuitry. The way in which output voltage is sensed and regulated determines the output voltage regulation accuracy. Unregulated isolated DC/DC converters feature lowest cost and simplest circuitry, but have no regulation. Regulated isolated DC/DC converters provide a tight regulation over line, load, and temperature ranges, but require either an optocoupler or a digital isolator IC. Semi-regulated isolated DC/DC converters make a trade-off between the output voltage regulation and circuit complexity. A most suitable solution should be selected based on specific application needs.

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References

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2. Fly-Buck converter using LM5017
3. Unregulated push-pull converter using SN6501
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7. Haifeng Fan, "How to design boost, SEPIC and flyback regulators with wide VIN boost power management ICs," White Paper (SLYY062), Texas Instruments, August 2014

Also see:

- [48-V constant on-time synchronous step-down converter]
- [Product How-to: Fly-Buck adds well-regulated isolated outputs to a buck without optocouplers]
- [How to achieve low radiated emissions with fully integrated data and power isolation]