ISSUE: September 2025

Energizing Output Filter Inductor Enables Instantaneous PSU Activation

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Any regulated power converter incorporates an output LC-filter as an integral element, pulling out the dc component from a voltage waveform input with both ac and dc components. Ramping up the filter inductor current or capacitor voltage at the initial start-up of the converter is associated with an increase of the energy stored in these components. However, this cannot be done instantly, because such an action would require a source of infinite power, which is not physically realizable.

Even accelerating the charge of LC-filter components can lead to large transients that can overstress the converter's active components. That is why conventional PSUs use a so-called soft start,[1] which produces a gradual increase of pumped energy over time. The soft start "slowly" dispenses the additional energy needed to charge output filter caps and to smooth the process of resonant energy exchange between the filter components.

Normally, the soft-start time exceeds the output LC resonant ac cycle by an order of magnitude, and a typical converter transition into steady state takes up to a few tens of milliseconds. However, in already energized systems with a redundant or backup power delivery architecture, this time can be shortened by using a capacitor pre-charge method employed in cold redundant power distribution arrangements.[2]

A cold redundancy technique[2] can also be used to wake up a battery backup module, allowing for accelerated redundant power supply wake-up using an active PSU "dc fault" signal. The cold redundancy method is based on the concept that output capacitors are pre-charged to their steady-state voltage levels either from an output common dc bus or other active (e.g., standby) low-power source. In this non-resonant transition case, a soft start (gradual operating duty cycle increase) is not required, as only the filter inductor needs to be charged to the current matching the current consumed by the load.

The process of inductor current ramping in such a power delivery arrangement was discussed in detail in reference 2. As shown in reference 2, faster activation of a backup or redundant power stage with a precharged output cap allows for a narrower converter operating input voltage range and, consequently, results in a higher efficiency of the PSU dc-dc stage.

Although a full power stage activation in this case typically lasts a few hundred microseconds, which is orders of magnitude faster than in the soft-start modes, the usage of this technique still requires much larger dc bus capacitor values than would be needed in the "ideal" instantaneous wakeup case. Such an increase of the cap value is driven by the requirement of keeping the dc bus voltage within regulation limits during the finite off-on transition time intervals.

To overcome that limitation, this article discusses the opportunity to "precharge" the output filter inductor along with the output capacitor, to further accelerate the module activation process and achieve virtually instantaneous power converter wakeup.

Potential Benefits Of Instantaneous Backup PSU Activation

A backup or redundant power supply is a PSU module that provides seamless power delivery during ac interruptions in the primary electricity source, or when an active power supply module fails. Redundant and backup power delivery architectures are widely used in industries like IT, banking, and manufacturing, where even a brief power disruption or fluctuation can result in significant losses. Thus, a backup PSU capable of instantaneous activation ensures continuous, reliable system operation, which makes it a critical component in protecting sensitive equipment.

To provide such seamless power delivery, backup or redundant PSUs use sizable input and output caps, allowing for maintaining dc bus voltage within spec ranges, i.e., to ride through transition times when ac power gets interrupted and the power subsystem needs to get power from a UPS or when an active module fails. In many cases, instantaneous activation of a backup module can simplify PSU holdup time requirements, narrow down the input voltage operating range, and increase PSU efficiency.

Let's evaluate how much the dc bus capacitance can be reduced if the linear current ramp characteristic for the capacitor precharged case[2] is replaced by a step function representing instantaneous backup PSU activation. The buffer cap value required to maintain the bus voltage within regulation range depends on the amp-second area under a cap current waveform $i_C(t)$ plotted over the ramp time interval. At the maximum load current level it can be determined as follows:

$$C = \frac{1}{\Delta V}\int_0^T i_C(t)dt = \frac{1}{\Delta V}\int_0^T I_{L.max}(1-\frac{t}{T})dt = \frac{I_{L.max}T}{2\Delta V},$$

where T is the ramp duration, $I_{L.max}$ is the maximum load current, and ΔV is the allowed supply voltage sag during module activation.

If, for example, for the 12-V dc bus $I_{L.max} = 100\,A,\ T = 300\,\mu s,$ and $\Delta V = 400\,mV$, the cap value required for seamless active-backup module transition is: $C = 37500\,\mu F$. This cap must be placed either inside the PSU module or on the load side (common dc bus). In many cases, it may be considered beneficial to eliminate such a sizeable buffer cap for size and cost reduction**.**

Charging The Inductor

By definition, if the initial conditions of a circuit containing energy-intensive components are set to match the steady-state values, the excitation transient gets eliminated. In this case, the module is in equilibrium at the start, the natural response (a.k.a. the self-response) becomes zero, and no transient behavior (which the natural response describes) is triggered. This means that the module can be transitioned into an active state virtually instantly without any overstress.

To provide this condition, energy-intensive converter components in the power delivery path (L and C) must be energized before startup. As mentioned above, output capacitors can be pre-charged to their steady-state voltage levels either from a common bus or another active (e.g., standby) low-power source. Such a precharge is not associated with any noticeable power dissipation.

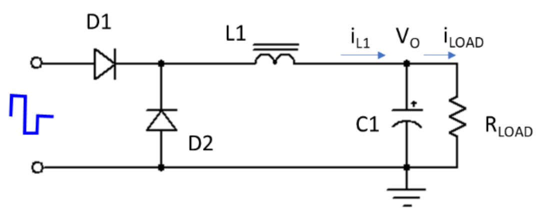
On the other hand, charging the inductor positioned in the main dc power flow path may require significant power to perform this function. Concerning an inductor, energizing this component essentially means the formation of a magnetic field in its core and storing steady-state-level energy within that field.

Let's take a closer look at the filter inductor precharge options using, as a model, a simple forward converter output network (Fig. 1a) representing the vast majority of converter topologies used in such applications.[1] To store energy in the inductor by directly making the inductor L1 current in Fig. 1a reach the I_{LOAD} level (Fig. 1a) before the module starts would require a sizable high-power-rated converter, which is impractical due to the impact that would have on energy efficiency. That is why energizing this component makes it relevant to consider a different approach, which would permit achieving this goal with much lower power.

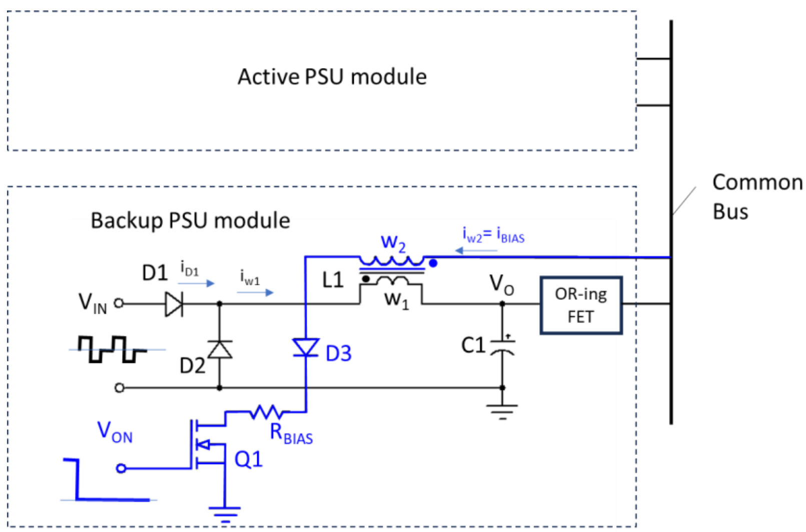
The power required to charge the inductor can be significantly reduced by using a control winding positioned on the same magnetic core. Such a winding could generate the same magnetizing force in the inductor core as does the main winding in a steady state. A magnetizing force created by the current flowing through this control winding can shift the core operating point to the position on the B-H curve corresponding to the current i_{L1} (Fig. 1a) flowing through the main inductor winding. In that case, interrupting the control current at turn-on will generate an EMF across the windings and automatically transfer the energy stored in the core magnetic field to the only available main power delivery path.

The example network realizing such an inductor precharge technique is shown in Fig. 1b. In this circuit arrangement, inductor L1, in addition to the main winding w1, is provided with a control (bias) winding w2 ($w_2 >> w_1$). When the backup module is inactive, a dc bias current i_{BIAS} flows through this winding, causing the core operating point to shift to the position on the B-H curve corresponding to the current level in the inductor winding w1 that it would reach in the active state. That is, if the current through w1 $i_{w1} = I_{LOAD}$, the required bias current level can be determined from the magnetizing forces equality condition ($I_{LOAD}w_1 = I_{BIAS}w_2$):

$$\boldsymbol{I_{BIAS}} = \frac{\boldsymbol{I_{LOAD}w_1}}{\boldsymbol{w_2}} \qquad (1)$$



(a)



(b)

Fig. 1. Forward converter output networks. Conventional (a) and with an added inductor precharging circuit (b), allowing for energy storage in the inductor magnetic field and providing instantaneous backup module activation.

In the diagram in Fig. 1b, this current is supplied by the active module generating dc power on the common dc bus. The bias current generating network can be implemented in many different ways by making the bias current follow the load current, using a separate i_{BIAS} current source operating in a switch mode, etc.

In the given linear bias network example, illustrating the use of the method, the bias current flows through diode D3, R_{BIAS} setting its value, and a closed switch Q1.

At the time the backup module gets activated and generates the first voltage pulse leading edge at the input to the output circuit (V_{IN} in Fig. 1b) the switch Q1 turns off and the energy stored in the core magnetic field gets transferred to the main power delivery path. Thus, when the first V_{IN} voltage pulse is applied to the filter input, both filter components appear to be fully energized—the inductor current is equal to the load current, and the cap voltage, neglecting the switching frequency ripple, remains equal to the nominal level. Timing diagrams illustrating the module activation process are shown in Fig. 2.

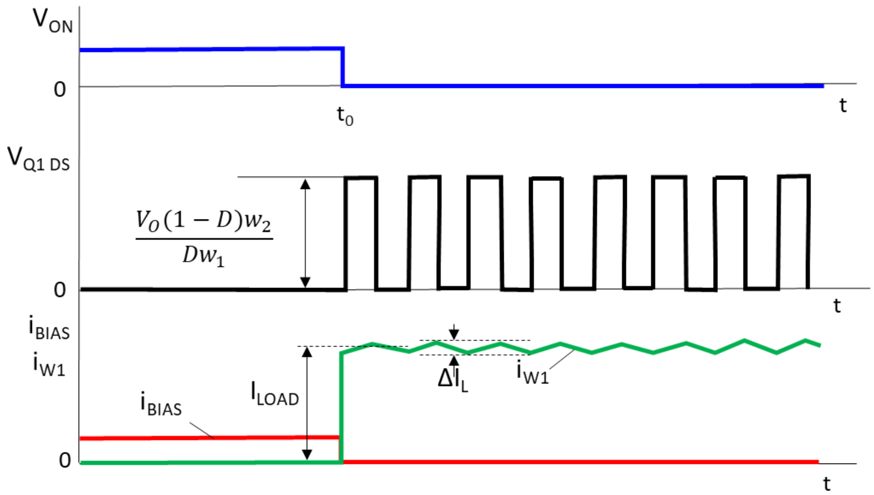


Fig.2 Theoretical timing diagrams of voltages and currents in the forward converter output network in Fig.1b providing instantaneous backup module activation.

Initially, V_{ON} (blue trace in the top diagram) level is high, which keeps switch Q1 in the on state ($V_{Q1DS} = 0$), the current through winding w2 (red trace in the bottom diagram) has reached its steady state level i_{BIAS}. At the module activation time (t_0), Q1 turns off, and the energy stored in the inductor gets released through the winding w1, injecting current into the main power delivery path.

If the bias current is set at the (I_{LOAD} - $\Delta I_L/2)w_1/w_2$ level, where ΔI_L is the inductor current ripple (Fig. 2), and V_{IN} is positive, this current flows through diode D1, making filter components operate in a steady state starting right from the moment t_0. The closer the bias current is to this level, the smoother the transition to the steady state.

The positive voltage magnitude generated across the switch is equal to

$$V_{Q1DSmax} = \frac{V_O(1-D)w_2}{Dw_1},$$

where D is the operating duty cycle of the pulses V_{IN} generated at the circuit input. The higher the w_2/w_1 ratio, the lower the bias power needed (equation(1)) to enable this technique, but the higher the voltage the switch needs to withstand.

Diode D3 blocks the reverse current flow and reversed polarity voltage across the switch, which prevents the influence of the bias circuit on converter operation when voltages across the inductor windings change polarity. The presence of this diode is especially critical if the switch turn-off lags the rising edge of the first positive voltage pulse generated at the filter input. In such a case, the closed switch Q1 on the "secondary" (w2) side of the inductor will shunt the "primary" (w1) side and cause a current spike in the main power delivery path.

In Fig.2, the switch turns off coincidentally with the rising edge of the first positive voltage pulse. In practice, it's appropriate to turn off Q1 up to one period of the switching cycle before V_{IN} sees voltage input.

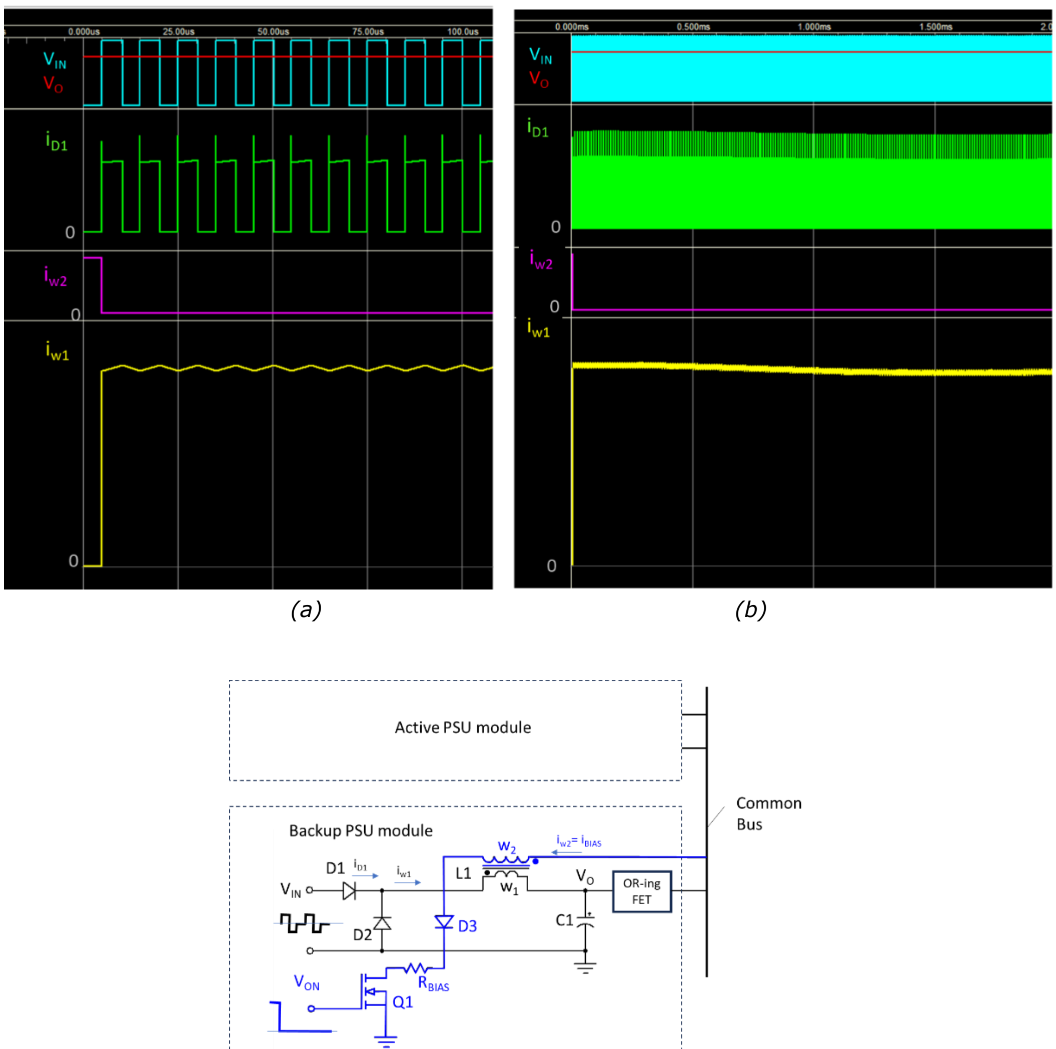
$$t_0 - T_{SW} \leq t_{OFF} \leq t_0$$

where T_{SW} is the switching frequency cycle.

Simulation Results

The goal of the conducted simulations was to verify whether the proposed technique can further accelerate the module activation process as compared to using just the cap precharge option.

Simulations were performed using a SPICE program on a 12-V, 100-A converter operating in continuous conduction mode with L_1 = 20 µH, C_1 = 10 mF, and switching frequency =100 kHz (the proposed precharge circuit is repeated below in Fig. 3c for the reader's convenience). The simulation results are shown in Fig. 3a and b for microsecond and millisecond time scales, respectively. These results demonstrate no transient, no output voltage glitches, and instant module availability at the activation time, which appears several hundred microseconds faster than in the cap-only precharging case and which is in good agreement with theoretical predictions.



(a) (b)

(c)

Fig. 3. 12-V to 100-A converter module activation simulation results shown at the microsecond (a) and millisecond (b) time scales. The precharge circuit is repeated here (c).

Implementation Aspects

Although the bias network optimization is not a focus of this paper, there are a few implementation aspects that may be useful to mention. The usage of the proposed inductor precharge technique for the fast activation of redundant or backup modules is most beneficial when the power required for the charging circuitry is minimized. To make the technique energy efficient, the power consumed by the bias network must be considerably lower than the power that would be dissipated in a hot redundant arrangement.

Since the inductor charging time is practically unlimited, the bias circuit power reduction can be achieved in a number of ways. These include lowering the bias current through an increase in the w_2/w_1 turns ratio, using a lower dc supply voltage for the bias circuit generated by a stepdown switching regulator, recycling the bias power back to the common bus, and similar methods. Thus, the actual implementation of the precharge network depends on tradeoffs for achieving required efficiency, size, and complexity.

With large w_2/w_1 turns ratios, the coupling coefficient may be considerably lower than one, and the leakage inductance between the windings may cause an additional voltage spike across the switch (Q1) at the moment t_0, which may require the usage of a higher-voltage-rated component. Alternative solutions include the use of a snubber circuit or eliminating the spike by slowing down the falling edge of the control signal V_{ON} (Fig. 2) and the switch turn-off.

The module will be instantly and fully active whenever the injected current equals or exceeds the steady-state inductor current. The closer the bias current level is to the value determined by equation (1), the smoother the transient associated with the module activation. To eliminate the transient at any current level, the bias current in the backup module needs to accurately mirror the load current.

Conclusions

Switch-mode power supplies used in backup or cold redundant power delivery architectures can benefit from providing the PSUs with instantaneous turn-on. Such a feature can increase their efficiency and reduce dc bus buffer cap size. To achieve this goal, energy-intensive converter components in the power delivery path must be energized before startup. The proposed technique for energizing a filter inductor can accelerate dc-dc converter wakeup, shortening the activation time by several hundred microseconds. It enables the backup PSU, operating in a cold redundant state, to function as a hot redundant module, i.e., to be ready to take over immediately in the event of the active module's failure.

References

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About The Author

Viktor Vogman is currently retired from Power Conversion Consulting where he applied his skills as an analog design engineer specializing in the design of various power test tools for ac and dc power delivery applications. Prior to this, he spent over 20 years at Intel, focused on hardware engineering and power delivery architectures. Viktor obtained an MS degree in Radio Communication, Television and Multimedia Technology and a PhD in Power Electronics from the Saint Petersburg University of Telecommunications, Russia. Vogman holds over 50 U.S. and foreign patents and has authored over 20 articles on various aspects of power delivery and analog design.

For more on power protection in power supply design, see How2Power's Design Guide, locate the "Design area" category and select "Power Protection".