01 Feb 2008

Projected Cross Point -- A New Average Current-Mode Control Approach

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***Abstract*-Projected cross point, a new current-mode control technique, is introduced and analyzed in this paper. Despite having an analog nature, the proposed method combines the advantages of both analog and digital control techniques. Unlike the conventional analog control methods, it accurately controls the average value of the inductor current with no need to a current compensator or an external ramp. In addition, while resembling the deadbeat characteristics of digital controllers, projected cross point control does not suffer from computational time delay, limit cycling, and quantization and truncation errors. Dynamic performance of the proposed approach is compared with the existing control methods. Analytical analysis and simulation results show the superior accuracy and transient response of projected cross point control approach.**

***Keywords*-average current-mode control; dc-dc converter; projected cross point control**

I. INTRODUCTION

Analog control approaches [1-13], including voltage- and current-mode control, have conventionally been used to provide line and load regulation in power electronic converters. They are popular due to their simplicity, high bandwidth, and low implementation cost. Current-mode control technique has a faster dynamic response than its voltage-mode counterpart. However, its main disadvantage is the need for external ramp compensation. As a result of this, the inductor current does not accurately track the reference current. Furthermore, in most of the operating situations, the current control loop is over-compensated to assure stability and therefore slow. Digital controllers have had a substantial development over the past few years [14-26]. Although digital control schemes have several advantages compared to analog approaches, they have some disadvantages including high cost, computational time delay, limit cycling, and quantization and truncation errors.

Projected cross point control (PCPC), a new average current-mode control technique, is introduced in this paper. PCPC is analog in nature; however, it resembles the deadbeat characteristic of digital approaches [14, 15]. Unlike conventional approaches, PCPC does not need a current compensator and controls the true average value of the inductor current with no sub-harmonic oscillations. It has a very fast dynamic response and is not sensitive to the output voltage noise. Furthermore, PCPC avoids the disadvantages of digital controllers. PCPC first projects the equation of the inductor current in the negative slope area; then, it locates the cross point of the positive slope inductor current and the projected line to find the accurate value of the duty ratio.

In Section II, advantages and disadvantages of conventional current-mode control is presented. Digital control of dc-dc converters is briefly reviewed in Section III. Principles of operation and implementation of PCPC are provided in Section IV. Comparison between the dynamic performance of the conventional current-mode controllers and PCPC approach are discussed in Section V. Finally, Section VI draws the conclusions and presents an overall evaluation of the newly proposed control method.

II. CONVENTIONAL CURRENT-MODE CONTROL

Conventional analog control approaches for dc-dc converters practiced in industry include voltage-mode and current-mode control. Voltage-mode control is a single-loop controller. It uses measured output and the reference voltage to generate the control voltage signal. Then the control voltage signal is used to determine the switching duty ratio by being compared with a fixed frequency sawtooth waveform.

Voltage-mode control of dc-dc converters has several disadvantages including poor reliability of the main switch; degraded reliability, stability, or performance when several converters are placed in parallel supplying a single load; complex and often inefficient methods of keeping the main transformer of a push-pull converter operating in the center of its linear region; and a slow system response time which may be several tens of switching cycles.

In contrast, current-mode control is a dual loop control method, including current and voltage control loops. In this method, the error signal between output voltage v_o and reference voltage v_{ref} is used to generate reference current i_{ref}. Then this reference current is compared with sensed inductor current i_L to control the duty cycle, as shown in Fig. 1. Through this method, the inductor current will track the reference current and the output voltage will become equal to the reference voltage. There are three basic types of current-mode control peak, valley, and average.

A. Advantages of current-mode control

A converter with a current-mode controller has additional good properties which voltage-mode controlled converters lack. 1) Improved transient response: The current-mode controlled converter is a first order system. It is much easier to design a feedback circuit and the overall transient response is

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greatly improved. 2) Output immunity to the input noise: The output of the constant current converter is nearly independent of the input. It puts a fixed current into the load so input transients do not have to be corrected by external feedback. 3) Suitable for paralleled converters: If current-mode control in used for converters operating in paralleled, there is only one external feedback circuit to regulate the voltage. The paralleled converters will receive the same control voltage, so there will be equal load sharing. 4) Self-protection against overload: The current-mode control converter needs no short circuit protection because it is a current source. The control voltage is internally limited, so even if the external control voltage goes to some high value, the output current just goes to the allowed maximum. 5) Over-current protection for the main switches: The current threshold is internally limited to a maximum value. So the maximum switch current is automatically limited. This feature improves reliability by protecting the switches during startup, overloads, and other potentially damaging transients. 6) Anti-saturation: The current threshold control circuit automatically keeps the core in the center of its B-H curve because the current in each switch is shut off at the same level. Any magnetizing current unbalance automatically causes the switch timing to cancel the unbalance and there is near zero dc in the transformer primary.

B. Disadvantages of current-mode control

Current-mode control also has some disadvantages. It becomes unstable when the duty ratio exceeds 0.5 in peak current-mode control [12, 13]. This effect is depicted in Fig. 2. In this figure, the solid line is the inductor current waveform of the converter in steady-state operation, while the dashed line shows the waveform of the perturbed inductor current. The inductor current has a rising slop of m_1 and a falling slope $-m_2$. If there is a perturbation of ΔI_0 in the inductor current relative to the steady state at the beginning of a period, after n periods, this perturbation will become

$$\Delta I_n = -\left(\frac{m_2}{m_1}\right)^n \Delta I_0 = \left(-\frac{d}{1-d}\right)^n \Delta I_0 \tag{1}$$

Where d is the duty ratio. From (1), the error will be enlarged after several cycles and the system will become unstable when the duty ratio is greater than 0.5.

An external ramp is used to solve this problem. A cyclic falling slope of $-m$ is added to the reference current in Fig. 3. By using the external ramp $-m$, the perturbation ΔI_0 will become

$$\Delta I_n = \left(-\frac{m_2 - m}{m_1 + m}\right)^n \Delta I_0 \tag{2}$$

after n cycles. It can be seen from (2), the perturbation will die out after several cycles if the external ramp $-m$ is selected appropriately, even if the duty ratio is greater than 0.5. In particular, m is chosen to be equal to m_2. Thus, the perturbation of the inductor current will disappear in one cycle. The system will be stable and simultaneously provide the fastest possible transient response of the programmed current.

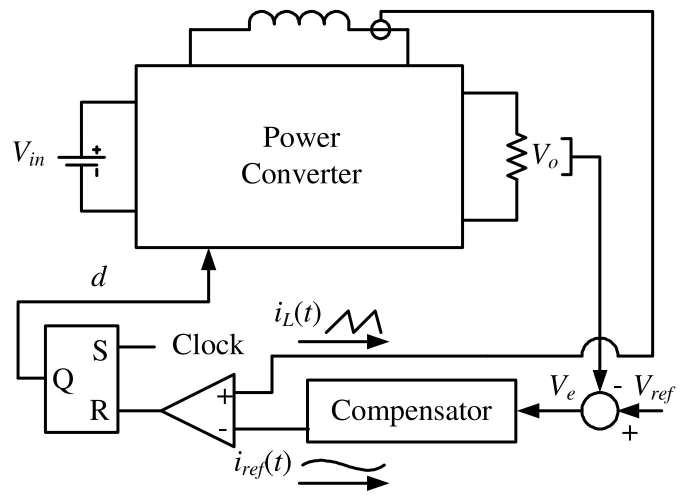

Figure 1. Block diagram of a peak current-mode controller.

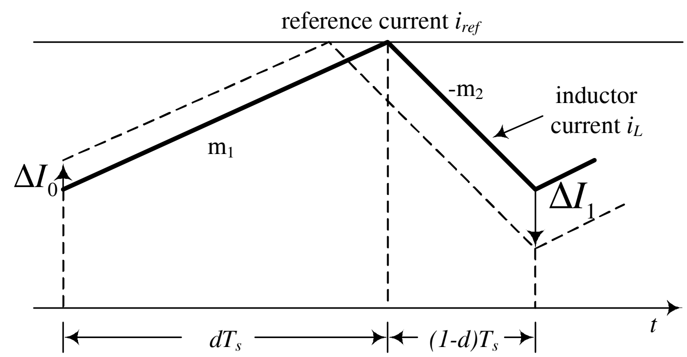

Figure 2. Propagation of a perturbation when *d* is greater than 0.5.

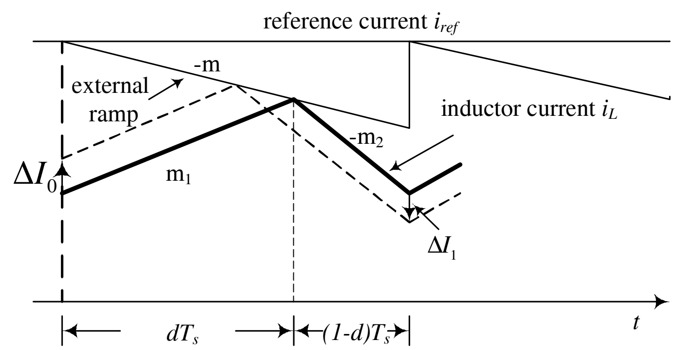

Figure 3. Propagation of a perturbation in the presence of a suitable ramp (Stability can be maintained for all d).

In average current-mode control, a low-pass filter is used after current sensor to get the average value of the inductor current. This filter causes some time delay in the current loop which deteriorates the dynamic response.

III. DIGITAL CURRENT-MODE CONTROL

Different types of digital controllers have been introduced recently [14-26]. Fig. 4 depicts the block diagram of a digital current-mode controller implemented using a DSP. In digital current-mode control, the sampled inductor current and input and output voltages are used to compute the duty ratio in the current or next switching cycle. In digital current-mode control, the objective is to force the peak, average, or valley value of the inductor current to follow reference current i_{ref}. In most applications, the reference current itself is obtained from the voltage compensator.

A. Advantages of digital current-mode control

Compared with analog circuits, digital control systems offer a numbers of advantages. Digital control has high flexibility. In digital control, different control algorithms can be easily implemented by software in the same hardware control system. The control algorithm can easily be changed according to the design requirement. Communication, protection, prevention and monitoring circuits could be easily built in the digital control system. Fewer components are used in digital controllers compared with analog circuits. Hence, digital control system has better reliability than analog circuits. It is much easier to implement the advanced control techniques into digital control system. As a result, the system dynamic performance could be significantly improved.

B. Disadvantages of digital current-mode control

One of the main drawbacks of digital control is the limited bandwidth due to the inherent time delay required for A/D conversion, computation, and PWM generation. In switch mode power supplies, this delay is usually equal to one sampling period. Such time delay degrades the control loop performance, resulting in slower response and less rejection to dc bus ripple and load disturbance. Also, the signal amplitude quantizers such as A/D converters used in digital controllers cause the problems of limit cycling, which causes undesirable and unpredicted output voltage variations in the steady-state.

IV. PROJECTED CROSS POINT CONTROL APPROACH

A new current-mode control technique named projected cross point control (PCPC) is introduced in here to overcome the drawback of existing analog and digital approaches. PCPC is an analog control appraoch in nature. It combines the advantages of both analog and digital control techniques. Unlike the conventional analog methods, it accurately controls the average value of the inductor current with no need to a current compensator or an external ramp. In addition, while resembling the deadbeat characteristics of digital controllers, PCPC does not suffer from computational time delay, limit cycling, and quantization and truncation errors.

In this paper, without loss of generality, a buck converter is used to introduce the principles of operation of PCPC method. Typical waveform of the inductor current is shown in Fig. 5. In this figure, i_{ref} indicates the reference current, which is the output signal of the voltage compensator. Without loss of generality and for the ease of demonstration, reference current i_{ref} is drawn as a straight line in Fig. 5. The desired inductor current in the steady-state is sketched in dashed lines and associated labels are identified by a ss (steady-state) subscript.

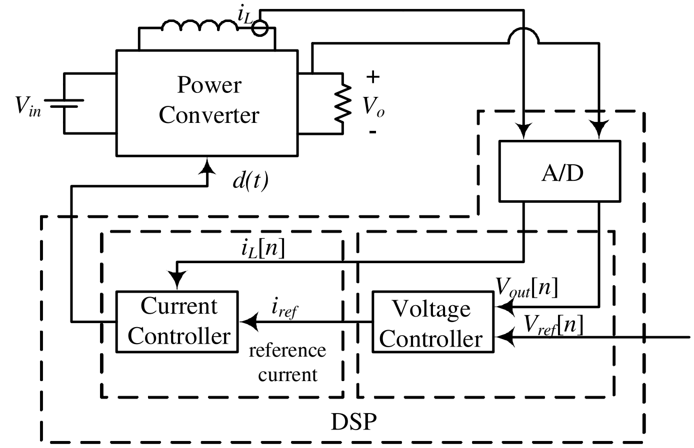

Figure 4. Block diagram of the digital current-mode controller.

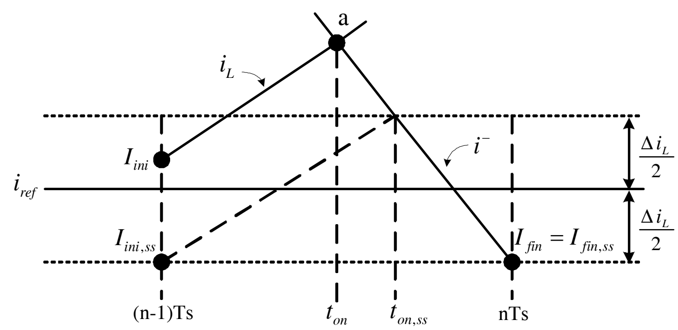

Figure 5. Typical current waveform of a buck converter.

It is worth mentioning that the initial and final values of the inductor current in the steady-state operation are identical and the average value of the inductor current follows the current reference. In Fig. 5, perturbed inductor current is sketched in solid lines. The control objective is to make sure that the final value of the inductor current returns to its steady state value no matter what the initial value of the inductor current is. In other words

$$i_L(t = nT_s) = i_{fin,ss} = i_{ref} - \frac{\Delta i_L}{2} \tag{3}$$

$$\Delta i_L = \frac{V_o}{L}(1-d)T_s = \frac{V_o}{L}(1-\frac{V_o}{V_{in}})T_s \tag{4}$$

Where, $i_{fin,ss}$ is the final value of the inductor current in steady-state operation and Δi_L is the steady-state peak-to-peak ripple of the inductor current. It is obvious that if the control objective (3) is satisfied, in the next switching cycle, average value of the inductor current will be identical with the reference current. This can be proven by considering the average value of inductor current in the selected switching period, which can be described as

$$I_{avg} = I_{ini} + \frac{V_{in} - V_o}{2L}\frac{V_o}{V_{in}}T_s \tag{5}$$

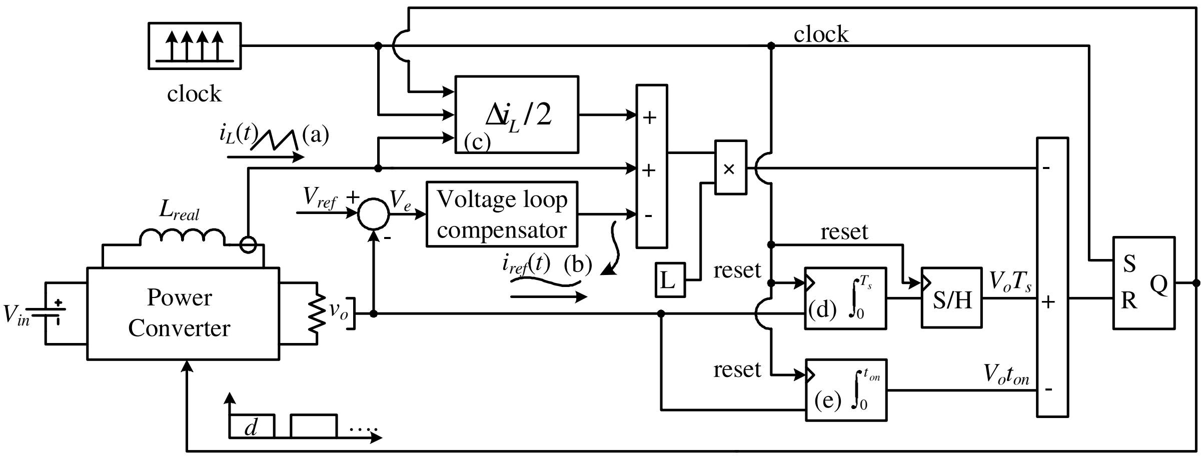

Figure 6. Block diagram of PCPC approach.

If I_{ini} is forced to be equal with i_{ref}-$\Delta i_L/2$, then (5) will yield $I_{avg}=i_{ref}$. Hence, PCPC method is an average current-mode control approach. In order to satisfy the control objective, the proposed controller needs to find the cross point of lines i_L and i^- (the inductor current in the negative slope area) which is indicated as point '*a*' in Fig. 5. The equation for i^- is

$$i^- = i_{ref} - \frac{\Delta i_L}{2} + \frac{v_o}{L}T_s - \frac{v_o}{L}t \tag{6}$$

In order to find t_{on}, the cross point of i_L and (6) will have to be identified; therefore,

$$i_L(t = t_{on}) = i^-(t = t_{on}) \tag{7}$$

$$i_L(t = t_{on}) = i_{ref} - \frac{\Delta i_L}{2} + \frac{v_o}{L}T_s - \frac{v_o}{L}t_{on} \tag{8}$$

Equation (8) can be simplified as

$$\underbrace{L(i_L(t = t_{on})}_{(a)} - \underbrace{i_{ref}(t = t_{on})}_{(b)} + \underbrace{\Delta i_L/2)}_{(c)} = \underbrace{v_oT_s}_{(d)} - \underbrace{v_ot_{on}}_{(e)} \tag{9}$$

PCPC solves (9) for t_{on} and duty ratio in real time as shown in the block diagram in Fig. 6. Different expressions in (9) that are labeled (a) through (e) are found as follow: (a) Inductor current i_L is measured. (b) Reference current i_{ref} is measured. (c) Δi_L is the steady-state peak-to-peak ripple of the inductor current. $\Delta i_L/2$ is found based on the previous measured values of i_L and i_{ref}, as shown in Fig. 7. Δi_{max} is defined as the difference between the maximum value of i_L and i_{ref} sampled at the turn-off time of the switch, which is generated by the reset input of the SR latch. Δi_{min} is defined as the difference between the minimum value of i_L and i_{ref} sampled at the turn-on time of the switch, which is generated by the clock signal. Average values of Δi_{max} and Δi_{min}, measured in each switching cycle, are then found by a simple analog circuitry. $\Delta i_L/2$ is then found using a low pass filter (LPF). An LPF is used to make sure that transients and tracking errors have no effect on the accurate measurement of $\Delta i_L/2$. The transfer function of LPF used in this work is $(1+80*10^{-6}S)^{-1}$. (d) Output voltage is relatively constant; therefore, v_oT_s can be found by integrating the output voltage over the previous switching cycle. (e) v_ot_{on} can be found by integrating the output voltage during the on-time of the switch.

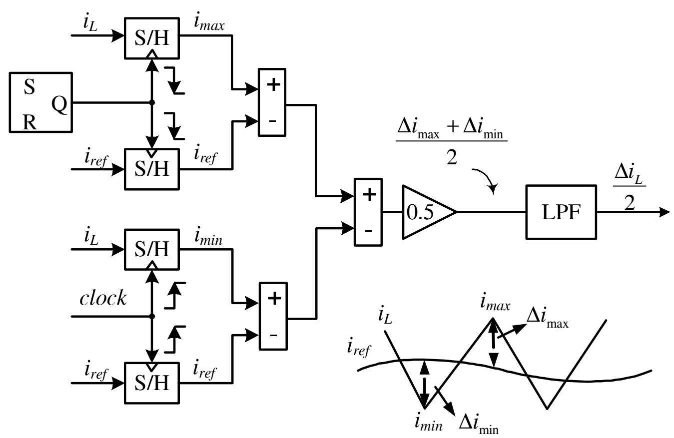

Figure 7. Block diagram of the steady-state peak-to-peak ripple finder.

PCPC method can be compared with its digital counterparts. The equation of i_L is shown in (10),

$$i_L = I_{ini} + \frac{V_{in} - V_o}{L}t \tag{10}$$

From (6), (7), and (10), one obtains

$$\frac{V_{in}}{L}t_{on} = i_{ref} - \frac{\Delta i_L}{2} + \frac{V_oT_s}{L} - I_{ini} \tag{11}$$

The following are some standard notions in digital applications,

$$I_{ini} = i_L[n-1], i_{ref} = i_{ref}[n-1], t_{on} = d[n]T_s \tag{12}$$

Substituting (12) into (10), one obtains

$$\frac{V_{in}}{L}d[n]T_s = i_{ref}[n-1] - i_L[n-1] - \frac{\Delta i_L}{2} + \frac{V_oT_s}{L} \tag{13}$$

which can be expressed as,

$$d[n] = \frac{L}{V_{in}T_s}(i_{ref}[n-1] - i_L[n-1] - \frac{T_sV_o}{2V_{in}} \cdot \frac{V_{in} - V_o}{L}) + \frac{V_o}{V_{in}} \tag{14}$$

Equation (14) is the same equation of average digital current-mode control method introduced in [16] and [17].

V. SIMULATION RESULTS

In order to observe the performance of the new proposed method, two conventional control approaches, an average current-mode controller [10] and a peak current-mode controller with external ramp are used. A buck converter with the following parameters is used as the power stage. Reference voltage $V_{ref} = 2$ V, Inductor value $L = 20$ uH, Capacitor value $C = 330$ uF, Switching frequency $f_s = 100$ kHz, Input voltage V_{in} abruptly changes from 3 V to 6 V at 0.01 s, and Load resistance R abruptly changes from 2 Ω to 3 Ω at 0.02s.

The voltage loop compensator used for all of these control methods is the same, which is

$$\frac{27447}{s}\frac{1/(6.0518*10^3)s+1}{1/(1.3076*10^5)s+1} \tag{15}$$

The current loop compensator for the conventional average current-mode controller is considered to be

$$\frac{11455}{s}\frac{1/(1.1905*10^4)s+1}{1/(3.1494*10^5)s+1} \tag{16}$$

Fig. 8 depicts the tracking accuracy of PCPC scheme. In this simulation, voltage loop is open and reference current i_{ref} is subjected to positive and negative slopes and step changes. As it can be observed, the inductor current can precisely track its reference with no time delay. PCPC truly and accurately controls the average value of the inductor current. Furthermore, there is no sign of sub-harmonic oscillations. Having the voltage loop closed, waveforms of the output voltage and the inductor current and its reference when there is a step change in input voltage V_{in} are shown in Figs. 9 and 10, respectively. It is worth mentioning that in the conventional peak current-mode control external ramp is added to the reference current which makes the overall waveform to be negative at some points. The results show that the proposed PCPC method has a superior transient performance for line regulation. Waveforms of the output voltage and the inductor current and its reference when there is a step change in the load resistance are shown in Figs.11 and 12, respectively.

VI. CONCLUSION

Projected cross point control (PCPC), a new average current-mode control method, is presented in this paper. The proposed method is analog based and simple. It is cheap to implement and has a very fast dynamic response. Compared with digital approaches, the proposed control method does not suffer from computational time delay, limit cycle, and truncation problems. Compared with conventional analog approaches, the presented control scheme is stable for all values of the duty ratio; hence, it does not need any external ramp compensation. Furthermore, PCPC does not need any current compensation circuit. In addition, it accurately controls the true average value of the inductor current. Simulation results prove its superior transient performance.

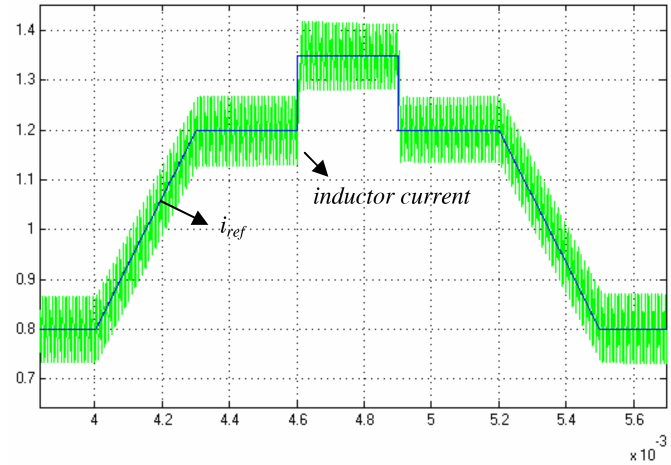

Figure 8. The inductor current waveform using PCPC approach.

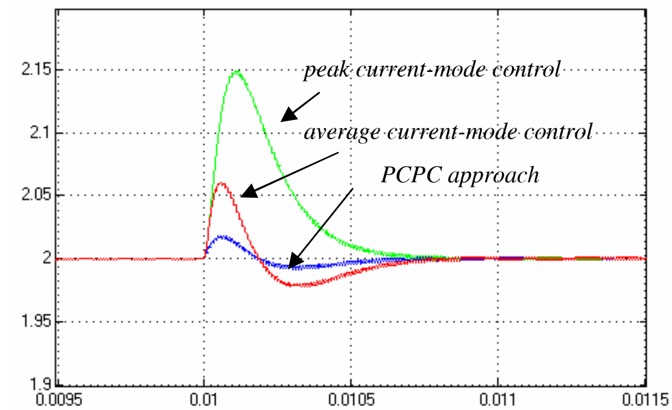

Figure 9. Transients in the output voltage when input voltage V_{in} changes from 3 V to 6 V at 0.01 s.

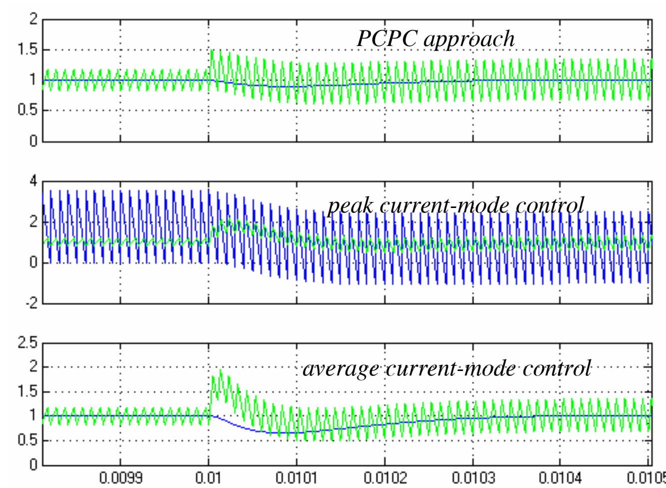

Figure. 10 Inductor current and its reference waveforms when V_{in} changes from 3 V to 6 V at 0.01 s.

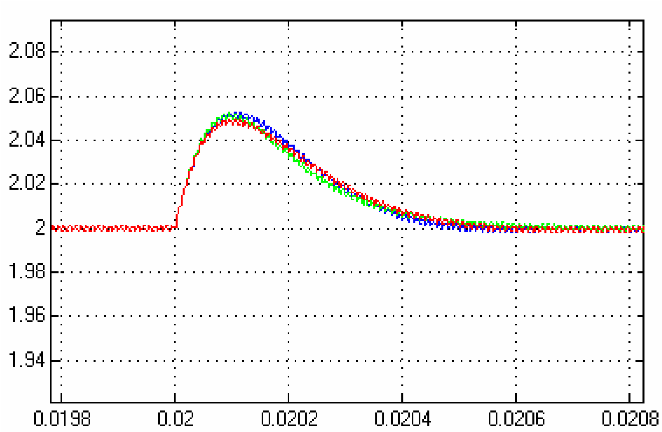

Figure 11. Output voltage waveforms when load changes from 2 Ω to 3 Ω at 0.02 s.

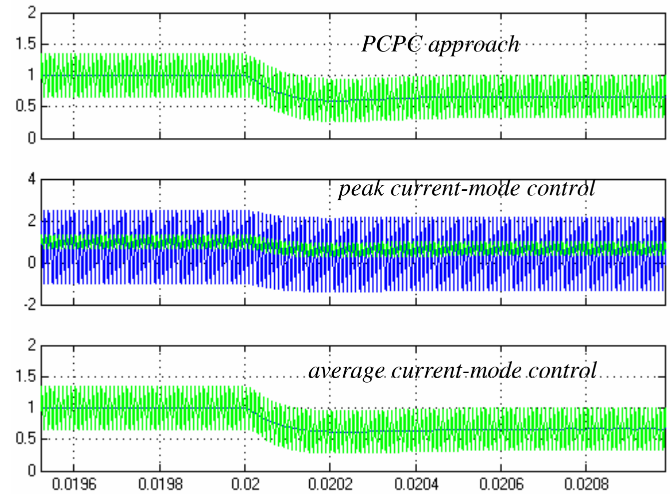

Figure 12. Inductor current and its reference waveforms when load changes from 2 Ω to 3 Ωat 0.02 s.

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