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

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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. Part one in this series[1] introduced the different SMPS concepts that can satisfy the high-voltage requirement including the novel pre-regulator that is the subject of this article. Here in part two, the operation of this pre-regulator and its advantages are described in greater detail.

Specifically, the interconnection of the pre-regulator to a classical flyback SMPS and the pre-regulator's circuit operation are explained. The circuit protection features of the pre-regulator, its bulk capacitance requirements for a specified hold-up time, and the efficiency of the overall power supply design are also discussed. Finally, a detailed analysis of the cost benefits of the pre-regulator design is presented with the cost of an SMPS employing the pre-regulator compared against an SMPS using a cascode-based solution. Limitations of this pre-regulator approach are also explained.

The New Pre-Regulator Design

The new solution inserts a voltage regulator at the input to the SMPS, as shown in Fig. 1.

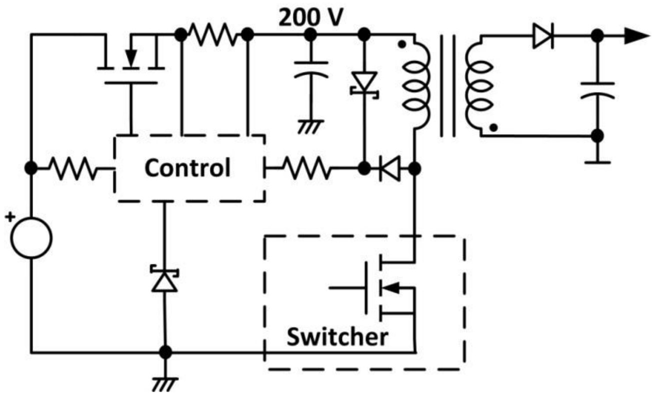


Fig. 1. The pre-regulator simplifies converter design and allows smaller, lower-cost components.

In this case, the pre-regulator acts like a low dropout regulator (LDO), providing the 200-V dc regulated voltage, allowing any conventional flyback converter design to be used. The high supply voltage is only supported by the front-end pre-regulator, before the bulk capacitor. By providing a higher voltage than the bulk capacitor, the SMPS snubber can be used to easily control and drive the pre-regulator n-channel MOSFET.

The New Pre-Regulator Schematic

The overall schematic solution provides the voltage regulator to be inserted between the mains supply and the bulk capacitor supply, as shown in Fig. 2

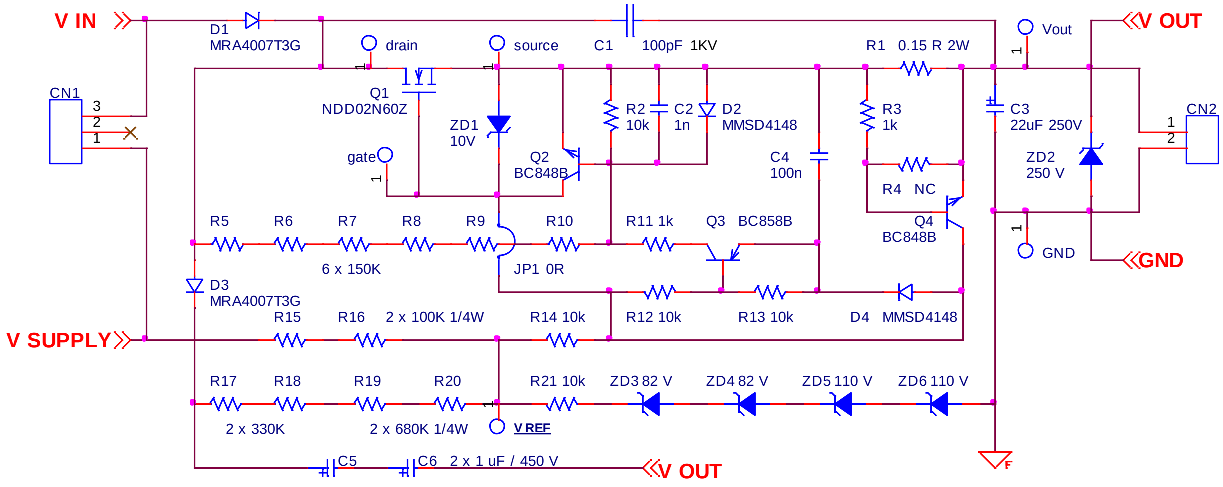


Fig. 2. The pre-regulator's complete schematic including interconnections to the SMPS.

Interconnection With A Classical Flyback SMPS

To insert the pre-regulator into the power supply circuit, there are just a few simple connections that must be made. First, the V_{IN} of the pre-regulator needs to be connected to the mains supply after the EMI filters (with a single diode (D1) for half-wave rectification).

Next, V_{OUT} of the pre-regulator must be connected to the bulk capacitor (in parallel with or instead of the original one) as the supply to the SMPS. Finally, V_{SUPPLY} must be connected to the flyback voltage clamp (or snubber) providing a higher voltage than V_{OUT} to control the gate of our n-channel MOSFET, Q1. The fourth and last connection is ground.

Pre-Regulator Operation Simplified

Thanks to the V_{SUPPLY} from the SMPS's snubber, V_{REF} clamped by the Zener ZD3 – ZD6 provides a voltage source capable of driving the power MOSFET Q1 as soon as the drain voltage (V_{IN}) is higher than the source (V_{OUT}). The drain current will follow the slow rise of the mains (V_{IN}) voltage with a triangular waveform to charge the output bulk capacitor to the supply voltage level.

During this time, the power MOSFET will be fully saturated until V_{OUT} reaches the regulation point. As soon as the voltage between the gate ($\sim V_{REF}$) and the source (V_{OUT}) falls to a low level (<5 V), the power MOSFET will start to de-saturate. When Q1 is no longer saturated, the drain-to-source voltage will rise quickly, following the shape of the mains voltage.

When the drain-to-source voltage of Q1 is up to ~50 V, thanks to resistance divider R5 – R10 and R2, the transistor Q2 will switch on to drop down the gate of Q1 and speed-up its turn-off, which will reduce its switching losses. While Q1 is turning off, the drain voltage will be rising further to secure the drive of Q2 and lock the overall turn-off process.

During Q1 conduction time, the capacitor C4 is charged to ~10 V through the diode D4. When Q2 is on, thanks to R11, the transistor Q3 is switched on to ensure the conduction of Q2 until C4 is discharged through R11. This will avoid any conduction of Q1 despite possible strong oscillations on the drain, which may stop Q2. The capacitor C4 should not be so large as to be completely discharged after some milliseconds, allowing the next cycle of conduction to occur (this is the difference between half- and full-wave rectification.)

If for any reason, the current in Q1 exceeds the given limit defined by the power resistor R1, transistor Q4 will conduct, reducing the drive (gate voltage) of Q1. This will cause Q1 to de-saturate and the turn-off process (using Q2 and Q3) will immediately begin.

The high-voltage spike on the power MOSFET (see Fig. 3) is linked to the leakage inductance of the isolation transformer used to allow tests with a standard (nonsolated) oscilloscope. Due to the parasitic body diode of the power MOSFET, the drain voltage is never smaller than the output.

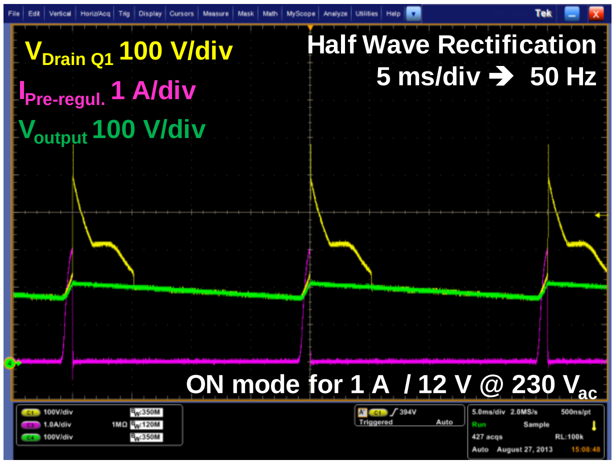


Fig. 3. Pre-regulator behavior measured with 230-V ac, 50-Hz input and 12-V, 1-A output produced by the SMPS.

Fig. 4 shows a measurement of Q1's drain voltage taken without the isolation transformer installed. In this case, the supply is connected across two phases, so the voltage goes up to ~620 V. But because the output voltage of the pre-regulator >180 V, the voltage between the drain and source of our power MOSFET stays below 450 V. We may use the avalanche protection of our MOSFET during the startup phase without issue as this will allow charging of the bulk capacitor without sustaining this condition for too long.

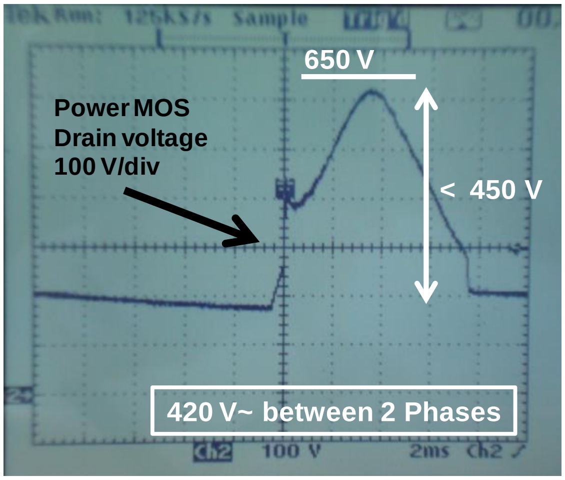


Fig. 4. Drain voltage measured without an isolation transformer, with the SMPS directly connected across two phases of the 420-V mains supply, does not show any peak overvoltage during MOSFET turn-off.

The startup phase requires an additional circuit as the snubber is not able to provide any supply voltage (when the SMPS is OFF.) The only available energy is from the mains supply through V_{IN}. Capacitors C5 and C6 are charged to V_{IN} peak voltage through D3 to drive Q1 through high impedance resistors R17 – R20.

Both capacitors C5 and C6 are in series to support any single short circuit (safety tests) without damage. They are connected to V_{OUT} instead of GND to reduce the voltage applied to the capacitors. During start-up, the cycle-by-cycle current limiting will be activated, preventing the current from exceeding the limit and acting as a perfect inrush current limiter. This eliminates the need to use a resistor or NTC as an inrush limiter in the SMPS.

Responses To Safety Tests

The most critical and common safety test is the short circuit of the electrolytic bulk capacitor. In the case of the classical SMPS, this test will immediately blow the fuse, completely disconnecting the SMPS from the mains supply and requiring service and repair of the power supply. But when the pre-regulator—with its very good current limitation—is present, the power MOSFET will keep operating at the current limit as in the on mode, without any timed turn-off or thermal runaway, because of the serial current sensing (Fig. 5.)

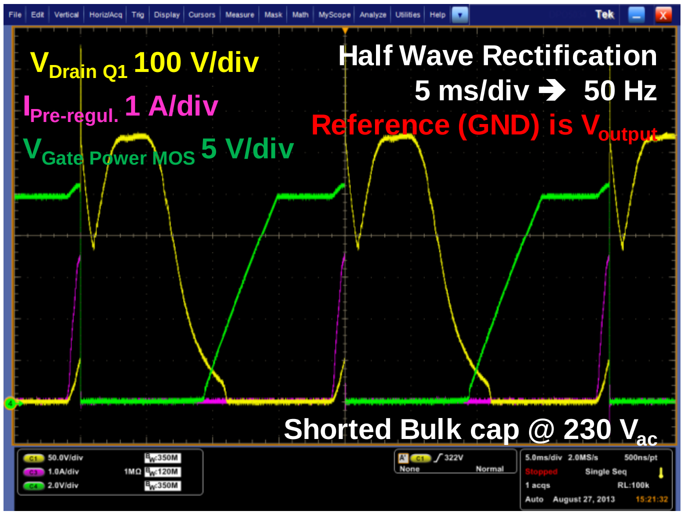


Fig. 5. Pre-regulator behavior with bulk capacitor shorted to GND.

When the short circuit is removed, the overall system will go back to normal operation with the output voltage on the bulk capacitor returning to 200 V.

A second critical short circuit is the direct short from the drain to source of the power MOSFET Q1. In this case, the pre-regulator's current limiting will not be able to limit the current. However, the voltage on bulk capacitor C3 will be limited by the transient voltage suppressor ZD2 until the mains fuse blows.

EMI And Surge Protection

To reduce EMI, a capacitor is connected between the drain and source of the power MOSFET. This capacitor C1 will limit the rise of the drain voltage and reduce the peak voltage and possible high-frequency parasitic oscillations on the power MOSFET caused by the sum of the serial inductances (including the EMI filter.)

Due to the low switching frequency, we can use a large 2.2 nF without impacting the overall behavior: the capacitor is fully discharged before the next cycle and does not impact the transistor's turn-on behavior. This capacitor C1 will also protect the pre-regulator during surge tests, limiting the voltage on the power MOSFET to less than the device's max rating.

Hold-Up Time Design And Pre-Regulator Advantages

Hold-up time requires that energy be stored in capacitors to prevent the output voltage from dropping too fast when the mains supply disappears. As most output voltages are very low (<12 V), the $\frac{1}{2}CV^2$ (energy stored in capacitor C under voltage V) is more efficient for the input bulk capacitor.

The hold-up time should be defined for the given output power, the minimum time to be supported and the minimum mains supply voltage to be considered. As the pre-regulator solution will store energy at the same voltage whatever the mains supply is, this solution will provide the same performance over the whole mains supply range. This capability is important because most applications require hold-up performance to be maintained even when the mains supply drops to 180 V ac.

If C is the value of the bulk capacitor, V_0 the initial voltage before mains off (200 V in our case), V_F the min supply voltage for the flyback SMPS (~30 V), P_{OUT} the power to be delivered during hold time t with SMPS efficiency Eff., we have:

$$\frac{1}{2}C * (V_0^2 - V_F^2) = (P_{OUT}/\text{Eff.}) * t$$

which is applicable for any application.

In the scope capture below (Fig. 6), we can see that hold-up time requirements could lead to large input bulk capacitors. This is particularly true for e-meter applications that commonly ask for more than 300 ms, with 2-W output and 180-V ac supply.

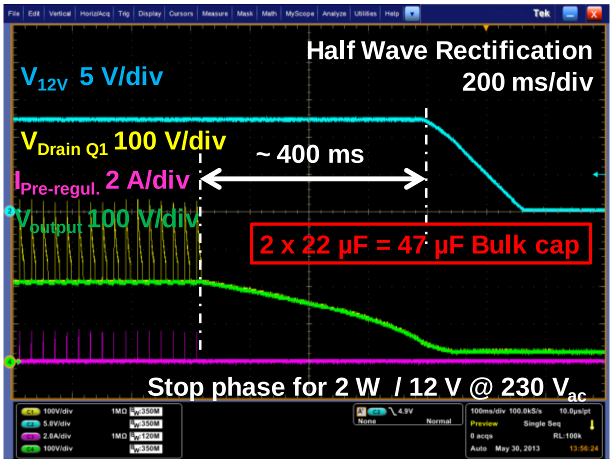


Fig. 6. Hold-up time with a 47-µF bulk capacitor at 2-W output.

To meet this specification, a conventional SMPS solution would require two 100-µF 400-V (16- x 25-mm) type capacitors in series to support the high supply voltage (>600 V). In contrast, an SMPS using the proposed pre-regulator section will need only a single 47-µF 250-V (12.5- x 20-mm) bulk cap. Looking at the size difference, we should expect the two 400-V type caps to be almost four times the cost of the single 250-V.

The doubling of cost in U.S. dollars for a single 400-V 100-µF cap versus the single 250-V 47-µF cap assumes that the cap used specifies the standard 2,000 hours of operation at 105°C. However, the price difference will be much higher as soon as we move to better cap technology such as 5,000 hours at 105°C or if the capacitor value has to be increased to sustain a longer hold-up time.

Overall System Efficiency

Thanks to the reduced and regulated supply, the post flyback converter will have better efficiency. The high-voltage margin on the switcher power MOSFET will allow a strong reduction of the voltage clamp and the corresponding power dissipation. The higher reflected voltage on the primary side of the transformer will allow 1) a larger primary inductance and reduced primary current and 2) a reduced reverse voltage rating for the secondary diode moving from ultra-fast to schottky with much lower V_F, reduced power dissipation, size and cost.

And since the regulated supply avoids too much on-time and switching frequency variation, too high dv/dt and the corresponding switching losses and EMI, the flyback's switching frequency can be increased to over 100 kHz. This reduces the size and cost of the transformer without impacting the power supply's overall performance.

Because of its low switching frequency and the zero voltage switching, the pre-regulator has very good efficiency, close to 90% with small variations depending on the mains supply and output power.

When the front-end pre-regulator is tested with a classical SMPS with wide input range (90 to 264 V ac) and 12-V, 10-W output (rather than an SMPS redesigned to take advantage of the regulated 200-V supply), the following results are obtained (see Table 1.)

Table 1. "No load" power consumption and overall (pre-regulator + flyback) efficiency.

Pre + fly	No load power consumption	Efficiency			
		1 W	2 W	5 W	10 W
290 V ac	97 mW	66%	71.3%	74.6%	71.4%
264 V ac	82 mW	66%	71.8%	75.3%	73.5%
230 V ac	67 mW	67%	72.4%	76.2%	74%
180 Vac	55 mW	68%	72%	79%	77%
150 V ac	43 mW	74%	77.5%	77%	81%
90 V ac	29 mW	77%	79%	75%	74.4%

If those results are very similar to current solutions obtained with a high-voltage power MOSFET or cascode solution, a redesign of the flyback converter to take advantage of a regulated 200-V supply should provide an efficiency improvement of approximately 5% with additional cost reduction.

Application Example

To simplify the design and demonstrate the flexibility of the pre-regulator solution, a demo board has been developed to be interconnected to an existing classical wide-range 10-W flyback SMPS as shown in Fig. 7.

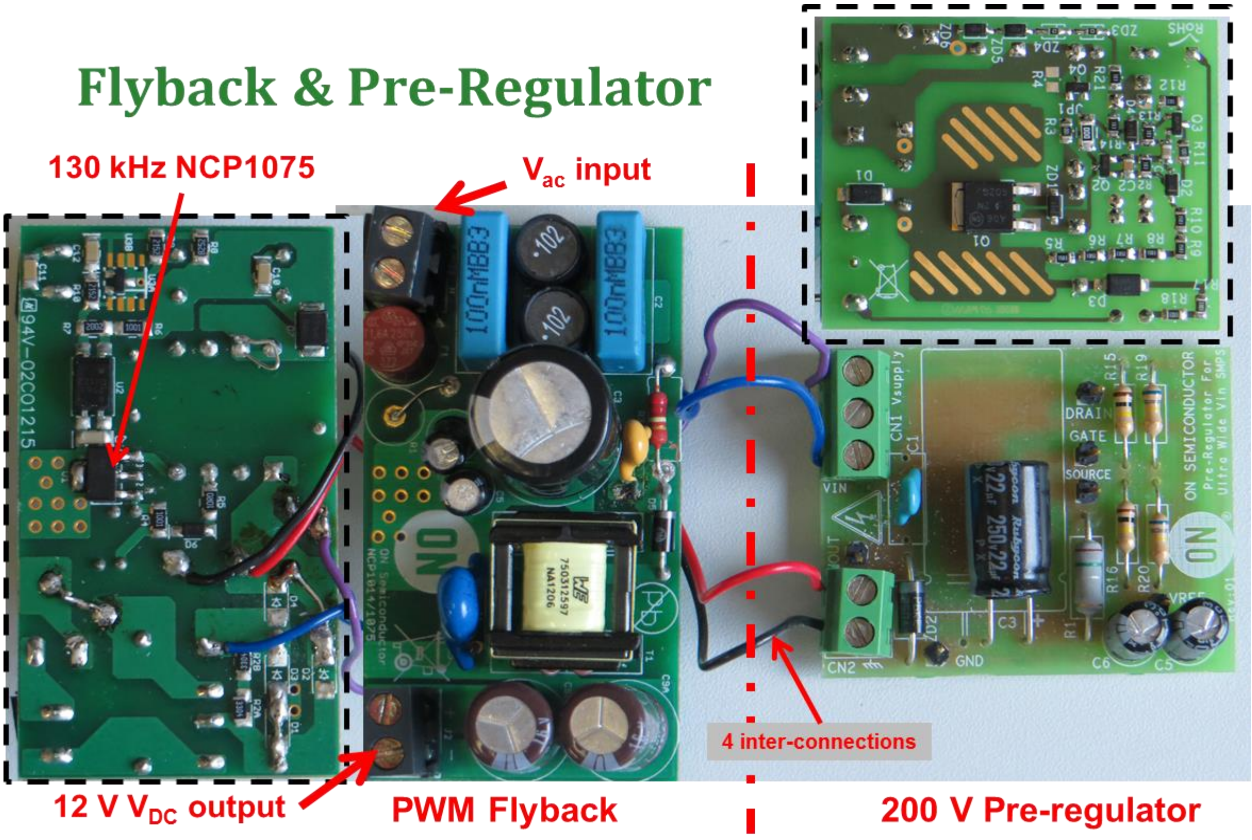


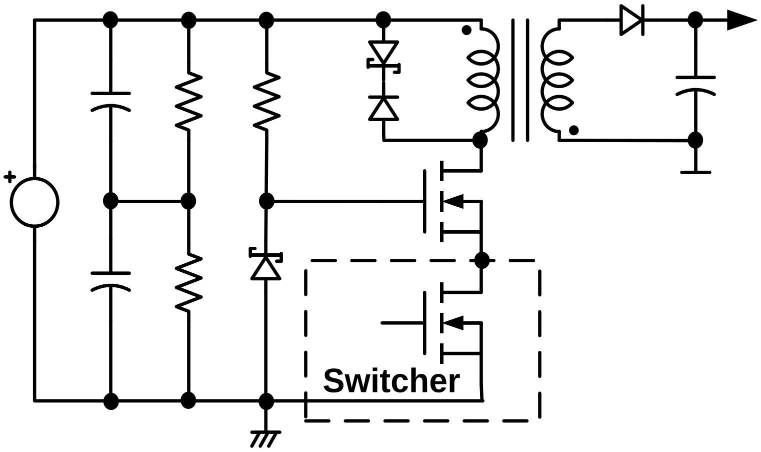
Fig. 7. Modified existing 10-W flyback SMPS with added new pre-regulator submodule. The bottom sides of the PWM flyback board and the 200-V pre-regulator board are shown in the dotted lines.

Limited modification of an existing SMPS design with four-wire interconnections allows the new pre-regulator to be connected. In this modified design, two bulk capacitors are connected in parallel while only a single may be used in the final design implemented on a single board.

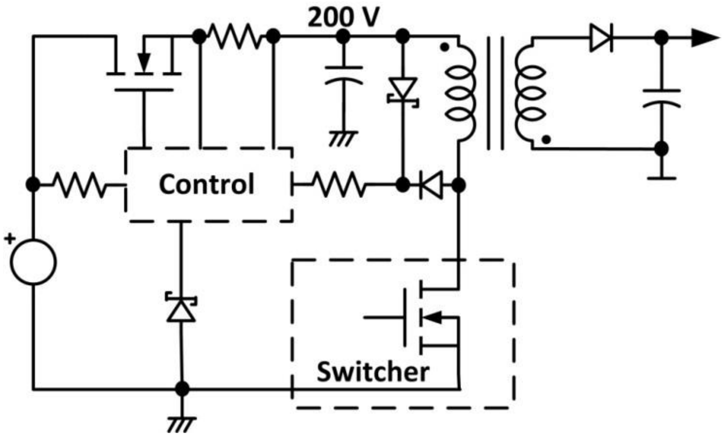
The 50-mm x 40-mm pre-regulator's PCB is "oversized" to allow a larger bulk capacitor when needed. The small DPAK power MOSFET has some PCB surface used for cooling. Multiple resistors have been used in series with each other in order to use standard resistance values and to keep voltages below 50% of the maximum limit to avoid any reliability issues.

Cost Comparison For Both Solutions

The comparison here is with the previously discussed cascode solution, which is considered as the classical solution (state of the art) to be used for such a high-voltage supply (Fig. 8.) To simplify the overall cost study, we will focus on the differences between the pre-regulator and cascode concepts, ignoring the calculation of costs for any parts or functions that are common to both approaches.



(a)



(b)

Fig. 8. The cascode (a) and pre-regulator (b) solutions.

Starting from the mains supply side, we find that the main input fuse, EMI filters and diodes rectifiers are not considered similar for both. For the cascode, two bulk capacitors should be connected in series with correct voltage balancing and an inrush current limiter with a small added circuit (consisting of resistors and zener diodes as listed in Table 2) allowing correct control of the added power MOSFET. For the pre-regulator solution, we don't need those components, using more standard control parts instead.

For the flyback SMPS, if both solutions can use the same fully integrated switcher, then—due to the reduced supply voltage—the pre-regulator solution will allow a reduction in the size of the transformer. It will also reduce the reverse voltage requirement for the secondary diode, allowing use of a lower-voltage schottky. This leads to a cost savings of ~$0.04.

As both the power MOSFET and integrated switcher are similar for the cascode and pre-regulator designs, we will not take them into account for cost comparison. The output capacitors, V_{CC} supply, and secondary output voltage regulation circuit are also not considered as they are similar for both.

Detailed Bill Of Materials And Function Costs

While the design of the overall circuit does not vary much according to the power to be delivered, the bulk capacitors are strongly linked to the application and their specifications are determined largely by the required hold-up time. For this reason, we will consider the impact of the bulk capacitors' cost on the overall cost in a later step, allowing fine tuning according to the application's hold-up time specifications.

Despite the higher number of parts in the pre-regulator design, the BOM cost comparison shown in Table 2 reveals that even without considering bulk capacitors, a cost saving of $0.05 is achieved with the new pre-regulator solution compared to the original cascode.

Table 2. BOM and cost comparison of cascode and pre-regulator solutions (without bulk capacitors, power MOSFET and high-voltage switcher) for the high-voltage power supply.

Function	Cascode + 700-V switcher	200-V voltage regulator
	Description	Description
Input fuse		
EMI filters		
Bridge diodes		
Input capacitors	4 x Y µF 400-V 105°C X khours	
Voltage balancing	2 x 470 kΩ ½ W	
OVP/cap shortage	2 x P6KE450A	
Inrush limiter	1 x 1OR NTC	
Pre-regulator		1 x CC 2.2 nF 1 kV
		2 x CE 1 µF 450 V
		NDD2N60ZT4G/DPAK
		2 x 100-V zener
		10 x RCF
		2 x CPM
		3 x BC847/857
		1 x 16-V zener
		2 x 1N4148
		1 x RW 0.12R/1 W
		TVS diode, 600 W
Input capacitor		2 x Y µF 250 V 105°C X khours
Cascode circuit	NDD02N60ZT4G/DPAK	
	2 x 470K ½ W	
	1 x P6KE450A	
	1 x 16-V zener	
Total pre-regulator	$0.314	$0.302
Post regulator	700-V monolithic switcher	700-V monolithic switcher
Transformer	Added cost for HV	
Secondary diode	Added cost for HV	
Total pre-regulator	$0.04	
Total solution	$0.354	$0.302
Savings for regulator versus cascode (without input cap)		$0.052

Impact Of Hold-up Time Specification On Bulk Capacitors

As explained above, the hold-up time will require oversized bulk capacitors, keeping energy stored and avoiding too fast a drop in output voltage after the mains voltage is turned off.

The simple equation $\frac{1}{2}C * (V_0^2 - V_F^2) = (P_{OUT}/Eff.) * t$ defines the right value of capacitors for any application. In the case of the pre-regulator, V_0 is always equal to 200 V, while for the cascode solution this value is directly linked to the value of the mains supply voltage before it is turned off.

For the lowest mains supply of 180 Vac, the voltage V_0 stored on bulk capacitor will be limited to 200 V for the pre-regulator but not limited for the cascode. In the cacode case, V_0 will be higher—up to 250 V. This higher voltage V_0 (250 V versus 200 V) allows smaller bulk capacitors C for the cascosde solution (assuming that $\frac{1}{2}C * V_0^2$ is the same for both solutions with larger ripple for the reduced cascode’s capacitors.)

And while the peak power could be up to 10 W for e-meter applications, the hold-up time is generally defined for much lower power levels (between 4 W and 2 W). Table 3 compares the bulk capacitor requirements of the cascode and pre-regulator solutions as a function of the two given power levels and the specified hold-up times. (Hold-up times are allowed to vary slightly to accommodate standard capacitor values.)

Table. 3. Impact of output power and hold-up time requirements on input bulk capacitor values for cascode and pre-regulator solutions. Minimum hold-up time at 180-V supply with 75% overall efficiency and 80%/min bulk capacitor C.

Output P	Function	Small bulk capacitors			Medium bulk capacitors			Large bulk capacitors		
2 W		Description	C (µF)	t (ms)	Description	C (µF)	t (ms)	Description	C (µF)	t (ms)
	Cascode input capacitors	2 x 33 µF 400 V	13	138	2 x 47 µF 400 V	19	202	4 x 33 µF 400 V	26	276
	Pre-reg input capacitor	1 x 22 µF 250 V	18	132	1 x 33 µF 250 V	27	198	1 x 47 µF 250 V	38	279
4W		Description	C (µF)	t (ms)	Description	C (µF)	t (ms)	Description	C (µF)	t (ms)
	Cascode input capacitors	2 x 33 µF 400 V	13	69	2 x 47 µF 400 V	19	101	4 x 33 µF 400 V	26	138
	Pre-reg input capacitor	1 x 22 µF 250 V	18	66	1 x 33 µF 250 V	27	99	1 x 47 µF 250 V	38	139

Table 3 allows easy selection and comparison of the hold-up times and capacitor requirements for the both solutions.

For the cascode with “large bulk capacitors,” we are forced to consider two 33-µF caps as 68-µF values are not always available with 400-V ratings or are oversized (height > 25 mm) for e-meter applications.

Even if applications don’t demand a severe hold-up time specification, it could still be critical to reduce the value of the bulk capacitors as the rms current rating of these capacitors needs to be large enough to avoid reliability issues for industrial applications where the expected lifetime is over 10 years.

Impact Of Bulk Capacitors On Overall Application Cost

Following the definition of the bulk capacitors necessary to support hold-up time specifications, we can now consider their impact on the overall application and compare the overall cost of the cascode and pre-regulator solutions.

Despite the limited power level, all bulk capacitors are the 105°C type to avoid any reliability issues and to support over 10 years of expected lifetime under difficult conditions. We assume limited or no cooling, leading to a higher ambient temperature for these capacitors.

As Table 4 demonstrates, even with the smaller bulk capacitors, the pre-regulator solution allows a substantial cost savings—close to $0.50—versus the cascode solution. This is close to the combined cost of the power MOSFET and high-voltage switcher, providing them almost for free. The $0.50 difference, when compared to the total SMPS cost, equates to a cost saving of >15%.

Table 4. Impact of input bulk capacitors on overall solution cost.

Function	Short hold-up T & 2,000 hours 105°C			Medium hold-up T & 2,000 hours 105°C			Large hold-up T & 2,000 hours 105°C		
	Description	Unit	Total	Description	Unit	Total	Description	Unit	Total
Cascode + 700-V switcher input capacitors	2 x 33 µF 400 V	$0.240	$0.480	2 x 47 µF 400 V	$0.290	$0.580	4 x 33 µF 400 V	$0.240	$0.960
200-V voltage regulator input capacitor	1 x 22 µF 250 V	$0.072	$0.072	1 x 33 µF 250 V	$0.100	$0.100	1 x 47 µF 250 V	$0.144	$0.144
Input capacitor savings for regulator versus cascode			$0.408			$0.480			$0.816
Savings: regulator vs. cascode (without input cap)			$0.052			$0.052			$0.052
Total solution savings: regulator vs. cascode			$0.460			$0.532			$0.868

For most e-metering applications, the transfer of data should be done (for a given time) despite a mains off condition. This requires a long hold-up time and correspondingly large bulk capacitors. In that case, the cost difference between both solutions will increase, allowing the pre-regulator to provide a cost savings of $1, which is >20% of the total SMPS cost as shown in table 5 for extended hold-up time using larger bulk capacitors.

Table 5. Impact of input bulk capacitors on overall cost calculation for extra-long hold-up time.

Function	Long holdup T & 2,000 hours 105°C			Extra-long holdup T & 2,000 hours 105°C		
	Description	Unit	Total	Description	Unit	Total
Cascode + 700-V switcher input capacitors	4 x 33 µF 400 V	$0.240	$0.960	4 x 47 µF 400 V	$0.297	$1.188
200-V voltage regulator input capacitor	1 x 47 µF 250 V	$0.144	$0.144	2 x 33 µF 250 V	$0.100	$0.200
Input capacitor savings: regulator versus cascode			$0.816			$0.988
Savings: regulator versus cascode (without input cap)			$0.052			$0.052
Total solution savings: regulator versus cascode			$0.868			$1.040

Impact Of Capacitors' Extended Lifetime On Overall Application Cost

For high-reliability/extended-lifetime products like industrial or e-metering applications, 105°C 2,000-hour electrolytic capacitors may not be enough to guarantee over 10 years' lifetime. (Applications may have to work without any cooling under high ambient temperature.)

As electrolytic capacitors are one of the most critical parts/technologies for overall application expected lifetime, we may need to consider using a better capacitor type despite the cost increase. Moving from a 105°C standard 2,000-hour type to 5,000-hours will allow a doubling of the expected lifetime under the same conditions. Table 6 provides a comparison between 2,000-hour and 5,000-hour electrolytic capacitors focusing on large values/long hold-up time (The difference will increase with larger bulk capacitors.)

Table 6. Impact of input bulk capacitors' extended lifetime on overall solution cost.

Function	Long holdup T & 2,000 hours 105°C			Long holdup T & 5,000 hours 105°C		
	Description	Unit	Total	Description	Unit	Total
Cascode + 700-V switcher input capacitors	4 x 33 µF 400 V	$0.240	$0.960	4 x 33 µF 400 V	$0.320	$1.280
200-V voltage regulator input capacitor	1 x 47 µF 250 V	$0.144	$0.144	1 x 47 µF 250 V	$0.150	$0.150
Input capacitor savings: regulator versus cascode			$0.816			$1.130
Savings: regulator versus cascode (without input cap)			$0.052			$0.052
Total solution savings: regulator versus cascade			$0.868			$1.182

It is very interesting to see that the cost difference between the two solutions is increased by using 105°C 5,000-hour extended lifetime capacitors but more interesting to compare the impact on each application. If, for the cascode we have a large cost increase of $0.32 to get the improved lifetime, the cost is only raised by

$0.06 for the pre-regulator with 250-V capacitors. This shows that, on top of the cost reduction, the pre-regulator could provide an extended lifetime/reliability for almost no cost increase while this modification will be very expensive for the classical cascode solution.

Pre-Regulator And Application Limitations

There are no limitations on supply configurations for the cascode solution. Using standard bridge (half- or full-wave) diode rectification, the post converter will be supplied by the peak voltage stored in the capacitors and fill every cycle through the diodes.

For the pre-regulator, circuit behavior is different. As the solution is controlling the voltage difference between input supply and output bulk capacitor, the ripple of the input supply should be large enough to be at one time of the overall cycle (of the mains frequency) below the output supply (on the bulk capacitor) to allow the next switching cycle. If this is always the case for a single-phase supply with half-wave rectification, this is much more critical for a three-phase supply and/or full-wave rectification with much-lower ripple on the input supply.

An alternative approach is to provide a higher bulk voltage supply: Moving up the regulation to 350 V allows a "higher min" input supply (a supply with more phases or full-wave rectification.) This will reduce the cost difference between the pre-regulator and cascode solutions as a single 400-V bulk capacitor is now required with the pre-regulator solution.

The bulk voltage will follow the mains supply until the clamp, limiting the post flyback converter supply to ~350 V even under line fault conditions (similar to standard wide range applications.) This modification can easily be made by adjusting the values of the added zener diodes ZD3 and ZD4 (see pre-regulator schematic in Fig. 2) to raise the reference voltage to the requested value. Table 7 below lists the various possibilities, from one- to three-phase supplies, with or without neutral connection, and with half- of full-wave rectification.

Table 7. Options for accommodating ac line connections up to three phases and the corresponding limitations of the pre-regulator solution.

SMPS ac line connections	Bridge rectification	V dc	Pre-regulator output (V)	Output bulk capacitor	Results
Three phase	Full wave	620	N/A	2 x 400 V min	Cascode approach
	Half wave	330	350 V	1 x 400 V	OK
Three phase with only 2 connected	Full wave	620	350 V	1 x 400 V	OK
Three phase without neutral	Full wave	620	N/A	2 x 400 V min	Cascode approach
	Half wave	0	N/A	N/A	No dc supply available
Three phase with neutral connected to one phase	Full wave	620	350 V	1 x 400 V	OK
	Half wave	610	200 V	1 x 250 V	OK
Single phase	Full wave	330	350 V	1 x 400 V	OK
	Half wave	330	200 V	1 x 250 V	OK
Single phase with neutral connected to second phase	Full wave	620	350 V	1 x 400 V	OK
	Half wave	620	200 V	1 x 250 V	OK

Given these requirements and limitations, the preferred solution for the pre-regulator is the single-phase supply with half-wave rectification. This configuration allows very good performance with the input supply always below the output supply during a minimum time to reset the control circuit. The half-wave rectification is not an issue for this power level, enabling use of the 250 V-capacitor.

Conclusion

The 200-V pre-regulator acts like an ultra-efficient LDO, and can be use with any type of flyback SMPS. However, overall power should be kept below 15 W to avoid excessive peak current on the mains supply. Otherwise, full-wave rectification may be required raising the output voltage to 350 V.

However, when designed for less than 15 W with half-wave rectification, this solution will support any incorrectly connected supply (such as two phases reversed) with input to the downstream flyback converter maintained at 200 V. This solution simplifies the design of the flyback converter, while enabling very good performance with better efficiency (~5%) than the cascode solution for the intended power range with very good safety (including the case of the shorted bulk capacitor.) The solution is particularly attractive for e-metering applications as well as an auxiliary supply for white goods or industrial applications.

With its ability to operate using just a single bulk capacitor at a reduced voltage, the pre-regulator solution provides a large cost savings in the range of 15% to 20% (up to $1 US) versus a standard cascode-based design, depending on the requested hold-up time.

This pre-regulator solution contains ON Semiconductor’s intellectual property. But as noted previously, the company is offering royalty-free use of this IP for customers that purchase its PWM controller/regulator/MOSFET.

References

1. “Pre-Regulator Design Protects High-Voltage Power Supplies From Phase Faults (Part One),” by Jean-Paul Louvel, How2Power Today, January 2015 issue.

2. “Pre-Regulator for High Voltage Supply,” ON Semiconductor application note AND9172 by Jean-Paul Louvel.

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.