State Trajectory Prediction Control for Boost Converters

Kelvin K.S. Leung and Henry S.H. Chung†

Department of Electronic Engineering
City University of Hong Kong
83 Tat Chee Avenue, Kowloon Tong, Kowloon, Hong Kong
†Fax.: (852) 2788 7791
†Email: eeshc@cityu.edu.hk

Abstract **– Boost and flyback converters have a right-half-plane zero in their control-to-output transfer function. This property makes the controller difficult to be designed with the classical frequency-domain approach to ensure good output regulation and fast response over wide frequency bandwidth of input voltage and output load perturbations. Instead of a small-signal design approach, this paper presents a cycle-by-cycle state trajectory prediction (STP) control method for boost converters. The method is based on predicting the output voltage after a hypothesized switching action. The output can revert to steady state in two switching actions under large-signal input voltage and output load disturbances. Theoretical predictions are verified with experimental results of a 120W 18/24V prototype.**

I. INTRODUCTION

Over the last three decades much effort have been made to research new control schemes for switching converters to achieve good output regulation and dynamic response. As switching converters are inherently nonlinear, most of the design strategies are based on small-signal techniques [1]. However, some converters, like boost and flyback converters, have a right-half-plane zero in their control-to-output transfer function. This property makes the controller difficult to be designed with the classical frequency-domain approach for ensuring good output regulation and fast response over wide bandwidth of input voltage and output load perturbations [2].

There has been considerable work along large-signal modeling and control of switching converters. A direct and viable approach of designing the control scheme is to apply some nonlinear system control techniques, in which the nonlinear power stage is represented by state-space averaged models [3]. Typical design strategy is to use the Lyapunov asymptotic stability theory to derive a control law that ensures a global stability region and optimizes both state trajectories and control energy [4]. Other approaches use robust nonlinear control algorithms for the small-signal models that achieves global or semi-global stability [5].

Another approach is based on cycle-by-cycle control schemes, in which the controlled switch is dictated by the instantaneous values of the circuit variables. Examples of these are the one-cycle control of [6], the sliding mode control schemes of [7], the bang-bang control [8], and the digital control [9]. However, the control using one-cycle control has no information on the output load disturbances and is for buck converters only. In the sliding-mode control, the trajectory is restricted along the sliding surface and will converge to the operating point after many switching cycles. Bang-bang or hysteresis control can provide a fast dynamic response and tracking of the control variables. However, the hysteresis control does not work with all types of systems. If a control of this type, based on the output voltage, is tested with a boost converter, the results are disastrous. Paper [8] proposes the use of state-trajectories control that the converter can achieve steady-state operation for a step change in input voltage or output current in one on/off control, but the control requires either sophisticated digital processor or analog computation.

Concluding the above control methods, the best solution is the one that can achieve the ultimate goals proposed in [8], but with a simple implementation. This paper presents a cycle-by-cycle STP control method for boost converters. The method is based on predicting the output voltage after a hypothesized switching action. Several switching criteria are derived to dictate the state of the main switch. Theoretical predictions are verified with experimental results of a 120W 18/24V converter prototype.

II. PRINCIPLES OF OPERATIONS

A. *Steady-state operation*

Fig. 1 shows the schematic of the boost converter, which has three possible topologies. In Topology 1, the switch *S* is on and the diode *D* is off. The inductor *L* is charging up from the input source v_i. The output load *R* is supplied from the output capacitor *C*. The output voltage is v_o. Thus,

$$\frac{di_L}{dt} = \frac{1}{L} v_i \tag{1}$$

and

$$\frac{dv_o}{dt} = \frac{dv_C}{dt} = \frac{1}{C} i_C \tag{2}$$

where i_L is the inductor current, v_C is the capacitor voltage, and i_C is the capacitor current.

In Topology 2, *S* is off and *D* is on. The energy stored in *L* will release to the load, together with the input source. Thus,

$$\frac{di_L}{dt} = \frac{1}{L}(v_i - v_o) \tag{3}$$

and

$$\frac{dv_o}{dt} = \frac{dv_C}{dt} = \frac{1}{C} i_C \tag{4}$$

In Topology 3, S and D are off. No energy remains in L. The output load is supplied from C.

$$\frac{di_L}{dt} = 0 \tag{5}$$

and

$$\frac{dv_o}{dt} = \frac{dv_C}{dt} = \frac{1}{C} i_C \tag{6}$$

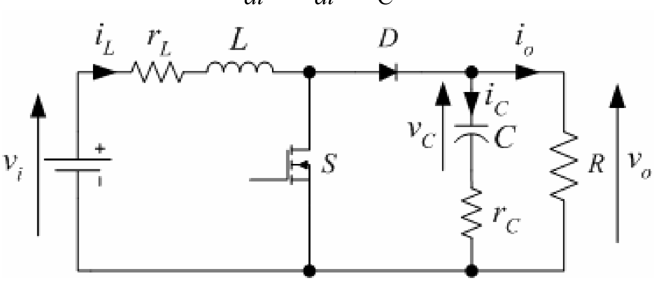


Fig. 1 Schematic of boost converter.

If the output ripple voltage is much smaller than the average output voltage in the steady state, it can be assumed that the output current i_o is a constant. Fig. 2 shows the typical waveforms of the v_o and i_C varies between $v_{o,\max}$ and $v_{o,\min}$. The state of S is determined by predicting the area under i_C with a hypothesized switching action till $i_C = 0$ and comparing the area with a fixed ratio of the output error at that instant. The control scheme is depicted in Fig. 3.

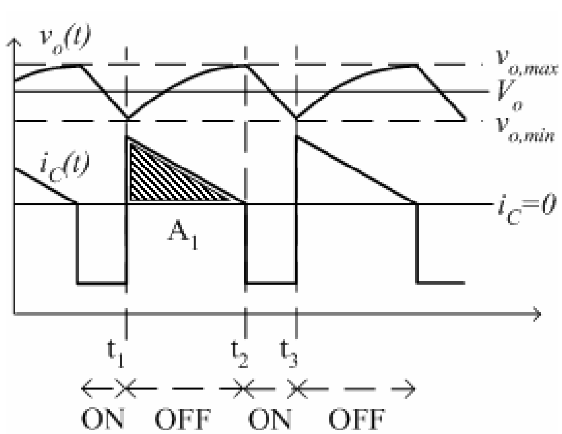


Fig 2 Typical waveforms of v_o and i_C.

v_{gate} is derived from the output 'Q' of an RS flip-flop. The input 'R' is v_{g_off}, which commands S off. The input 'S' is v_{g_on}, which commands S on. When v_{g_off} and v_{g_on} are in logic 'HIGH', the state of S will be changed.

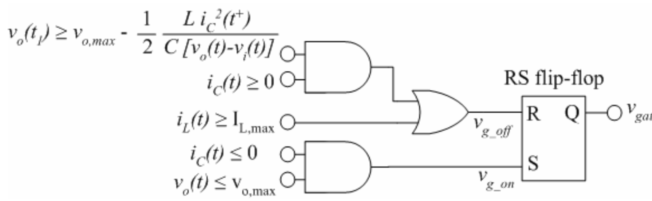


Fig. 3 Control Circuit of STP boost converter.

1) Generation of v_{g_off} for switching S off

As shown in Fig. 2, S is originally in the on state and is switched off at t_1. The objective is to determine t_1, so that v_o equals $v_{o,\max}$ at t_2 (at which $i_C = 0$). The shaded area A_1 under i_C is integrated from t_1 to t_2. Thus,

$$\Delta v_o = v_o(t_2) - v_o(t_1) = v_{o,\max} - v_o(t_1) = \frac{1}{C}\int_{t_1}^{t_2} i_C \, dt \tag{7}$$

If A_1 is approximated by a triangle, it can be shown that

$$\int_{t_1}^{t_2} i_C \, dt = \frac{1}{2}\frac{L \cdot i_C^2(t_1^+)}{[v_o(t_1) - v_i(t_1)]} \tag{8}$$

where $i_C(t_1^+)$ is the value of i_C after S is switched off.

i_C is inconsistent before and after switching S off at t_1,

$$i_C(t_1^-) \neq i_C(t_1^+) \tag{9}$$

$i_C(t_1^+)$ is obtained by subtracting $i_o(t_1^-)$ from $i_L(t_1^-)$,

$$i_C(t_1^+) \cong i_L(t_1^-) - i_o(t_1^-) \tag{10}$$

S has to be switched off, in order to ensure that v_o will not exceed $v_{o,\max}$ in the subsequent topology. Thus, by substituting (8) into (7), the criteria for switching S off are

$$v_o(t_1) \geq v_{o,\max} - \frac{1}{2}\frac{L \cdot i_C^2(t_1^+)}{C \cdot [v_o(t_1) - v_i(t_1)]} \tag{11}$$

and

$$i_C(t_1^+) \geq 0 \tag{12}$$

For the sake of safety, S will also be switched off if i_L is larger than $I_{L\_\max}$. That is,

$$i_L(t) \ge I_{L\_\max} \tag{13}$$

Fig. 3 shows how v_{g_off} is generated from (11)-(13). The second term of the right-hand-side in (11) is realized by using an analog computational unit [8] that perform the function of

$$v_{off} = v_y \left(\frac{v_z}{v_x}\right)^m \tag{14}$$

where $m = 2$, $v_x = 1$, $v_y = \frac{1}{2}\frac{L}{C\cdot[v_o(t_1) - v_i(t_1)]}$, and $v_Z = i_C(t_1^+)$.

v_{off} is then subtracted from $v_{o,\max}$ and compared with v_o to implement (11).

2) Generation of v_{g_on} for switching S on

As shown in Fig. 2, S can be switched on at t_2 when $v_o = v_{o,\max}$ and $i_C = 0$. Thus,

$$i_C(t_2) \le 0 \tag{15}$$

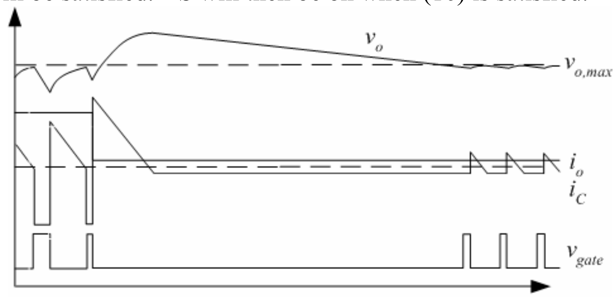
and

$$v_o(t_2) \le v_{o,\max} \tag{16}$$

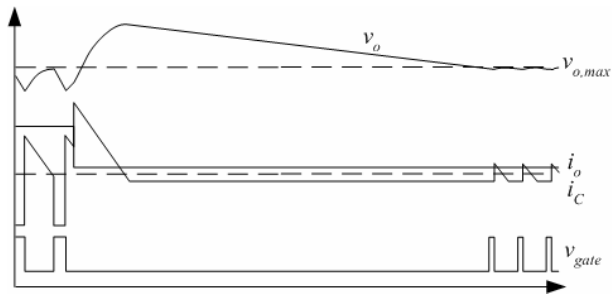
Fig. 3 shows how v_{g_on} is generated from (15) and (16).

B. Transient response

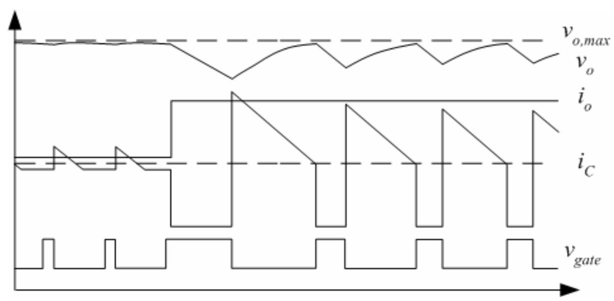
The criteria of (11)-(16) are applicable for both steady-state operation and large-signal disturbances. Followings illustrate the transient responses of the converter under a load change with different initial switching condition. Fig. 4(a) shows the corresponding waveforms, when i_o is suddenly decreased and S is on initially. Since i_L cannot change suddenly, i_C will increase significantly. Eqs. (11) and (12) are satisfied. v_{g_off} is generated. S is then switched off. The converter may go into the discontinuous conduction mode, showing that the control method is independent on the mode. Fig. 4(b) shows the corresponding waveforms when i_o is decreased suddenly and S is initially off. i_C increases. Eqs. (11) and (12) are satisfied. Thus, S will keep on in the off state, until v_{g_on} commands S to on. Fig. 4(c) shows the corresponding waveforms when i_o is increased suddenly and S is initially on. i_C decreases instantaneously. Eqs. (11) and (12) are not satisfied. Eq. (15) will be satisfied and (16) may be satisfied. S will keep on in the on state. Fig. 4(d) shows the corresponding waveforms when i_o is increased suddenly and S is initially off. i_C decreases instantaneously. Eq. (15) will be satisfied. S will then be on when (16) is satisfied.



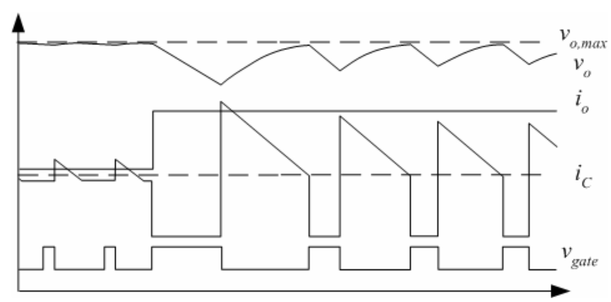
(a) i_o decreases when S is ON.



(b) i_o decreases when S is OFF.



(c) i_o increases when S is ON.

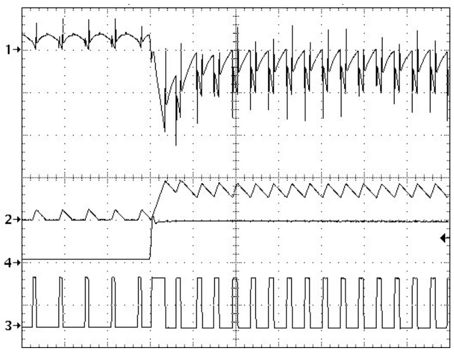


(d) i_o increases when S is OFF.

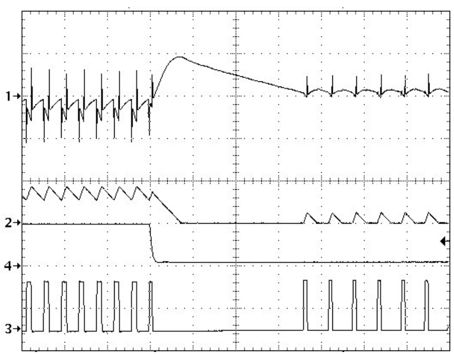
Fig. 4 Waveform of v_o, i_o, i_C and v_{gate} under load change.

III. Experimental Prototype

A 120W prototype has been built. The component values are: L = 12μH and C = 300 μF. v_o is regulated at 24V and the nominal input voltage is 18V. Fig. 5(a) shows the transient responses of the converter when i_o is changed from 0.5A (12W) to 5A (120W). Fig. 5(b) shows the transient responses when i_o is changed from 5A (120W) to 0.5A (12W).

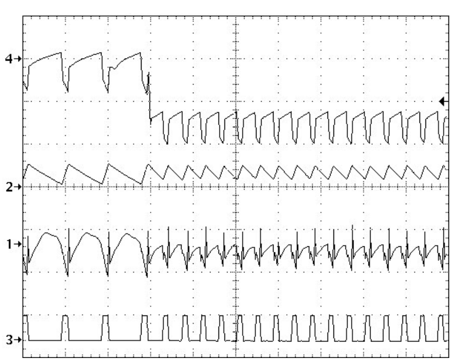


(a) i_o is changed from 0.5A(12W) to 5A(120W). [Ch1: v_{out} (50mV/div)].

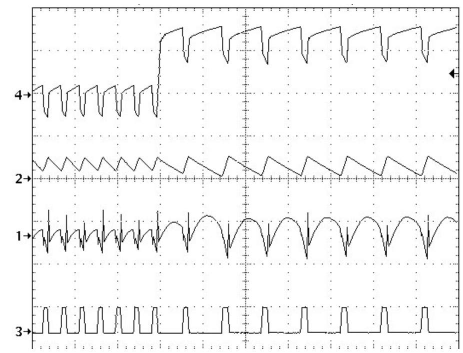


(b) i_o is changed from 5A(120W) to 0.5A(12W). [Ch1: v_{out} (100mV/div)]

Fig. 5 Transient response under output current change [Ch2: i_L (10A/div); Ch3: v_{gate} (5V/div); Ch4: i_o (5A/div)]



(a) v_i is changed from 20V to 18V.



(b) v_i is changed from 18V to 20V.

Fig. 6 Transient responses under input voltage change. [Ch1: v_{out} (50mV/div); Ch2: i_L (10A/div); Ch3: v_{gate} (10V/div); Ch4: v_i (2V/div)]

Fig. 6(a) shows the transient responses of the converter when v_i is changed from 20V to 18V. Fig. 6(b) shows the transient responses of the converter when v_i is changed from 18V to 20V.

IV. Conclusions

An STP technique that is applied to achieve fast transient response of the boost converter is presented. The output voltage can revert to steady state within two switching actions when it is subject to large-signal disturbances. The STP performances have been studied experimentally with a 120W 18/24V converter prototype.

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