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Pre-Regulator Design Protects High-Voltage Power Supplies From Phase Faults (Part One)

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Power supplies for applications such as e-meters and high-power appliances designed to run from a three-phase supply must be able to withstand incorrect connection between phases that can cause very high voltages to appear at the input. This article discusses several approaches for designing a fault-tolerant power supply, including a new pre-regulator topology that helps simplify circuit design and component selection while ensuring high efficiency and reliability. Here in part one, the pre-regulator topology is introduced and an overview of its operation and impact on the power supply design is presented. Later in part two of this article, the operation of this pre-regulator and its cost advantages will be described in greater detail.

This pre-regulator is currently implemented discretely. Although ON Semiconductor has a license on this application, the company is offering royalty-free use of this IP for customers that purchase the PWM controller/regulator/MOSFET. With the system-level cost savings, this approach still results in a lower total system cost and the ON Semiconductor parts are "free," so the company views this as a win-win. The pre-regulator is being considered for integration in an IC but the decision to do so will be based on market acceptance of the discrete solution.

Immunity To Phase Faults

If an incorrect connection fault occurs in the ac supply to an e-meter, or if a high-power load like an air-conditioning unit or induction cooker running from a three-phase supply is incorrectly connected across two phases, a very high voltage can appear at the power supply input. To survive these types of faults, the main ac-dc power supply must be capable of withstanding an applied voltage of around double the usual mains RMS supply voltage.

For a system operating in the U.S., where the normal mains supply voltage is 110 V ac, a regular switched-mode power supply (SMPS) with universal mains input can meet this requirement. However, in Europe or Asia, the SMPS must be capable of withstanding an applied voltage of 460 V (over 600 V dc when rectified.) This can be achieved by modifying a standard SMPS input with two bulk capacitors connected in series at the input. This may then feed a classical flyback converter built with a MOSFET of 1000 V or higher rating, or a modified flyback architecture using two MOSFETs in cascode connection.

As far as the bulk capacitor circuit is concerned, there are no suitable bulk capacitors on the market with a voltage rating higher than 450 V. Hence two capacitors are required in series to support a voltage of 600 V or greater. Since the capacitors are connected in series, their capacitance values should be doubled to keep the same overall energy stored for hold-up time. To avoid an unbalanced voltage spread between the capacitors, resistors should be connected in parallel with each capacitor. These add I^2R losses and hence impair power supply efficiency. Additional transient voltage suppressors (TVSs) are also required, to protect against capacitor short-circuit faults. (Each capacitor needs its own TVS to protect against a short on the other capacitor.)

Fig. 1 shows the modified bulk capacitor circuit supplying a conventional flyback converter. Although this approach requires no additional switching block, a MOSFET with a voltage rating of 1000 V or more must be used to support the transformer flyback voltage on top of the increased fault voltage at the input. Designing the SMPS for a wider input-voltage range also requires corresponding wide-frequency dynamics or MOSFET on-time (t_{on}) variations to maintain regulation across the increased voltage range. In addition, higher dV/dt at the MOSFET increases switching losses, resulting in lower efficiency, and also increases the risk of interference (EMI).

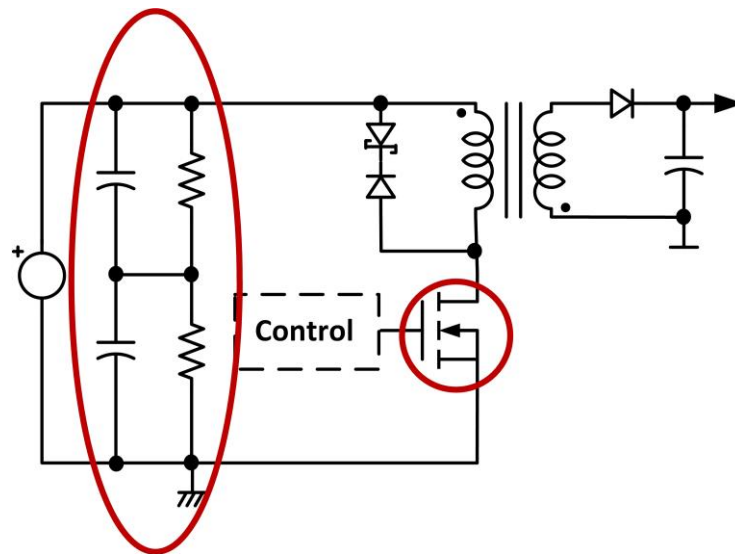


Fig. 1. The inclusion of a series bulk capacitor circuit and a single 1000-V MOSFET enables a flyback converter to withstand an applied voltage of 460 V ac, which is over 600 V dc when rectified.

Alternatively, the single MOSFET can be replaced with two MOSFETs in a cascode configuration as shown in Fig. 2. An ordinary 700-V switcher and 600-V power MOS, together, are sufficient to sustain the sum of the flyback voltage and the rectified input voltage.

As the circuit shows, an additional TVS is required at the gate of the 600-V MOSFET. As with the standard flyback, the SMPS should be designed for a wide input-voltage range with a correspondingly large switching-frequency excursion or t_{ON} dynamics to ensure correct output-voltage regulation. The switching losses and risk of a complex EMI signature are also similar.

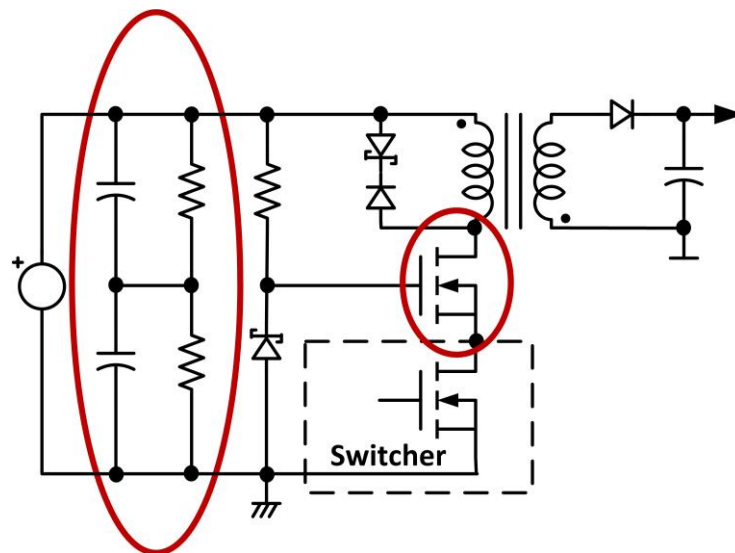


Fig. 2. This high-voltage input SMPS with MOSFET and switcher in cascode configuration offers another option for providing high-voltage-withstand capability.

Alternatively, very careful design can allow a solution to be achieved using a classical topology with an 800-V power MOSFET or integrated switcher. However, care must be taken to minimize the reflected voltage from the transformer to keep the maximum transistor voltage below 800 V even when the supply voltage is at its highest under fault conditions (around 620 V.) This requires a low turns ratio (N_p/N_s) and low primary inductance in the

transformer. The MOSFET on-time, t_{ON} , must be extremely short when the input voltage is high and output power is low, while the secondary diode has a long conduction time.

Several factors can restrict the performance, impair the reliability and add to the cost of such a solution. The very short t_{ON} may create regulation instability and force the SMPS to work down to low frequency if not burst mode. In addition, although a 10% voltage margin is usually considered adequate for an avalanche-proof power MOSFET, a margin of 20% should be considered for nonavalanche-proof devices to avoid any reliability issues during transients and the start-up phase. As far as the secondary diode is concerned, a high reverse-voltage capability is required. This tends to demand a diode that is expensive, bulky, and with a large V_F , which reduces efficiency.

The peak voltage induced by the transformer leakage inductance should also be kept very low to stay below the 800-V limit. This requires a large snubber circuit, which increases power dissipation and hence impairs overall efficiency.

A New Pre-Regulator Design

A new alternative solution proposes to insert a voltage regulator at the input to the SMPS, as shown in Fig. 3. This avoids the need for series bulk capacitors and their associated circuitry, and also allows a conventional flyback converter design to be used, thereby avoiding the need for special high-voltage components.

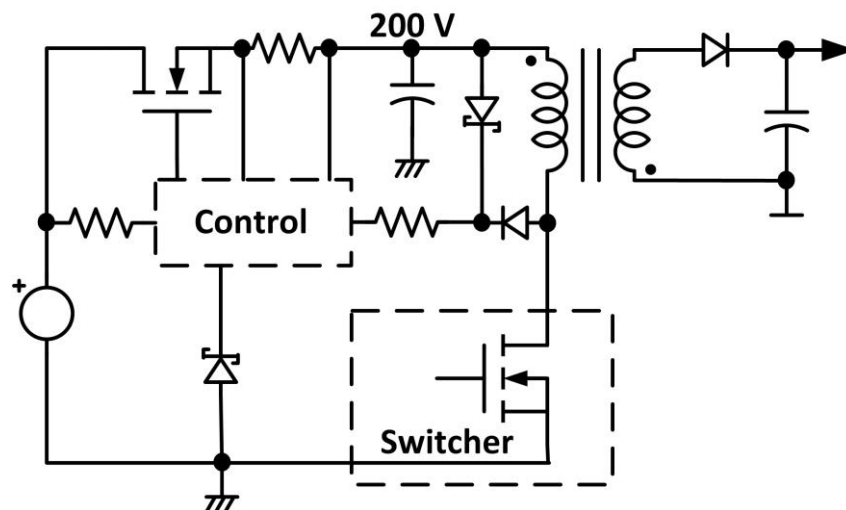


Fig. 3. The pre-regulator simplifies converter design and allows smaller, lower-cost components.

It is possible to design the regulator simply to prevent the SMPS input voltage from exceeding the normal maximum of 380 V dc produced by the input rectifier. This would allow the use of a single standard 450-V bulk capacitor and 700-V integrated switcher without voltage and design issues. However, greater advantages can be gained by reducing the regulated output voltage further to keep the SMPS input at the minimum voltage of 200 V dc ($140 \text{ Vac} \times \sqrt{2}$.) In this case, the pre-regulator acts like a low dropout regulator (LDO), providing the 200-V dc regulated voltage, but its switching behavior avoids excessive power dissipation, large heat sink and reliability issues. In place of dual 400-V or 450-V bulk capacitors, a single 250-V capacitor can be used, delivering size and cost savings. The SMPS snubber can be used to control and drive the pre-regulator MOSFET.

For maximum efficiency, the switching pre-regulator is synchronized with the mains supply so as to provide energy to the bulk capacitor with minimum voltage drop through the regulator MOSFET. This helps boost efficiency to around 90%. The design uses half-wave mains rectification, rather than full wave, which helps avoid excessively short on-time and reduces switching losses. The proposed pre-regulator design also has circuitry to limit inrush current during the start-up phase.

With a pre-regulator in the system, the design of the SMPS is also simplified. Since the input voltage range is significantly reduced, there is no requirement to support large variations in frequency and t_{ON} . In addition, using a smaller 250-V bulk capacitor allows hold-up time to be improved with minimal impact on overall size

and cost, since 250-V capacitors are smaller and more economical than 450-V devices. Moreover, the lower supply voltage, as seen at the bulk capacitor, allows the snubber circuit capacitance to be reduced. The snubber resistance can be increased accordingly.

The reduced supply voltage also gives greater flexibility to design the transformer for a larger reflected voltage capability. This capability not only allows the snubber size and power dissipation to be reduced, resulting in greater efficiency, it also permits the secondary diode to have lower reverse-voltage capability and consequently lower V_F . Further benefits of the reduced supply voltage include improved switching losses and lower EMI. Overall, the pre-regulator allows improved SMPS efficiency, delivering significant size and cost savings.

Several other points are worth mentioning. The standard mains filter requires no modification, as the current will not exceed the current delivered by the minimum supply voltage in a standard flyback converter. In addition, the NTC device typically used to limit inrush current can be removed as the pre-regulator's current limiter now provides this function. The SMPS also requires no half-wave or bridge rectifier, since rectification is performed before the pre-regulator.

Conclusion

The 200-V pre-regulator acts like an ultra-efficient LDO, and helps simplify the design of power supplies capable of accepting extremely high input voltage. It is well suited to use in single-phase supplies that must withstand high input voltages due to faults such as open neutral or incorrect connection between two phases.

Using this pre-regulator helps simplify bulk-capacitor selection while reducing the size and number of capacitors required. The single, low-voltage bulk capacitor is able to support long hold-up time in addition to saving space and cost compared to classical approaches that require two large capacitors and balancing resistances. The need for a 250-V bulk capacitor, rather than 450 V, allows use of better technology capacitors, providing extended lifetime for high ambient temperatures.

A further advantage is that a single 700-V integrated switcher can be used instead of a high-voltage MOSFET with discrete controller, or cascode connection of a MOSFET and high-voltage switcher. Moreover, transformer design can be simplified and smaller secondary diodes can be used. This is a key point for applications such as e-meters, which are often required to provide over ten years' continuous service under severe conditions.

About The Author



Jean-Paul LOUVEL joined ON Semiconductor in March 2007 as a senior system application engineer working on overall system solutions. Since developing the LIPS solution for CCFL backlights, Jean-Paul has worked on new solutions for reduced standby power consumption and a specific solution for very high supply voltage (mainly for e-metering applications.) He also develops new TV power solutions. One of them is a simple primary-side-regulated solution for single-edge LED string backlights. With ON Semiconductor, he holds four issued U.S. patents pertinent to control techniques, with three others pending. Prior to joining ON, Jean-Paul spent three years with TCL Multimedia and over 22 years with Thomson Multimedia in Germany where he performed power development work (mainly for TVs). Overall, he holds over 30 patents pertinent to power conversion.

For further reading on fault protection issues in power supply design, see the [How2Power Design Guide](#), select the Advanced Search option, go to Search by Design Guide Category and select "Power Protection" in the Design Area category.