Duplex Pulse Frequency Modulation Mode Controlled Series Resonant High Voltage Converter for X-Ray Power Generator

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Abstract- A variety of high voltage DC power supplies employing the high frequency inverter are difficult to achieve soft switching considering a quick response and no overshoot response under the wide load variation ranges which are used in medical-use x-ray high voltage generator from 20kV to 150kV in the output voltage and from 0.5mA to 1250mA, respectively. The authors develops soft switching high voltage DC power supply designed for x-ray power generator applications, which uses series resonant inverter circuit topology with a multistage voltage multiplier instead of a conventional high voltage diode rectifier connected to the second-side of a high-voltage transformer with a large turn ratio. A constant on-time dual mode frequency control scheme operating under a principle of zero-current soft switching commutation is described. Introducing the multistage voltage multiplier, the secondary transformer turn-numbers and stray capacitance of high-voltage transformer is effective to be greatly reduced. It is proved that the proposed high-voltage converter topology with dual mode frequency modulation mode control scheme is able to be the transient response and steady-state performance in high-voltage x-ray tube load. The effectiveness of this high voltage converter is evaluated and discussed on the basis of simulation analysis and observed data in experiment.

Keywords- DC-DC resonant converter, High frequency transformer link, Dual mode PFM control, Zero current soft switching, X-ray power generator

I. INTRODUCTION

The research and development on a variety of An application of the high-voltage DC power supply systems which is able to be used for an high-voltage X-ray power generator in medical power electronics have attracted special interest. In general, the X-ray power generator must have the special capability to adjust its wide range DC output voltage applied to the X-ray tube in order to ensure the best quality image for each specified pattern of a body part to be imaged. Higher DC output voltages with good dynamic and steady state responses are required so as to diagnose more dense body parts of all types of bones, and lower voltages may be adequately used for diagnosing soft tissues of the organs. Therefore, it is more necessary to control the DC output voltage across the X-ray tube over widely specified setting ranges by using DC-DC power converter. In case of introducing the high-voltage transformers, there are several serious problems in the PWM DC-DC power topologies with a high frequency link. The large turns ratio of the transformer includes the parasitic circuit parameter and the transformer non-idealities the system performances. In particular, the leakage inductance and the parasitic capacitance formed by the secondary winding of the transformer can significantly make worse the converter total system behavior. The former one causes undesirable voltage spikes, which can damage circuit components, power semiconductor devices and current spikes and slow rise time. Especially, the secondary winding capacitance of the transformer with a adds an additional element to this tank circuit, which prevents the output rectifiers from switching. During this time, all output diodes are reverse-biased and no charge is transferred to the output. Consequently, the output voltage is lowered somewhat from the ideal series resonant DC-DC converter, while the series resonant tank and switch currents are increased. Both non-idealities can lead to greatly increase switching and snubber losses and reduced converter efficiency and reliability.

An attractive alternative topology for high-voltage DC-DC applications is based on the use of a multistage voltage multiplier instead of a conventional high voltage diode rectifier connected to the secondary side of the high-voltage transformer with a large turn ratio. The capacitor-diode ladder type multistage voltage multiplier is AC to DC power conversion devices composed of the diodes and the capacitors that produce high DC voltage from a low voltage AC source. According to the introduction of the multistage voltage multiplier, the secondary turn numbers, and the lumped stray capacitance of the high-voltage transformer as well as the voltage ratings of the high-voltage rectifier diode can be greatly reduced. This paper presents a newly-developed high frequency high voltage series-resonant zero current DC-DC converter including a multistage diode-capacitor voltage multiplier with a constant on-time PFM control strategy. A dual mode changing control scheme of two-step frequency switching is proposed to perform the desired output responses. The operating principle of this power converter is described. The remarkable features of the rapid rising time in transient and low ripple factor in steady state which are required for the medical-use x-ray power supply are described by the proposed control scheme over wide variations of output high-voltage output. Finally, the dynamic and steady state performances of this power converter are evaluated discussed on the basis of the computer simulation and laboratory experimental set-up.

II. CONVERTER SYSTEM DESCRIPTION

Fig.1 illustrates a schematic high-voltage DC power conversion circuit and system including a high-frequency

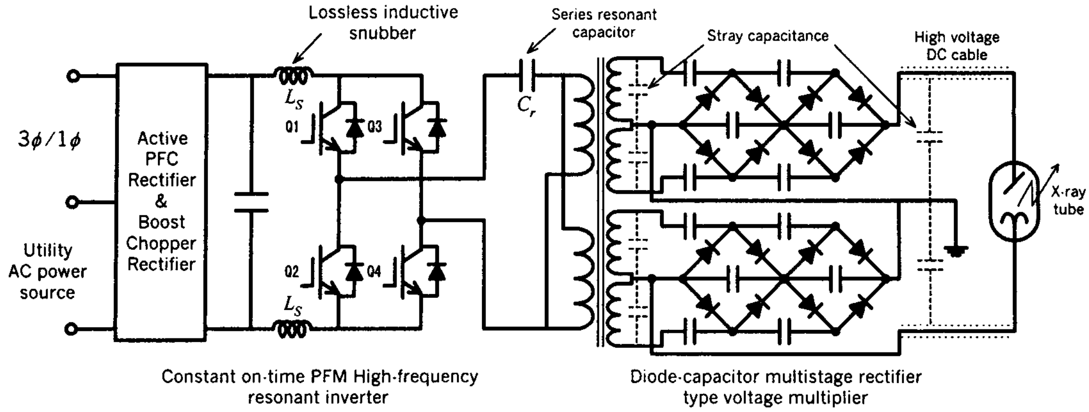


Fig. 1 Schematic high-voltage DC power conversion circuit and system

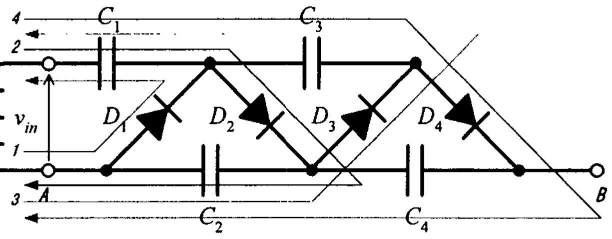


Fig. 2 Half-wave series multiplier

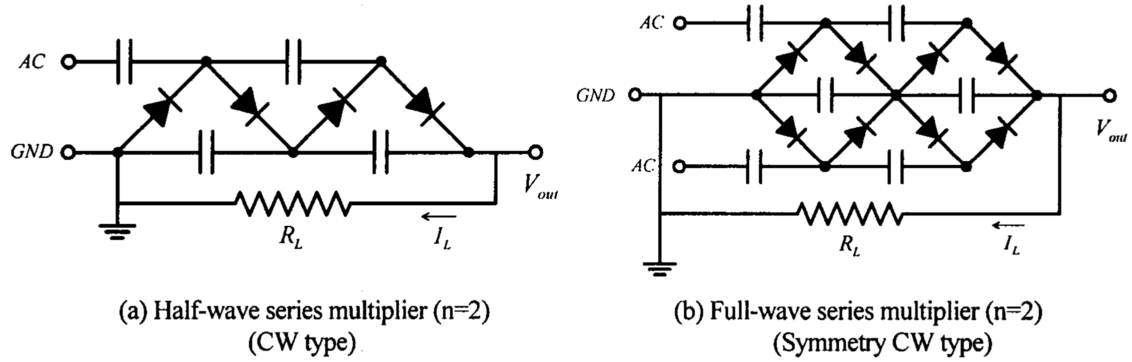


Fig. 3 Topologies of multiplier circuits

PFM inverter using the latest IGBTs for a medical-use X-ray power generator. This X-ray high voltage power generator for the medical use basically consists of high frequency transformer, full bridge high frequency PFM inverter using IGBTs, multistage diode-capacitor type

There are AC to DC power conversion voltage multipliers of diodes and capacitors that produce a high DC voltage from a low voltage AC source obtained from the inverter. The voltage multiplier is achived by Cockroft Walton (CW) circuit. The most commonly used DC Voltage multiplier circuit is the half-wave capacitor-diode multiplier illustrated in Figure 2. All the other DC voltage multipliers can be derived from its operating principle. The operating principle of the voltage multiplier circuit can be described as follows.

DC voltage multiplier used to convert low AC voltage to high voltage, and the X-ray tube and its heater controlled power converter. The anode and cathode of the X-ray tube is connected to the multistage diode-capacitor type voltage multiplier through the high voltage DC cables.

1). In care of vin=negative peak value (-Epk):
C1 charges through D1 to Epk
2). In care of vin=positive peak value (Epk):
Epk of vin adds arithmetically to existing potential C1, thus C2 charges to 2Epk through D2
3). In care of vin=negative peak value (-Epk):
C3 is charged up to Epk through D3
4). In care of vin =positive peak value (Epk):
C4 is charged up to 2Epk through D4

Figure3 shows the main capacitor-diode multistage multiplier topologies derived from the multiplier illustrated in Figure 2. In practice, however, because of the load current i_L, the voltage across each capacitor is not balanced, and voltage drops ΔV as well as ripple voltage components δV appear in the output voltage. Table 1 indicates the ΔV and δV for different types of circuit CW topologies.

As shown in Table 1, ΔV and δV are directly dependent on the switching frequency f; lower switching frequency will lead to larger ΔV and δV, the applications of the voltage multiplier circuit are restricted. On the other hand, higher frequency can reduce the ΔV and δV. Hence, introducing the high-frequency resonant inverter can improve the control performance of the DC-DC power converter with the CW high voltage circuit.

III. OPERATION PRINCIPLE AND OUTPUTVOLTAGE CONTROL

There are two modes of operation for a constant on-time PFM series resonant converter which are defined as a discontinuous conduction mode (DCM) and a continuous conduction mode (CCM). In DCM operation, the inductor current remain zero for some interval, and this mode occurs when the switching frequency f_0 is less than half of the resonant frequency fr. In CCM operation, it occurs when $0.5fr<f_0<fr$.

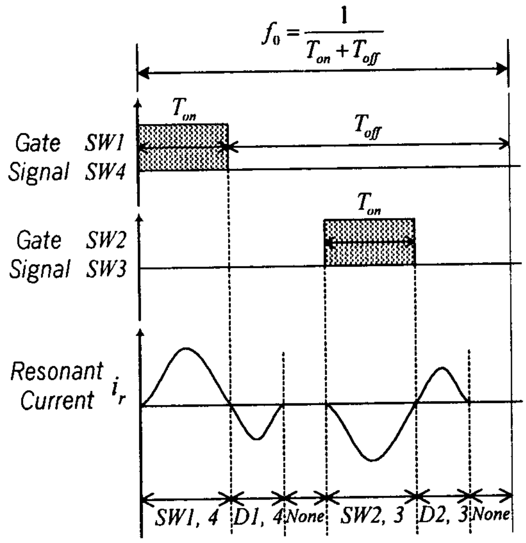
Figure 4 shows the constant on-time PFM pulse signals and resonant current waveforms. Because one-half cycle of the inverter operating frequency exceeds the resonant period Tr of the resonant frequency fr, and therefore in this mode of operation, fo<fr/2 (see Figure 4(a)). In this mode of operation, the active power switches turn off naturally under zero current and zero voltage, since the inductor current goes through zero, the switches turn on under zero current. Figure 4(b) shows the waveforms in the mode of 0.5fr <fo<fr, the turn-off switch occurs naturally at zero current and at zero voltage as the inductor current through them goes to zero and reverse through the freewheeling diodes.

The switching frequency of the series-resonant converter is varied with a constant on time PFM scheme to control the resonant pulse current flowing through the primary winding of the high frequency transformer. The ratio of switching frequency with respect to the resonant frequency can regulate the current flowing through the series-resonant circuit.

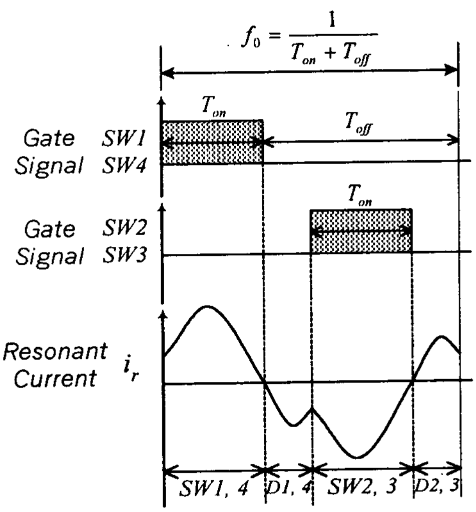
Zero current turn-off switching is achieved completely switching frequency is less than resonant frequency. To ensure zero-current switching in the DC-DC power converter, the on-time of active power switches S1 and S4 or S2 and S3 are respectively fixed to be equal to the one-half of the resonant period Tr/2. This pulse on-time maintains constant while the switching frequency is varied with respect to the resonant frequency to control current flowing through the primary windings of the high frequency transformer.

Table 1 Comparison of various circuit of multiplier

	Output Voltage V_{out}	Voltage drop ΔV	Ripple Voltage δV
CW Type	$2nE_{pk}$	$\frac{i_L}{Cf}A(n)$	$\frac{i_L}{Cf}\cdot\frac{n(n+1)}{2}$
Symmetry CW Type	$2nE_{pk}$	$\frac{i_L}{Cf}B(n)$	$\frac{i_L}{Cf}\cdot\frac{n}{2}$
$A(n)=\frac{2}{3}n^3+\frac{1}{2}n^2+\frac{1}{3}n$		$B(n)=\frac{1}{6}n^3-\frac{1}{4}n^2+\frac{1}{3}n$	
n: number of stages		f: frequency of input voltage	
E_{pk}: peak value of input voltage		i_L: load current	



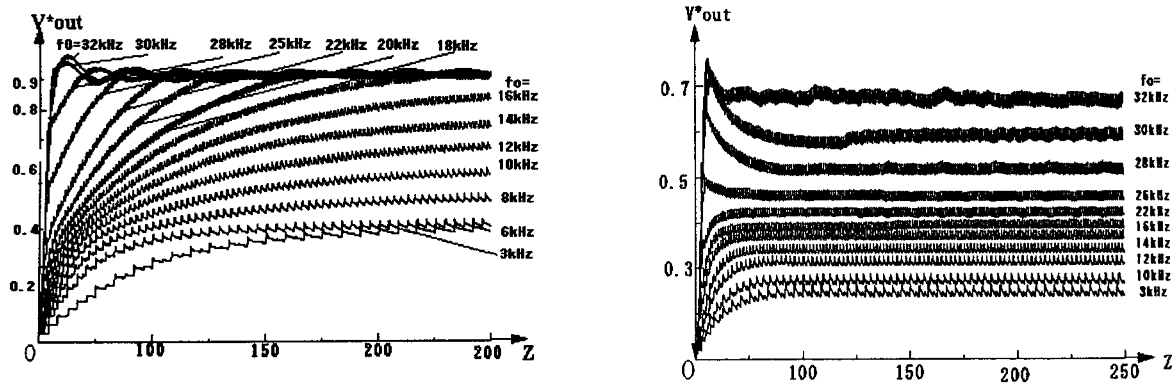
(a) Current discontinuous mode



(b) Current continuous mode

Fig. 4 Constant on-time PFM control principle

IV. OPEN-LOOP VOLTAGE RESPONSE CHARACTERISTICS



(a) Light load (Q=0.1)

(b) Heavy Load (Q=1)

Fig. 5 Open-loop responses of X-ray tube voltage

Table 2 Base values and Normalized values of Parameters

	Base Values	*Normalized Values*
Voltage	DC supply voltage E=50V	$v^{*}=\frac{v}{E}$
Capacitor	Series resonant capacitor C_r=0.172μF	$C^{*}=\frac{C}{C_r}$
Inductor	Leakage inductor L_r=145μH	$L^{*}=\frac{L}{L_r}$
Characteristics Impedance	$Z_0=2\sqrt{\frac{L_r}{C_r}}=58\Omega$	$R^{*}=\frac{R}{Z_0}$
Current	$I=\frac{E}{Z_0}$	$i^{*}=\frac{i}{I}$
Frequency	$f_r=\frac{1}{2\pi\sqrt{L_rC_r}}$ =32 kHz	$\mu=\frac{f_0}{f_r}$ f_0: Inverter operating frequency
Time	$T_r=\frac{1}{f_r}$	$z=\frac{t}{T_r}$

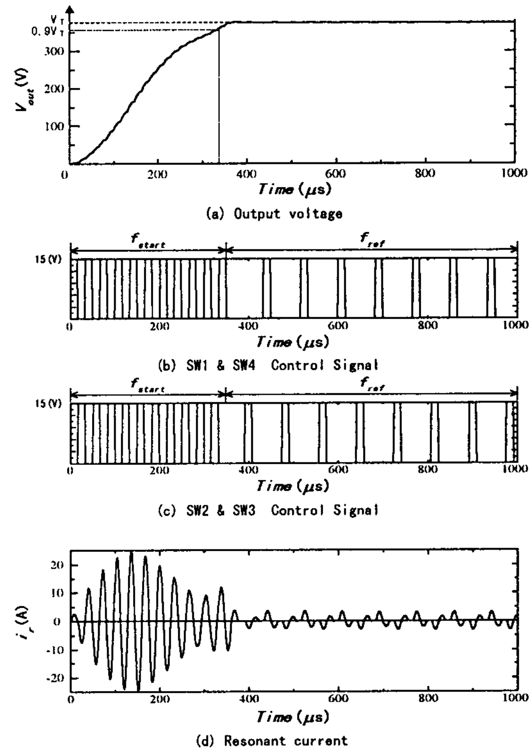


Fig. 6 Control principle of two-step frequency switching converter control system to obtain stable tube-voltage waveforms under conditions of widely-changed load variations.

Table 2 indicates the normalized and base values of parameters, these parameters can be determined by the feasible X-ray power generator.

Figure 5 illustrates the simulating open-loop response waveforms of a normalized X-ray tube voltage V*out in case of using quality factor in case of heavy (Q=1.0) and light (Q=0.1) loads. The higher switching frequency is, the shorter the rise-time is, but an overshoot is ease to happen, inversely. In case of lower switching frequency, though the overshoot do not happen, the rise-time becomes longer. Once the overshoot causes, the voltage charged in the equivalent capacitance of the high-voltage cables is going to discharge through only the load circuit.Thus, the output voltage of this converter is gradually attenuated after an overshoot behavior.

Therefore, it is important to develop a new power

V CONVERTER SYSTEM IMPLEMENTATION WITH TWO-STEP FREQUENCY SWITCHING CONTROL

The characteristics listed below are essentially necessary for the medical use the X ray power generator.

1) The transient responses are as fast as possible in spite of wide variation ranges of load resistance R_L.
2) The overshoot of output voltage must not absolutely generate.
3) The steady-state ripple factor of the converter output voltage is as small as possible in the steady-state for each desired value.

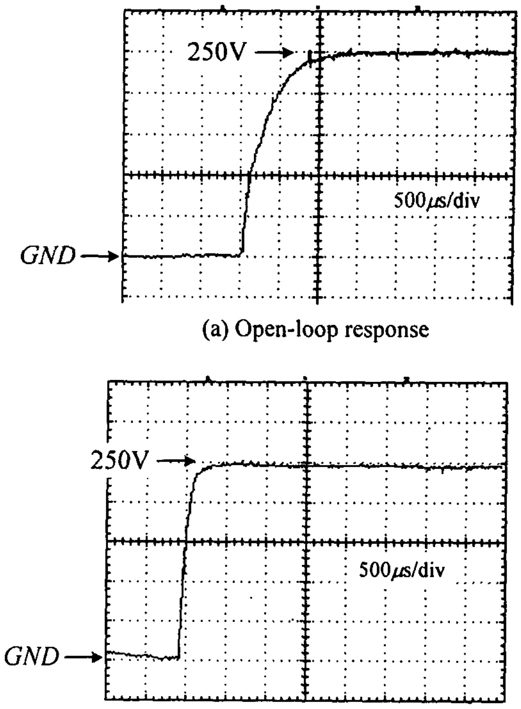
It is impossible to meet all the conditions 1)~3) mentioned above at the same time by using a conventional feedback linear control theory. Hence, the control scheme of two-step frequency switching will be introduced.

The rule of two-step changing frequency switching is that starting the converter under a high switching frequency fs which is slightly less than the resonant frequency fr in order to obtain a fast start-up, and by sensing the output voltage, the switching frequency will be switched to the frequency fref which corresponds to the target output voltage until the output DC voltage reaches about 90% of the target voltage V_T. The switching frequency of the 90% of the target voltage can effectively decrease overshooting in the target voltage. The transient and steady-state operation of the series-resonant converter is shown in Figure 6.

As seen in this figure, the inverter operates at the switching maximum frequency (fs=28kHz in this case) until the output voltage reaches about 90% of the target voltage V_T. At this point, the switching frequency is switched to the reference switching frequency fref that is proportional to the desired target voltage. Observing the waveforms, it is understood that the desired output responses with short rise time and no-overshoot can be achieved by the proposed control method on the basis of dual mode frequency changing.

VI. EXPERIMENTAL RESULTS

The system parameters and design specifications for laboratory set-up areas follows: V_{DC}=50V, Vout-max=350V, output current=1mA~800mA, resonant frequency fr =32kHz, resonant period Tr =31.25μs, constant on-time Ton =15μs, series resonant inductor Lr =142μH, series compensated resonant capacitor Cr=0.172μF, and two of Cockcroft-Walton (CW) full-wave multipliers. Figure 7 illustrates the operating waveform of output voltage applied to the x ray tube. In case of the open-loop response results long rise-time. According to the proposed control method, the output voltage can rapidly rise up.



(a) Open-loop response

(b) Closed-loop response

Fig. 7 Output voltage responses

VII. CONCLUSIONS

The transformer linked voltage source type series resonant high-voltage DC-DC power converter with a multistage diode-capacitor voltage multiplier and constant on-time PFM control scheme discussed in this paper has been proved to be applicable and suitable for an small scale x-ray power generator from a practical viewpoint. This power converter allowwd zero current soft switching to minimize switching power losses under a condition of high frequency switching. In addition, the multistage diode-capacitor multiplier war introduced to largely reduce the number of secondary turns, layers, and stray lumped capacitance of the high-frequency high-voltage transformer so as to improve the efficiency and reliability of the high-voltage DC-DC power converter. The control scheme of two-step (dual) frequency switching which is developed for this series resonant PFM inverter-fed DC-DC power converter used as an X-ray power generator has been introduced and discussed herein. It was pointed out that the desired output responses could be obtained over a wide range of the output voltage regardless lo of wide ad regulation range on the basis of the proposed dual mode PFMcontrol procedure.

REFERENCES

(1) K.M.Kazimizerczukand D.Czarkowski, "Resonant power converter", Jhon Wiley, 1995

(2) K.M.Kazimizerczuk, "Synthesis of phase-modulated resonant DC/AC inverters and DC-DC converters", IEE pp.387-394, July, 1992 Proc. Part B, Electric Power Appl., vol. 139,

(3) Y.Cheron, H.Foch, and J.Salesses, "Study of a resonant converter using power transistor in a 25-kW X-ray tube power supply", *Records. of IEEE PESC and ESA Proc,* Vol.2 pp.295-306, June 1985

(4) H.Hino, T.Hatakeyama and M.Nakaoka, "Resonant DC-DC converter using parasitic impedances of high-voltage transformer", *Proc. of International Conf. on PCIM-Europe,* Vol. 1, 15 ,June,1987

(5) H.Takano, H.Uemura,, M.Nakaoka; "Advanced constant-frequency PWM resonant DC-DC converter with real time digital control for X-ray power generator", *Proc. of European Power Electronics EPE Conference,* Vol.1, pp.544-560, Sept. 1991

(6) H.Takano, T.Hatakeyama, J.M.Sun, L.Gamage, and M.Nakaoka, "Feasible characteristic evaluations of resonant PWM inverter-linked DC-DC power converter

using high-voltage transformer parasitic circuit components", *Proc. of IEE Conf. on Power Electronics and Variable Speed Drives,* pp.525-533, Sept.1996

(7) S.D.Johnson, A.F.Witulski, R.W.Erickson, "Comparison of resonant topology in high-voltage DC application" IEEE Trans. on Aerospace and Electronic Systems, Vol.24, NO.3, May 1988

(8) B.S. Jacobson and R.A. DiPerna, "Fixed Frequency Resonant Converter for High Voltage High Density Applications", IEEE PESC 1993 Record, pp.357-36

(9) S.N.Manis and G.Kostakis "Modular DC-DC Converter for High-output Voltage Applications", IEE Proceedings-B, Vol.140, No.2,pp.97, March 1993

(10) A.J.Forsyth and Y.K.E.Ho; "Dynamic Characteristics and Closed-Loop Performance of the Series-parallel Resonant Converter", Iee Proc.-Electr. Appl., Vol143, pp345-353, No. 5, September 1996

(11) J.Borka, M.Horvath and K.Lupa: "Problems of X-Ray Generator For Industrial Purpose", Proc. of Power Electronics & Motion Control Conference (PEMC), pp.8-110-115, Sept. 1998.

(12) L.Hongwoo, H.Euamyong, B.Hyunglae and L.Seongkil; "The Characteristics of Output for Inverter Type X-Ray Generator", Proc. of International Conference on Power Electronics (ICPE),pp.431-435, Oct. 1998.

(13) D.M.Divan: "Design consideration for very high frequency resonant mode DC/DC converters", in IEEE IAS Conf. Rec., pp.640-647,1986

(14) J.S.Brugler; "Theoretical performances of voltage multiplier circuits", IEEE Journal of Solid-State Circuits, pp.132-135, June 1971

(15) V.Gacfa, M.Rico, J.Sebastian, M.M.Hernando and J.Uceda; "An optimized DC-DC converter topology for high-voltage pulsed-load applications", IEEE-PESC Conf. Rec., pp.1413-1421, 1994

(16) E.Everhart and P.Lorrain" The cockcroft-walton voltage multiplying circuit", The Review of Scientific Intruments, Volum 24, Number 3, pp221-226, March 1953

(17) J.D.Cockcroft and E.T.S.Walton;" Experiments with high-voltage high-velosity positive ions-(I) futher developments in the method of obtaining high-velosity positive ions", Proc. Roy. Soc., A, 136, pp.618, 1932

(18) T:F Wu and J.C. Hung, " A PDM Controlled Series Level Converter Applied for X ray Generators" , *Proc. of IEEE PESC*, Vol. 2, pp. 1177-1182, June, 1999

(19) Ralph E.Tarter,P.E: "Solid-State Power Conversion Handbook", John Wiley & Sons, INC, (1993)

(20) Muhammad H. Rashid: "Power Electrinics", Prentice-hall International, Inc.(1993)

(21) Ned Mohan, Tore M. Undeland, William P. Robbins: "Power Electronics converters, Applications, and Design Second Edition", John Wiley & Sons, INC,(1995).