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Simulink Behavior Models for DC–DC Switching Converter Circuits using PWM Control ICs*

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Simulink behavior models of DC–DC switching converter circuits using pulse-width modulation (PWM) control ICs are devised in this paper. Although some assumptions are made to simplify the Simulink behavior models, the likeness between the simulation and experimental results for both transient and steady-state responses shows that these behavior models capture almost all the important characteristics of the DC–DC switching converter circuits. Therefore, these behavior models can be very good teaching aids for students to learn the differences between ideal circuits and practical implementations. With these Simulink behavior models, students can also validate quickly whether or not their designs of feedback controllers for DC–DC switching converter circuits implemented with PWM control ICs meet the prescribed performance requirements.

INTRODUCTION

THE EXTENSIVE use of DC–DC switching converter circuits in electronic systems makes the fundamental understanding of switching converter circuits a necessity for students and electronic engineers. Because the design philosophy of the switching converter circuits includes many areas of knowledge, e.g., the converter circuits and electronics, linear and nonlinear control system theory, and magnetics, the application of user-friendly and powerful computer-aided simulation software tools to help students get acquainted with the dynamic behavior of the DC–DC switching converter circuits is inevitable [1–4]. Although previous results [1–4] have already discussed the use of Simulink behavior models for simulation of DC–DC switching converter circuits, none of them deals with practical implementation issues when the switching converter circuits are constructed by using PWM control ICs, especially the output saturation effect of the error amplifiers. It is therefore the purpose of this paper to bridge the gap between the Simulink behavior models and the experimental DC–DC switching converter circuits using PWM control ICs. With the help of these behavior models, students and electronic engineers can learn not only theoretical circuit operations, but also practical implementation issues and the corresponding theoretical explanations.

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The alternative simulation program, SPICE, is actually quite popular among electronic engineers, but the software views mostly on circuit level in constructing the entire circuit for simulation. SPICE cannot provide the dynamic transfer functions of DC–DC switching converters working on a steady-state operation point, unless the simulation data is used in a different software tool to identify the parameters of the dynamic transfer functions [5]. Furthermore, the complexity of device models and the switching nature of the switching converter circuits make simulation difficult to converge in SPICE [4, 6]. This would make students spend too much time on adjusting the device models and simulation parameters, and then lose their focus on learning the dynamics and feedback controller design of DC–DC switching converters [4].

The benefits of using Simulink as the simulation environment for learning the feedback controller design techniques of DC–DC switching converters have been recognized by many researchers [1–4] for both basic linear feedback controllers and advanced nonlinear digital feedback controllers. The results provided in this paper consider the influences of non-idealities in PWM control ICs in practical DC–DC switching converter circuits, and therefore, these results complement previous results [1–4] in power electronics courses. The most influential non-ideality in PWM control ICs is identified in this paper to be the saturation effect and output range limits of error amplifiers.

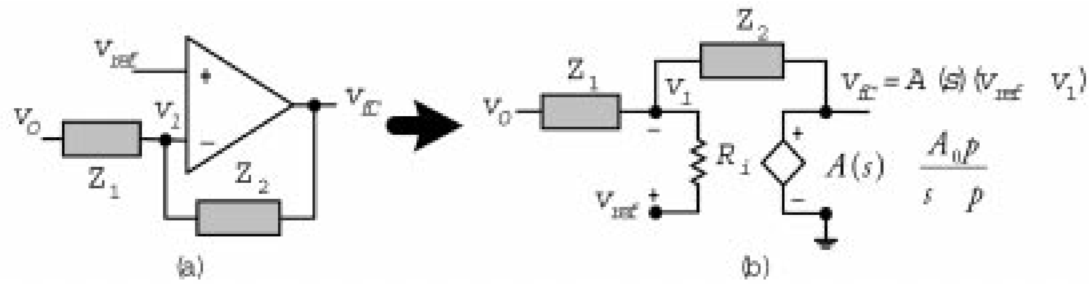

Fig. 1. (a) A general form of feedback controller implemented by using an OPA; (b) its equivalent circuit.

Moreover, during the process of constructing the Simulink behavior models, students can learn the influences of the non-idealities of the circuit elements and PWM control ICs on the start-up and load change transient responses of the DC–DC switching converter circuits.

SIMULINK BEHAVIOR MODELS FOR DC–DC SWITCHING CONVERTER CIRCUITS

Behavior models for feedback controllers implemented by using operational amplifiers with output saturation

In most PWM control ICs, there is always an error amplifier for users to construct their feedback controller. Unfortunately, the output of the error amplifier can be easily saturated because its output range is small. This would make simulations of the start-up transient incorrect and show large overshoot or oscillations in output responses, if the saturation effect is not taken into consideration. Suppose that a general form of feedback controller implemented by using an operational amplifier (OPA) and its equivalent circuit [7] are given in Fig. 1.

Assume that the input resistance R_i of the OPA is so large that the input current of the OPA can be omitted. Therefore, the dynamics of the feedback controller can be described by the following equations:

$$\frac{v_O - v_1}{Z_1} \cong \frac{v_1 - v_C}{Z_2} \Rightarrow v_C = v_1 - (v_O - v_1)\frac{Z_2}{Z_1} \quad (1)$$

$$v_C = (v_{ref} - v_1)A(s) \quad (2)$$

where the open loop transfer function $A(s)$ of the OPA can be approximated by using a first-order low-pass filter:

$$A(s) = \frac{A_0 p}{s + p} \quad (3)$$

whose pole is at p and DC-gain is A_0. These parameters can be easily obtained from the datasheets of PWM control ICs [8–9].

To simulate the output saturation effect of the OPA in Fig. 1a, a Simulink behavior model in Fig. 2 is devised to model the open loop transfer function $A(s)$. Since the integrator output corresponds to the output of the OPA, the output saturation effect of the OPA can be implemented by constraining the output of the integrator to the range reported in the datasheets. The range can also be set in the Simulink environment as an input parameter of the corresponding masked subsystem. The idea is similar to that described in [14].

This approach that deals with dynamic systems with output saturation is simpler than that proposed in [10] because the integration block in the Simulink environment can handle all the necessary functions described in [10].

Furthermore, from Equation (1) one can have:

$$v_1 = v_O + \frac{Z_1}{Z_2}v_C - \frac{Z_1}{Z_2}v_1 \quad (4)$$

Equations (2–4) can then be seen to be equivalent to the block diagram in Fig. 3.

Basic DC–DC switching converter circuits with parasitic elements

Consider the boost-type DC–DC switching converter circuit in Fig. 4, in which r_L and r_C stand for the equivalent series resistance of the inductor and capacitor, respectively. By using the approach proposed in [2], the non-idealities of the power transistor Q and the power diode D can also

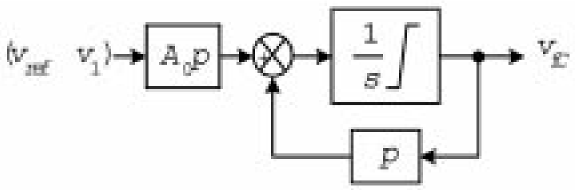

Fig. 2. A Simulink behavior model that implements the open loop transfer function in Equation (3) of an OPA.

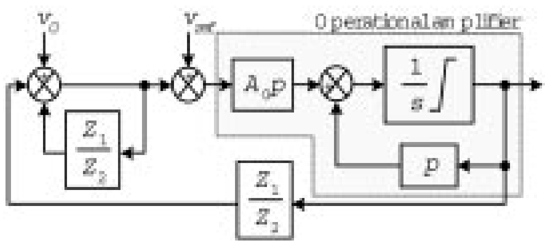

Fig. 3. The signal flow block diagram equivalent to the feedback controller in Fig. 1.

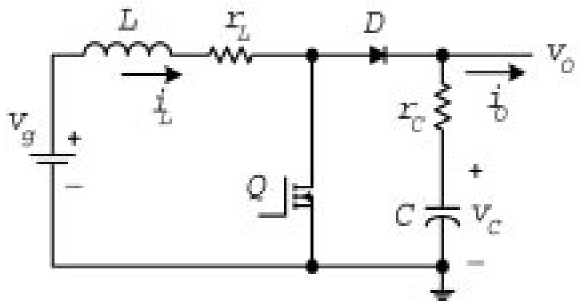

Fig. 4. The boost-type switching converter circuit.

be considered in its corresponding behavior model shown in Fig. 5. The MOSFET power transistor Q is modeled as a resistor r_{ds}, and the power diode D is modeled as a voltage drop in series with a resistor r_d when they are in their on-state. Note that the output current in Fig. 5 is configured as an input signal because it is determined by the load circuit it is connected [3]. The current i_Q through the power transistor Q is also configured as an output signal which can be used in the current mode feedback controller design [11].

SIMULATION AND VERIFICATION EXAMPLES

The following examples show how Simulink behavior models are used to simulate and verify the transient and steady-state responses of experimental DC–DC switching converter circuits using PWM control ICs.

Example 1: A current mode feedback controller without slope compensation

Consider the boost-type switching converter circuit using PWM control IC UC3843 [9] shown in Fig. 6.

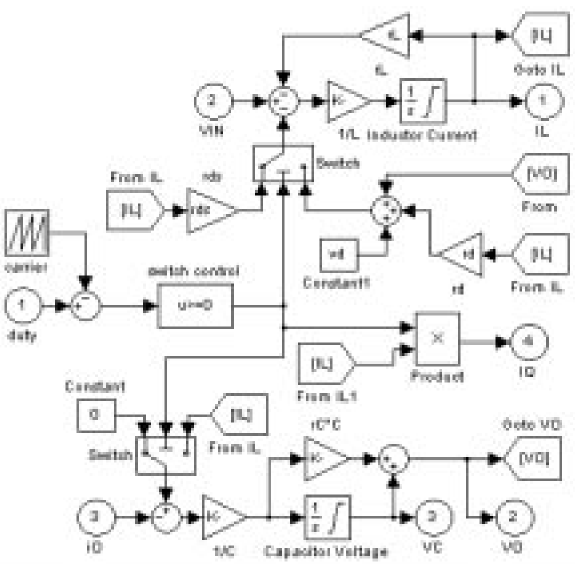

Fig. 5. The Simulink behavior model of a boost-type switching converter circuit with parasitic parameters and power switch current output.

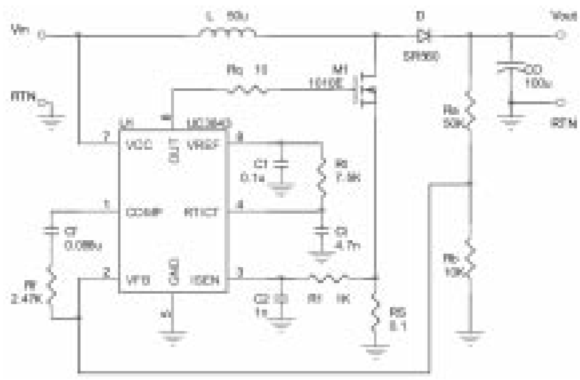

Fig. 6. A boost-type experimental switching converter circuit using UC3843 without slope compensation.

A current mode, linear averaged, feedback controller can be designed step by step in the frequency domain with the help of the averaged modeling techniques [2, 11] to meet predefined specifications. Since the linear averaged current-mode controller is devised without slope compensation, the duty ratio should be confined to the range [0, 0.5] for stable operation [11]. Therefore, the input and desired output voltage are set to 10 V and 15 V, respectively, such that the steady-state duty ratio would be around 0.33. The corresponding Simulink behavior model for the circuit in Fig. 6 can be divided into two parts. The first one is the behavior model for the boost-type DC–DC switching converter circuit, which has already been shown above. The second one is the behavior model for the PWM control IC UC3843. Given the block diagram of UC3843 [9] and the feedback controller structure in Fig. 6, students can then construct the behavior model step by step by following the procedure listed below:

1. Omit those unnecessary circuit blocks in the block diagram of UC3843 [9] for creating the reference voltage and clock signals. The rest of the block diagram and the resistors Ra, Rb, Rf, R1, RS, capacitors Cf, C2 in Fig. 6 forms the control circuit to drive the power transistor. It is shown in Fig. 7.
2. Construct the behavior model of the feedback controller by using the method proposed above. The dynamics and the output range of the error amplifier are determined according to the datasheet of UC3843 provided by the manufacturer. The values of p and A_0 which correspond to the bandwidth and DC-gain are found to be around 200 Hz and 70 dB [9]. The output range is [0.7, 6] from datasheet [9], though the upper limit is found to be 5 in the experimental circuit.
3. Assume that the input current to pin 3 of the comparator is sufficiently small. Therefore, the circuit used to sense the power transistor current i_Q in Fig. 7 can be modeled as a voltage source, $0.1 i_Q$, and a first-order low-pass filter with its pole located at $-1/1000.1\Omega \times 1\,\text{nF} \approx -10^{-6}$ by using the Thevenin's theorem.

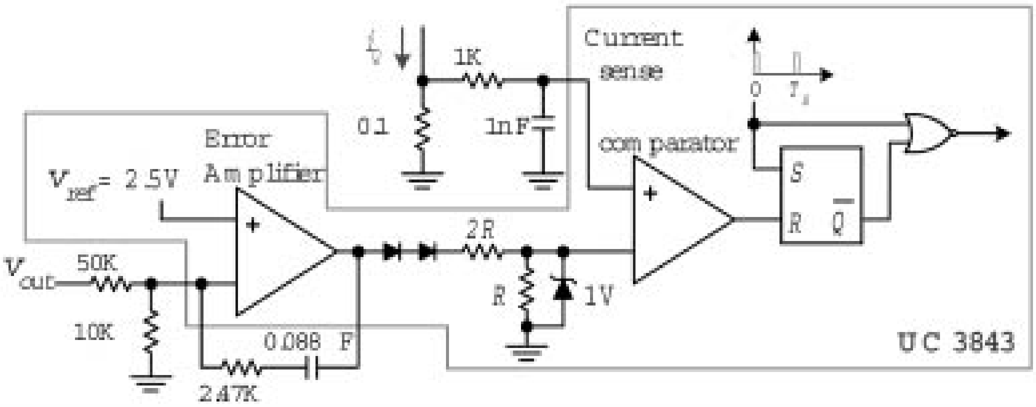

Fig. 7. The control circuit diagram to drive the power transistor in Fig. 6.

4. The two diodes, the voltage divider, and the zener diode that connect the output signal of the error amplifier and the comparator can be simplified as voltage drops, a pure gain and saturation of signals, respectively.
5. Because the reference voltage signal in UC3843 is not obtained right after the power is on, it is therefore modeled by using a step function passing through a low pass filter. According to measurements of the experimental circuit, the reference voltage and its rise time are adjusted to 2.37 V and 0.1 ms, respectively. This would make the steady state output voltage level stay at about 14 V but not 15 V.
6. A relay in conjunction with the reset input of the SR flip-flop is used to prevent dead lock during simulation.

The corresponding behavior model of the experimental switching converter circuit in Fig. 6 and the behavior model of the PWM control IC UC3843 are shown in Fig. 8a and 8b, respectively. Students can not only learn the function of each block in PWM control IC, UC3843, in the abovementioned process, but also the effects of these blocks when parameters are changed during simulations. Since the saturation effect of error amplifiers is identified to be the most important factor that affects both start-up and load change transient responses, some theoretical explanations found in control textbooks as 'wind-up' effect and 'anti-windup' controllers [12] can also be discussed during classes.

The behavior model is validated by comparing the simulation and experimental results of the output voltage and inductor current, when the load resistor is about 20 Ω. The simulation results of the start-up transient responses of the inductor current and the output voltage provided by the Simulink behavior model can be seen to agree closely with those obtained from the experimental circuit in Fig. 9. This shows the effectiveness of the behavior model to help students validate quickly whether or not their designs of feedback controllers for DC–DC switching converter circuits meet the prescribed performance requirements.

The Simulink behavior model is also capable of showing the unstable oscillation [11] when the duty ratio is greater than 0.5. This working condition

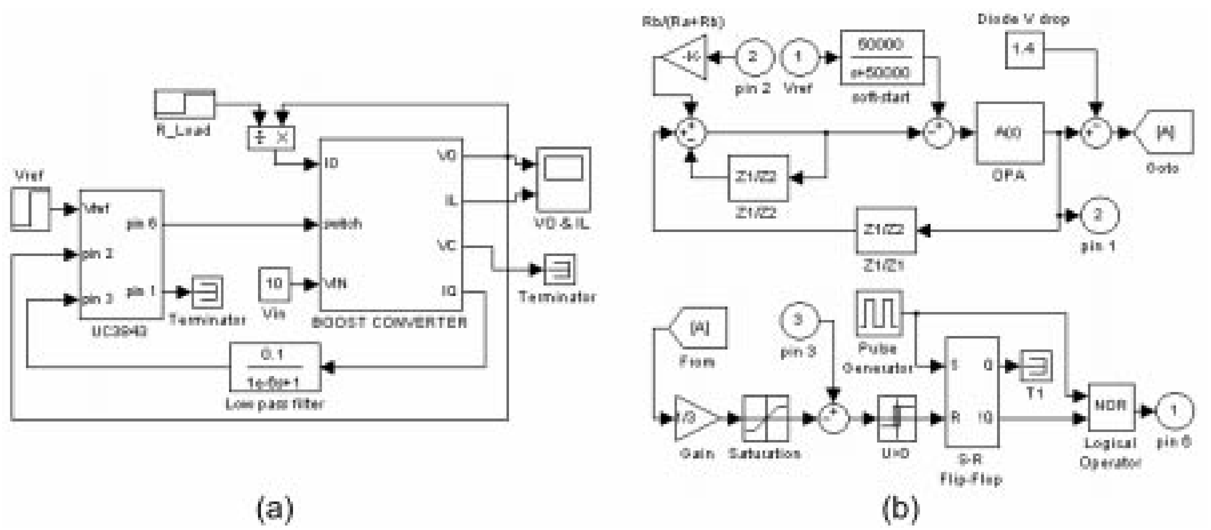

Fig. 8. (a) The Simulink behavior model of the experimental circuit in Fig. 6; (b) the behavior model of the PWM control IC UC3843.

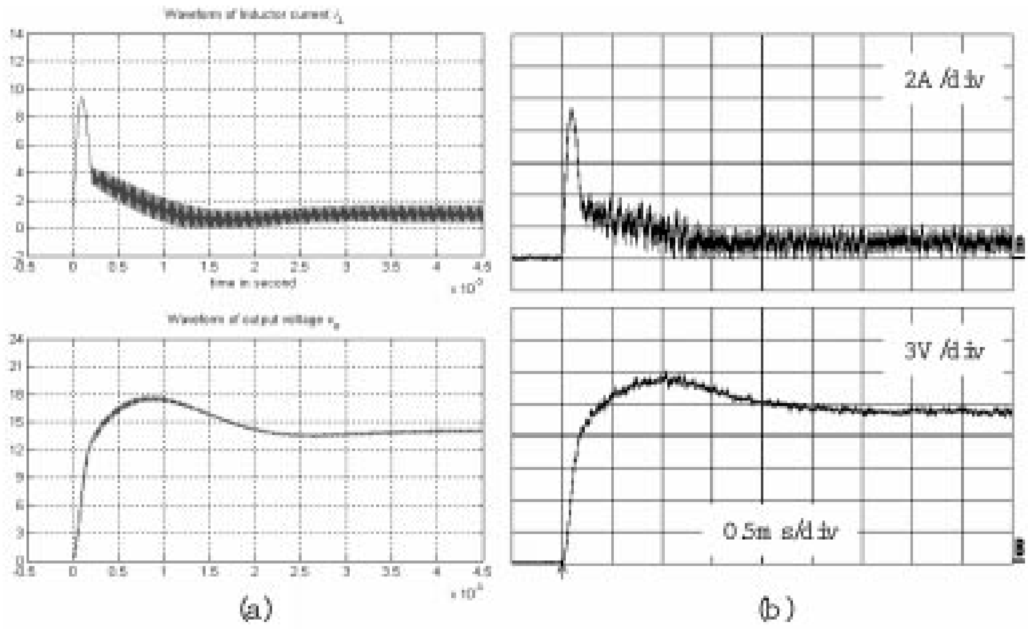

Fig. 9. The (a) simulation and (b) experimental start-up transient responses of the DC–DC switching converter circuit in Fig. 6.

can be created when the resistor Ra = 50 kΩ in Fig. 6 is replaced with a 90 kΩ resistor. Since the reference voltage is always set to 2.5 V in UC3843, the value change of the resistor Ra in the voltage divider feedback network would then give an output voltage of about 25 V. Theoretically, this would make the steady-state duty ratio stay at about 0.6. The simulation and experimental results of the inductor current waveforms are shown in Fig. 10, which can be seen to agree very well with each other.

Example 2: A current mode averaged feedback controller with slope compensation

Consider the boost-type switching converter circuit in Fig. 11, which is the same as that in Fig. 6 except that the slope compensation [9, 11] is implemented. This could make the circuit stable even when the duty ratio is beyond 50%. A fraction of the oscillator ramp at pin 4 is resistively summed through Q_1 and R_1 with the sensed current signal to provide slope compensation to the control signal at pin 3 of UC3843. Since the signal level

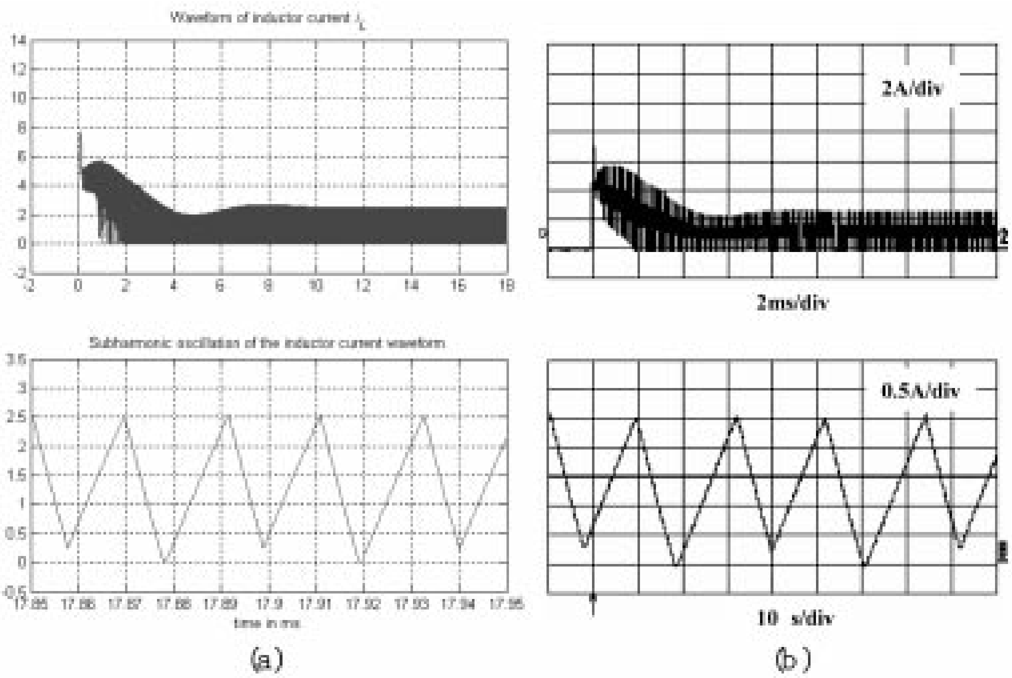

Fig. 10. Sub-harmonic oscillation phenomenon in the (a) simulation and (b) experimental start-up inductor current responses of the switching converter circuit in Fig. 6.

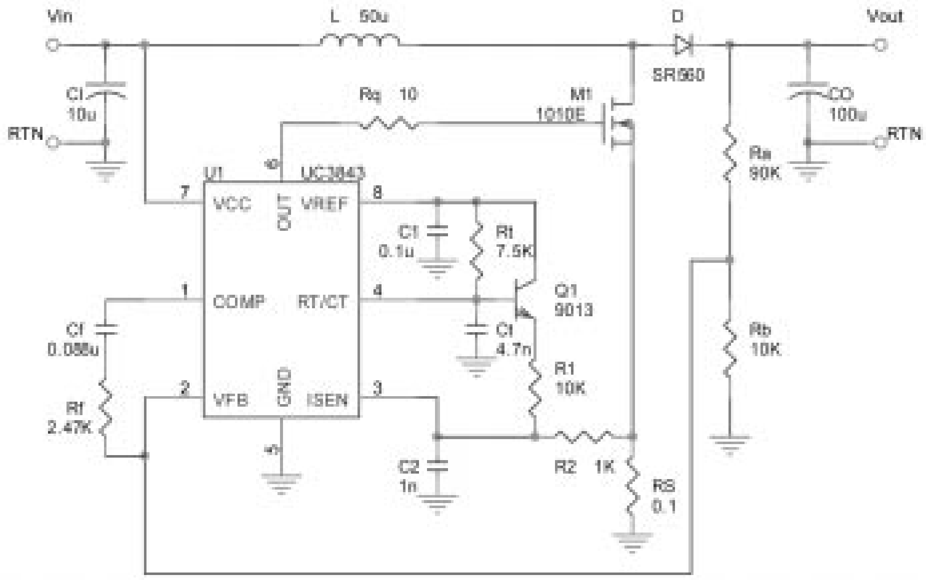

Fig. 11. A boost-type experimental switching converter circuit using UC3843 with slope compensation.

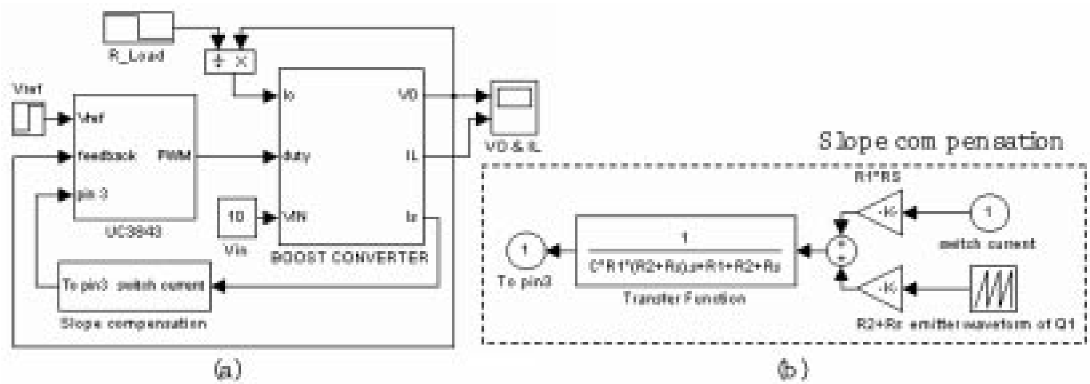

Fig. 12. The (a) Simulink behavior model of the experimental circuit in Fig. 11; (b) the behavior model of the slope compensation circuit.

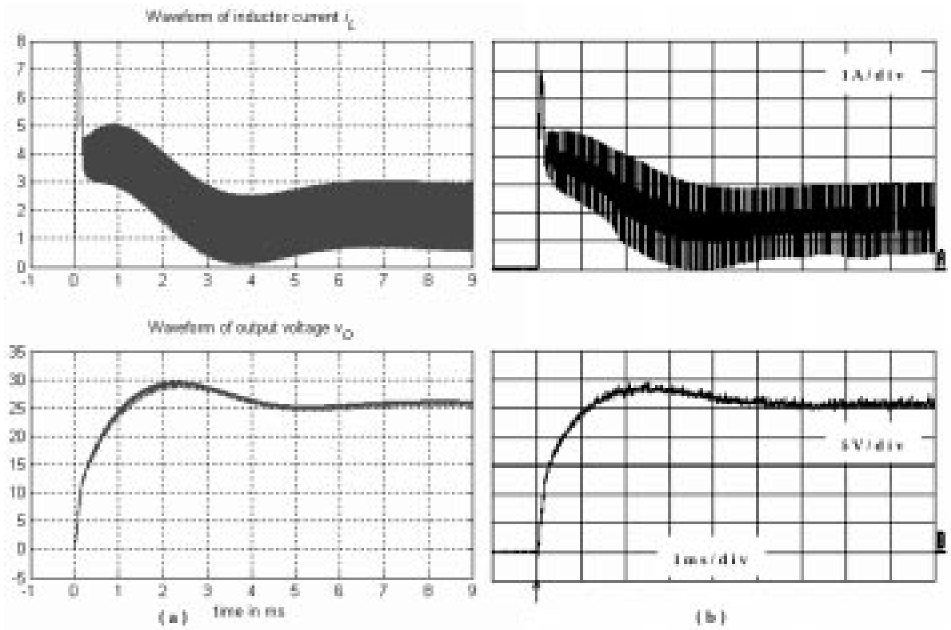

Fig. 13. The (a) simulation and (b) experimental start-up transients of the boost converter circuit in Fig. 11.

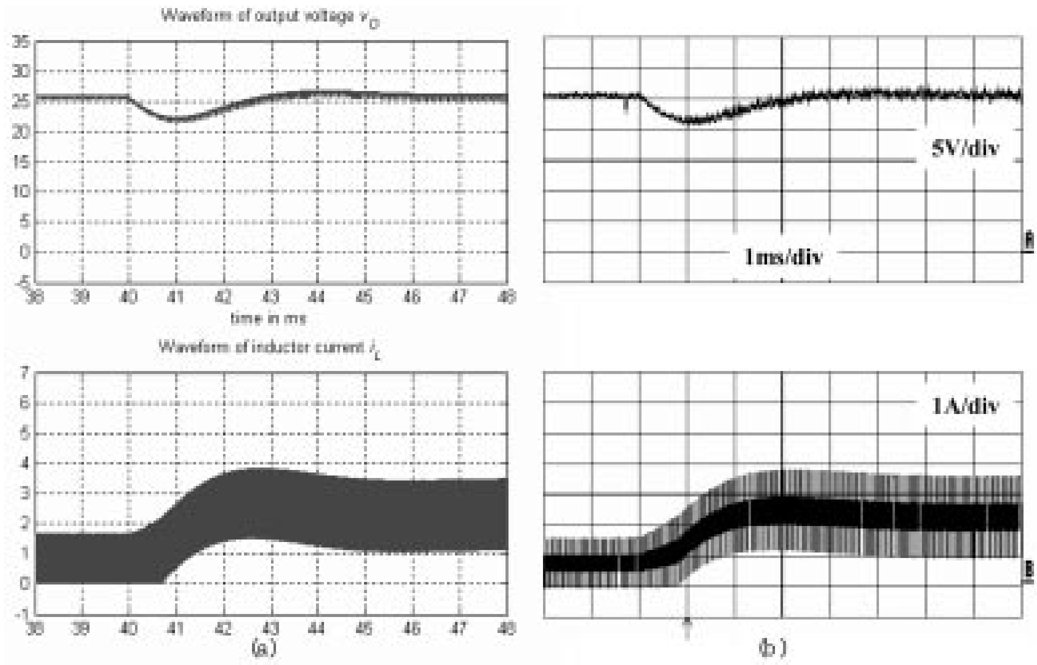

Fig. 14. The (a) simulation and (b) experimental results of the load change transient responses of the boost converter circuit in Fig. 11.

and waveform at pin 4 of UC3843 are measured to be at the interval of [1.1–2.8]V and of saw-tooth shape, the signal at the emitter of the transistor Q_1 can be determined by using the voltage drop v_{BE} value in the datasheet [13]. It is then used as a voltage source in finding the Thevenin's equivalent circuit of the slope compensation circuit. The corresponding behavior model is constructed by adding the slope compensation block shown in Fig. 12b to the behavior model obtained in Example 1.

The verification of the Simulink behavior model in Fig. 12 is performed by comparing the simulation and experimental results of the output voltage and inductor current transient responses due to start-up and load change from 150 Ω to 31.58 (150//40) Ω. They are shown in Fig. 13 and 14. They can again be seen to agree closely with each other, and show the effectiveness of the behavior model.

CONCLUSIONS

In this paper, the simplicity and usefulness of the Simulink behavior models for DC–DC switching converter circuits using PWM control ICs are demonstrated in the following aspects:

1. The devised Simulink behavior models capture almost all the important characteristics of the experimental circuits, even if some assumptions are made to simplify the corresponding behavior models. This is because the simulation results of the inductor current and the output voltage for both start-up and load change transients agree very well with those obtained from experimental circuits. This can help students find out those important factors that affect the performance of the DC–DC switching converter circuits most.
2. By using these Simulink behavior models, the influences of non-idealities in practical circuits, such as error amplifiers with saturation effects and output range limits in PWM control ICs, equivalent series resistances (ESRs) of output capacitors, etc. on the circuit performances can be demonstrated to students in class.
3. Students can learn to analyze the operating principles of PWM control ICs when they construct their own SIMULINIK behavior models in class.
4. These Simulink behavior models can also be used to validate quickly whether or not their designs of feedback controllers for DC–DC switching converter circuits meet the prescribed performance requirements before the circuits are implemented by using PWM control ICs.

The idea presented in this paper can also be applied to any PWM control IC, and students can easily construct their own corresponding behavior model. Therefore, these Simulink behavior models can serve as very good teaching aids for students to learn the differences between ideal circuits and practical implementations in power electronic courses.

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