A novel charge-mode control algorithm for PFC

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Introduction

In a control system, if you want to control something, you need to sense it; this applies to power factor correction (PFC) applications as well. In offline power supplies with power levels >75W, PFC controls the input current to create a sinusoidal waveform (in other words, following the sinusoidal input AC voltage). In order to control the input current, it needs to be sensed.

The most common current-sensing method places a shunt resistor at the PFC ground return path (designated as R in **Figure 1**) to sense the input current. The sensed input current signal (I_{SENSE}) is then sent to an average current-mode controller [1] (shown in **Figure 2**). Because the current reference (I_{REF}) is modulated by the input voltage (V_{IN}), it is a sinusoidal waveform. The control loop forces the input current to follow I_{REF}, thus achieving a sinusoidal waveform.

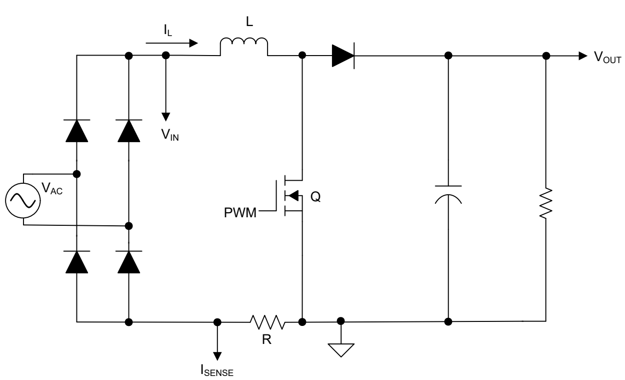

Figure 1. *A common current-sensing method for PFC.*

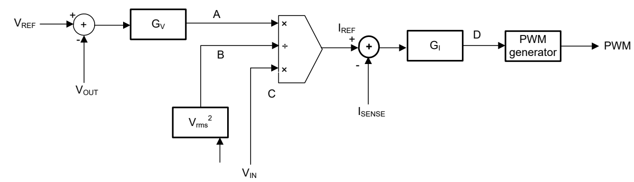

Figure 2. *Traditional average current-mode control for PFC.*

Almost all continuous conduction mode (CCM) PFC controllers use traditional average current-mode control. Although traditional average current-mode control achieves a good power factor and has low total harmonic distortion, it also has some limitations, especially in totem-pole bridgeless PFC. This article presents a brand-new control algorithm: charge-mode control [2].

Charge-mode control

The charge-mode control algorithm is a new control concept: to control an object, you don't really need to sense it – you can sense its consequence and then indirectly control the object. For PFC, instead of controlling the input current directly, this control algorithm controls how much electric charge is delivered to the PFC output in each switching cycle, and employs a special control law such that the input current becomes a sinusoidal waveform by controlling the electric charge.

There are a few ways to obtain the electric charge information. **Figure 3** shows an example of using a current shunt and an operational amplifier (op amp) circuit, with the op amp configured as an integrator. When the PFC boost switch turns off, the inductor current starts to charge the PFC bulk capacitor. The shunt resistor senses this current, which is then integrated through the integrator. The peak value of the integrator output represents the total electric charge delivered to the PFC output in each switching cycle. This electric charge (V_{CHARGE}) is sampled by the controller as a control-loop feedback signal. The integrator discharges to zero through Q1 before the boost switch turns off.

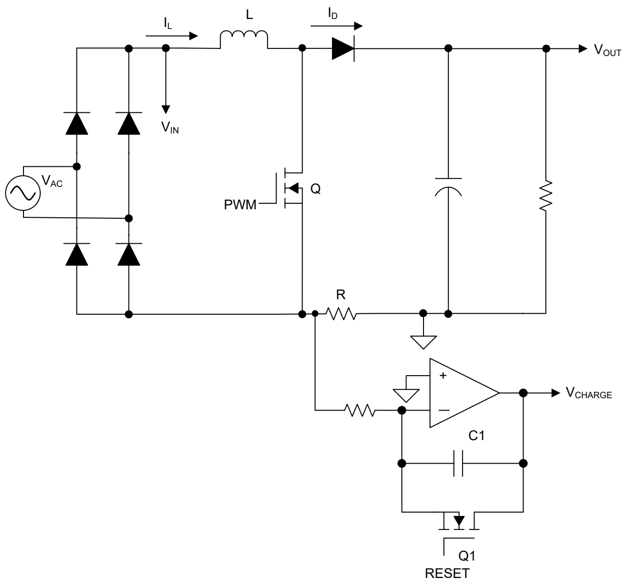

Figure 3. Using the current shunt and op amp to obtain an electric charge.

Figure 4 shows another method, which employs a current transformer (CT) on the PFC output side. The CT output connects to capacitor C1. When the PFC boost switch turns off, the inductor current starts to charge the PFC bulk capacitor. The CT senses this current and its output charges C1. The voltage on C1 rises up; its peak voltage represents the total charge delivered to the PFC output. The controller samples the peak voltage V_{CHARGE} as a control-loop feedback signal. C1 discharges to 0V through Q1 before the boost switch turns off.

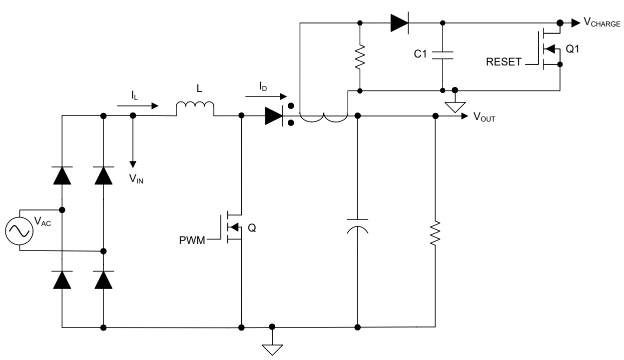

Figure 4. Using a CT to obtain an electric charge.

Figure 5 shows the typical signal waveform for charge-mode control.

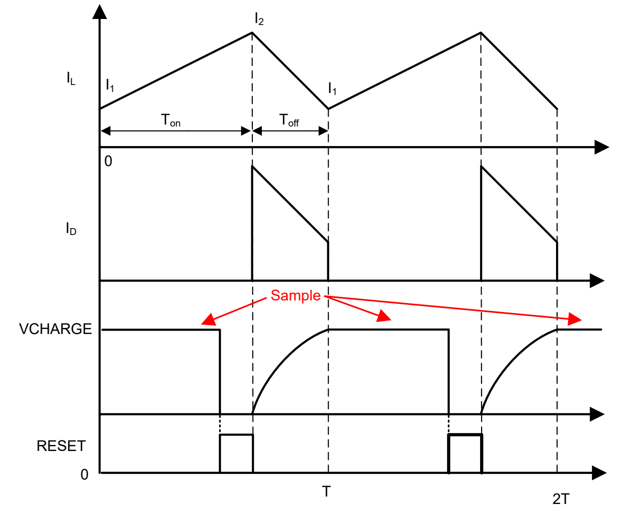

Figure 5. Typical signal waveforms for charge-mode control.

Control law

Now that you know how to obtain the electric charge information for each switching cycle, let's take a look at how to get the sinusoidal input current waveform using the new control law, see Figure 6.

Compared to the traditional control law shown in Figure 2, there are two differences:

- The current-loop reference is modulated by $V_{IN}{}^2$, not by V_{IN}.
- The feedback signal is the electric charge V_{CHARGE}, not I_{SENSE}.

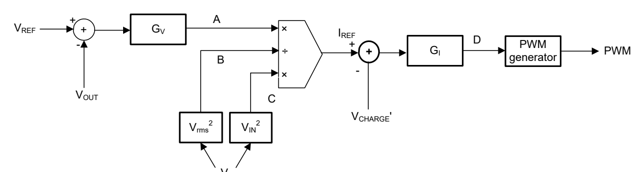

Figure 6. Charge-mode control law for PFC.

From Figure 6, the current reference I_{REF} is given by:

$$I_{REF} = \frac{A\ C}{B} \tag{1}$$

where, I_{REF} is the current-loop reference, A is the voltage-loop output G_V, B is $Vrms^2$ used for V_{IN} feedforward control, and C is $V_{IN}{}^2$.

Looking at **Figure 5**, **Equation 2** expresses the average inductor current in each switching cycle as:

$$I_{AVG} = \frac{(I_1 + I_2)\ (T_{on} + T_{off})}{2\ T} \quad (2)$$

where, I_{AVG} is the average inductor current, I_1 is the inductor current at the beginning of each switching cycle, I_2 is the inductor current peak value in each switching cycle, T_{on} is the boost switch Q turn on time, T_{off} is the boost diode D conduction time, and T is the switching period.

Equation 3 calculates the peak voltage of C1 (V_{CHARGE}) in each switching cycle as:

$$V_{CHARGE} = \frac{(I_1\ +\ I_2)\ T_{off}}{2\ C} \quad (3)$$

where, C is the capacitance of C1.

In steady state, the control loop forces V_{CHARGE} to equal I_{REF} (see **Equation 4**):

$$V_{CHARGE} = I_{REF} \quad (4)$$

For a boost-type converter in steady-state operation, the volt-seconds applied to the boost inductor must be balanced in each switching period (see **Equation 5**):

$$T_{on}\ V_{IN} = T_{off}\ (V_{OUT} - V_{IN}) \quad (5)$$

Equation 6 combines **Equation 1** through **Equation 5**:

$$I_{AVG} = \frac{G_V\ V_{OUT}\ C}{V_{rms}^2\ T}\ V_{IN} \quad (6)$$

In **Equation 6**, since both C and T are constant, and G_V, V_{OUT} and $Vrms^2$ do not change in steady state, I_{AVG} follows V_{IN}. When V_{IN} is a sinusoidal waveform, I_{AVG} is also a sinusoidal waveform, thus achieving PFC. Note that **Equation 2** and **Equation 3** are valid for both CCM and discontinuous conduction mode (DCM); therefore, **Equation 6** is valid for both CCM and DCM operation.

RHPZ effect and solution

The loop compensation for charge-mode control is simple when the PFC operates in DCM. Loop compensation becomes a challenge, however, because a right-half-plane zero (RHPZ) appears in the control loop when the boost converter operates in CCM [3]. The RHPZ induces a phase drop that negatively impacts the potential phase margin of the control loop. **Equation 7** expresses the small-signal model for the control loop as:

$$\frac{\hat{v}_{CHARGE}}{\hat{d}} = \frac{V_{OUT}(1-D)T}{sLC}\left(1 - \frac{sL}{(1-D)^2 R_{LOAD}}\right) = \frac{1 - \frac{s}{\omega_Z}}{\frac{S}{\omega_0}} \quad (7)$$

where R_{LOAD} is the output load of PFC, D is the pulse-width-modulation duty cycle, $\omega_0 = \frac{V_{OUT}T(1-D)}{sLC}$ and $\omega_z = \frac{R_{LOAD}T(1-D)^2}{L}$.

Equation 7 clearly shows the RHPZ ω_Z. Its frequency varies with load, boost inductance and D (D varies with the input and output voltage), which makes loop compensation very difficult.

To eliminate the RHPZ, **Equation 8** modifies the feedback signal:

$$V'_{CHARGE} = \frac{V_{CHARGE}}{T_{off}} \quad (8)$$

Figure 7 modifies the control law, where you can see that I_{REF} is now modulated by V_{IN}, not by $V_{IN}{}^2$.

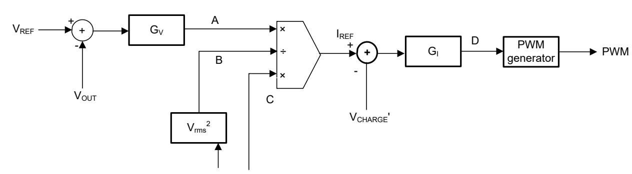

Figure 7. Charge-mode control law for PFC after eliminating RHPZ.

With this modification, **Equation 9** expresses the small-signal model of the control loop as:

$$\frac{\hat{v}'_{CHARGE}}{\hat{d}} = \frac{V_{OUT}}{sL} \quad (9)$$

The RHPZ disappears and the system becomes a first-order system, which is very easy to compensate.

Figure 8 illustrates the verification of the new control algorithm through simulation, achieving a sinusoidal input current waveform.

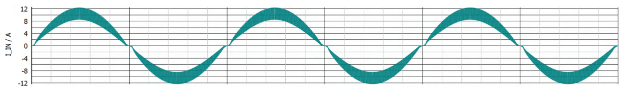

Figure 8. *Simulation result: a sinusoidal input current waveform.*

Conclusion

Instead of controlling the input current directly, charge mode controls how much electric charge to deliver to the PFC output in each switching cycle. This algorithm works for all PFC topologies, but it is especially useful for totem-pole bridgeless PFC, which has traditionally required a sensor such as Hall-effect sensor to sense the bidirectional inductor current. The problem is that Hall-effect sensors are not only expensive, but also have limitations such as limited bandwidth, sensitive to magnetic field and DC offset shifting with temperature, etc. Because charge-mode control eliminates the need to sense inductor current, there is no need for an expensive bidirectional current sensor. Instead, you can use a current-sense resistor along with a low-bandwidth op amp or a CT, which are much less expensive.

Because of its high efficiency, totem-pole bridgeless PFC is attractive for applications that require high efficiency. Its high cost was always a barrier for its broader adoption, but this new control algorithm is now an option in applications that require both high efficiency and low cost. It is possible to implement charge-mode control with existing digital controllers such as Texas Instruments C2000™ microcontrollers and the UCD3138 controller, or you can employ it in the development of a new analog PFC controller.

References

1. Texas Instruments: ***High Power Factor Preregulator for Off-Line Power Supplies***.
2. **Charge Mode Control for Power Factor Correction Circuit**. U.S. Patent 11,705,808 B2, filed Sept. 30, 2021, and issued July 18, 2023.
3. Texas Instruments: ***The Right-Half-Plane Zero – A Simplified Explanation***.