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A New Estimative Current Mode Control Technique for DC-DC Converters Operating in Discontinuous Conduction Mode

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***Abstract*— A new digital control technique for power converters operating in discontinuous conduction mode (DCM) is introduced and applied to a Boost converter. In contrast to the conventional analog control methods, the principal idea of this new control scheme is to use real-time analysis and estimate the required on-time of the switch based on the dynamic of the system. The proposed control algorithm can easily be programmed in a Digital Signal Processor (DSP). This novel technique is applicable to any converter operating in DCM including Power Factor Correctors (PFC). However, this work mainly focuses on the Boost topology. In this paper, the main mathematical concept of the new control algorithm is introduced, as well as the robustness investigation of the proposed method, simulation, and experimental results.**

Keywords-power converter; power factor correction; digital control; boost converter; digital siganl processor; estimative current mode control

I. INTRODUCTION

The output voltage regulation of the DC-DC converters has conventionally been achieved via frequency domain control techniques using analog control approaches. However, the major disadvantage of the analog controllers for the switched mode power converters is their extreme sensitivity to noise and component drift due to the switching action and noise polluted measured signals. Furthermore, the implementation of advanced control schemes remains inherently difficult using analog systems.

Real-time controllers for power converters, on the other hand, enjoy growing popularity due to their accuracy, flexibility, and robustness [1-6]. These controllers can easily be digitally implemented, therefore they gain benefits of digital circuits such as: less susceptibility to aging, parameter, and environmental variations, high noise immunity, and easier implementation of advanced and sophisticated control schemes where the complexity is mostly contained in the software. In addition, changing the controller does not require a change in the hardware.

Discontinuous conduction mode operation happens when the current of one or all of the inductors of the converter reaches zero value before the starting point of the next switching interval [7]. Converters operating in DCM enjoy higher efficiency as well as lower EMI noise due to the zero current switching of the active devices. However, the properties of the converters drastically change in the discontinuous conduction mode. For instance, the voltage conversion ratio becomes load dependent. Control and modeling of the converters in DCM has been the subject of plenty of recent researches [8,9].

In recent years, due to the growing popularity of digital systems, more complicated and accurate current mode controllers have been developed using digital techniques. This paper introduces a new real-time control method of discontinuous conduction mode power converters to achieve line and load regulation as well as power factor correction. The proposed method is simple and easy to implement using a DSP. This control method is robust against the converter parameter variations.

Section II discusses the mathematical concepts of the estimative current controller. Section III investigates the robustness of the proposed control method against the parameter variations. In section IV, application of this method for a Boost power factor corrector is presented. The experimental results are presented in section V. Finally, section VI draws conclusions and presents an overall evaluation of this new control technique.

II. ESTIMATIVE CURRENT MODE CONTROL

Fig. 1 depicts the block diagram of a step-up Boost converter. This topology is mostly being used as a DC-DC converter as well as a Power Factor Corrector (PFC). The typical current waveforms of the inductor ($i_{L(t)}$) and the diode ($i_{D(t)}$) during a single switching period while operating in discontinuous conduction mode (DCM) are sketched in Fig. 2.

Assuming that the AC ripple of the input voltage (V_{in}) is changing with a frequency much less than the switching frequency of the converter and the output capacitor is large enough to filter out the output voltage ripple, we can write:

$$I_{max} = d_1 T m_1 \quad (1)$$

$$d_2 T = I_{max} / m_2 \quad (2)$$

where $m_1=(V_{in})/L$, $m_2=(V_o-V_{in})/L$ and T is the switching period.

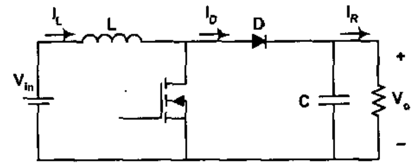

Figure 1. Boost converter.

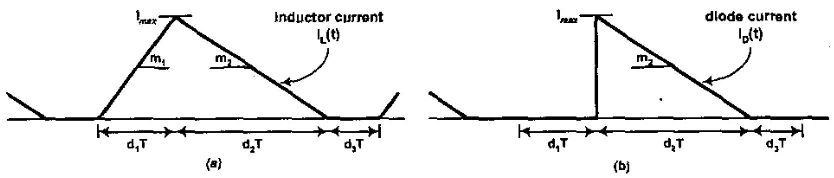

Figure 2. Typical current waveforms of (a) inductor and (b) diode operating in DCM.

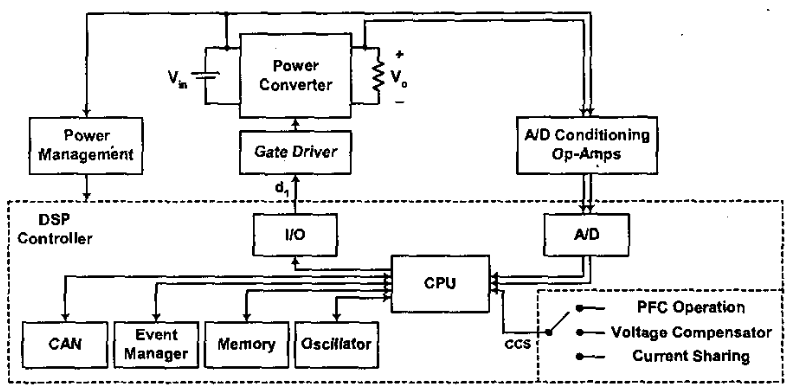

Figure 3. Block diagram of the digital current controller.

The current passing through the diode ($i_{D(t)}$) is being filtered and delivered to the load, thus the average value of the diode current is indeed the load current (i_R). By combining (1) and (2) using the definition of m_1 and m_2, the average value of the diode current in one switching interval can be obtained:

$$i_R = i_{D(av)} = \frac{T}{2L}\left(\frac{V_{in}^2}{V_o - V_{in}}\right)d_1^2 \qquad (3)$$

Solution for d_1 yields:

$$d_1 = \sqrt{\frac{2L}{T}} * \frac{1}{V_{in}} * \sqrt{i_{D(av)}(V_o - V_{in})} \qquad (4)$$

This formula can be used as a new approach to estimate the required on-time duration of the switch in a way that the average current of the diode follows the desired Current Command Signal (CCS). The current command signal could be; i) the output of the voltage compensator circuit, which conducts the output voltage regulation, or ii) the output of the load-sharing controller, which tries to balance the output current of the converters operating in parallel, or iii) the output of the power factor corrector, which tempts to generate sinusoidal input current.

Therefore, at the beginning of each switching interval, input and output voltages as well as the current command signal, if it is not already a digital signal, are being sampled. Then, knowing the dynamic of the converter (equation (4)), and based on the required load current demand (CCS), the controller computes the desired value of the duty cycle (d_1). Applying this value of duty cycle to the converter makes the average value of the diode current ($i_{D(av)}$ measured at the end of the switching cycle), which is indeed the load current in the corresponding switching interval, follow the current command signal. The required mathematical computations can be easily programmed in a DSP. Fig. 3 shows the block diagram of the controller. Based on the specific application, the current command signal can be obtained using the same DSP, or another DSP with a higher level, or an analog circuit.

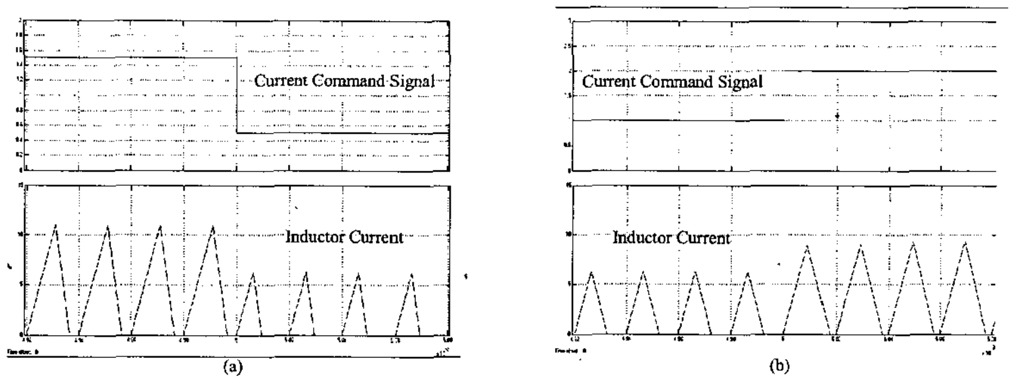

Figure 4. Simulation results of the inductor current transient response to a step change in the current command (a) step down and (b) step up.

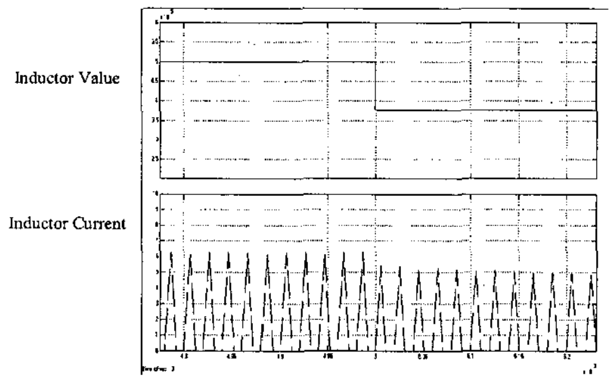

Figure 5. Simulation results of the open loop response to a 25% step change of the inductor value.

Fig. 4(a) and (b) show the simulation results of the transient response of the converter to the step down and up changes in the current command signal. The inductor current is sketched in the figures, however the estimation is being made based on the average value of the diode current. As can be observed, the inductor current pattern immediately follows the current command changes in a way that provides the required average current in the diode. This delay-free tracking characteristic provides a fast dynamic response.

III. Error In Inductance Estimation

As we can observe from (4), the controller employs the numeric value of the inductor (L) to calculate the desired value of the duty cycle (d_l). The rest of the variables in (4) are being sampled in each period. Therefore, the accuracy of the calculations depends on the accuracy of the inductor value. As a result, an error in the estimation of L deteriorates the tracking accuracy of the steady state response of the converter. If ΔL represents the error in the numeric value of L, applying $L+\Delta L$ into (4) yields:

$$d_1 = \sqrt{\frac{2(L+\Delta L)}{T}} * \frac{1}{V_{in}} * \sqrt{i_{D(av)}(V_o - V_{in})} \qquad (5)$$

Rearranging the terms in (5) leads us to:

$$d_1 = \sqrt{\frac{2L}{T}} * \frac{1}{V_{in}} * \sqrt{(1+\frac{\Delta L}{L})i_{D(av)}(V_o - V_{in})} \qquad (6)$$

The third term in (6) can be interpreted as an error in the reference current ($i_{D(av)}$). So the generated current will slightly be different from the current command signal. Since the variation of L is slow and basically temperature or age dependent, even a very low-bandwidth voltage control loop can easily damp this error to zero. Fig. 5 depicts the simulation results of the response of a Boost converter, with its voltage loop open, if a 25% step error happens in the assumed value of the inductor (L). As we can observe from (6) and the simulation results, even applying a 25% instant error has a slight effect on the operating point of the converter. Therefore, the control algorithm is not sensitive to the numeric value of the inductor, which is the only presumed parameter in (4).

IV. Power Factor Correction

Using the estimative current control technique, any desired current tracking task is achievable, for instance, Power Factor Correction (PFC). In the discontinuous

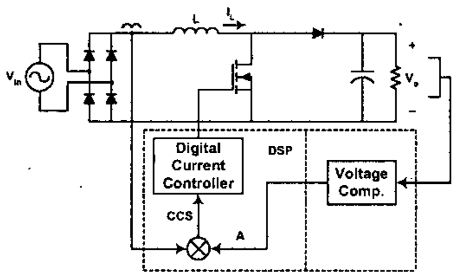

Figure 6. Block diagram of the PFC converter.

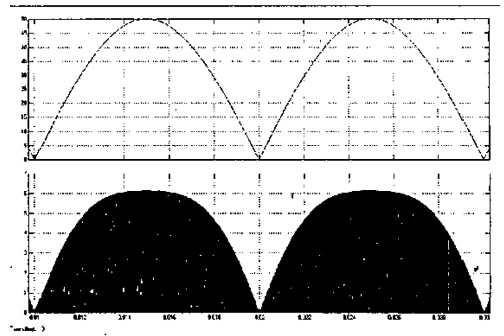

Figure 7. Simulation result of (a) input voltage and (b)current waveform in PFC application using estimative current control.

conduction mode PFC applications, the controller intends to shape the average value of the input current, in a way that it follows the sinusoidal input voltage waveform. The only difference with the previous discussion is that we need to shape the input current instead of making the output current follow the desired signal. It is worth to note that this difference will only affect the software part of the control algorithm. Considering a Boost converter and its inductor current waveform (input current) in Fig. 2(a), we can write:

$$i_{L(av)} = \frac{I_{max}}{2}(d_1 + d_2)T \tag{7}$$

Combining with (1) and (2) yields:

$$i_{L(av)} = \frac{T}{2L}\left(\frac{V_o V_{in}}{V_o - V_{in}}\right)d_1^2 \tag{8}$$

which is slightly different from the average value of the diode current in (3). Solution for d_1 yields:

$$d_1 = \sqrt{\frac{2L}{T}} * \sqrt{i_{L(av)}\frac{V_o - V_{in}}{V_o V_{in}}} \tag{9}$$

In the PFC application $i_{L(av)}$ needs to be proportional to the rectified input voltage waveform. Thus we can write:

$$i_{L(av)} = A|Vin| \tag{10}$$

where gain A is determined by the voltage compensator based on the required output power. In the above equation, the full-rectified sinusoidal input voltage is used as the current command signal in a way that the input current tracks the wave shape of the input voltage. Therefore, the samples of the rectified input voltage are being utilized as the current command signal as well as in the mathematical computation of (9). Fig. 6 depicts the block diagram of the Boost PFC converter being controlled using the new estimative method. The DSP converter can include the voltage compensation part as well.

Fig. 7 sketches the simulation results of the input current of the PFC converter using the new digital scheme. As can be observed, the average value of the input current follows the sinusoidal wave shape of the input voltage.

V. EXPERIMENTAL RESULTS

The TMS320LF2407A has been employed for the experimental implementation of the new estimative current mode control. This digital signal processor (DSP) is designed to meet a wide range of embedded control applications and real-time signal processing.

This DSP is based on a 16-bit, fixed-point, low-power CPU, and uses new combinations of on-chip memory with a wide range of peripherals. These include; Analog-to-Digital converters (ADC), Controller Area Network (CAN), event manager, serial communications ports, and safety features such as watchdogs timer and power drive protection. In addition, most of the instructions of this DSP are single cycle. Therefore, multiple control algorithms can be executed at high speed, thus making it possible to achieve the required high sampling rate for a fast dynamic response. Table 1 summarizes the main features of 2407A.

TABLE I. DSP FEATURES

Frequency	40 MHz
MIPS	40
PWM	16 Channels
Timer	4
10-bit A/D	16 Channels
A/D Conversion Time	500 ns
RAM	2.5 K Words
Flash	32 K Words
External Memory Interface	YES
Power Management	YES

Fig. (8) and (9) show the experimental results of the Boost converter being controlled with the estimative digital current control. These figures depict the transient response of the inductor current after a step change being applied to the current command signal. The experimental results highly agree with the simulation results and the system has a very fast dynamic response.

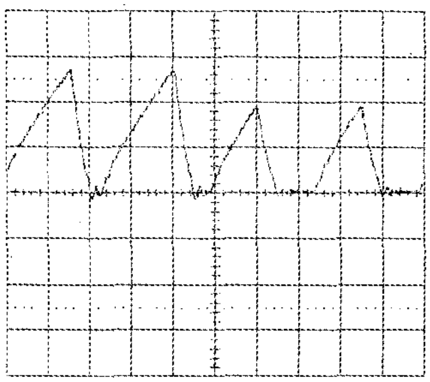

Figure 8. Inductor current transient response to a step down change in the current command signal (2A/div, 10μs/div).

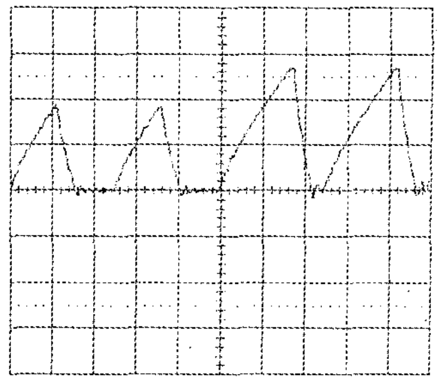

Figure 9. Inductor current transient response response to a step up change in the current command signal (2A/div, 10μs/div).

VI. CONCLUSION

The predictive current mode control technique that has been introduced in this report enjoys the following advantages: I) It has a very fast transient response. II) It is stable for any value of the duty cycle. III) It is easy to be implemented by a digital processor. IV) It is not sensitive to the circuit parameter variations. This method was simulated and experimentally verified and found to give stable and smooth operation.

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