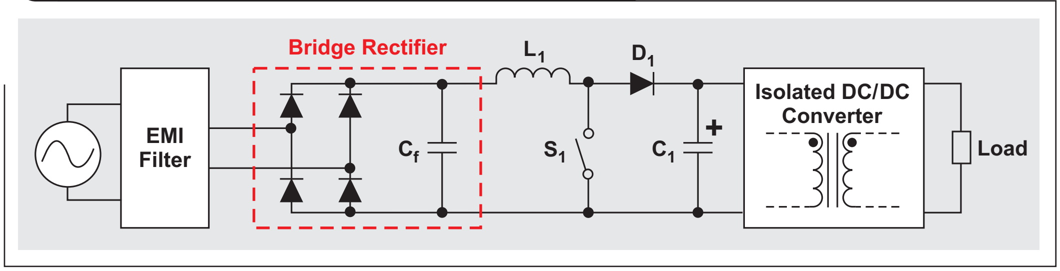
Design a transition-mode, bridgeless PFC with a standard PFC controller

By Sheng-Yang Yu
Application Engineer, Power Design Services

Figure 1. Conventional two-stage power-supply system with high power-factor requirements



Introduction

This article presents design information for using a standard, low-cost, power factor correction (PFC) controller to construct a high-efficiency transition-mode (TM) bridgeless-PFC power supply. Driven by the Northwest Energy Efficiency Alliance's 80 PLUS® program,[1] computer power-supply manufacturers are eager to investigate ways to improve converter efficiency. A standard power-supply system with high power-factor requirements is shown in Figure 1.

The rectified input voltage is boosted to a level higher than the maximum input to ensure that a high power factor is achieved over the whole input range. After the boost PFC, an isolated DC/DC converter steps the boost voltage down through a safety isolated transformer. For a two-stage power supply with 400-W output power, power dissipation of the bridge diodes could go up to 6 W with a full load and the input at 120 VAC/60 Hz. That is a 1.5% efficiency reduction just because of the power dissipation by the bridge diodes. As a result, bridgeless PFCs[2] (a combination of rectifier and boost converters) replace conventional PFCs for better converter efficiency. However, the complexity of bridgeless-PFC control makes its controller more expensive than a standard analog-PFC controller. Additionally, the parasitic capacitance on the bridgeless-PFC MOSFETs creates more electromagnetic interference (EMI) than the conventional PFC.[3]

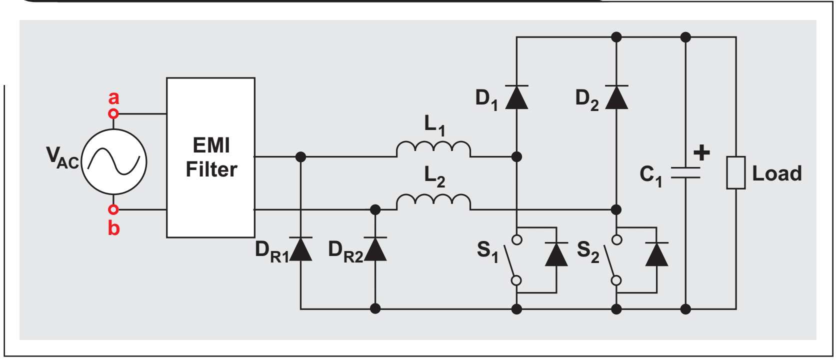
The aforementioned issues greatly increase the cost of a bridgeless PFC circuit. An alternative bridgeless PFC with return diodes[4] is shown in Figure 2.

Slow-recovery return diodes, D_{R1} and D_{R2} in Figure 2, alleviate EMI concerns. Moreover, the same pulse-width modulation (PWM) signal can be used to drive both MOSFETs, which greatly reduces control complexity and controller cost.

This article focuses on the design considerations of using low-cost standard analog-PFC controllers for TM-bridgeless PFCs with return diodes. Two 370-W reference boards were built for performance evaluations with the UCC28051 TM-PFC controller; a TM-bridgeless PFC and a TM-conventional PFC. The results show that over 97% efficiency can be achieved with the TM-bridgeless PFC prototype at 120 VAC, which is about 1% higher than that of the TM-conventional PFC prototype.

Digital controllers such as TI's C2000™ real-time microcontrollers[5] are also widely used for controlling bridgeless PFCs.

Figure 2. Bridgeless PFC with return diodes

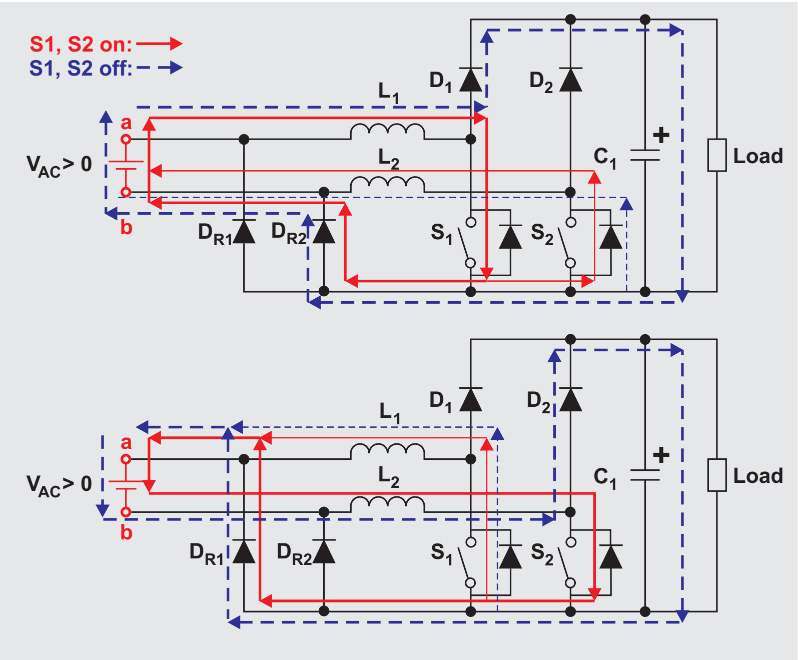


Circuit operations and design considerations

Circuit operations

The circuit operations of a TM-bridgeless PFC, shown in Figure 3, are similar to a boost converter. When $V_{AC} > 0$ (or $V_a - V_b > 0$), the main currents flow through the first boost converter components, L_1, S_1, D_1, C_1 and the load, then back to the source through D_{R2}. When $V_{AC} < 0$ (or $V_a - V_b < 0$), the main currents flow through the second boost converter components, L_2, S_2, D_2, C_1 and the load, then back to the source through D_{R1}. The return diodes allow both switches S_1 and S_2 to be on and off at the same time to keep the boost converters operating normally.

Figure 3. Operations of bridgeless PFC with return diodes



Design considerations

A standard TM-PFC controller relies on the sensing results of current-sensing and zero-current-detection (ZCD) circuits as the on/off trigger of the driving signal. A current-sensing circuit is used to detect the peak value of the inductor current to turn off the switch. A ZCD circuit detects the zero-current point of the inductor current to turn on the switch.

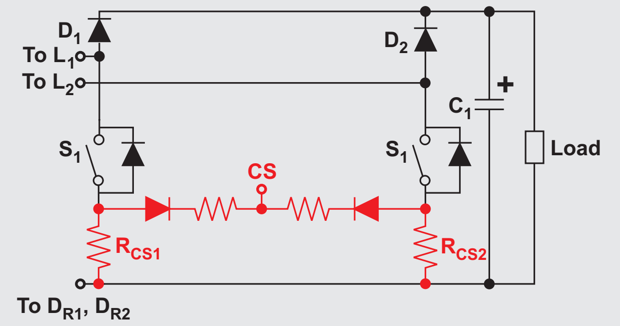
Another characteristic of a standard TM-PFC controller is that the switching-frequency range is much narrower than costly digital controllers. It is important to properly design the PFC inductors because they determine the switching frequency. There are three key considerations when applying a standard TM-PFC controller to the TM-bridgeless PFC: Current-sensing circuit design, ZCD design, and PFC-inductor design.

Current-sensing design

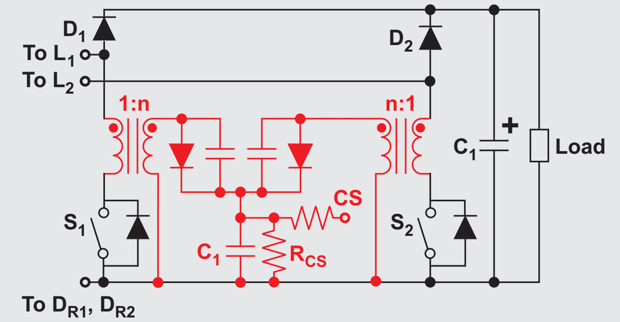
Power resistors for a peak current-sensing circuit (R_{CS1} and R_{CS2} in Figure 4a) are no longer the first choice for bridgeless-PFC current sensing. This is mainly because there are two switch legs to be sensed. If each switch is in series with a current-sensing resistor, then additional circuitry is needed to be sure the controller receives the current-sensing signal from the desired switch leg. Because these circuits generally require higher current-sensing resistance, higher power losses occur with current-sensing resistors. Higher resistance is needed for R_{CS1} and R_{CS2} because of the diode voltage drop.

Instead of using current-sensing resistors, current transformers for current sensing are suggested as shown in Figure 4b. Diodes in the current-sensing circuit with current transformers ensure that peak-current from the desired switching leg is detected and also minimize power losses in the current-sensing circuit.

Figure 4. Current-sensing circuits



(a) Sensing with power resistors



(b) Sensing with current transformers

Zero-current-detection design

In a standard TM-boost PFC, ZCD is achieved by detecting the voltage signal from an auxiliary winding of the PFC inductor (Figure 5a). This ZCD circuit uses the inductor's voltage-second characteristic. When boost diode D_1 is conducting, positive voltage appears at the IC's ZCD pin. Also, with a proper turns-ratio design of L_1, V_{ZCD} is greater than V_{REF}. Once the inductor current decreases to zero, the inductor's voltage changes its polarity. Now the ZCD voltage changes from positive ($V_{ZCD} > V_{REF}$) to negative ($V_{ZCD} < V_{REF}$). This voltage polarity-changing transient is detected by the internal comparator and pulls the driving signal high to turn on S_1.

When using a TM-bridgeless PFC, all zero-current events must be detected. It may be necessary to apply the ZCD circuit for a TM-boost PFC to both inductors in the TM-bridgeless PFC and include blocking diodes. However, blocking diodes extend the V_{ZCD} falling duration and make the ZCD pin sensitive to noise, which causes incorrect trigger and protection. Instead of using the inductor auxiliary winding, a series-connected RC circuit (Figure 5b) provides a simple detection option.

When both S_1 and S_2 are turned off, there is still one switch (generally MOSFET) conducting current through its body diode. Hence, a voltage difference is created between the two switch legs. The capacitors in the ZCD circuit are charged and result in $V_{ZCD} > V_{REF}$. The voltage difference becomes zero when the inductor current goes to zero, which makes $V_{ZCD} < V_{REF}$ and triggers the turn-on event. In short, this circuit uses the capacitor charge/discharge to achieve ZCD.

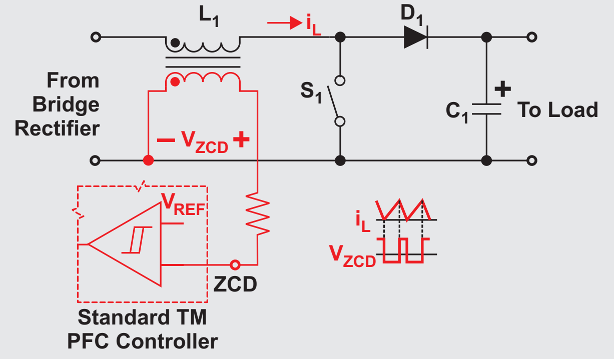
PFC inductor design

Unlike a continuous-conduction-mode (CCM) PFC circuit, a TM PFC requires various switching frequencies in an AC cycle to ensure that the inductor current is discharged to zero before the next switching cycle begins. Generally, an analog TM-PFC controller has a narrower operational frequency range than a digital controller. Therefore, choosing the proper inductance for the boost inductors in the TM-bridgeless PFC becomes an important task to ensure that the switching frequencies are within the IC limits in most conditions. The inductor value can be calculated.

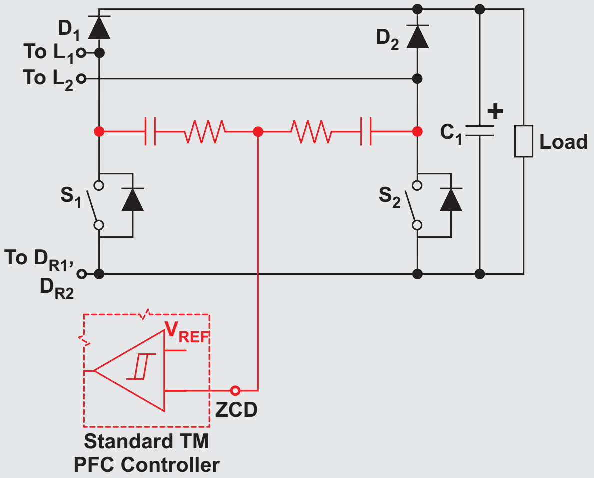
$$\begin{aligned} L_1 &= \frac{V_{in\_min(rms)}}{2I_{in(rms)}\left[\text{at } V_{in\_min(rms)}\right]} \times t_{on\_max} \\ &= \frac{V_{in\_min(rms)}}{2I_{in(rms)}\left[\text{at } V_{in\_min(rms)}\right]} \times \frac{V_{out} - \sqrt{2} \times V_{in\_min(rms)}}{V_{out} \times f_{sw\_min}} \end{aligned} \qquad (1)$$

where t_{on_max} is the maximum on time of switches S_1 and S_2 at the minimum input voltage (V_{in_min}), and f_{sw_min} is the minimum switching frequency at V_{in_min}. The rms value of the input current ($I_{in(rms)}$), can be determined by $I_{in(rms)} = P_{out}/(V_{in(rms)} \times \eta)$, where η is the PFC efficiency.

Figure 5. Zero current detection circuits



(a) ZCD for boost PFC



(b) ZCD for bridgeless PFC

Once inductance is determined, the converter switching frequencies over an AC switching period with a fixed-input AC voltage can be found.

$$f_i = \frac{D_i}{t_{on}} = \frac{V_{out} - \left|\sqrt{2} \times V_{in(rms)} \times \sin\left(\omega_{AC} x_i\right)\right|}{V_{out} \times t_{on}} \qquad (2)$$

where D_i is the duty cycle in the i-th switching action, $\omega_{AC} = 2\pi f_{AC}$ and f_{AC} is the AC switching frequency. The time that the i-th switching begins is x_i, so with $x_1 = 0$, x_{i+1} can be determined.

$$x_{i+1} = \sum_{j=1}^{i} \frac{t_{on}}{D_j} \qquad (3)$$

Now consider a TM-bridgeless PFC with a 380-V output voltage, 380-W output power, and universal AC input range of 90 to 264 VAC. With f_{sw_min} set to be 65 kHz and η assumed to be 96%, the inductance can be calculated as 104 µH with Equation 1. Now apply equations 2 and 3 with the calculated inductance. The switching frequency variations at 120 VAC and 240 VAC are shown in Figure 6. The results show that a high power factor can be ensured in both low-line and high-line inputs for this design ($f_{sw\_max} \cong 400$ kHz) because the switching frequencies during high-current operation are all below the controller's frequency limitation.

Circuit implementation and experimental verifications

Two 380-W, TM-PFC reference boards (conventional-boost and bridgeless) were built to compare performance. For boost switches, an N-channel MOSFET with $R_{DS(on)}$ = 140 mΩ was used for the boost PFC and N-channel MOSFETs with $R_{DS(on)}$ = 199 mΩ were used for the bridgeless PFC. The UCC28051 TM-PFC controller and inductors with a PQ3220 ferrite core were applied to both reference boards. Note that two 260-µH inductors were connected in parallel for the boost PFC reference board to share the magnetic flux density and power losses on the boost inductor. Two 100-µH inductors were used as boost inductors in the bridgeless-PFC reference board. Identical low-cost bridge diodes were used for the rectifier in the conventional-boost PFC and for the return diodes in the bridgeless PFC. Current sensing with current transformers and a RC-connected ZCD circuit was applied to the bridgeless-PFC reference board.

Inductor current waveforms of the TM-bridgeless PFC are shown in Figure 7. Notice that when one inductor processes a switching operation, the other inductor conducts negative current. This is because the inductance of the boost inductors is very low at the 50-/60-Hz frequencies. Therefore, part of the return current flows back to the source through the boost inductors instead of the return diodes.

Figure 6. Switching frequencies of TM-bridgeless PFC over a half AC cycle

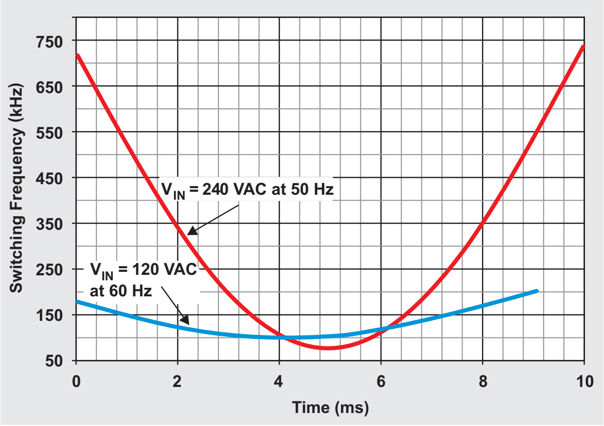
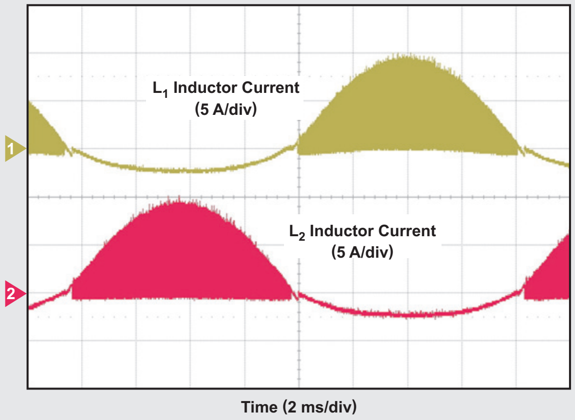
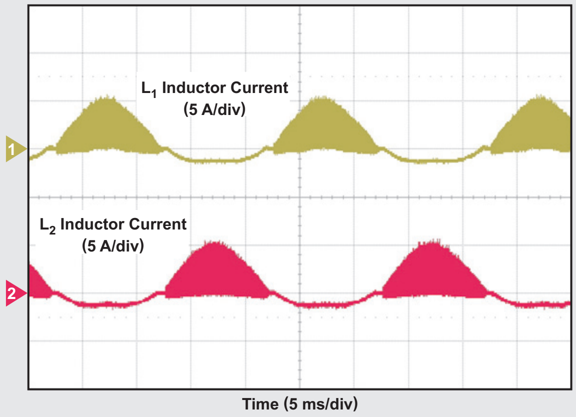


Figure 7. Inductor current of TM-bridgeless PFC at 350-W output



(a) 120 VAC at 60 Hz



(b) 240 VAC at 50 Hz

Figure 8 compares the efficiency of these two prototypes. In the light- to mid-load range, an efficiency improvement of approximate 1% was noted for the TM-bridgeless PFC compared to the boost PFC. The power-factor measurements of the prototypes are shown in Figure 9. The high power factor was obtained for both 120 VAC and 240 VAC, which verifies the previous analysis.

Conclusion

Design considerations of a low-cost TM-bridgeless PFC show that standard PFC controllers can be used to greatly reduce overall circuit cost while keeping the advantages of a bridgeless PFC circuit. Experimental comparisons to the conventional TM PFC show strong evidence of efficiency improvement with the TM-bridgeless PFC.

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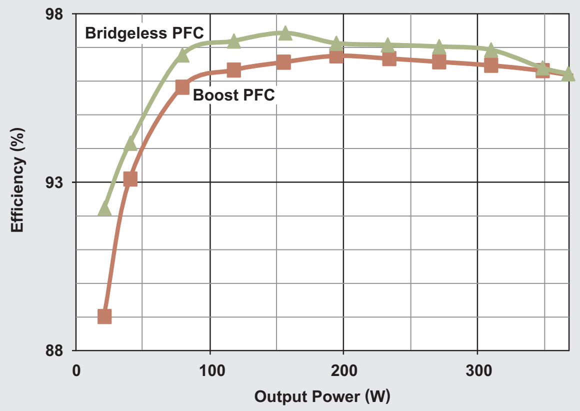
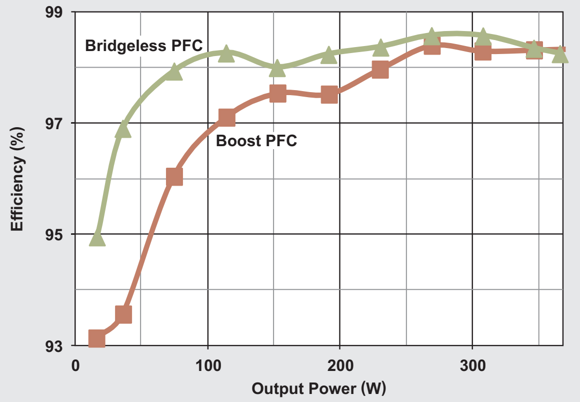
Figure 8. Converter efficiencies for reference boards

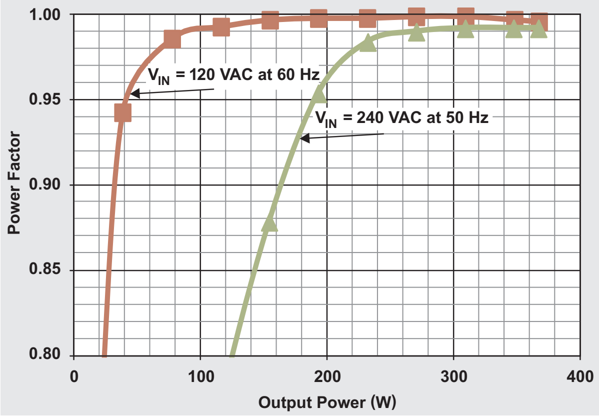


(a) 120 VAC at 60 Hz



(b) 240 VAC at 50 Hz

Figure 9. Power factor for TM-bridgeless PFC



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