Digital Control for Improved Efficiency and Reduced Harmonic Distortion over Wide Load Range in Boost PFC Rectifiers

Fu-Zen Chen and Dragan Maksimovic
Colorado Power Electronics Center
ECE Department, University of Colorado, Boulder, CO 80309-0425
{fchen, maksimov}@colorado.edu

Abstract—This paper addresses control techniques aimed at improving light-load efficiency and reducing harmonic distortion in digitally controlled single-phase boost power factor correction (PFC) rectifiers. Based on a discontinuous conduction mode (DCM) detection circuit, it is shown how an extension to the predictive current control law leads to improved current regulation over wide load range in both continuous conduction mode (CCM) and in DCM. Furthermore, adaptive switching and adaptive switching frequency techniques are introduced to reduce switching losses and improve efficiency at light loads. Experimental results are shown for a 300W boost PFC rectifier.

I. INTRODUCTION

Single-phase boost power factor corrector (PFC) rectifier (Fig. 1) rated at about 100-200W and above are usually designed to operate at constant frequency in continuous conduction mode (CCM) at full load. Issues in digital control of boost PFC rectifiers have been addressed in numerous publications (e.g. [1-6]), including digital average current mode control and predictive current algorithms for low-harmonic current shaping in CCM. At intermediate loads, the boost PFC operates in discontinuous conduction mode (DCM) over a portion of the ac line period. At light loads, the boost PFC operates in DCM over the entire ac line period. Various current control techniques addressing DCM operation have been addressed in [7-10].

It has been shown that DCM operation and CCM/DCM mode transitions can result in increased input current distortion in digitally controlled boost PFC rectifiers [6]. The increased distortion in DCM is due to the effects of ringing between the boost inductor and parasitic switch-node capacitance. In addition, DCM operation affects the dynamics of the current control loop, which may result in poor current regulation, requiring modifications to the CCM current control law [6, 7].

In this paper, the focus on DCM and DCM/CCM operation of boost PFC rectifiers over wide load range is further motivated by the increased interest in extending high-efficiency operation to intermediate and light loads. The paper is organized as follows. Predictive current control techniques, including CCM and modified CCM/DCM approaches are discussed in Section II. Adaptive switching and adaptive switching frequency techniques aimed at improving light load efficiency are introduced in Section III. Experimental results on a 300W digitally controlled boost PFC rectifier shown in Fig. 1 are given in Section IV. Section V concludes the paper.

II. PREDICTIVE CURRENT CONTROL

A. CCM Predictive Current Control

Predictive current control techniques for CCM operation, such as the methods described in [4, 7], enable effective, high-performance current control and relatively simple digital implementation. In order to reduce the current analog-to-digital (A/D) sampling rate requirements, inductor current can be sampled once per switching period. Assuming CCM operation, if the current sample is taken in the middle of the transistor conduction interval or in the middle of the diode conduction interval, it approximately represents the average inductor current over the entire switching period. Based on the geometry of the inductor current waveform, a predictive current control law can be constructed to minimize the error between the current reference \(i_{L,ref}\) and the current sample \(i_{L,sense}\):

\[
T_{on}[n+1] = \frac{L}{V_o}(i_{L,ref} - i_{L,sense}) + (1 - \frac{V_o}{V_s})T_s
\]

where \(T_{on}\) is the transistor on-time in the next switching period, \(T_s = 1/f_s\) is the switching period, \(V_s\) is the input voltage, and \(V_o\) is the output voltage. A block diagram of the controller...
capable of implementing the predictive current control law is shown in Fig. 1. Note that the CCM predictive current control law (1) includes a proportional term $T_{cm}$ based on the current error, and a feed-forward term $T_{on, ff}$ based on the input-to-output voltage ratio $v_p/v_o$. As shown in Fig. 1, the current reference $i_{ref}$ in the boost PFC is obtained by multiplication of the sampled input voltage $v_{s,a}$, and the power control signal $u$ at the output of the output voltage-loop controller.

B. CCM/DCM Predictive Current Control

The CCM predictive current control (1) is very effective when the boost converter operates in CCM [4, 7]. However, under intermediate or light load conditions, when the boost converter operates in DCM, the current sensed in the middle of the transistor or the diode conduction is no longer representing the average inductor current. In addition, the CCM current control dynamics are different from that in DCM. This results in more current distortion in DCM. A current correction approach has been proposed in [7] to extend the predictive current control law to DCM operation. A current correction factor (3) is introduced to correct for the difference between the sensed current ($i_{L,sense}$) and the average current (<i_L>),

$$\frac{2L}{R_T} \left( \frac{V_o}{V_a} \right)$$

which has been shown to reduce the current distortion at light load and in CCM/DCM mode transitions [7].

![Fig. 2 Waveforms illustrating operation of the DCM comparator](image)

In order to simplify the calculation of the current sensing correction factor (3), and to facilitate the adaptive switching technique described in Section III, an auxiliary inductor winding and a voltage comparator (“DCM comparator” in Fig. 1) are used to detect zero crossings of the inductor voltage ($v_L$) in the CCM/DCM current controller proposed in this paper. The DCM comparator output signal ($s_{DCM}$) is shown in Fig. 2 together with the inductor current waveform in DCM. It can be calculated simply by

$$(1) \frac{T_{on}}{T}$$

The complete CCM/DCM predictive current control law, including a proportional/integral (PI) feedback action and the DCM correction is given in (4)-(7),

$$T_{on}[n] = e[n] + e[n-1] + T_{on}[n-1]$$

$$e[n] = T_s \cdot T_{on} \cdot T_{on, ff}$$

$$T_{on} = \frac{(1 - v_p)}{V_o} \cdot \frac{T_s}{T_i} \cdot CCM$$

$$T_{on, ff} = \sqrt{\frac{2L}{T_s} \cdot u \cdot \left( \frac{v_p}{V_o} \right) \cdot \frac{T_i}{DCM}}$$

Input emulated resistance ($R_e$) is equal to (1/a), is the gain of the predictive controller; $T_s$ is related to the location of the zero in the PI compensator. $T_i$ is the switching period.

A block diagram of the CCM/DCM predictive current controller is shown in Fig. 3.

![Fig. 3 Block diagram of the CCM/DCM predictive current controller](image)

III. CONTROL TECHNIQUES FOR IMPROVED EFFICIENCY AND REDUCED DISTORTION

A. Adaptive Switching CCM/DCM Current Control

When a constant-frequency boost PFC rectifier operates in DCM, ringing can be observed at the time when both transistor Q and diode D are turned-off, as illustrated by the experimental waveforms of the inductor current $i_L$, transistor control signal $g$ and transistor drain voltage $v_{ds}$ shown in Fig. 4. The ringing is due to the resonance between the boost inductor and the total parasitic capacitance at the switching node. The oscillation period and amplitude are dependent on the inductance and capacitance values as well as the operating point. At the time when the transistor is turned on, the values of the drain voltage and the inductor current can vary significantly. The resulting average inductor current is a

![Fig. 4 Experimental boost converter waveforms in DCM](image)
highly nonlinear function of the transistor duty ratio. In DCM operation of the boost PFC rectifier using standard current control algorithms optimized for CCM operation, this oscillation results in a significant current distortion. This problem has been identified in [6], and a solution was proposed based on damping the oscillation using a dissipative snubber. The input current distortion is significantly reduced, but at the expense of slightly increased losses and reduced efficiency in both CCM and DCM operation.

An adaptive switching control technique is proposed here to address the above mentioned problem while simultaneously reducing the switching losses. The method is based on extending the transistor turn-off time until the drain voltage \(V_{DS}\) rings to a minimum, as illustrated by the waveforms of Fig. 5. Similar ideas of approaching zero-voltage switching based on DCM ringing have been previously applied to flyback DC-DC converters [14, 15]. The approach described here is based on the assumption that the DCM oscillation period \(T_{swm}\) does not change much between two consecutive switching periods. The digital controller uses the DCM comparator signal \(s_{DCM}\) to measure and store the oscillation period \(T_{swm}\). After expiration of the nominal (CCM) switching period \(T_s\), the controller waits for a low-to-high transition of \(s_{DCM}\) and extends the off time by \(T_{swm}/2\) so that the next DCM oscillation cycle ends at the point when the inductor current is zero and the drain voltage is at a minimum (as shown in Fig. 5). As a result of the adaptive switching period adjustment, switching losses are reduced, and the inductor current is very close to zero each time the transistor is turned on, thus reducing input current distortion in DCM.

The adaptive switching control law is the same as the CCM/DCM control law (4)-(7), except that (6) is replaced by

\[
e(n) = T_{sw} \left( i_{ref}(T_{sw} \ T_{swm}) \ i_{sense}\right)
\]

where the current error is computed based on the actual adaptively adjusted switching period \(T_{sw}\) as opposed to the fixed CCM switching period \(T_s\). Fig. 6 shows an example of experimental waveforms demonstrating operation of the adaptive switching CCM/DCM predictive current controller over several switching periods.

**B. Adaptive Frequency CCM/DCM Current Control**

In order to further increase the light-load efficiency, one approach is to reduce the switching frequency in order to reduce switching losses. In the adaptive frequency CCM/DCM current controller proposed in this paper, only the DCM switching frequency is adjusted, while keeping approximately constant CCM switching frequency, \(f_{max} = 1/T_{min}\). The DCM switching frequency variation described here is based on keeping the transistor duty cycle constant in DCM. For a particular load (120 W) in the PFC rectifier of Fig. 1, Fig. 7 shows variations of the transistor duty ratio and the switching period over one half line period. When the converter operates at constant frequency in CCM, the switch duty ratio is approximately independent of load. In DCM, a lower duty
ratio is required as the load is reduced, assuming constant switching frequency. The proposed adaptive frequency controller keeps the same duty ratio during DCM operation by allowing the switching period to vary. The switching period variation is shown in the bottom part of Fig. 7. Note that the constant DCM duty ratio approach also enables a smooth transition between CCM and DCM operation of the controller. The controller is also taking advantage of the adaptive switching CCM/DCM control described in Section III.A, in which the transistor is turned on at the lowest drain voltage.

Depending on the selection of the minimum switching period $T_{s,\text{min}}$ and the lowest load, the adaptive frequency CCM/DCM controller may operate under 20kHz, which may cause audio noise. A limit to the maximum allowed switching period ($T_{s,\text{max}}$) is imposed to limit the minimum allowed switching frequency. The complete set of adaptive frequency CCM/DCM controller equations is as follows:

$$T_{\text{sw}}[n+1] = T_{\text{sw}}[n] + T_{\text{on,ff}}$$ (9)

$$T_s[n+1] = \max[T_{s,\text{min}}, T_{s,\text{DCM}}]$$ (10)

$$T_{s,\text{DCM}} = \min[T_{s,\text{min}}, T_s^2 \cdot \min(1, \frac{v_s}{V_o} \cdot \frac{R_s}{2L})]$$ (11)

$$T_{\text{sw}}[n] = e[n] + e[n - 1] + T_{\text{sw}}[n - 1]$$ (12)

$$e[n] = T_{\text{sw}} \cdot i_{\text{ref}} \cdot (T_{\text{sw}}) \cdot t_{\text{on,ff}}$$ (13)

$$T_{\text{on,ff}} = \min[1, \frac{v_s}{V_o} \cdot T_{s,\text{min}} \cdot \frac{2L}{R_s} \cdot T_{s,\text{max}}]$$ (14)

$T_{s,\text{on}}$ is constant switching period selected for CCM operation; $T_{s,\text{max}}$ is the maximum allowed switching period.

IV. EXPERIMENTAL RESULTS

A 300W boost PFC rectifier ($f_s = 80$ kHz; $L = 0.5$ mH; $C = 220$ μF) has been built as shown in Fig. 1, using a field programmable gate array (FPGA) development platform to implement the digital controller. Fig. 8 shows the experimental setup. The operation is tested under four different controllers, including the standard predictive CCM current controller (Section II.A), CCM/DCM predictive current controller (Section II.B), the proposed adaptive switching CCM/DCM current controller (Section III.A) and the adaptive frequency CCM/DCM current controller (Section III.B) over wide load range (15-300 W). At high power, in CCM operation, all of the controllers operate exactly the same as the standard predictive controller in CCM, resulting in low-harmonic current waveform, as shown in Fig. 9.

At a reduced load, when DCM occurs only near the zero-crossings of the ac line, the CCM/DCM transition results in some distortion, as shown in Fig. 10(a). Since the inductor current around zero crossings is very low, the duty cycle is nearly 100%. The low inductor current cannot charge the switching node capacitance up to the output voltage. The DCM comparator used to detect the discontinuous conduction period ($T_{\text{dcw}}$), gives a value slightly shorter compared to the actual $T_{\text{dcw}}$. As a result, the CCM/DCM and the adaptive switching CCM/DCM controller run as CCM controllers through the entire line period, resulting in the same distortion of the line current as the standard CCM predictive controller. Using the adaptive frequency controller, the transistor turn-off time around zero-crossing increases, which reduces the distortion around zero crossings, as shown in Fig. 10(b).

At an intermediate load, when DCM occurs during a part of the line period, lower distortion can be observed in the waveforms obtained using the proposed CCM/DCM controller, as shown in Figs. 11(a) and 11(b). The DCM current correction improves current control and reduces distortion.

At light loads, when the converter operates in DCM at all times, input current distortion using the adaptive switching CCM/DCM controller (Fig. 13(b)) is significantly reduced compared to the CCM/DCM controller (Fig. 13(a)). The DCM distortion is reduced by switching at the lowest drain voltage,
thus reducing nonlinear effects of inductor current ringing on the current regulation performance. Furthermore, efficiency is improved as shown in Fig. 12. The remaining distortion in the adaptive switching CCM/DCM controller is a result of the switching period discretized by the DCM oscillation period ($T_{osc}$). Hence, some current distortion happens around the jump between $n$ to $n+1$ DCM oscillation cycles.

Fig. 12 shows that the adaptive frequency CCM/DCM current controller improves efficiency further at light loads by reducing the switching losses. In the experimental circuit, the maximum (CCM) switching frequency is 80 kHz; while the minimum switching frequency is 20kHz.

At very light loads, using the adaptive frequency CCM/DCM controller, the converter operates at the lowest allowed frequency most of the time, which is why the current harmonic distortion increases somewhat.

Experimental results for 15W (5% of the rated load) are
shown in Figs. 14(a)-14(d). Finally, Table I summarizes performance of the four considered controllers.

V. CONCLUSIONS

This paper addresses efficiency improvements and reductions in input current harmonic distortion in digitally controlled single-phase boost power factor correction (PFC) rectifiers operating over wide range of loads. Proposed predictive current control methods enable low-harmonic operation in both continuous conduction mode (CCM) and discontinuous conduction mode (DCM). A DCM detection circuit is used to facilitate a CCM/DCM predictive current control law, and adaptive switching at the minimum of the transistor drain voltage. These techniques result in improved efficiency and reduced current distortion. Furthermore, an approach to adaptive switching frequency adjustment is proposed, leading to further efficiency improvements at light loads. Experimental results are shown for a 300 W digitally controlled boost PFC rectifier

VI. REFERENCES


TABLE I Performance comparison of experimental CCM predictive current controller, CCM/DCM predictive current control, adaptive switching CCM/DCM current control, and adaptive frequency CCM/DCM current control.

<table>
<thead>
<tr>
<th></th>
<th>Output Power</th>
<th>Efficiency</th>
<th>Power Factor</th>
<th>THD</th>
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<tr>
<td>CCM Predictive Current Control</td>
<td>300W</td>
<td>94.9 %</td>
<td>0.999</td>
<td>2.2 %</td>
</tr>
<tr>
<td>CCM/DCM Predictive Current Control</td>
<td>300W</td>
<td>94.9 %</td>
<td>0.999</td>
<td>2.2 %</td>
</tr>
<tr>
<td>Adaptive Switching CCM/DCM Current Control</td>
<td>300W</td>
<td>94.9 %</td>
<td>0.999</td>
<td>2.2 %</td>
</tr>
<tr>
<td>Adaptive Frequency CCM/DCM Current Control</td>
<td>300W</td>
<td>94.9 %</td>
<td>0.999</td>
<td>2.2 %</td>
</tr>
<tr>
<td>CCM Predictive Current Control</td>
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<td>0.985</td>
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<tr>
<td>CCM/DCM Predictive Current Control</td>
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<td>0.993</td>
<td>16.9 %</td>
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<td>Adaptive Switching CCM/DCM Current Control</td>
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<td>0.993</td>
<td>5.8 %</td>
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<tr>
<td>Adaptive Frequency CCM/DCM Current Control</td>
<td>50W</td>
<td>95.1 %</td>
<td>0.995</td>
<td>3.8 %</td>
</tr>
<tr>
<td>CCM Predictive Current Control</td>
<td>15W</td>
<td>91.1 %</td>
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<tr>
<td>CCM/DCM Predictive Current Control</td>
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<tr>
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Fig. 14 Rectifier line voltage ($V_g$) and line current ($I_{dc}$). (80kHz, 15W)

(a) CCM predictive current control
(b) CCM/DCM predictive current control
(c) Adaptive switching CCM/DCM current control
(d) Adaptive frequency CCM/DCM current control


