A New ZVS DC/DC Converter with Fully Regulated Dual Outputs

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Abstract -- **In this paper, a new type of dual output zero voltage switched (ZVS) DC/DC converter is proposed. One output is dependent on the effective duty ratio and the other is largely dependent on the switching frequency. Two completely regulated outputs are obtained with only one bridge circuit by combining the different configurations of secondary output. Using ZVS technique, switching loss can be reduced to quite low at several hundred kHz.**

I. INTRODUCTION

Most of the electronic systems require several regulated DC voltages. Thus multi-output pulse width modulated (PWM) converters with multi-secondary windings are usually used. In multi-output PWM converters, feedback control circuit regulates only one output and the others are dependent on the secondary winding turn ratios. In high switching frequency, all output voltages are not possible in multi-output PWM converter because of the quantized turn ratio. Furthermore transient and steady state cross-regulations are not good because of leakage inductance, winding resistance, diode and switch voltage drops, etc.

If more than one outputs should be well regulated simultaneously, it is necessary to provide post-regulators or other methods. Reference [1] well explains the post-regulation techniques using such as linear regulator, magnetic amplifier and another switching regulator. If post-regulator is used, the efficiency of converter, complexity, and cost must be sacrificed for full performance.

Dual converter (or double converter) is another approach, in which the two outputs can be fully regulated by pulse width and pulse frequency control without using additional switch.[2-7] This approach is desirable if soft switching is possible and if duty ratio is not limited.

Those who engage in the area of power electronics desire to make switching frequency as high as possible because numerous benefits can be obtained. However with hard switching, high frequency switching is difficult because of high switching loss. Thus a lot of works have been directed toward to develop soft switching technologies. Resonant converters, quasi-resonant converters and partial resonant PWM converters are good examples. However they have cross-regulation problem in multi-output schemes although their performance is excellent in mono-output schemes.

In this paper, a new ZVS converter scheme that overcomes cross-regulation problem is proposed.

II. DESCRIPTION OF PROPOSED CONVERTER

A. *The ZVS-PWM Converter*

The ZVS-PWM converter and its rough waveforms are shown in Fig.1 and its operation is well explained in [8-12]. In phase-shift control, output filter inductor current freewheels through primary switch and diode. For this reason the energy that enables the zero voltage switching still remains in resonant inductor at the end of turn-off time. After switching transient, the operation of the ZVS-PWM converter is similar to the traditional PWM converter. Thus the ZVS-PWM converter has the merits of both resonant converter and PWM converter simultaneously while avoiding their major drawbacks. Switching loss is as low as that of the resonant converter while conduction loss is a little bit larger than that of the PWM converter. The efficiency is still high in several hundred kHz switching frequency.

In the ZVS-PWM converter output voltage is dependent on both duty ratio and output resistance. Under appropriate assumption, their relations are given by

$$D_{eff} = \frac{D}{1 + 4 L_r N^2 f_s / R_o} \qquad (1)$$

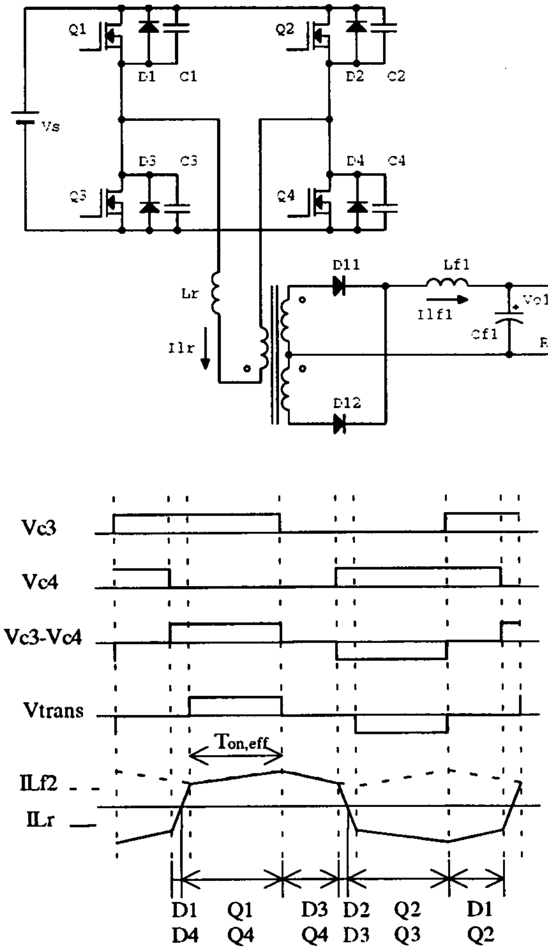


Fig.1 The ZVS-PWM converter and its rough waveforms

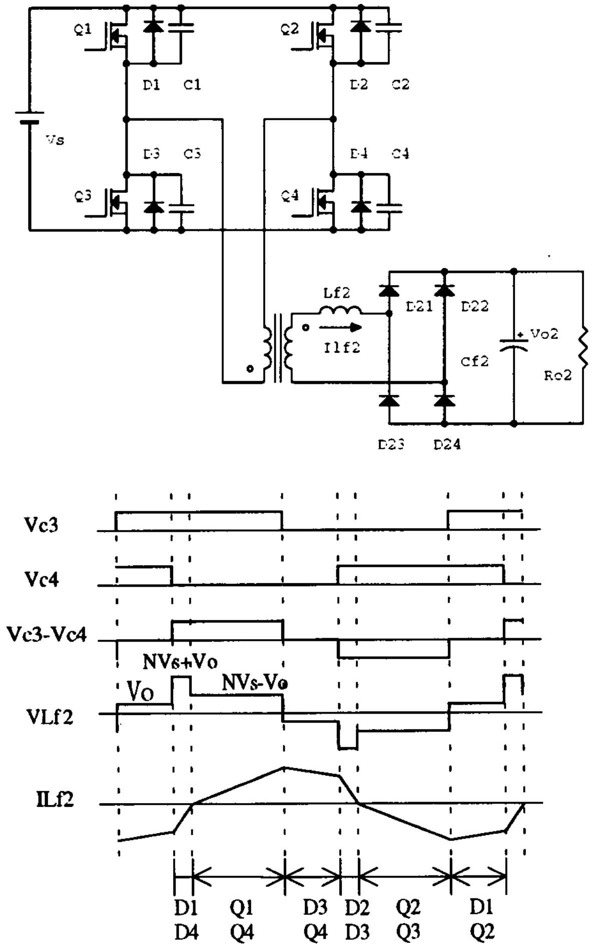


Fig.2. The ZVS-PFM converter and its rough waveforms

$$V_o = ND_{eff}V_s \tag{2}$$

where the duty ratio is $D = T_{on}/T$, and the transformer turn ratio is $N = N_s/N_p$.

B. The ZVS-PFM Converter

The ZVS-PFM converter and its rough waveforms are shown in Fig.1. All of the switches including rectifier diodes are switched softly and the reverse recovery problems of the diodes are avoided. As a result, switching losses become very small with a little bit increase in conduction losses.[13-14]

The operation of the ZVS-PFM converter is similar to that of the ZVS-PWM converter. The main difference is the existence of L_{f1}. The inductor L_{f2} plays a role of L_r, consequently, the current of L_{f2} is similar to that of L_r but it is quasi-triangular due to the absence of L_{f1}.

Although the output voltage is high, schottky barrier diodes can be used as rectifier diodes the because voltage stress is limited to the output voltage. Thus conduction losses can somewhat be reduced.

It is easily understandable that the output current is directly proportional to the switching frequency and dependent on the duty ratio. For this reason the output voltage can be controlled by switching frequency if the duty ratio is changed within a reasonable range. Under appropriate assumption, their relations are

$$V_o = \frac{ND_{eff}(2-D_{eff})V_s}{2N^2L_{f2}f_s/R_{o2} + \sqrt{(2N^2L_{f2}f_s/R_{o2})^2 + D_{eff}(2-D_{eff})}} \tag{3}$$

in continuous conduction mode and

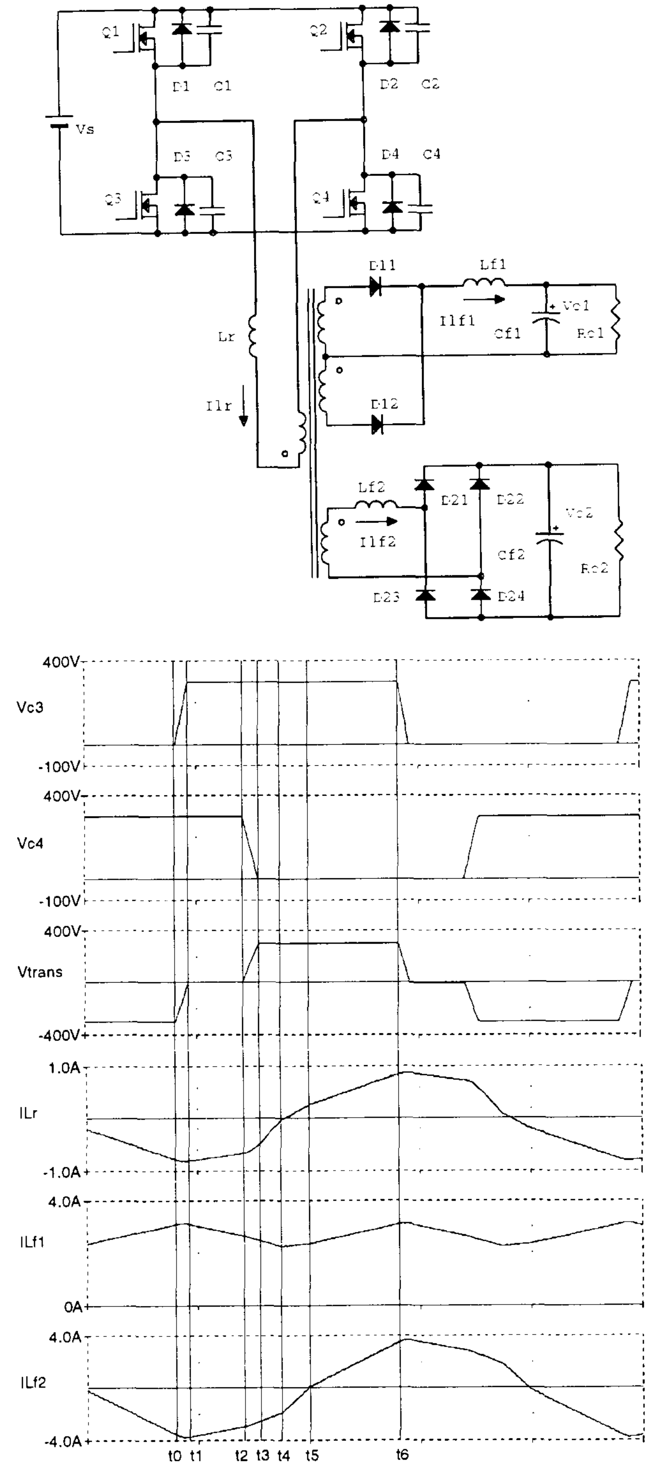


Fig.3 The proposed converter and its waveforms simulated with PSPICE

$$V_o = \frac{2}{1+\sqrt{1+8N^2L_{f2}f_s/R_{o2}D_{eff}^2}} \qquad (4)$$

in discontinuous conduction mode.

C. *The Proposed Converter*

The proposed converter and its waveforms simulated by PSPICE are shown in Fig.3. The proposed converter is obtained by the superposition of the ZVS-PWM converter and ZVS-PFM converter. In spite of superposition, the properties of each converter are not changed. Thus the sum of the waveforms of Fig.1 and Fig.2 becomes like Fig.3. One output is dependent on duty ratio and the other is dependent on switching frequency and somewhat duty ratio. Using two control variables fully regulated two outputs can be obtained with one bridge circuit.

III. OPERATION OF THE PROPOSED CONVERTER

As shown in Fig.3, the operation of the proposed converter can be divided into symmetrical six modes (total twelve modes) if I_{Lf2} is continuous. In discontinuous case, Mode 5 does not exist. The circuits formed in respective modes are shown in Fig.4.

A. *Mode 1 [t_0 - t_1]*

Mode 1 begins at the time of turning off Q_3 and ends when V_{C3} is equal to V_s. During Mode 1, C_1 and C_3 resonate with L_r, L_{f1} and L_{f2}, but the voltage and current waveforms seem to be linear because resonant period is sufficiently longer than the switching transient time. Turn-off switching loss is very low because drain-source voltage of Q_3 is low during the turn-off time.

B. *Mode 2 [t_1 - t_2]*

During Mode 2, I_{Lf1} and I_{Lf2} freewheel through primary switches. If Q_1 is turned on at any time during Mode 2, turn-on switching loss is zero because V_{DS} of Q_1 is zero.

C. *Mode 3 [t_2 - t_3]*

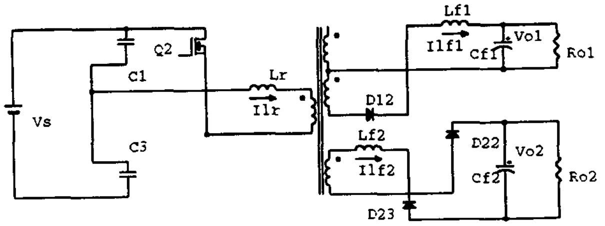
Mode 3 begins at the time of turning off Q_2 and ends when V_{C4} is zero. During Mode 3, C_2 and C_4 resonate with L_r if $I_{Lf1} > I_{Lf2}$, or with L_r and L_{f2} if $I_{Lf1} < I_{Lf2}$. I_{Lr} must be sufficiently large in order to guarantee zero voltage turn of Q_4, then Mode 4 follows.

D. *Mode 4 [t_3 - t_4]*

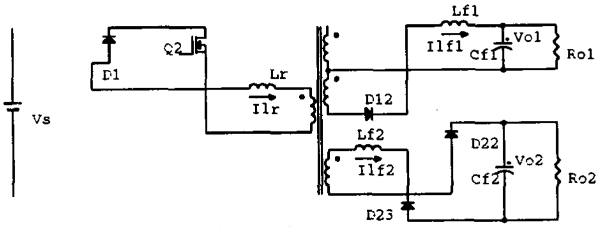
During Mode 4, D_1 and D_4 conduct, thus L_r regenerates energy to source. If $I_{Lf1} < I_{Lf2}$, L_{f2} regenerates energy to source, too. By turning off Q_4 at any time in Mode 4, turn-on loss of Q_4 can be made zero. Mode 4 ends at the time when I_{Lr} becomes zero.

E. *Mode 5 [t_4 - t_5]*

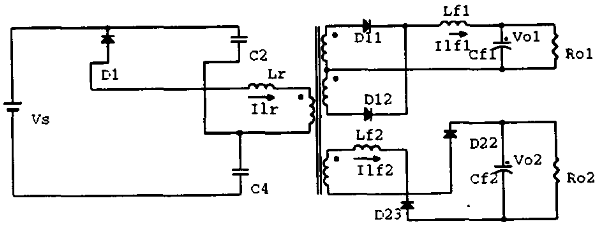
Mode 5 begins at the time when Q_1 and Q_4 start to conduct and ends when I_{Lf2} is zero. During Mode 5, energy of L_{Lf2} regenerates to the other output.



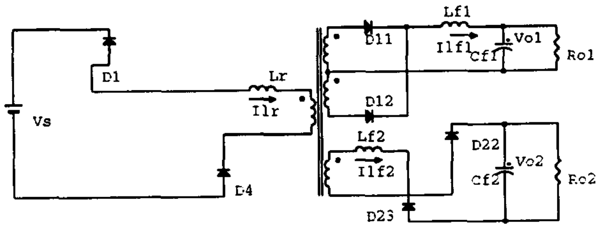
(a) MODE1



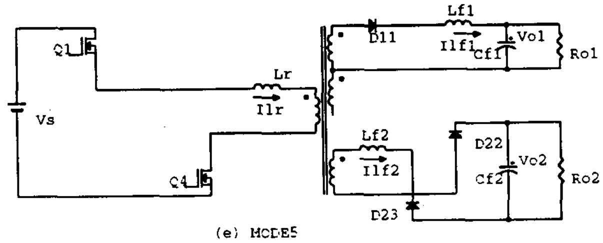
(b) MODE2



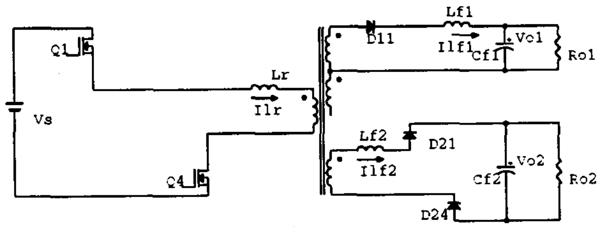
(c) MODE3



(d) MODE4



(e) MODE5



(f) MODE6

Fig.4 Mode diagrams of the proposed converter

F. Mode 6 [t_5 - t_6]

Mode 6 begins at the time when polarity of I_{Lf2} is reversed and ends at the time of turning off Q_1. During Mode 6, the operation is the same as turn-on time of traditional PWM converter. During mode 5 and Mode 6, the slop of I_{Lr} is changed only once when the effective turn-on time starts.

Next six modes are symmetrical to previous six modes. Exactly reversed or delayed waveforms are obtained by changing Q_1 with Q_3, Q_2 with Q_4, C_1 with C_3, C_2 with C_4, etc.

IV. EXPERIMENTAL VERIFICATIONS

A 150W prototype of the proposed converter is implemented on the bread board. Input and output specifications are as follows:

Input : 300V
Output : 5V 15A (75W)
15V 5A (75W).

Components used in the experiment are as follows:

Q_1 - Q_4 : IRF730 (SAMSUNG)
C_1 - C_4 : internal capacitor, 50pF each
D_{11},D_{12} : D83-004
D_{21} - D_{24} : CTB-24
Transformer : PC40, PQ2620, 30:1:4
L_r : 47μH, PC40, PQ2016
L_{f1} : 2μH, PC30, PQ2016
L_{f2} : 4μH, PC40, PQ2016

Using conventional PWM controller (UC3825), PWM-FM phase shift controller is implemented. It is easy to assemble a gate driver using isolation transformer because duty ratio is almost 50%.

The switch voltage and inductor currents are shown in Fig.5. The experimental results are in good agreement with the simulation results of Fig.3.

Transient response of the proposed converter and the traditional PWM converter are compared in Fig.6. The output voltages of the traditional PWM converter are 5V and 24V. The oscillograms show the changes of the output voltages when the PWM load or feedback controlled load changes in between 33% and 100%. The oscillograms show that the cross-regulation of the proposed converter is excellent even in transient interval.

Steady state cross-regulation property of the proposed converter and the traditional PWM converter is compared in Fig.7. Even if the PWM load is changed, PFM output voltage is maintained constant, which is desirable property.

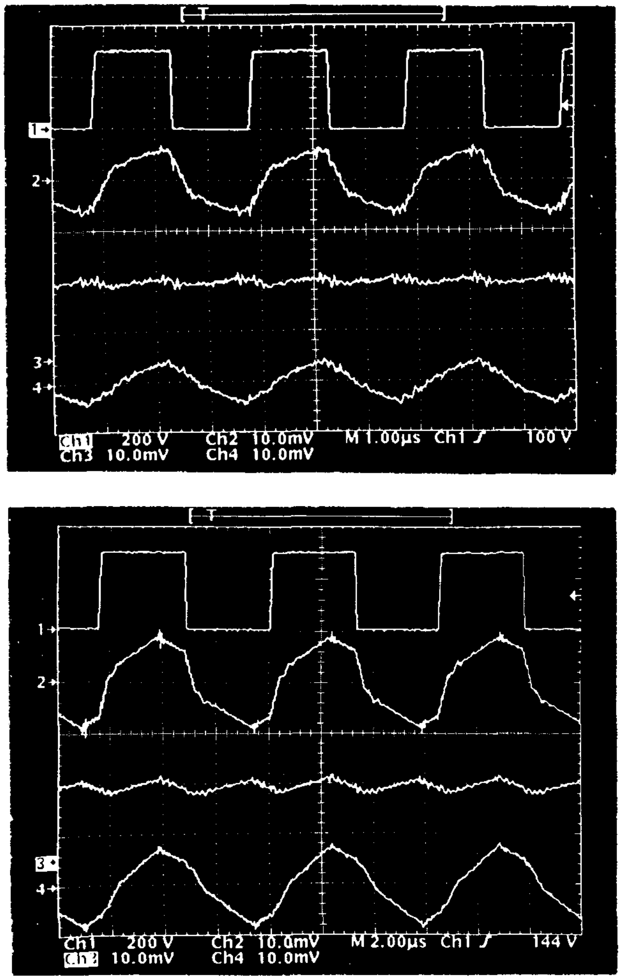


Fig.5 Voltage and current waveforms of the proposed converter
upper : PWM-full load, PFM-half load
lower : PWM-full load, PFM-full load
CH.1 V_{DS3} 200V/div.
CH.2 I_{Lr} 2A/div.
CH.3 I_{Lf1} 10A/div.
CH.4 I_{Lf2} 10A/div.

The conversion efficiency without considering control power is shown in Fig.8. This figure shows the efficiency is between 87.6% and 90.35% for all of the cases. The maximum efficiency is obtained at the minimum PWM load and half PFM load. By using schottky barrier diodes as PFM rectifier diodes, the conversion efficiency increases about 3% more.

The switching frequency variation with load change is shown in Fig.9. It shows that the switching frequency is almost directly proportional to PFM load.

V. CONCLUSION

A new type of dual output ZVS DC/DC converter is proposed. Two output voltages can be completely regulated without adding additional circuits. The cross-regulation of the proposed converter is excellent in both transient and steady state. Switching loss is also low because the switches operate under ZVS condition. As a result, high-efficiency, high-frequency dual converter is realized. The operation and performance are verified by PSPICE simulation and experiments.

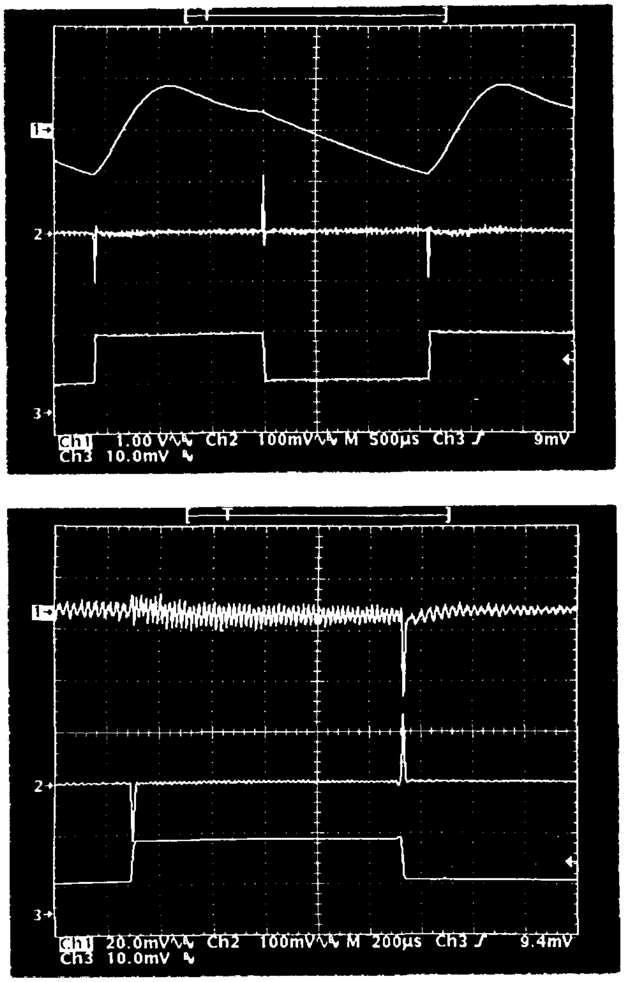


Fig.6 Transient response of the traditional PWM converter and the proposed converter.
upper : the traditional PWM converter (5V and 24V output)
CH.1 V_{O2} 1V/div. without control
CH.2 V_{O1} 100mV/div. with control
CH.3 I_{O1} 10A/div.
lower : the proposed converter
CH.1 V_{OPFM} 20mV/div.
CH.2 V_{OPWM} 100mV/div.
CH.3 I_{OPWM} 10A/div.

REFERENCES

[1] C. L. Jamerson, *"Post-Regulation Technique for 100kHz to 300kHz Multiple-Output PWM Supplies (Limitation, Trends, and Predictions)"*, HFPC 1989. PP.260-273.

[2] A. Dauhajre and R. D. Middlebrook, *"Simple PWM-FM Control for an Independently Regulated Dual Output Converter"*, Powercon 10, March, 1983, D-3.

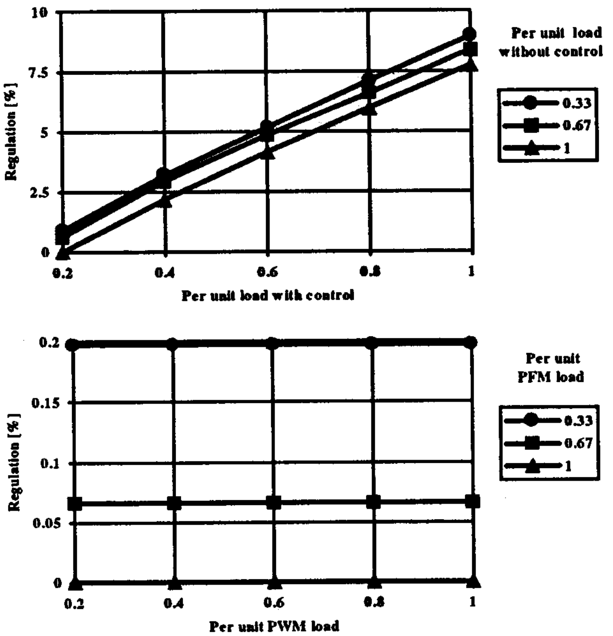


Fig.7 Steady state cross-regulation property.
upper : the traditional PWM converter
lower : the proposed converter

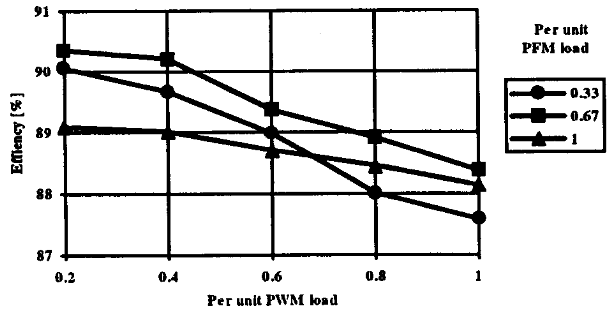


Fig.8 Conversion efficiency of the proposed converter.

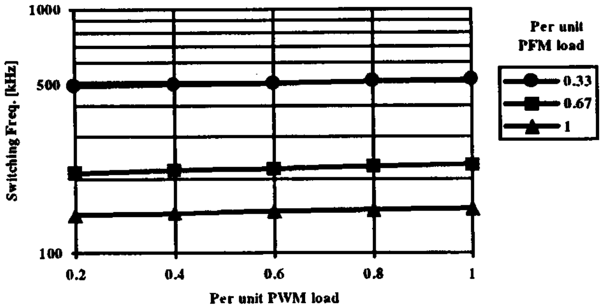


Fig.9 Switching frequency variation of the proposed converter

[3] R. Mahadevan, S. El-Hamasy, W. M. Polivka and S. Cuk, *"A Converter with Three Switched-networks Improves Regulation, Dynamics, and Control"*, Powercon 10, March, 1983, E-1.

[4] J. Sebastian and J. Uceda, *"The Double Converter : A Fully Regulated Two-Output DC-to-DC Converter"*, IEEE PESC 1985, PP.117-126

[5] J. Sebastian and J. Uceda, *"New Topologies of Fully Regulated Two-Output DC-to-DC Converter with Small Frequency Variation Range"*, IEEE PESC 1986, PP.264-271.

[6] J. Sebastian and J. Uceda, *"An Approach to Modeling Double Converter"*, IEEE PESC 1986, PP.176-185.

[7] T. Charanasomboon, M. J. Devaney and R. G. Hoft, *"Single Switch Dual Output DC-DC Converter"*, IEEE PESC 1988, PP.157-163.

[8] K. Liu, and F. C. Lee, *"Zero-Voltage Switching Technique in DC/DC Converters"*, IEEE PESC 1986, PP.58-70.

[9] R. A. Fisher, K. D. T. Ngo and M. H. Kuo, *"500kHz 250W DC-DC Converter"*, HFPC 1988, PP.100-110.

[10] C. P. Henze, H. C. Martin and D. W. Parsley, *"Zero Voltage Switching in High Frequency Power Converters Using Pulse Width Modulation"*, IEEE APEC 1988, PP.33-40.

[11] J. A. Sabate, V. Vlatkovic, R. B. Ridly, F. C. Lee, B. H. Cho, *"Design Considerations for High-Voltage, High-Power, Full-Bridge, Zero-Voltage-Switched PWM Converter"*, IEEE PESC 1990, PP.275-284.

[12] I. D. Kim, E. C. Nho and G. H. Cho, *"A Soft Switching Constant Frequency PWM DC/DC Converter with Low Switch Stress and Wide Linearity"*, IEEE IECON 1990, PP.902-908.

[13] O. D. Patterson, D. M. Divan, *"Pseudo-Resonant Full-Bridge DC-DC Converter"*, IEEE PESC 1987, PP.424-430.

[14] E. C. Nho and G. H. Cho, *" A New High Performance Zero-Voltage Zero-Current Mixed Mode Switching DC/DC Converter"*, IEEE PESC 1989, PP.902-908.