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A Zero-Voltage-Switching Quasi-Resonant Flyback and Forward Composite DC-DC Converter

Yukihiro OHTA[†a)], **Chika WATANABE**[†], *and* **Kenzo WATANABE**[†], *Regular Members*

SUMMARY A DC-DC converter using two transformers is proposed. One transformer delivers the energy to a load when a switch is on and the other transfers the flyback energy to a load when a switch is off. The primary windings of the two transformers function as choke inductance alternately, and thus the output voltage control by means of the duty ratio and the zero-voltage-switching are possible without an additional inductor. The breadboarded prototypes of the single output and the two outputs have confirmed the principles of operation and demonstrated the high conversion efficiency.

key words: *DC-DC converter, flyback, forward, ZVS*

1. Introduction

Transformerized switching DC-DC converters using one switching device can be classified into the flyback and forward converters [1], [2]. The flyback converter, referred often to as the ringing choke converter (RCC), is the same as the buck converter in the principles of operation, and the output voltage can be controlled by means of the duty ratio of the switching signal. Since such a control function can easily be accommodated into the self-oscillating configuration, it is widely applied to a low-cost, off-line switching power supply with the output capability up to several tens of W. A bipolar transistor is used as the switching device and the switching frequency is typically several tens of kHz to avoid the excess power loss due to the switching delay. A much higher switching speed is possible with a power MOSFET, but the power loss due to the discharge of the parasitic capacitance between the drain and the source increases in turn.

The power loss due to the capacitance discharge can be greatly reduced by the quasi-resonant zero-voltage-switching (ZVS) technique [3], [4]. Incorporating the ZVS function into the flyback converter is difficult, if not impossible, and the forward converter is better suited because the primary winding of the transformer when the switch is off is available for the inductor of the resonant switch. In addition, the transformer transfers the energy without storing it. Therefore, a high-efficiency and a high power-density are achievable with the forward architecture. To control the output voltage by means of the duty ratio, however, it requires the buck converter consisting of the choke inductance and the flywheel diode. This burdens the forward converter especially when multi-outputs are required because each secondary winding should be followed by the buck stage of its own.

The burden will be reduced if the buck stage is incorporated into the primary side of the transformer so that it is common to all the secondary windings. Based on this idea, a flyback and forward composite architecture is developed. The forward converter takes a main part of the energy transfer while the flyback converter plays a part of the buck stage to control the output voltage. This paper describes simulated and measured performances of the prototype converters.

2. Architectures

Figure 1 shows a basic circuit of a conventional forward converter.

Driven by the switching signal, the switch Q converts the input DC voltage V_{in} into the AC voltage. The AC voltage is stepped up or down by the turn ratio n of the transformer T and rectified by the diode D_1. The diode D_1 also operates as the switch of the buck converter consisting of the choke inductor L and the flywheeling diode D_2. Assuming the continuous mode, the output voltage V_o is given by

$$V_o = \frac{D}{n} V_{in}, \tag{1}$$

where n is the turn ratio between the primary and secondary windings and D is the duty ratio of the switching signal given by

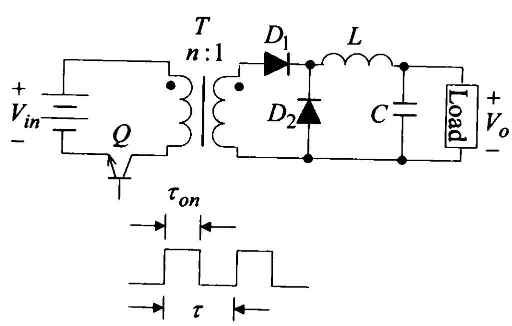

Fig. 1 A conventional forward DC/DC converter.

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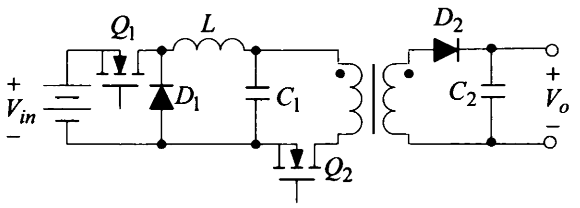
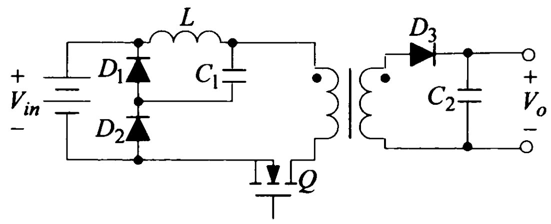
[†]The authors are with the Research Institute of Electronics, Shizuoka University, Hamamatsu-shi, 432-8011 Japan.
a) E-mail: watanabe-k@rie.shizuoka.ac.jp



(a) Buck converter with a transistor switch.



(b) Buck converter with a diode switch.

Fig. 2 Forward converter topologies for preceding buck conversion.

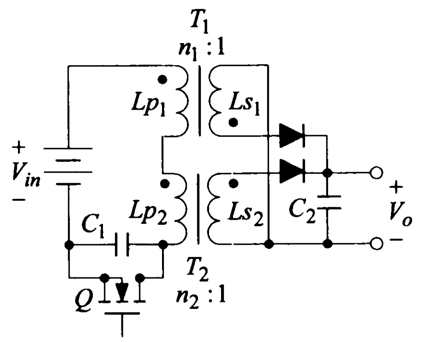


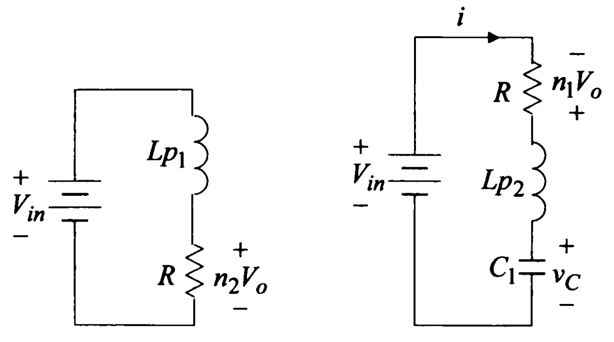
Fig. 3 The zero-voltage-switching quasi-resonant flyback and forward composite DC-DC converter.

$$D = \frac{\tau_{on}}{\tau} \tag{2}$$

If the transformer is provided additional secondary windings for multiple outputs, then each secondary winding should be followed by the buck converter stage. This duplication can be avoided if the DC/DC conversion by the buck converter precedes the DC/AC conversion. Such straightforward topologies are shown in Fig. 2.

These topologies require additional switches, the transistor Q_1 in Fig. 2(a) and the diode D_1 in Fig. 2(b) [5], [6], which degrade the conversion efficiency. In addition to the power loss due to additional switches, some of the energy stored in the choke inductor is lost in the buck converter because it loads differently from the switch Q_2 on and off.

These issues of the straightforward topologies can be dissolved by replacing the choke inductor by the flyback transformer. The topology thus synthesized is shown in Fig. 3. The transformer T_1 and the switch Q form the flyback converter, whereas T_2 and Q form the forward converter. Capacitor C_1 is connected in parallel with Q for the quasi-resonant ZVS. The equivalent circuits when Q is on and off are shown in Fig. 4,



(a) (b)

Fig. 4 Equivalent circuits when switch is on (a) and off (b).

where R is the load resistance referred to the primary side of the transformer, V_D is the voltage drop across the rectifying diode, Lp_1 and Lp_2 are the inductance of the primary windings of T_1 and T_2, respectively.

Referring to Fig. 4(b), one can obtain the current $i(t)$ flowing through and the voltage $v_C(t)$ across C_1 as follows,

$$i(t) = \frac{V_{in} + n_1(V_o + V_D)}{\omega Lp_2} \sin \omega t + I(0) \cos \omega t, \tag{3}$$

$$v_C(t) = [V_{in} + n_1(V_o + V_D)](1 - \cos \omega t) + \frac{I(0)}{\omega C_1} \sin \omega t, \tag{4}$$

where

$$\omega = \frac{1}{\sqrt{Lp_2 C_2}}, \tag{5}$$

and $I(0)$ is the initial current when Q is off. Referring to Fig. 4(a), $I(0)$ is given by

$$I(0) = \frac{V_{in} - n_2(V_o + V_D)}{Lp_1} \tau_{on}, \tag{6}$$

where τ_{on} is the time during which the switch Q is on. The voltage $v_C(t)$ assumes the minimum value in the vicinity of $\omega t = (3/2)\pi$. ZVS requires the minimum value to be negative. The ZVS condition is thus expressed as

$$\sqrt{\frac{Lp_2}{C_1}} I(0) > V_{in} + n_1(V_o + V_D) \tag{7}$$

Assuming that the load current is supplied by T_2, one can derive the expression for the output voltage V_o as follows:

$$V_o = \frac{RD^2 \big/ 2fLp_1}{1 + RD^2 \big/ 2fLp_1} \left(\frac{V_{in}}{n_2} - V_D \right), \tag{8}$$

where f is the switching frequency. Substituting (6) and (8) into (7), one obtains the ZVS condition in terms of circuit parameters:

$$\sqrt{\frac{Lp_2}{C_1}} \left(1 - n_2 \frac{V_D}{V_{in}}\right) - \left(1 + \frac{n_1}{n_2}\right) \frac{RD}{2}$$

$$> \frac{fLp_1}{D}\left(1 + n_1\frac{V_D}{V_{in}}\right) \tag{9}$$

Equation (9) indicates that the resonant impedance $\sqrt{Lp_2/C_1}$ much higher than the impedance of the primary winding of T_1 is required for the ZVS condition to be met over the wide range of the load.

3. Performances

A main application of the proposed flyback and forward composite converter is an off-line switching power supply. The performances under such an application are tested by SPICE simulations and the breadboarded prototype converters. Table 1 lists the circuit parameters in the simulated and prototype converters.

The input is AC 100 V which is rectified by a diode-bridge and filtered by a capacitor. The DC input voltage V_{in} of the converter is thus about 140 V. Figure 5 shows simulated and measured waveforms of the current $i(t)$ through and the voltage $v_C(t)$ across the MOSFET Q. The switching frequency is 80 kHz and the duty ratio is 0.5. Good agreement between the simulated and measured waveforms can be seen. The ramp current i during τ_{on} and the quasi-sinusoidal voltage v_C during the switch off demonstrate the proper operation and validate the circuit analyses in the previous section.

Figure 6 shows the simulated and measured output voltage as a function of the duty ratio. In these experiments, the switch on-time τ_{on} is changed while the switch off-time τ_{off} is kept fixed to 6.25 μs to assure the ZVS. These results indicate that the output voltage can be controlled by means of the duty ratio and (8) is available for designing the converter.

Figure 7 shows the measured AC-to-DC power conversion efficiency as a function of the duty ratio. τ_{off} is again fixed to 6.25 μs for the ZVS. When the duty ratio is 0.5, the apparent input power, the effective input power, and the output DC power are 26 W, 13.4 W, and 11.9 W, respectively. The power factor and the AC-to-DC conversion efficiency are thus 51.5% and 89%, respectively. The loss analyses show that the diode bridge for rectifying the input AC voltage and the diode at the secondary winding of the transformer each dissipate 0.5 W. The DC-to-DC conversion efficiency, the efficiency of the converter itself, is thus 92%. The diode losses dominate the conversion efficiency. The conversion efficiency decreases with decreasing duty ratio. This is because the output power decreases with the decreasing duty ratio while the power loss in the converter hardly depends on the duty ratio.

When the duty ratio D is constant, the output

Table 1 Circuit parameters.

Input : AC 100V		
Transformers		
T_1 :	Lp=425μH, Ls=26.7μH	
	Coupling factor	k=0.96
	Turn ratio	n=4
T_2 :	Lp=5850μH, Ls=342μH	
	Coupling factor	k=0.988
	Turn ratio	n=4.14
Capacitor :	C_1=200pF,	C_2=100μF
Load :	R_L=50Ω	

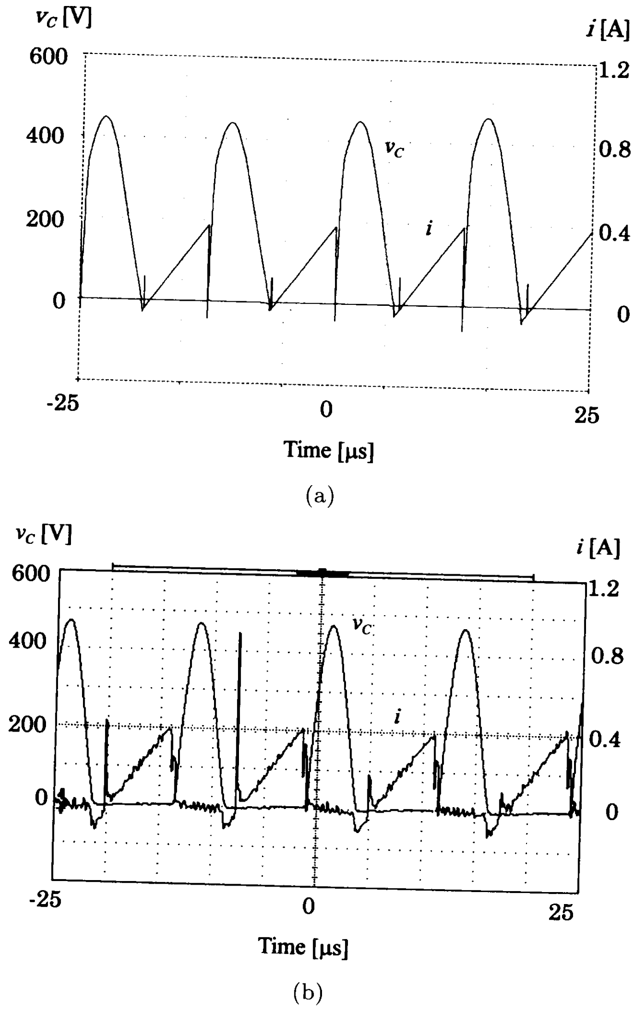


Fig. 5 Simulated (a) and measured (b) waveforms of the current i through and the voltage v_C across the switch Q.

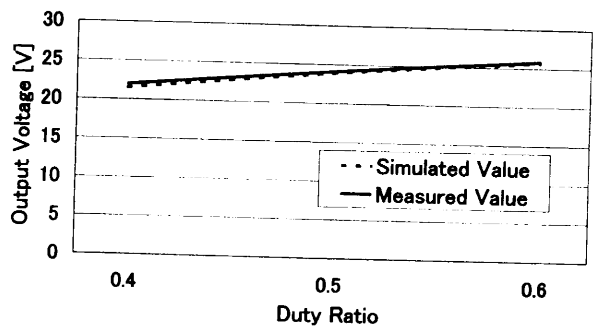


Fig. 6 The output voltage vs. the duty ratio.

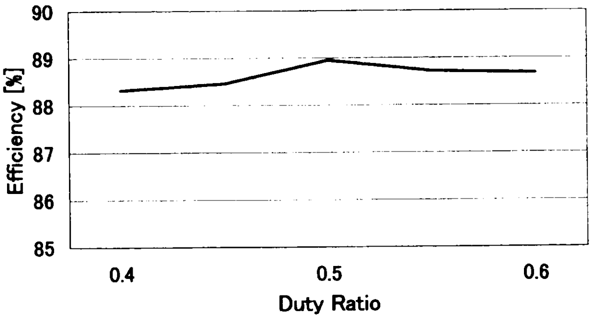


Fig. 7 AC-to-DC power conversion efficiency vs. the duty ratio.

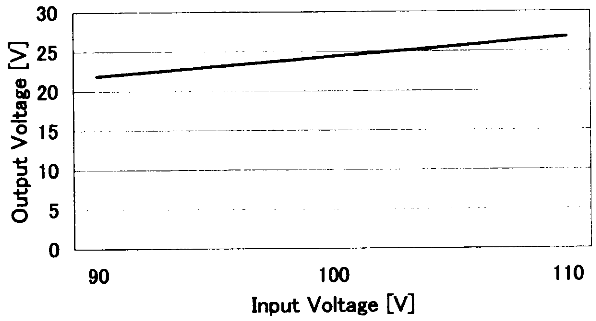


Fig. 8 The output voltage vs. the input voltage.

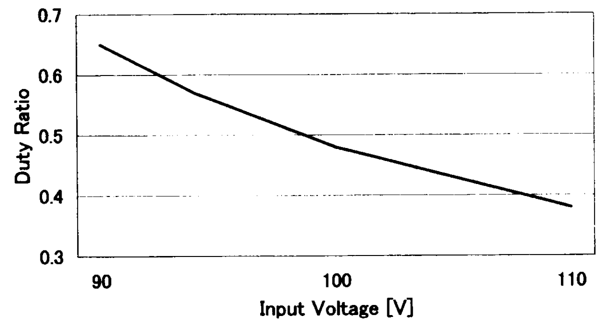


Fig. 9 The duty ratio vs. the input voltage to keep the output voltage at 24 V.

voltage changes linearly with the input voltage. Figure 8 shows such a linear dependence. For the ±10% change in the input voltage, the output voltage also changes by ±10%. Figure 9 shows the duty ratio to keep the output voltage at 24 V as a function of the input voltage.

These measurements confirm that the regulation for the input voltage is possible by mean of the duty ratio.

Similar performances are also measured for the prototype converter with two outputs. The circuit diagram and parameters are shown in Fig. 10 and Table 2, respectively. Figure 11 shows the measured output voltages as a function of the duty ratio. In this experiment, the switch on-time τ_{on} is changed while the switch off-time τ_{off} is kept fixed to 6.25 μs to assure the ZVS. It can be seen that the flyback converter operates as the buck stage common to the two outputs.

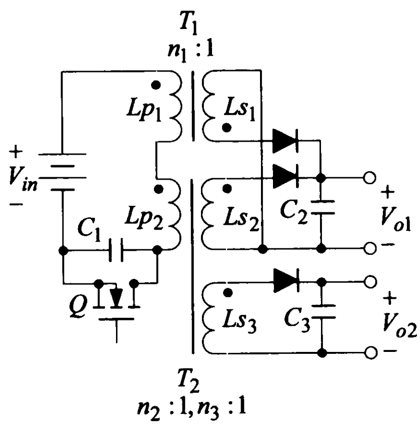


Fig. 10 The ZVS composite DC-DC converter with two outputs.

Table 2 Circuit parameters of the two-output converter.

Input : AC 100V		
Transformer		
T_1 :	Lp=425μH, Ls=26.7μH	
	Coupling factor	k=0.96
	Turn ratio	n_1=4
T_2 :	Lp_2=8590μH,	
	Ls_2=522μH, Ls_3=120μH	
	Coupling factor	k=0.99
	Turn ratio	n_2=4.14, n_3=8.46
Capacitor :	C_1=200pF,	C_2= C_3=100μF
Load :	R_{L1}= R_{L2}=50Ω	

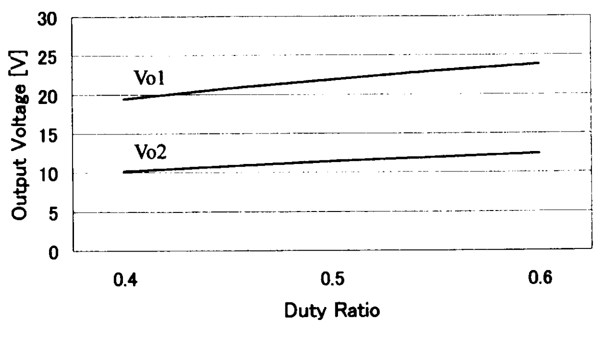


Fig. 11 The output voltage vs. the duty ratio.

Figure 12 shows the measured AC-to-DC power conversion efficiency as a function of the duty ratio. τ_{off} is again fixed to 6.25 μs for the ZVS. The loss analyses similar to the single-output converter shows that the conversion efficiency of the DC-to-DC converter stage itself exceeds 88%. Compared to the one-output converter, the efficiency is lower by 3%. This is due to the additional diode loss in the secondary winding.

Figure 13 shows the duty ratio required for the input regulation. Comparing it with Fig. 9, one notices that the smaller change in the duty ratio covers the same input voltage change from 90 to 110 V. This can

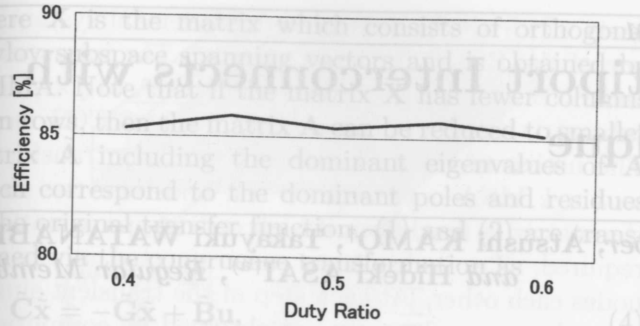


Fig. 12 AC-to-DC power conversion efficiency vs. the duty ratio.

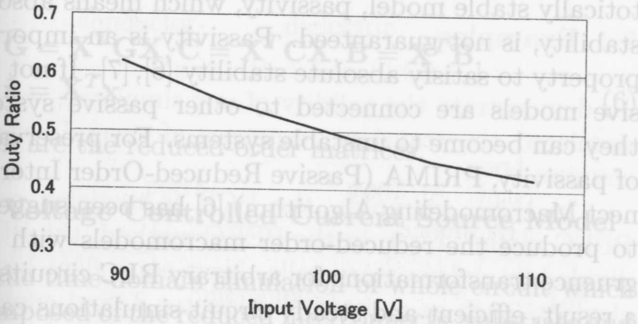


Fig. 13 The duty ratio vs. the input voltage to keep the output voltage at 11.5 V and 22 V.

be explained as follows. Differentiating (8), one can obtain the duty ratio for the input regulation:

$$\frac{\partial D}{D} = \frac{1 + RD^2 \big/ 2fLp_1}{2} \frac{\partial V_{in}}{V_{in}} \tag{10}$$

In deriving (10), the contribution of V_D to V_o is neglected. Equation (10) indicates that the change in duty ratio to compensate the given input voltage change becomes smaller with the heavier load. The load R of the single-output prototype converter referred to the primary side of the transformer is 860 Ω approximately, whereas that of the two-output converter is about 690 Ω. This difference in load corresponds to that in Figs. 9 and 13.

4. Conclusions

A ZVS quasi-resonant DC-DC converter consisting of two transformers has been presented. The simulated and measured performances have confirmed the principles of operation and demonstrated the power conversion efficiency higher than 88%. The efficiency is dominated by the diode loss. Replacing the diode by power MOS transistor for synchronous rectification will further improve the efficiency. The output DC voltage regulation against the line voltage and the load is also possible by means of the duty ratio. The DC-DC converter described herein is thus quite useful for an off-line switching power supply.

Miniaturization by increasing the switching frequency and improvement in the power factor are future works.

References

[1] S.S. Ang, Power-Switching Converters, Marcel Dekker, New York, 1995.

[2] N. Mohan, T.M. Undeland, and W.P. Robbins, Power Electronics: Converters, Applications, and Design, John Wiley & Sons, New York, 1995.

[3] T.-F. Wu and Y.-K. Chen, "Modeling PWM DC/DC converters out of basic converter units," IEEE Trans. Power Electronics, vol.13, pp.870–881, Sept. 1998.

[4] K. Siri, I. Batarseh, V. Caliskan, and P. Kornetzky, "PWM zero-voltage switching boost-derived converters with output isolation," IEEE Trans. Power Electronics, vol.11, pp.448–459, May 1996.

[5] B.P. Divakar and D. Sutanto, "Optimum buck converter with a single switch," IEEE Trans. Power Electronics, vol.12, pp.636–642, July 1999.

[6] I.A. Khan, "Synthesis and analysis of transformer-isolated converters," IEEE Trans. Power Electronics, vol.10, pp.409–418, July 1995.

Yukihiro Ohta received the B.E. and the M.E. degrees from Shinshu University in 1996 and 1999, respectively. He is studying high-efficiency power supplies at the Research Institute of Electronics, Shizuoka University, Hamamatsu, toward the Ph.D.

Chika Watanabe received the B.E. degree from Shizuoka University in 2000. She is studying high-efficiency power supplies at the Graduate School, Shizuoka University.

Kenzo Watanabe is a Professor of the Research Institute of Electronics, Shizuoka University, Hamamatsu, Japan. He received the B.E. and M.E. degrees in engineering from Shizuoka University in 1962 and 1966, respectively, and the Dr. Eng. degree from Kyoto University in 1976. He stayed at UCLA as a visiting Professor from 1982 to 1983. He received the Andrew R. Chi Best Paper Award and the IM Society Award from IEEE IM Society in 1984 and 1999, respectively, and the Saito Award from the Chion Institute in 1990 and the Takayanagi Memorial Award in 1994. He has also been designated an Emeritus Professor of Xidian University, Xi'an, China, in 1997. He is a Fellow, IEEE, and an Associate Editor of IEEE Transactions on Instrumentation and Measurement.