How to limit PFC re-rush current

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Introduction

The recently released Modular Hardware System – Common Redundant Power Supply (M-CRPS) specification [1] requires the re-rush current (which is different from the well-known inrush current) needs to be limited when the input voltage resumes after an input brownout or blackout event on the power supply used in data center. Previously, this re-rush current was unspecified, and no special control action for this event existed. In this article, I'll present a low-cost, simple and very effective method to meet the M-CRPS requirement.

Inrush current vs. re-rush current

Power factor correction (PFC) is required for front-end power supplies (PSUs) greater than 75W. PFC forces the input current to follow the input voltage so that the electronics load appears as a resistor. PFC usually has a large output capacitor. Before startup, the PFC output capacitor is fully discharged. Because the PFC structure provides a current path when $V_{AC} > V_{OUT}$, applying the AC voltage will generate a huge current, since the input voltage is essentially applied to the PFC output capacitor directly. This current is called the inrush current.

Placing a thermistor (R_T) with a positive temperature coefficient and a mechanical relay at the PFC input side will limit the inrush current, as shown in **Figure 1**. During PFC power up, the relay is off. The inrush current is limited by R_T to a low value, and the PFC output bulk capacitor (C_{BULK}) charges gradually. Once the output voltage (V_{OUT}) charges to equal the peak value of the AC voltage (V_{AC}), the inrush current drops to 0. Then the relay turns on, with R_T bypassed to reduce power losses during normal operation.

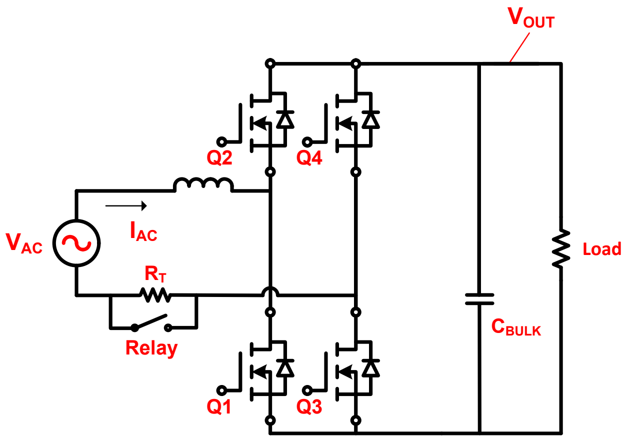

Figure 1. *Using R_T and a relay to limit the PFC inrush current.*

Re-rush current is different; it occurs during normal PFC operation. As shown in **Figure 2**, the AC input voltage suddenly drops out when PFC is operating normally. Since the load is still applied, the PFC V_{OUT} could drop to a lower value. Then when the AC voltage returns, if the AC input voltage is higher than V_{OUT}, there will be an inrush current again. This current is called the re-rush current.

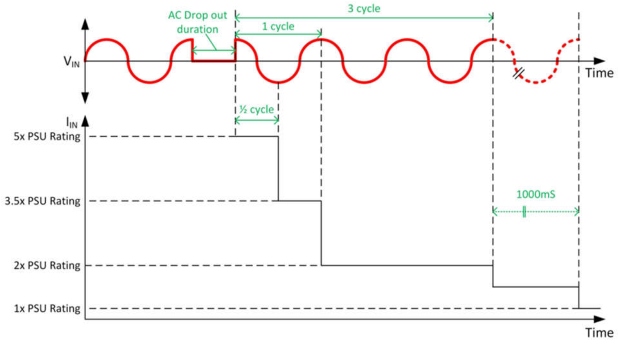

Figure 2. *M-CRPS re-rush current limit and timing.*

Previously, it is solely relies on the power stage components' ability to handle the re-rush current. Test results show that the re-rush current can jump to more than 10 times higher than the PFC-rated maximum input current. Such a high re-rush current can either damage the power supply or reduce its lifetime, which is why the M-CRPS specification limits the amount of re-rush current after the AC voltage returns. The root-mean-square value of the re-rush current should be less than five times the maximum PSU current rating ($5 \times I_{rated,RMS}$) over a half cycle of input frequency, and less than $3.5 \times I_{rated,RMS}$ over one cycle of input frequency. In addition, the input current should settle to a value $\leq 2 \times I_{rated,RMS}$ within two cycles of the input frequency after applying the AC input.

It gets more complicated when considering PFC pulse-width modulation (PWM) operation during this period. If the PFC is not well controlled, an inappropriate PWM duty cycle may occur when the AC voltage resumes, resulting in another large input current spike that may also exceed the M-CRPS specification.

On the other hand, when the AC voltage resumes, PFC needs to supply enough current to boost the PFC output voltage to its regulation level as soon as possible; otherwise, V_{OUT} will keep dropping because of the heavy load and eventually trip the input undervoltage lockout level of the DC/DC converter. Charging the PFC output capacitor once the AC voltage resumes will require a large input current, either from re-rush when $V_{IN} > V_{OUT}$ or from the PFC control loop when $V_{IN} < V_{OUT}$.

This paper provides a solution to handle this re-rush current so that when the AC voltage comes back from dropout, both the re-rush current (when $V_{IN} > V_{OUT}$) and the non-re-rush current (when $V_{IN} < V_{OUT}$) are well controlled and high enough to rapidly boost V_{OUT} but not exceed the M-CRPS limit specification.

Proposed re-rush current control method

Figure 3 illustrates the proposed low-cost re-rush current control method. There are two differences compared to Figure 1. First, R_T has moved from the AC side to the DC side. Second, a metal-oxide semiconductor field-effect transistor (MOSFET), Q_5, has replaced the traditional mechanical relay. The reason to choose a solid-state relay is that you need to rapidly turn the relay on and off, and a mechanical relay is too slow for this purpose. Also, because the MOSFET cannot turn off the AC voltage, it is put on the DC side. The inrush current limit works the same as the traditional method. The first time that the input voltage is applied to the PSU, R_T will limit the inrush current. Once the inrush current passes, Q_5 turns on and R_T is bypassed.

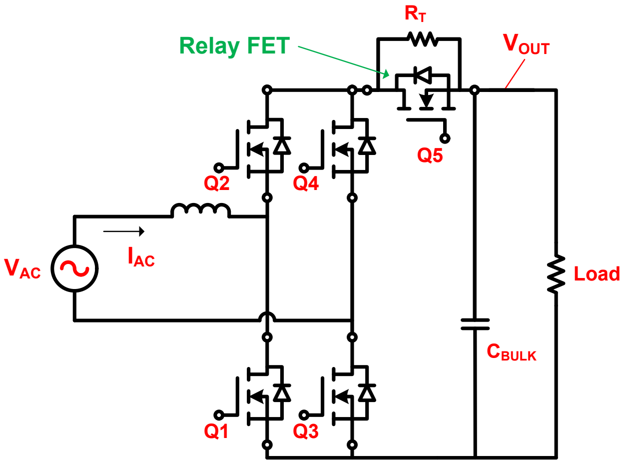

Figure 3. The proposed re-rush current limit hardware structure.

Figure 4 illustrates the proposed re-rush current control method. V_{AC} is the PFC input voltage, V_{OUT} is the PFC output voltage, and I_{AC} is the input current. Q_1 and Q_2 are high-frequency switches that work as either a PFC boost switch or a synchronous switch alternatively in each AC half cycle. The AC line drops for a period of 10ms and then comes back at its peak while the PFC operates at full load. This is the worst case for AC voltage dropout.

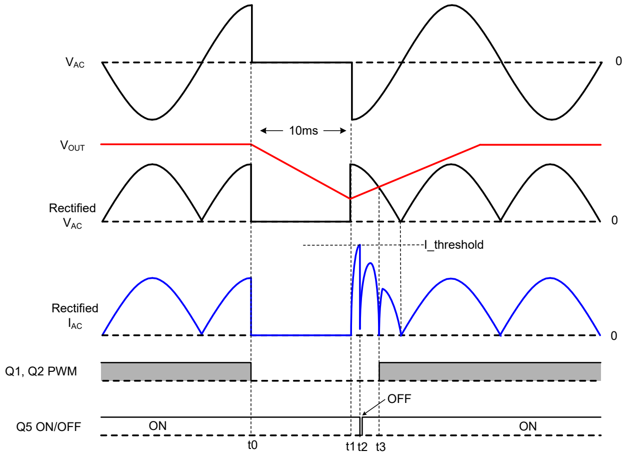

Figure 4. The proposed AC drop and re-rush current limit control algorithm.

This is the proposed re-rush current control method:

- At t_0: Upon detection of an AC voltage drop, Q_1 and Q_2 turn off. You must also turn off both the PFC voltage and current loops because if the voltage loop and current loop keep running, their integrators will accumulate. When the AC voltage comes back and PFC turns on, a large PWM duty cycle will then be present, resulting in a large current spike that may damage the power supply.
- Once the current loop is turned off, reset it to 0 and clear its integrator history. If you do not clear the integrator, when the AC voltage comes back and PFC turns on, PFC will turn on with the same PWM duty cycle before the AC voltage drop, and it may not be the appropriate duty cycle. For example, if the AC voltage dropout occurs at zero crossing, the PWM duty cycle is almost 100%. If the AC voltage comes back at the AC peak without a cleared current-loop integrator, an almost 100% duty cycle will occur at the AC peak and generate a large current spike, which could damage the power supply. For the voltage loop, once it turns off, freeze it to keep its internal value. The voltage loop output represents the load and is used for current loop-reference generation; therefore, you want to keep its value so that the load does not change during AC dropout.
- At t_1: The AC voltage returns. Because $V_{AC} > V_{OUT}$, a generated re-rush current will charge the bulk capacitor. Q_1 and Q_2 remain off.
- At t_2: The re-rush current exceeds a programmable threshold and trips a relay Q_5 turnoff event. The re-rush current is then limited by R_T when Q_5 is off, and its magnitude rapidly drops. Relay Q_5 only turns off for a very short period of time (for example, 10µs), then turns on again. Once Q_5 turns on, the re-rush current rises again until it exceeds the threshold. This process repeats until the re-rush current never exceeds the limit again. Figure 5 shows the flow chart for this process.
- At t_3: $V_{AC} < V_{OUT}$. Now it is time to turn on PFC. Set the voltage loop reference equal to the instantaneous V_{OUT} value at t_3, then turn on the voltage loop. After that, gradually increase the voltage loop reference until it reaches the normal setpoint. For the current loop, first calculate a duty cycle $D = (V_{OUT} - V_{AC})/V_{OUT}$ and inject it into the current loop such that the current loop output starts from the calculated D when the current loop is on. Then turn on the current loop. Finally, turn on Q_1 and Q_2 to allow PFC normal operation.

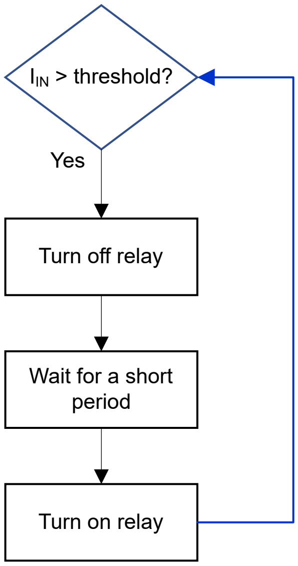

Figure 5. *Flowchart of the proposed relay on and off control algorithm.*

This process repeats until V_{OUT} exceeds V_{AC}.

Test result

I tested the proposed method on a 3.6kW totem-pole bridgeless PFC [2]. Figure 6 shows that when the AC voltage drops out, it comes back in 10ms at its peak. Channel 1 (blue) is the PFC input current waveform (I_{IN}), while channel 2 (turquoise) is the relay on and off control signal. Figure 7 is the zoom in at relay on and off. During the AC drop period, relay Q_5 remains on. C_{BULK} continuously delivers the stored energy to the load and V_{OUT} drops. After the AC voltage resumes, because the relay is on and $V_{AC} > V_{OUT}$, the re-rush current quickly rises. Once the re-rush current reaches a predefined current limit threshold (40A in this example), the relay turns off, and the re-rush current reduces to a very low value because of R_T. The relay only remains off for 10µs, then turns on again. The re-rush current rises once again. This entire process allows the limiting of re-rush current within the M-CRPS specification while still supplying substantial current to rapidly charge C_{BULK}. The waveform also shows that the non-re-rush current, where $V_{AC} < V_{OUT}$, is well controlled without large current spikes.

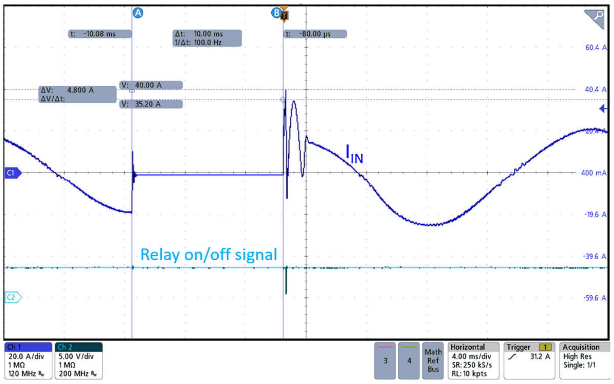

Figure 6. *Re-rush current control when the AC voltage resumes after dropout.*

Figure 7 shows the second re-rush current rising up with a limited slope, which occurs because the PFC input impedance – including the electromagnetic interference filter impedance and printed circuit board trace impedance – limit the current rising slope. The magnitude of the second re-rush current does not exceed the 40A threshold in this example; therefore, the relay turns off only once. If the second re-rush current also exceeds the threshold, the relay will turn off again.

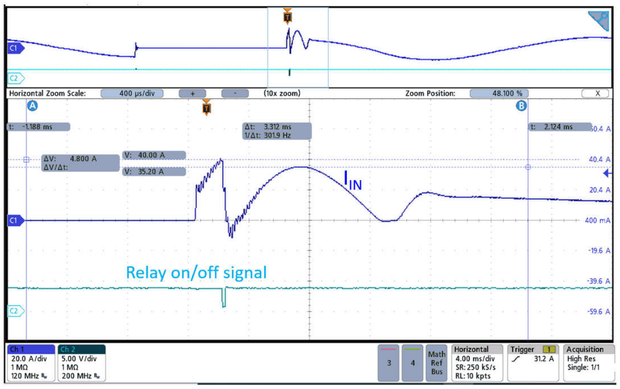

Figure 7. *Zoomed-in Figure 6 at the relay on and off instant.*

Conclusion

The power supply used in data centers requires the re-rush current when the AC voltage resumes from dropout should not exceed a limitation defined in M-CRPS specification. By replacing the traditional mechanical relay with a solid-state relay, and rapidly turn off/on the relay when re-rush current exceeds a programmable threshold, the re-rush current can be well controlled to not exceed the M-CRPS limit specification but high enough to rapidly boost V_{OUT}. Moreover, this firmware-based method leverages the existing R_T, resulting in a low-cost and very effective re-rush current control solution.

References

1. **Modular Hardware System – Common Redundant Power Supply (M-CRPS) Base Specification**. Version 1.05 RC5. Open Compute Project: Austin, Texas, Sep. 25, 2024.
2. Texas Instruments. n.d. **3.6kW Single-Phase Totem-Pole Bridgeless PFC Reference Design with E-Meter Functionality**. Texas Instruments reference design No. PMP23338. Accessed March 24, 2025.

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