Function Control—A Novel Strategy to Achieve Improved Performance of the DC-to-DC Switching Regulators

Yan-Fei Liu, *Student Member, IEEE*, Paresh C. Sen, *Fellow, IEEE*, and Shi-Peng Huang

***Abstract*—The control strategy of the dc-to-dc switching converters is studied to obtain the switching regulators with zero-voltage regulation. A novel control strategy, the Function Control, is presented for the dc-to-dc switching converters to achieve this objective. The control law and the corresponding feedbacks are derived directly from the equations governing the switching converters. With the Function Control strategy presented in the paper, the switching regulators become robust, i.e., the output is independent of the disturbances from either the supply voltage or the load and exhibits other desirable advantages. The strategy is applicable to all the four basic PWM converters, i.e., Buck, Boost, Buck-Boost, and Cuk. The analysis is confirmed by experiments and computer simulations.**

I. Introduction

THE four basic Switched-Mode PWM converters, Buck, Boost, Buck-Boost, and Cuk are shown in Fig. 1. These converters as well as other PWM converters [1], [2] provide low voltage and current ratings for the switching devices and constant switching frequency control. With the emergence of the high-speed devices, the switching frequency can be raised significantly in order to reduce the size of the power supply.

The control strategy for switching regulators should be formulated to achieve the following desirable features:

(a) The output voltage of the regulator remains unchanged even though there are disturbances from either the supply voltage or load current.
(b) The performance of the switching regulator can be predicted directly by the closed loop equations.
(c) The control circuit should be simple and flexible.

Various attempts have been made to formulate the control strategies for the switching regulators because their overall dynamic performances are largely determined by the control strategy. The most commonly used one is the so-called direct-duty ratio control [1]–[4], as shown in Fig. 2, where α is the duty ratio. It is a single-loop control. The output voltage is sensed and compared with the reference voltage and the error is used to control the duty ratio. Unfortunately, it suffers from such drawbacks as large response time, difficulty to compensate, etc. Its implementation is, however, simple when PWM controlled IC chips are used. But it does not provide the zero-voltage regulation.

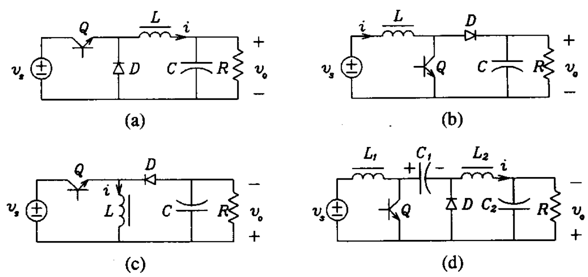


Fig. 1. Basic switched-mode PWM converters.

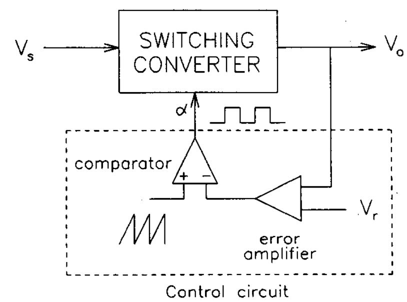


Fig. 2. Block diagram of the direct duty ratio control.

The current programming control [5]–[8], as shown in Fig. 3, is superior to the direct-duty ratio control. The inductor current i and the output voltage v_o of the switching converter are both fed back. The output of the voltage controller acts as a current reference for the current comparator. Consequently, it has the advantages of wide bandwidth and automatic current limiting. However, because of its inherent instability and sub-harmonic oscillation [9] when operated at the constant switching frequency, an extra compensating network is required.

The modern control theory has also been applied to control the switching regulators. The Sliding Mode Control (SLMC) [10]–[12] makes the closed-loop characteristics of a switching regulator determined solely by the control law. In Sliding Mode Control, the output voltage is independent of the parameters of power stage and the disturbances. Unfortunately, the switching frequency is not constant and the switching ripple is large.

Manuscript received August 28, 1992; revised June 18, 1994.

Y.-F. Liu was with the Power Electronics and Drives Laboratory, Department of Electrical Engineering, Queen's University, Kingston, Ontario, K7L 3N6 Canada. He is now with Bell Northern Research Limited, Ottawa, Ontario, K1Y 4H7 Canada.
P. C. Sen is with the Power Electronics and Drives Laboratory, Department of Electrical Engineering, Queen's University, Kingston, Ontario, K7L 3N6 Canada.
S.-P. Huang is with the Department of Electrical Engineering, Zhejiang University, Hangzhou 310027, China.

IEEE Log Number 9408814.

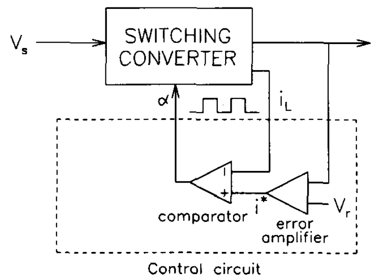


Fig. 3. Block diagram of the current programmed control.

In a large-signal adaptive control strategy [13], the control law is derived by linearizing the large-signal state equation around a "varying" operating point instead of a fixed one. As a result, the control equations are constantly adjusted according to the environmental changes. Unfortunately, the control law is too complicated to be implemented in real time. It cannot eliminate the effects of disturbances from either the supply voltage or the load current as well.

The authors in an earlier paper [14] attempted to synthesize the duty ratio α from the input and output quantities of the converter. With this control law, the switching regulator can eliminate the disturbance of the supply voltage. However, the load disturbance affects the output voltage and the analysis is in the small-signal domain.

The above review reveals that none of the foregoing control strategies achieve all the desirable characteristics of a switching regulator. In this paper, control strategies are studied in order to obtain the switching regulator with improved performance. A more general strategy of Function Control is presented for the dc-to-dc switching converters. The control law is constructed directly from the requirement of the power stage in order to provide zero-voltage regulation, making it independent of supply voltage and load disturbances. This new strategy is applied to the four basic switching converters, i.e., Buck, Boost, Buck-Boost, and Cuk converters. Zero-voltage regulation is achieved in all the four topologies. This control strategy is simple to implement, is found to be able to eliminate the limitations of the previously proposed control strategies, and is valid for both small-signal and large-signal variations. Both experimental results and computer simulations by PSPICE show that this strategy of Function Control possesses the desirable properties mentioned above.

II. Basic Principle of the Function Control

A switching regulator has two essential parts: the switching converter and the control circuit. The output voltage, v_o of the switching converter depends on the supply voltage v_s, duty ratio α, and a combination of intermediate variables of switching converter x. Mathematically, it can be expressed as

$$v_o = f(v_s, x, \alpha). \tag{1}$$

The output of the control circuit is the duty ratio α and is dependent on the feecbacks. The duty ratio α can also be expressed as

$$\alpha = g(y, v_o, V_r) \tag{2}$$

where V_r is the reference voltage, y denotes a combination of the circuit variables in the switching converter. The components of y are feedback signals and are to be determined. All the variables in (1) and (2) except V_r, are averaged time-variant quantities. Equation (2) expresses the general input–output relation of a control circuit. Mathematically, the duty ratio α produced by any control law can always be expressed in the form of (2). For example, in the case of direct duty ratio control with a PI controller, only the output voltage is fed back, i.e., $y = 0$. The function g consists of integral and proportional operation. As for the current programming control, y is inductor current i of the switching converter and the relation $g(i, v_o, V_r)$ is a more complicated one.

Combining (1) and (2), the closed-loop output voltage v_o can be solved mathematically. It usually depends on the supply voltage and load current, which implies that disturbances from the supply voltage and load current have some effect, more or less, on the output voltage. This is not desirable for a constant voltage regulator. In order to achieve zero-voltage regulation, the control strategy should be particularly constructed and the feedbacks should be properly selected so that the closed-loop output voltage is independent of either the supply voltage or the load current and is only determined by the reference voltage.

Fortunately, the power stage has already provided with sufficient information as: (a) how to construct the input and output relation of the control circuit and correspondingly; (b) how to select the feedbacks to achieve the desirable performance. This can be demonstrated more clearly if the duty ratio α in (1) is solved, assigned another symbol α_p, and expressed in terms of v_s, x and v_o, i.e.,

$$\alpha_p = h(v_s, x, v_o). \tag{3}$$

Equation (3) defines the duty ratio required by the switching converter at the operating point defined by v_s, x, and v_o.

The control circuit can now be constructed to generate this duty ratio. The input and output relation of the control circuit is now constructed as follows:

$$\alpha_c = h[v_s, x, K(V_r - v_o)]. \tag{4}$$

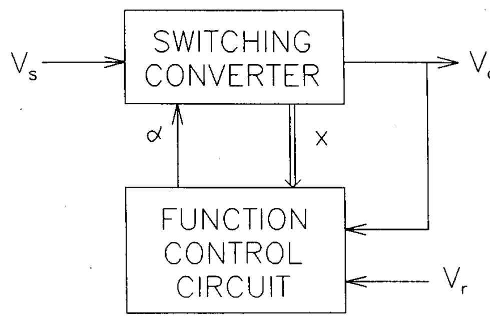
Equation (4) defines the control law. It is the input–output relation of the control circuit, where α_c denotes the duty ratio generated by the control circuit and K is the gain of the error amplifier. The term $(V_r - v_o)$ represents the negative feedback. As the duty ratio generated by the control circuit is used to drive the switch in the switching converter, α_p and α_c are the same. Therefore, the closed-loop characteristics of the switching regulator can be found by combining (3) and (4), as

$$h(v_s, x, v_o) = h[v_s, x, K(V_r - v_o)]. \tag{5}$$

From which the closed-loop output voltage of the switching regulator can be solved as:

$$v_o = K(V_r - v_o)$$
$$v_o = \frac{K}{K+1} V_r. \tag{6}$$

Since the duty ratio generated by the control circuit is expressed directly as a mathematical expression of the feedbacks,



$\alpha = h[v_s, x, K(V_r - v_o)]$

Fig. 4. Block diagram of Function Control.

this kind of control law is named as Function Control. Fig. 4 shows the block diagram of this control strategy.

Since no assumption is involved in the derivation of (6), this strategy of Function Control provides the following:

(a) The output voltage, v_o, is proportional to the reference and is independent of the supply voltage and load current.
(b) The result obtained is true for dynamic condition because all the variables, v_s, x, v_o, and V_r, are averaged time variant quantities.
(c) The result is also valid for both small-signal and large-signal variation because no small-signal assumption is made during the analysis.
(d) The control strategy is applicable to all switching converters because no particular topology is assigned in the derivation.

III. Application of the Function Control Strategy

From the discussion in the above section, there are three steps to construct the control law of the Function Control strategy for a given topology of power stage:

(a) Express the averaged time-variant output voltage v_o as a function of the duty ratio α, supply voltage v_s, and some other circuit variables x, i.e., (1).
(b) Rewrite the obtained equation so that the duty ratio α is expressed in terms of v_s, v_o, and x, i.e., (3).
(c) The control law, i.e., (4), can be deduced by substituting $K(V_r - v_o)$ for v_o in the equation obtained in step (b). The intermediate feedback variable can be found as x in step (b).

If the control strategy is constructed in this way, the closed-loop output voltage can become independent of the disturbance from either the supply voltage or the load current.

Consider the Buck converter, Fig. 1(a), as an example to illustrate the application of the Function Control strategy. Its low frequency averaged equivalent circuit is shown in Fig. 5 [15]. By this method, the active switch (transistor, MOSFET, etc.) is modeled by a controlled current source with its value equal to the averaging current through it (in this case αi) and the passive switch (diode) is modeled by a controlled voltage source with its value equal to the average voltage across it (in this case, αv_s). From the Kirchhoff voltage law, the following equation can be derived:

$$v_o = \alpha v_s - L\frac{di}{dt}. \quad (7)$$

The second step to derive the control law of Function Control strategy is to obtain an expression for the duty ratio α from (7)

$$\alpha = \frac{v_o + L\frac{di}{dt}}{v_s}. \quad (8)$$

The input and output of the control circuit is constructed by substituting $K(V_r - v_o)$ for v_o in (8)

$$\alpha = \frac{K(V_r - v_o) + L\frac{di}{dt}}{v_s}. \quad (9)$$

From (8) and (9), the closed loop output voltage is obtained as

$$v_o = \frac{K}{K+1}V_r. \quad (10)$$

Equation (10) shows that when the input–output relation of the control circuit is constructed according to (9), the output voltage of the closed-loop Buck switching regulator is proportional to the reference voltage and is independent of the supply voltage and load current. This result is not surprising after we inspect (9) more closely. The disturbance of the supply voltage is corrected instantaneously and is compensated exactly by the control circuit as any change of v_s will cause the corresponding adjustment of the duty ratio. When the load current has a tendency to change, the control circuit responds to it and makes the proper change of the duty ratio so that the output voltage remains constant.

In the same way, the Function Control strategies for the Boost, Buck-Boost, and Cuk converters (see Fig. 1), can also be derived. The control laws and the key equations for the four basic converters are listed in Table I.

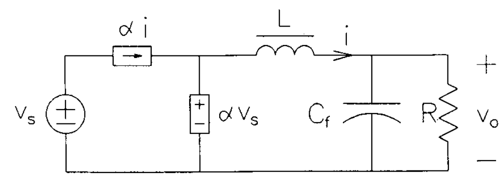


Fig. 5. Low-frequency equivalent circuit of Buck converter.

TABLE I
Key Equations and Control Laws for the Function Controlled Buck, Boost, Buck-Boost, and Cuk Regulators

	The equation from the power stage	The relation of the control circuit	The output voltage
Buck	$v_o = \alpha v_s - L\frac{di}{dt}$	$\alpha = \frac{K(V_r - v_o) + L\frac{di}{dt}}{v_s}$	$v_o = \frac{K}{K+1}V_r$
Boost	$v_o = -L\frac{di}{dt} + v_s + \alpha v_o$	$\alpha = \frac{K(V_r - v_o) - v_s + L\frac{di}{dt}}{K(V_r - v_o)}$	$v_o = \frac{K}{K+1}V_r$
Buck-boost	$v_o = -L\frac{di}{dt} + \alpha(v_o + v_s)$	$\alpha = \frac{K(V_r - v_o) + L\frac{di}{dt}}{K(V_r - v_o) + v_s}$	$v_o = \frac{K}{K+1}V_r$
Cuk	$v_o = \alpha v_c - L_2\frac{di}{dt}$	$\alpha = \frac{K(V_r - v_o) + L_2\frac{di}{dt}}{v_c}$	$v_o = \frac{K}{K+1}V_r$

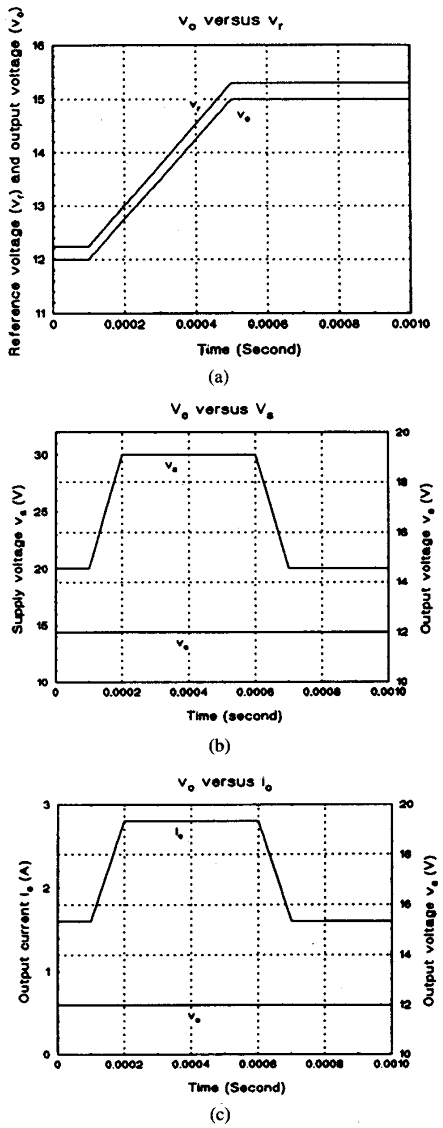


Fig. 6. Simulation results of the function controlled Buck regulator.

IV. Results of Computer Simulation and Experiment

Based on the above discussion, the computer simulation by PSPICE is made on a Function Controlled Buck switching regulator. The averaging model of the Buck converter, Fig. 5, is used in the simulation. The control law is the same as (9). The simulation result is shown in Fig. 6.

Fig. 6(a) is the simulation result when the reference voltage V_r ramps from 12.24 V to 15.3 V in 400 μs; the output voltage follows the reference voltage proportionally. The difference between v_o and V_r is because of the finite value of K. When the supply voltage v_s steps from 20 V to 30 V, the output voltage remains unchanged at 12 V, as shown in Fig. 6(b). When load current steps from 1.6 A to 2.8 A, the output voltage still remains unchanged at 12 V, as shown in Fig. 6(c).

From Table I, or (9) for the Buck converter, the information needed to implement the Function Control strategy is the

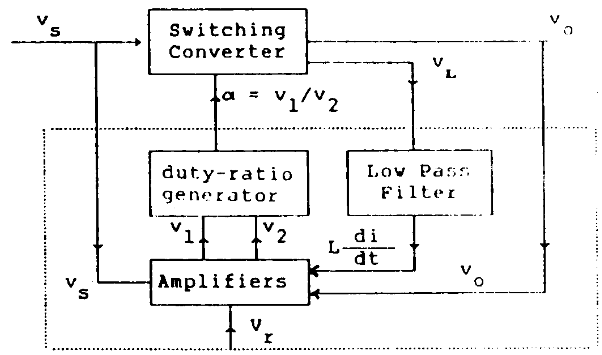


Fig. 7. Block diagram to realize the Function Control law.

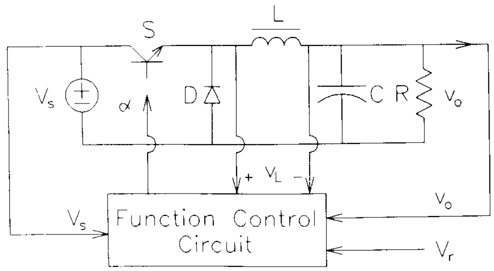
low-frequency component of the Ldi/dt, which is the low-frequency component of the inductor voltage v_L. Because of the switching action, the inductor voltage has a high-frequency component in it. Therefore, in the experimental prototype, Ldi/dt is retrieved by filtering the switching frequency component of v_L. Another benefit of doing so is that the control law is insensitive to the variation of the value of inductance because it is the inductor voltage that is useful in formulating the desired duty ratio.

It is also noted from Table I or (9) that a division operation is needed to get the required duty ratio. An analog divider followed by a modulator can be used here. However, this scheme is expensive and its bandwidth is limited by the divider. In the paper, a much simpler divider is used to generate the required duty ratio. The duty ratio generator has two inputs, the numerator v_1 (corresponding to numerator of (9)), and denominator v_2 (corresponding to the denominator of (9)). It generates a triangular signal whose peak value is proportional to the denominator v_2. The numerator v_1 sets the level at which a comparator is triggered. As a result, the output of the duty ratio generator is a pulse signal whose duty ratio α is proportional to the ratio of v_1 and v_2.

The implementation of the Function Control strategy is illustrated in Fig. 7 and is simple. The low pass filter is used to obtain the low-frequency component of the inductor voltage. The amplifiers are employed to synthesize the numerator and the denomination according to Table I or (9) for the Buck converter. The numerator (v_1) and denominator (v_2) are fed to the duty-ratio generator. The output of the duty-ratio generator is a pulse signal with its width proportional to the ratio of v_1 and v_2.

From the above discussion concerning the implementation of the control circuit, it is worthwhile to point out that by the Function Control strategy proposed in the paper, the control circuit becomes very flexible. When various power stages are used, the duty ratio generator and the low pass filter need not to be changed, as long as the switching frequency remains same. The only change in the control circuit is the connection of the amplifier, according to Table I.

A Buck switching regulator prototype controlled by the Function Control strategy, as shown in Fig. 8, is breadboarded in order to verify the analysis. The parameters are: $L = 240$ μH, $C = 600$ μF, $v_s =$ 20–30 V, $v_o = 12$ V, $i_o =$ 1.6–2.8 A. Figs. 9 and 10 show the experimental results.

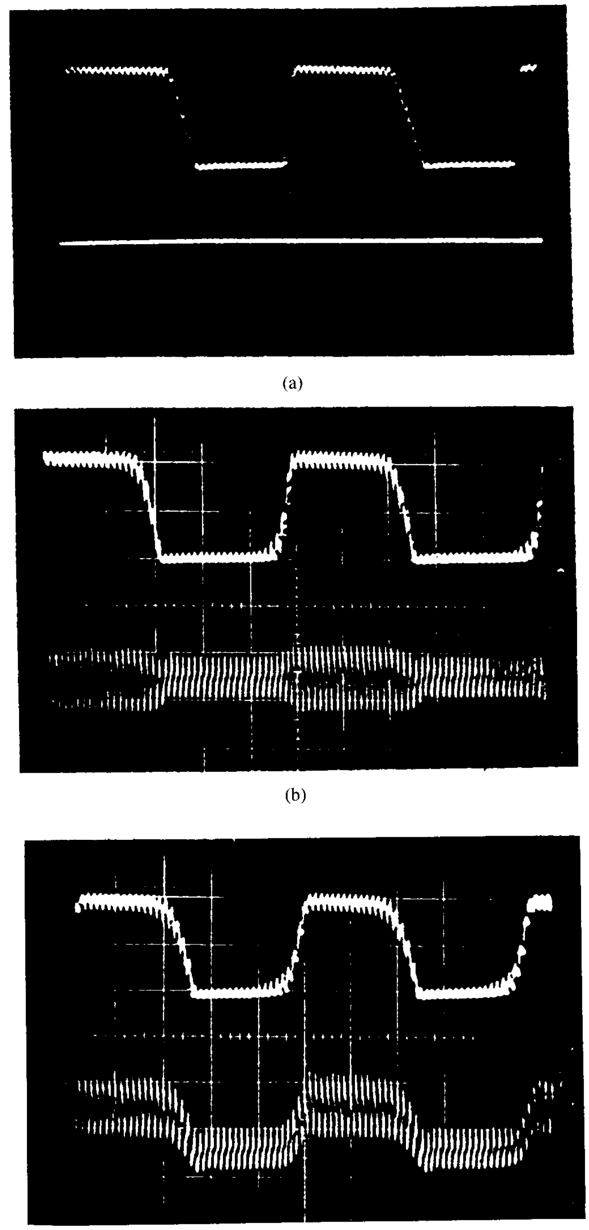


$$\alpha = \frac{K(V_r - V_o) + V_L}{V_s}$$

Fig. 8. Function controlled Buck converter.

Fig. 9(a) shows the waveform of the output voltage when the supply voltage steps between 20 V and 30 V. The output voltage v_o remains unchanged at 12 V. The waveform of v_o is amplified in Fig. 9(b). Only the amplitude of ripple is changed when the input voltage is changed. The average value of output voltage remains unchanged at 12 V. The effect of the feedforward is also tested. If the input voltage v_s is not fed forward, the change of the output voltage is visible when the supply voltage steps from 20 V to 30 V, as shown in Fig. 9(c). This demonstrates the usefulness of feeding forward v_s.

Fig. 10 gives the effect of load current change to the output voltage. When the load current changes from 1.6 A to 2.8 A, the response of the output voltage is shown in Fig. 10(a) and (b). No change of v_o is observed in Fig. 10(a). The detail of the variation of the output voltage is shown in Fig. 10(b), where the ripple in v_o is enlarged. There is a small change in the average value (4 mV) of the output voltage v_o (12 V), which can only be seen in Fig. 10(b). The percentage regulation is 0.004/12 = 0.033%, which is very small. This small voltage change is caused by the nonidealness of the circuit. Fig. 10(b) shows that the dynamic error (the voltage change during transition) is very small. In order to show the effectiveness of the inductance voltage feedback, measurement is also made when the inductor voltage v_L is not fed back. In this case, the response of the output voltage is shown in Fig. 10(c), when the load current steps from 1.6 A to 2.8 A. The dynamic error is clearly observed.



(a)

(b)

(c)

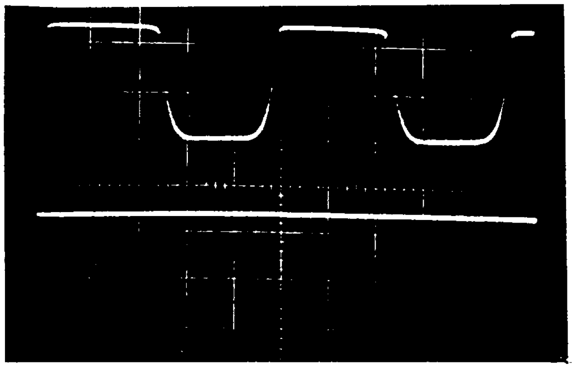
Fig. 9. Effect of supply voltage disturbance. Time: 200 μs/div. (a) Upper trace: v_s, 5 V/div, lower trace: v_o, 5 V/div. (b) Upper trace: v_s, 5 V/div, lower trace: v_o, 20 mV/div. (c) Upper trace: v_s, 5 V/div, lower trace: v_o, 20 mV/div.

V. Conclusion

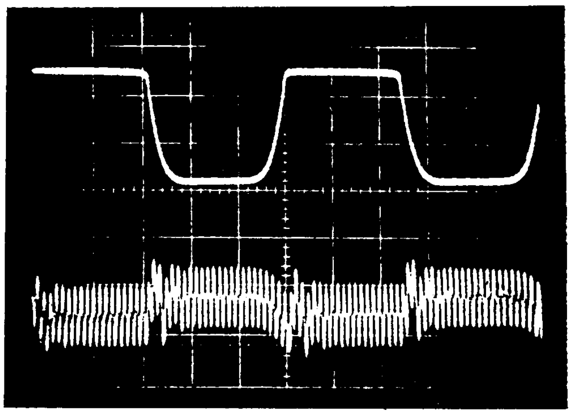
The control strategy of the dc-to-dc switching converter is studied in order to obtain switching regulators with zero-voltage regulation. This objective can be achieved by the Function Control strategy proposed in the paper. By this control strategy, the input and output relation of this control circuit is derived directly from the equation of the power stage. The basic principle is applicable to the four basic switching topologies. The analysis, experiments, and computer simulations for the Buck converter show that the switching regulators by the Function Control strategy can suppress the disturbance from both the supply voltage and the load current and thereby, provide zero voltage regulation. The implementation of the control circuit is simple and flexible.

A Buck switching regulator prototype by the Function Control strategy is breadboarded. The effectiveness of the control law is verified experimentally. Comparison is made when the supply voltage or the inductor voltage is fedback or not. Close agreement is obtained between analysis, simulations and experimental results.

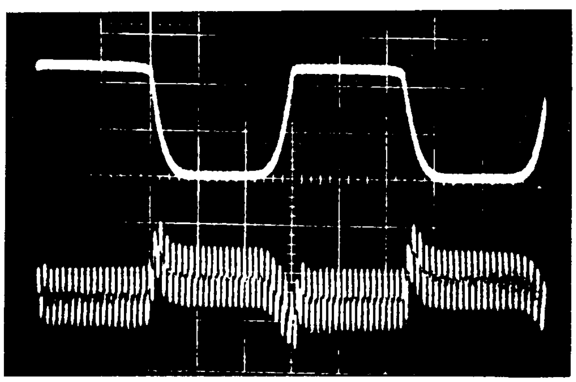
The study presented in the paper reveals many good features of the proposed control strategy, specifically, the zero voltage regulation of the output voltage under disturbances



(a)



(b)



(c)

Fig. 10. Effect of load current disturbance. Time: 200 μs/div. (a) Upper trace: i_o, 5 V/div, lower trace: v_o, 5 V/div. (b) Upper trace: i_o, 5 V/div, lower trace: v_o, 20 mV/div. (c) Upper trace: i_o, 5 V/div, lower trace: v_o, 20 mV/div.

from the supply voltage and load current. Further study on this control law, in particular, the implementation of this control law in Boost, Buck-Boost, and Cuk converter based switching regulators, is the subject matter of future investigation. Although no stability problem is encountered with the Buck converter, the stability of all the basic switching regulators using the proposed Function Control law will also be thoroughly analyzed.

REFERENCES

[1] M. H. Rasid, *Power Electronics: Circuits, Devices and Applications.* Englewood Cliffs, NJ: Prentice-Hall, 1988.

[2] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications and Design.* New York: Wiley, 1989.

[3] P. C. Sen, *Thyristor DC Drives.* New York: Wiley, 1981.

[4] ——, *Principle of Electric Machines and Power Electronics.* New York: Wiley, 1989.

[5] C. W. Deisch, "Simple switching control method changes power converter into a current source," *IEEE PESC Rec.*, pp. 300–306, 1978.

[6] A. Capel, G. Ferrante, D. Sullivan, and A. Weinberg, "Application of injected current model for the dynamic analysis of switching regulators with new concept of LC^3 modulator," *IEEE PESC Rec.*, pp. 135–147, 1987.

[7] R. Redl and N. O. Sokal, "Current-mode control, five different types with the three basic classes of power converters: Small-signal, ac and large-signal dc characterization, stability requirements and implementation of practical circuits," *IEEE PESC Rec.*, pp. 771–785, 1985.

[8] R. D. Middlebrook, "Topics in multiloop regulators and current mode programming," *IEEE PESC Rec.*, pp. 716–732, 1985.

[9] R. Redl and I. Novak, "Instabilities in current-mode controlled switching voltage regulators," *IEEE PESC Rec.*, pp. 17–28, 1981.

[10] F. Bilalovic, O. Music, and A. Sabanovic, "Buck converter regulator operating in the sliding mode," *PCI*, April, pp. 331–340, 1983.

[11] R. Venkataramanan, A. Sabanovic, and S. Cuk, "Sliding mode control of dc-to-dc converters," *IEEE IECON Rec.*, pp. 251–258, 1985.

[12] S. P. Huang, H. Q. Xu, and Y. F. Liu, "Sliding mode controlled Cuk switching regulator with fast response and first order dynamic characteristics," *IEEE PESC Rec.*, pp. 124–129, 1989.

[13] C. K. Tse and K. M. Adams, "An adaptive control for dc-to-dc converters," *IEEE PESC Rec.*, pp. 213–218, 1990.

[14] Y. F. Liu, X. Z. Zhang, and S. P. Huang, "Function Control and its application in dc-dc switching regulators," *IEEE PESC Rec.*, pp. 377–382, 1988.

[15] X. Z. Zhang and S. P. Huang, "Equivilant controlled source model for the PWM switching converters," *Electrical J.*, (in Chinese), no. 3, 1986.

Yan-Fei Liu (S'90) received the B.Sc. and M.Sc. degrees in electrical engineering from Zhejiang University, Hangzhou, China, in 1984 and 1987, respectively, and the Ph.D. degree from Queen's University, Kingston, Canada, in 1994.

He was an Assistant Professor at Zhejiang University from 1987 to 1990. From September 1990 to February 1994, he was at Queen's University, where he was employed as a research and teaching assistant. He was also employed as an Adjunct Instructor from September 1993 to December 1993. He is currently a Power Supply Designer with the Power Group, Bell Northern Research Limited, Ottawa, Canada. His research interests include new circuit configurations of soft switching converters, control techniques to improve the dynamic performance of PWM swtiching converters, and dynamic modeling of switching power converters.

Paresh C. Sen (M'67–SM'74–F'89), for a photograph and biography please see p. 49 of the February 1995 issue of this TRANSACTIONS.

Shi-Peng Huang received the B.S. and M.S. degrees in electrical engineering from Harbin Polytechnic University, Harbin, China, in 1954 and 1956, respectively.

Since 1956, he has been with the Department of Electrical Engineering, Zhejiang University, Hangzhou, China, where he was a professor and conducted research and education in the field of power electronics. He is now a consultant for several companies. His research interests include modeling, analysis, and control of switching power converters, new soft switching converter topologies, and power factor correction circuits.