Hybrid Control Method for Optimal Transient Response and Output Filter Minimization for Buck-Boost type Converters

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Abstract

This paper introduces a new digital control methodology for indirect energy transfer converters that is based on a hybrid controller concept. During transients, the control sets boundaries for inductor current and the output voltage based on the load conditions and the system requirements to facilitate rapid recovery and small output voltage variations. Once the output voltage is recovered, linear current programmed mode control operation is resumed. The control method significantly reduces the component stress requirements which leads to a smaller volume converter and can be realized on any digital current programmed mode control platform with very few additions. The operation of the controller was verified by simulation and experiments which found the new control scheme superior over the conventional linear control and time-optimal nonlinear control methods.

1. Introduction

Following the recent proliferation of portable electronics, there has been a sharp increase in the demand for more compact, lighter, more energy efficient, and more economical power sources [1-4]. As this trend continues, the requirements are becoming more and more challenging. Tighter output voltage regulation, faster response time to load and/or input voltage changes and lower volume – the major concerns in the design of present-day SMPSs – are creating a ‘bottle-neck’ in the advancement of the technology. The limitations stem primarily from the present lack of both advanced design methods for SMPSs and control methods that are specifically oriented toward load and line transient requirements.

Switch-mode converters normally operate in closed-loop to achieve the desired regulated output, stable operation, and the desired dynamic performance [1,5]. Currently, where fast response and cost-effective implementation are of key importance, analog linear controllers are mainly used [6-10]. However, following the rapid advancement of digital technology, the integration of digital controllers in switch-mode power applications has become a viable alternative. The main limitation of all the designs that are based on linear small-signal compensators, regardless of the extraction method, is that the system response is still bounded by the bandwidth of the design, which is constrained by other static and dynamic requirements, such as the steady-state error and stability. Moreover, the primary design objective of the compensators is to minimize the error between the value of the current output voltage and the desired reference value. This implies that any change in the loading conditions or in the input voltage will be corrected only after it has already affected the output voltage. These limitations have motivated the use of nonlinear compensation schemes that can be designed to respond more rapidly to load or line variations and are not bounded by the bandwidth of the system, which is regulated by the linear small-signal compensator.

Transient-oriented controllers, or time-optimal controllers [11-18], have demonstrated improvement in the dynamic response for a particular type of direct energy transfer converters (buck or forward). In this case, the time-optimal response always results in the minimum possible output voltage deviation and output capacitance value. However, for indirect energy transfer systems, such as a boost, buck-boost, or flyback converters, this is not the case. Here, the time-optimal response often produces a larger-than-minimum output voltage deviation and causes extra current stress of the components. The main reason for this is the fact that in order to charge the inductor to the new current value, it has to be disconnected from the load for a relatively long period of time, causing extra voltage drop.

The objective of this paper is to introduce a new control scheme for buck-boost type converters that is oriented toward the load transient response and minimizes the output voltage drop and the component current stress. The new hybrid controller can be realized on any digital peak current programmed mode (CPM) controller platform with very few modifications. The control methodology is based on the hybrid controller concept, which is formed by two main modules as shown in Fig.1. One module is a straight-forward linear CPM controller which is in charge of regulating the output during the steady-state operation of the converter, while the second module is a nonlinear controller that is activated during the transient response and is in charge of recovering the output voltage to the steady-state value. Load estimation is performed to provide information to provide information of the new load current.

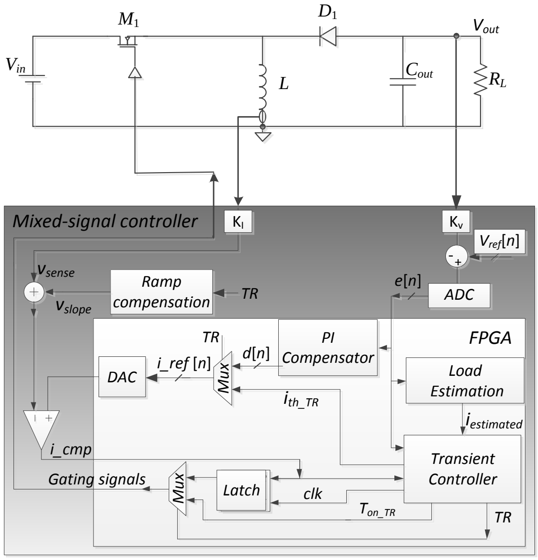

Fig. 1. Hybrid controller regulating operation of a buck-boost converter.

2. Principle of Operation

The concept of the new controller is drawn from the optimum-deviation concept for direct energy transfer converters [12]. That is, rather than minimizing the recovery time to reduce the voltage drop a more direct approach is taken. The controller design is centered around a pre-programmed maximum allowable voltage deviation, which is set based on the new load estimate and the system practical limitation such as the maximum allowable switching frequency.

The recovery to a new steady-state after a light-to-heavy load transient is performed in two phases. Upon the transient, the transistor is turned on. During this time, the controller estimates the new load current and accordingly, sets two lower limits to the output voltage and to the inductor current such that the peak inductor current is slightly larger than its new steady state value. This intuitive selection of the current reference is analytically validated in the following section. In the second phase, the voltage is gradually recovered over several switching cycles. During transient operation, the transistor on time is controlled by the voltage threshold reference and the off time is controlled by the current threshold value. Fig. 2 implies that at the expense of slightly slower recovery time, lower output voltage deviation and the current stress are obtained.

It can also be observed from Fig. 2 that the minimum voltage drop threshold is the intersection point of the first ‘on’ state trajectory and the current threshold, or the point in which the tangents of the on state and the off state are equal ('min', Fig. 2). However, this requires high switching frequency (infinite in the ideal case) and more cycles to reach steady-state which might not be practical in some applications. Therefore, a compromise has to be made between the allowed deviation, recovery time, switching frequency and current stress. For example, Fig. 3 shows a case where the switching frequency is limited to a practical value. This results in smaller output voltage drop and lower components stress than the time-optimal case [12].

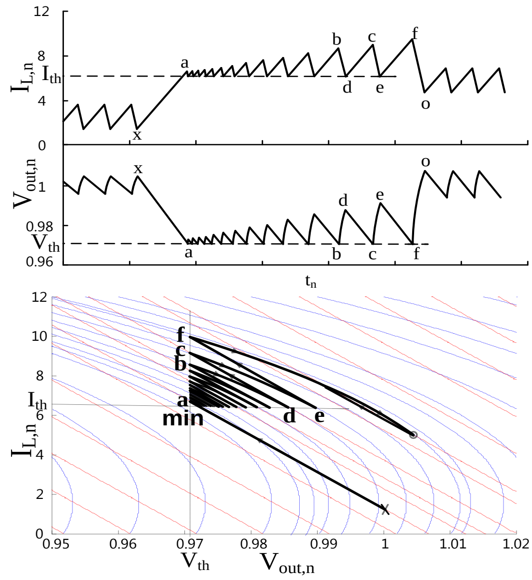

Fig. 2. Ideal operation of a minimum-deviation controller in a buck-boost converter for light to heavy load transient. Demonstrating a case that the operation is not limited by any practical constraints. Output voltage (upper), inductor current (middle) and state space plan (lower).

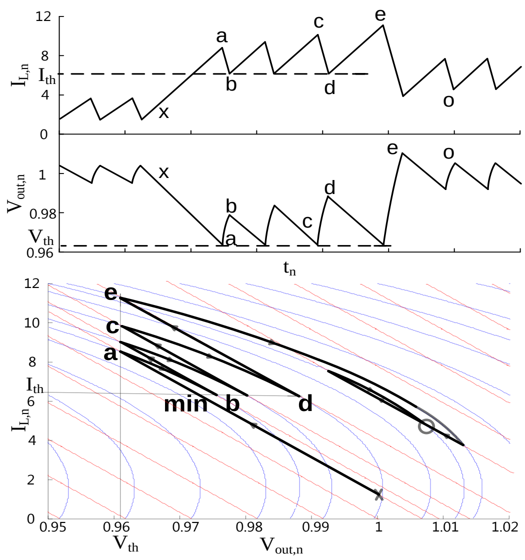

Fig. 3. Principal of operation of the proposed programmable-deviation controller in a buck-boost converter for light to heavy load transient. Maximum switching frequency is limited by practical constraints and a slightly larger deviation is allowed. Output voltage (upper), inductor current (middle) and state space plan (lower).

3. Analytical derivation of the state trajectories and the point of minimum deviation

To derive the value of minimum voltage deviation, the effect of a full on-off cycle on a buck-boost converter is considered. For the following derivations it is assumed that all the components are ideal and that the new load value is given and its behavior is of a current step. The state equations for the on and off states of a buck-boost converter can be expressed as:

$$\frac{di_L}{dt} = \frac{V_{in}}{L} \quad ; \quad \frac{dv_C}{dt} = -\frac{v_{C0}}{CR} \quad \text{on} \qquad (1)$$

$$\frac{di_L}{dt} = \frac{-v_{C0}}{L} \quad ; \quad \frac{dv_C}{dt} = \frac{1}{C}\left(i_L - \frac{v_{C0}}{R}\right) \quad \text{off} \qquad (2)$$

where, i_L and v_C are the state variables, V_{in} is the input voltage, L is the inductor value, C is the value of the output capacitor, and v_{C0} is the initial condition of the output capacitor, i.e. the target output voltage. All are in normalized form.

Solving the differential equations of (1) and (2) yields the on and off trajectories of the converter:

On trajectory: $v_C = -\frac{LI_{ref}}{CV_{in}}(i_L - i_{L0}) + v_{C0}$ (3)

Off trajectory: $v_C = -\frac{L}{2Cv_{C0}}(i_L^2 - i_{L1}^2) + \frac{LI_{ref}}{Cv_{C0}}(i_L - i_{L1}) + v_{C1}$ (4)

where, i_{L0} and i_{L1} are the inductor current initial conditions of the on and off states, v_{C1} is the capacitor initial condition at the beginning of an off state, and I_{ref} is the new load value.

The point of minimum deviation refers to the equilibrium point in which the inductor current is sufficiently high to supply the load, that is, the point in which the tangents of the on and off states are equal. Its value can be obtained by taking the derivative of the trajectories and equating them.

For the on state: $\frac{1}{m_{on}} = \frac{dv_C}{di_L} = -\frac{L}{CV_{in}} I_{ref}$ (5)

and for the off state: $\frac{1}{m_{off}} = \frac{dv_C}{di_L} = \frac{L}{Cv_{C0}}\left(I_{ref} - i_L\right)$ (6)

$$m_{on} = m_{off} \qquad (7)$$

$$v_{Cmin} = v_{C0} - \frac{Z_r^2 I_{ref}}{V_{in}}\left[\frac{I_{ref}}{D_{off}} - i_{L0}\right] \qquad (8)$$

$$i_{Lmin} = \frac{I_{ref}}{D_{off}} \qquad (9)$$

The pair of equations (8) and (9) is the generic analytical derivation of the tangential intersection point or minimum deviation point (point 'min', Fig. 2), for a case of a buck-boost converter, that is load-perturbed by a current source. It can be clearly observed from (9) that, as intuitively conjectured above and implemented in [12], the minimum voltage deviation occurs at the state in which the inductor current is charged to the reflected load value. From this point and on, the voltage may be recovered.

4. Verification by simulation

To demonstrate the optimal control concept, a PSIM simulation test bench has been developed. The setup consists of a buck-boost converter and realization of the hybrid controller of Fig. 1. The controller was implemented by a C block feature of PSIM. The test bench compared the proposed controller against the state-of-the-art time optimal controller. Fig. 4 shows that results of both control methods and the corresponding state trajectories.

It can be observed from Fig. 4 that on the account of slightly longer transient response, the voltage deviation and the inductor current ratings can be significatly reduced.

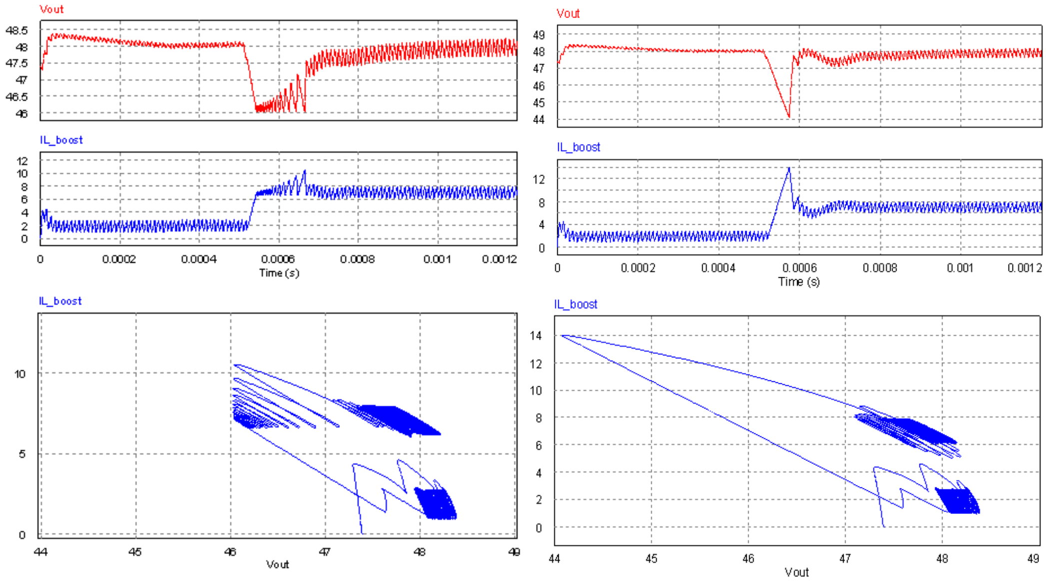

Fig. 4. Simulation results of light-to-heavy load transient response of buck-boost controlled by: optimal-deviation controller (a) and time optimal controller (b). Top: output voltage. Middle: inductor current. Bottom: State-space representation.

5. Experimental

Fig. 5 shows operation of the proposed method in light-to-heavy load transition compared to the CPM control approach for 6 times load step. The proposed method was found to be twice better with than the CPM method and faster to converge to the steady-state value.

Fig. 6 shows operation of the proposed method for heavy to light load transition compared to CPM control. The voltage deviation by the proposed method was found to be 3.7 times smaller than the conventional CPM approach.

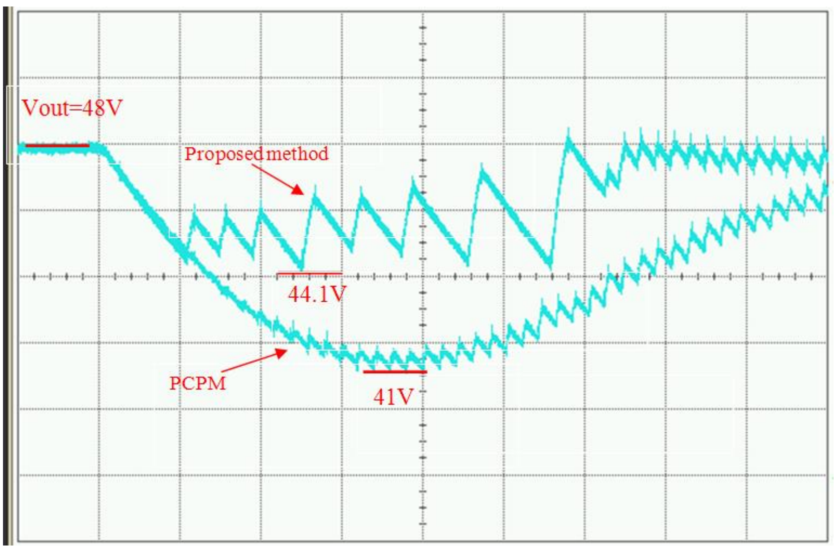

Fig. 5. Experimental results of light-to-heavy load transient response of buck-boost controlled by the hybrid optimal-deviation controller and compared to conventional CPM control scheme.

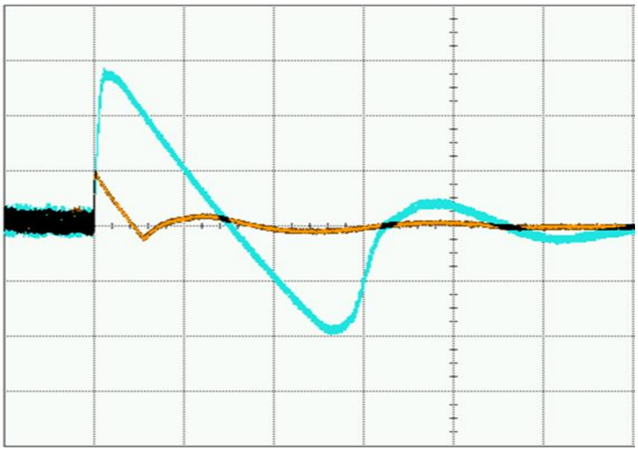

Fig. 6. Experimental results of heavy-to-light load transient response of buck-boost controlled by the hybrid optimal-deviation controller and compared to conventional CPM control scheme.

6. Conclusion

The new hybrid control method is based on mixed-mode CPM control for steady-state control and new non-linear control for large-signal variations. The approach extends the concept of state-space control to applications that are sensitive to large variations either at the output voltage or the components stress in which the use of time-optimal control cannot be applied. The method utilizes the advantages of time-domain based state-space control with simpler and more efficient realization and, in fact, can be imbedded with minor hardware modifications to any digital CPM controlled buck-boost converter.

The method was found to be superior compared to the conventional CPM control in both light-to-heavy and heavy-to-light load (will be given in the full paper) transitions by twice and 3.7 times, respectively.

7. Literature

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