TRANSFORMER RESONANT PHASE-SHIFTED PWM DC-DC CONVERTER WITH REPETITIVE LEARNING CONTROL SCHEME

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This paper presents a digital repetitive learning control scheme to realize quick response of output voltage for medical-use X-ray power generator using a converter fed by a phase-shifted PWM IGBT inverter which makes the most of high-frequency high-voltage transformer parasitic resonance. The effectiveness of digital control scheme is confirmed by several simulation analysis and experimental results.

Key Words: *PWM Dc-Dc Converter, High—Frequency High-Voltage Transformer, Parasitic Resonant Components, Repetitive Learning Control, Medical-Use X Ray generator*

1. INTRODUCTION

In recent years, a variety of phase-shifted PWM resonant mode DC-DC power converter configurations using high-frequency inverter have been studied and introduced for diverse specific applications. The authors have discussed some digital control procedures suitable for the high-performances of the X-ray power generator for medical-use. However, the high-voltage X-ray power generator using inverter for medical-use, in which tube voltage is actually set in wide ranges between 20kV to 150kV and its tube current ranges from 0.5mA to 1250mA, has to be rapidly and precisely controlled over extremely wide load range. Therefore, the adequate control system parameters must be adjusted for every load condition. As a result, parameter-adjustment even in digital control implementation depends on skilled-operator's experience. Thus, repetitive learning control approach often used in robot manipulator is to be effectively introduced to obtain a desired output.

The paper introduces the repetitive learning control procedure to this transformer resonant DC-DC converter with phase-shifted PWM strategy, which is used for X-ray power generator to improve the tube voltage response waveforms in dynamic and steady-state operation of this converter. In addition, a practical learning control method of the PWM Dc-Dc converter developed by X-ray power supply is discussed on the basis of the computer simulation. Furthermore, the proposed learning rule is also evaluated for this system, and simulation results obtained here are confirmed in experiments.

2.TRANSFORMER RESONANT CONVERTER

Fig.1 illustrates a newly-developed power conversion system of inverter-fed type X-ray power generator. The X-ray high-voltage power generator with high-frequency inverter using IGBTs consists of a single-phase or three-phase thyristor bridge rectifier, a fixed frequency phase-shifted PWM inverter using transformer parasitic resonant components, a high-voltage diode rectifier connected to high-voltage cables, and an X-ray tube as a load. The remarkable feature of this X-ray generator is to make the most of the parasitic lumped leakage-inductance (Lr) and secondary-side capacitance(Cp) existing in the high-voltage transformer to realize a desired circuit resonance, and use the input-side equivalent capacitance of the high-voltage cables for filtering output DC high-voltage. In order to ensure a stable and efficient converter circuit operation under

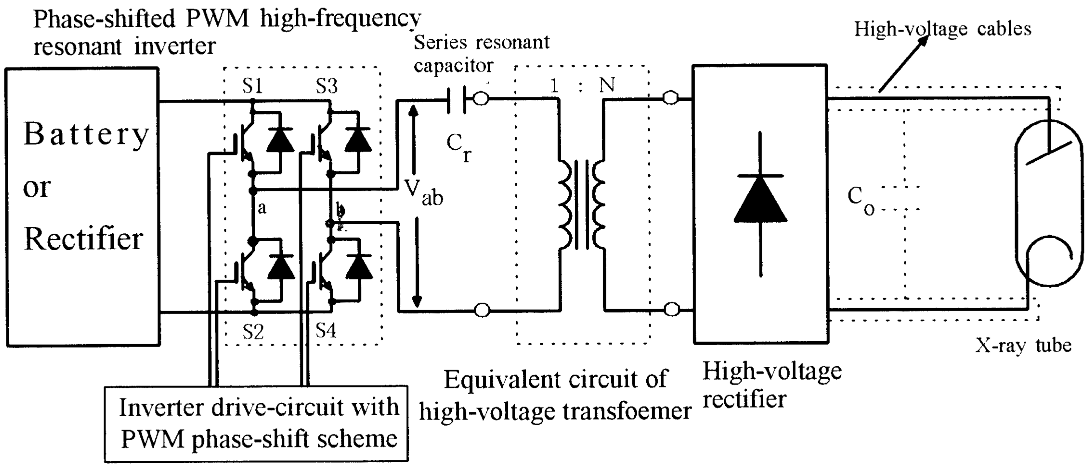
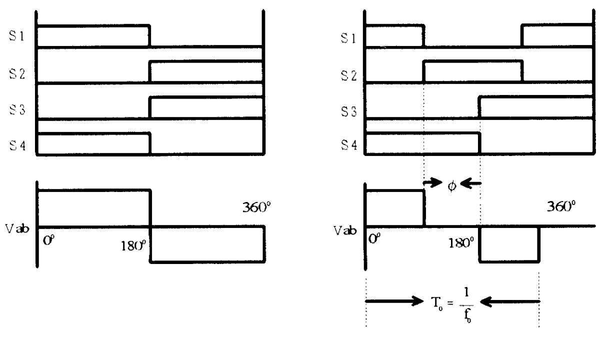


Fig. 1 Schematic diagram of inverter-fed type x-ray generator



(a) $\phi = 0^0$ (b) $\phi = 90^0$

Fig.2 Phase-shifted PWM control principle

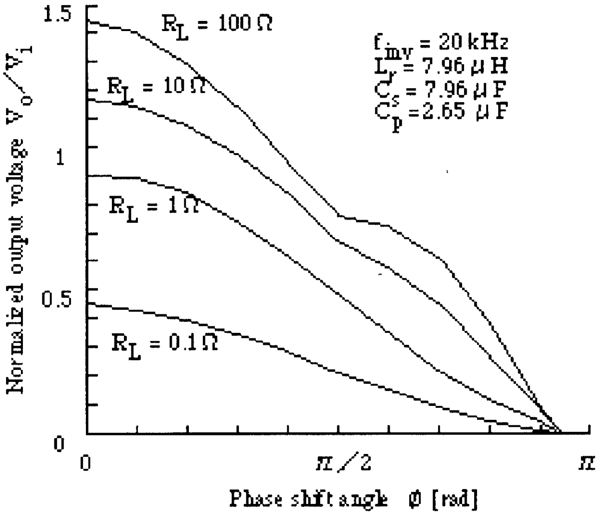


Fig.3 Output voltage regulation characteristics

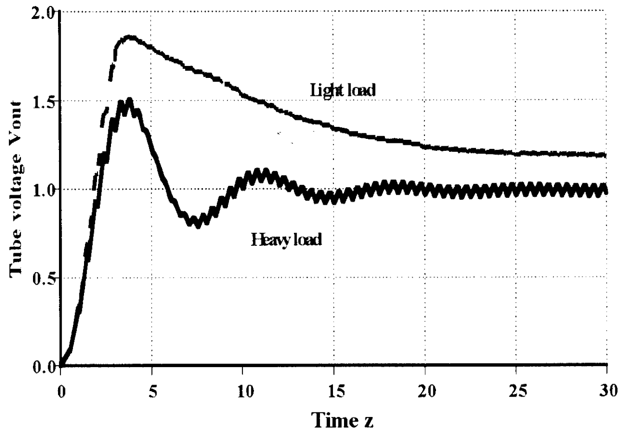


Fig.4 Transient responses of x-ray tube voltage

wide load conditions. The resonant capacitor Cs is connected to the primary side of high-voltage high-frequency transformer so as to resonate its leakage inductance.

The X-ray tube load is a kind of two-electrodes vacuum tube. In practice, it is noted that the X-ray tube has nonlinear characteristics owing to space charge limit current and thermal limit current.

3.OUTPUT-VOLTAGE REGULATION

There are two acceptable control schemes for the output voltage of this type of resonant DC-DC converter with a high-frequency link, which operates in the PFM or PWM schemes. In the case of PFM scheme, because inverter frequency is reduced at the low tube voltage, filter smoothing effect is not sufficient. So, tube-voltage ripple becomes extremely large. Therefore, phase-shifted PWM converter is more acceptable. Fig.2 illustrates the switching pulse sequence of phase-shifted PWM inverter using transformer parasitic resonance. The inverter frequency is set as a constant value f_0, on-off operation of every switch at right & left arms in the bridge configuration is at about 50% duty-ratio with a slight dead-time and by adjusting phase-shift ϕ, the output-voltage regulation is continuously performed. Fig.3 illustrates the output-voltage regulation characteristics under a principle of phase-shifted PWM strategy.

4. TRANSIENT RESPONSES

Fig.4 illustrates transient response waveforms of tube-voltage Vout to normalized load resistances ($\lambda = R_L / Z_s, where Z_s = 2\sqrt{L_r / C_r}$) $\lambda = 0.5$ (heavy load) & $\lambda = 5.0$(light load), respectively, under the condition of phase-shift angle $\phi = 0^0$. The tube-voltage V_{out} response waveform is similar to 2-second system in case of a heavy load. On the other hand, diode-bridge rectifier in inverter output stage is disconnected from load circuit owing to discontinuous operation. The response waveform is generally attenuated and is going to be stable after overshoot in an open loop scheme as indicated in Fig.4. Consequently, it is important to configurate control system in order to obtain a stable tube-voltage waveform in spite of load variations.

In X-ray control power system, the overshoot of X-ray tube voltage has to be suppressed, In addition, rapid response has to be improved and output voltage ripple across the X-ray tube in the steady-state has to be reduced.

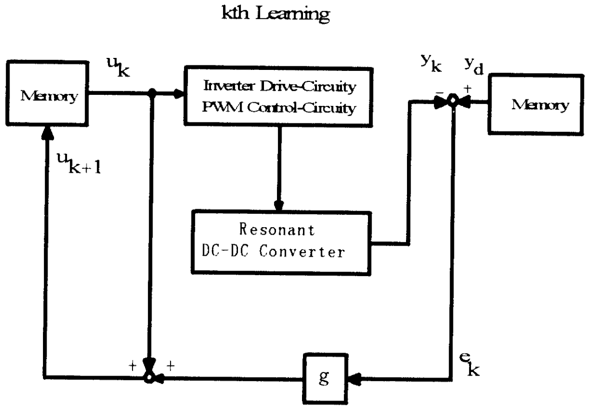


Fig.5 Algorithm of type P learning control scheme

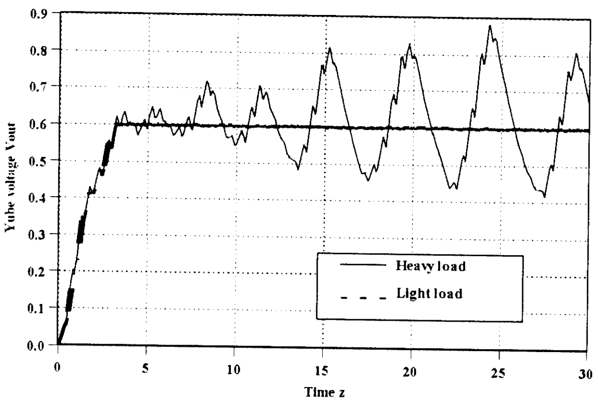
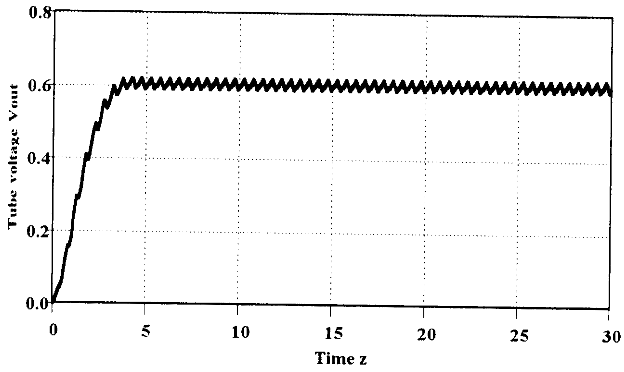
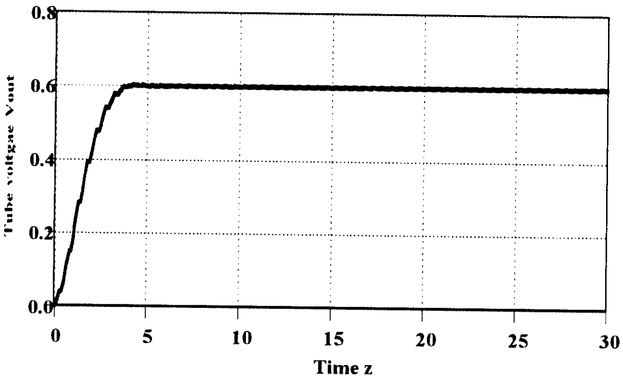


Fig.6 Simulating results of tube voltage in case of using $e_k(i+1)$



(a) λ=0.5 (Heavy load)



(b) λ=5.0 (Light load)

Fig.7 Simulating results of tube voltage in case of using Eqs.(8) and (9)

5. REPETITIVE LEARNING CONTROL

The repetitive learning control scheme often used widely in robot manipulator is effectively introduced in order to improve response characteristics and to reduce overshoot in X-ray power generator using resonant PWM inverter system with a high-frequency high-voltage transformer link. Furthermore, feedback control is used to stabilize abrupt drooping of DC filter output voltage of the rectifier connected to commercial utility-grid AC system and to reduce output voltage ripple on the steady-state.

(1). Repetitive Learning Control Scheme

Recently, advanced learning control system with fuzzy logic or neural networks has attracted special interest. The validity of learning control used well in robot manipulator control procedure has been studied. As compared with other control methods, it is simple and quick, so it can be practically performed with DSP implementation. Therefore, this control method can be used in resonant PWM DC-DC converter with high-voltage high-frequency transformer link.

The assumptions in theoretical considerations are pointed out as follows:

a)Every trial is short.

b)The desired output tube-voltage $y_d(t)$ is feedforward during every trial.

c)The initial value of input target value $u_k(t)$ for every trial is always the same.

d)Because tube voltage $y(t)$ can be pre-calculated, the calculation of arbitrary k-$_{th}$ error can be realized.

e)Next input $u_{k+1}(t)$ is formed as

$u_{k+1}(t) = F(u_k(t), e_k(t))$ as simply as possible.

Under the above conditions, phase-shifted PWM control will be carried out on the basis of learning control algorithm

(2) Performance Evaluations

As can be known, this resonant DC-DC converter is expressed as discrete-time system, so it is appropriate to introduce the digital control scheme into the resonant DC-DC converter for considering aspects of flexibility and reappearance.

(a)Output Reference Learning of Resonant DC-DC Converter

From phase-shift angle ϕ, input u can be calculated as

$$u = \frac{180 - \phi}{180} \tag{5}$$

P-pattern learning control is introduced here, so (k+1)-$_{th}$ input u_{k+1}(t) can be expressed as

$$u_{k+1}(i) = u_k(i) + g \cdot e_k(i+1) \tag{6}$$

This algorithm is schematically shown in Fig5

As shown in Fig.5, the input and desired output are memorized in every sampling interval. Here, gain "g" is normalized, and error $e_k(i+1)$ is the difference of $y_d(i+1)$ and $y_k(i+1)$, $e_k(i+1) = y_d(i+1) - g \cdot e_k(i+1)$。

Simulating results are shown in Fig.6, where, normalized load impendances λ are 0.5 and 5.0 in the case of both heavy and light loads, respectively.

Desired tube voltage waveform is broken-line decided by eq.(7):

$$y_d = \begin{cases} \dfrac{0.6 \cdot Z}{4} & (Z < 4) \\ 0.6 & (Z \geq 4) \end{cases} \tag{7}$$

where, Z: rising time

Tube voltage waveforms are convergent and divergent at light and heavy loads, respectively as shown in Fig.6.

In order to acquire desired voltage waveform, the desired tube voltage function has to be decided. Now, using error $e_k(i+2)$ to calculate input $u_{k+1}(i)$ as

$$u_{k+1}(i) = u_k(i) + g \cdot e_k(i+2) \tag{8}$$

where, g is taken as 0.7 in this case.

At the same time, desired tube voltage waveform is decided by eq.9

$$y_d = \begin{cases} y_{set} \sin\left(\dfrac{\pi}{2} \cdot \dfrac{Z}{4}\right) & (Z < 4) \\ y_{set} & (Z \geq 4) \end{cases} \tag{9}$$

Simulating results based on eq.8 and 9 are illustrated in Figs.7 and 8. Obviously, the tube voltage waveform is convergent even at heavy load.

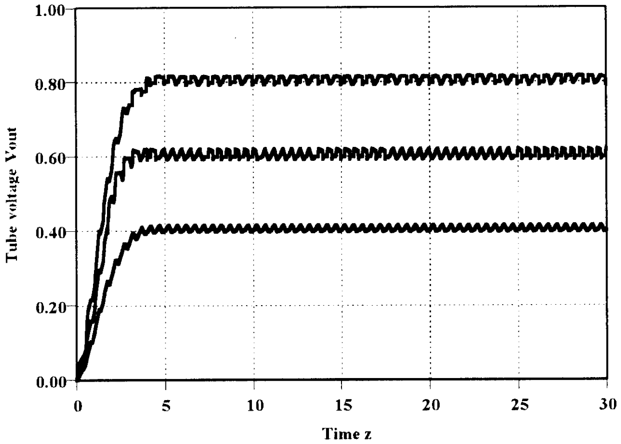


Fig.8 Simulating results of tube voltage for different desired output voltages in case of using Eqs.(8) and (9)

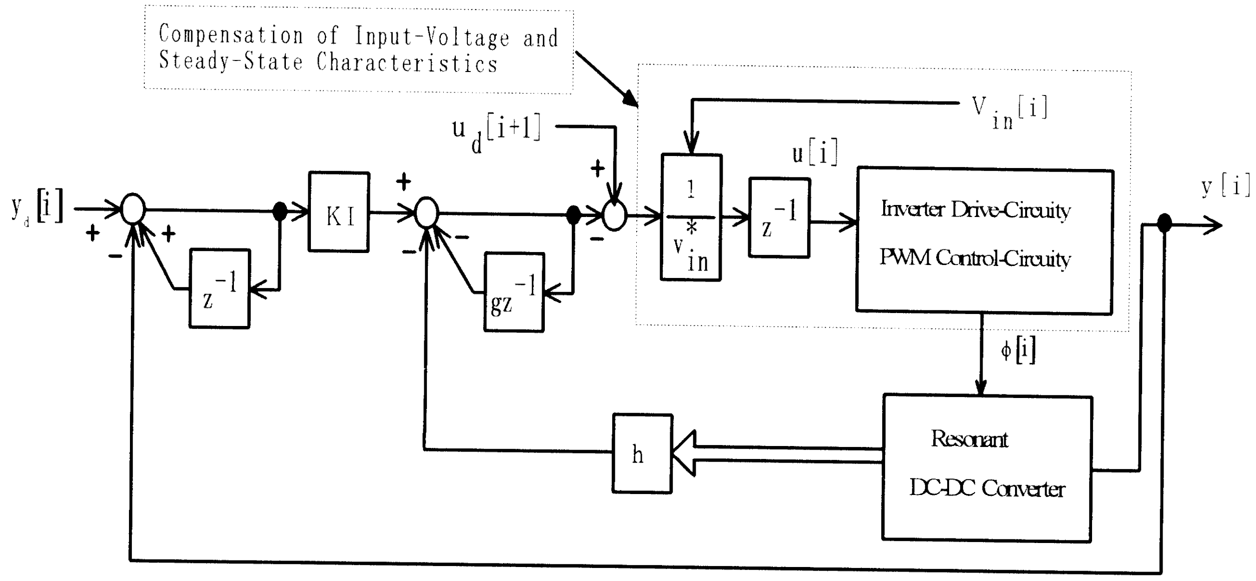
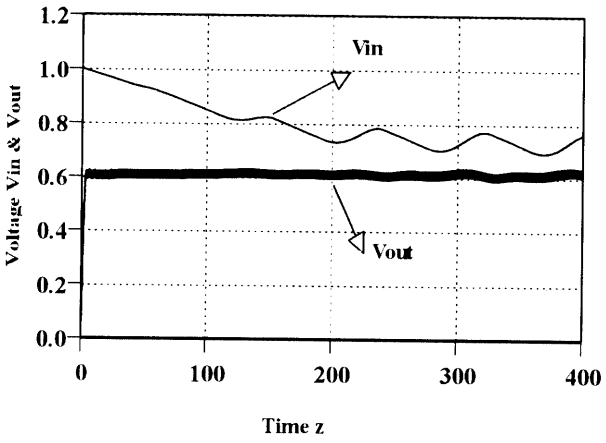
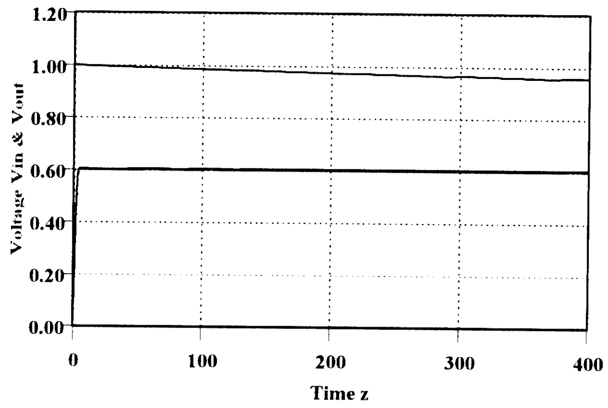


Fig.9 Typel digital servo control system with compensation loops

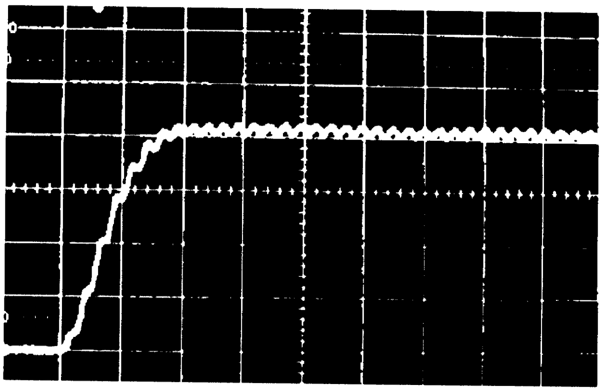


(a) λ =0.5 (Heavy load)



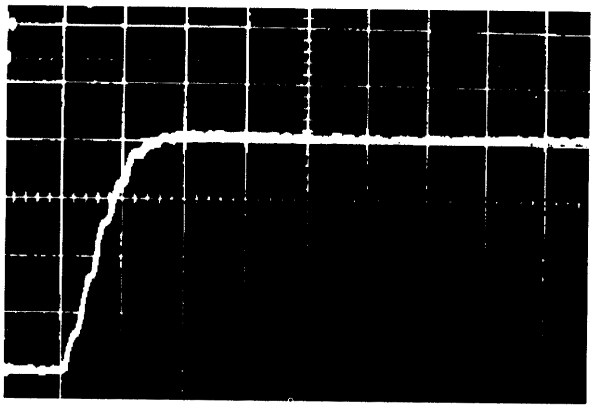
(b) λ =5.0 (Light load)

Fig.10 Simulating results in case of commercial utility-for heavy and light loads



(5V/div, 0.2msec/div)

(a) Rx=4.2 Ω (λ =0.5: Heavy-Load)



(5V/div, 0.2msec/div)

(b) Rx=45 Ω (λ =5.0: Light-Load)

Fig.11 Experimental results for heavy and light loads

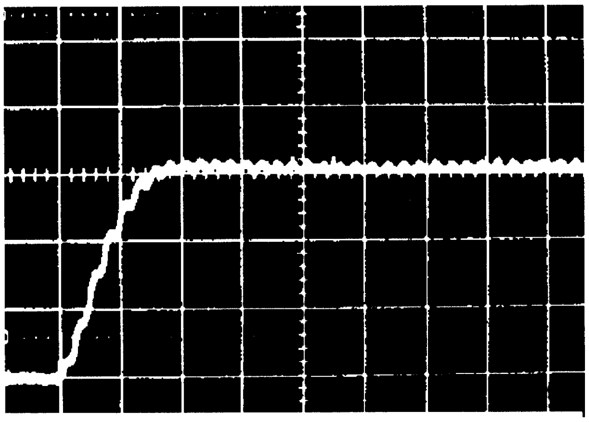

(5V/div, 0.2msec/div)

Fig.12 (a) Rx=4.2 Ω (λ =0.5: Heavy-Load), Desired Tube-voltage:15V

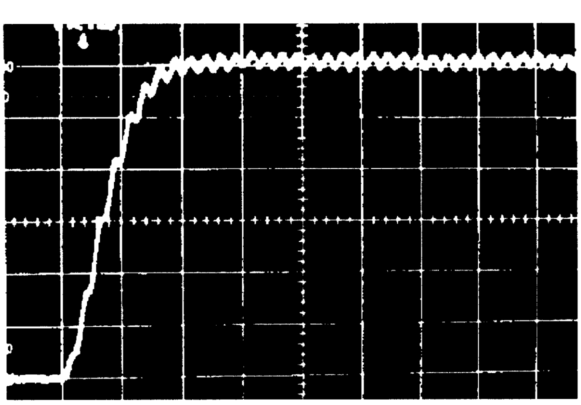

(5V/div, 0.2msec/div)

Fig.12(b) Rx=4.5 Ω (λ =0.5: Heavy-Load), Desired Tube-voltage:30V

Fig.12 Experimental results for different desired output tube voltages

As explained above, it is possible to introduce P-pattern learning control into the resonant DC-DC converter. In repetitive learning control, the desired tube voltage waveform and system gain have to be decided. It is important to present how to decide the equations of desired tube voltage waveform and the value of gain "g", however, no further detail on them will be provided here on this section due to space limitation and the rest of this section will be devoted to the feedback control and computer simulation.

(b). Feedback Control

Explanation has been done under the condition that batteries are used as DC voltage source in place of rectifier, but in practical, the converter system is connected to the rectified voltage produced by commercial utility-grid AC system. At this case, voltage drop at the start of converter as well as steady-state voltage ripple due to the periodic input voltage fluctuation in commercial utility-grid AC system influence upon the tube voltage. Therefore, 1 type digital servo control system with compensation loops is introduced as shown in Fig.9.

In this feedback control system consisting of $u_d(i+1)$ obtained from repetitive learning control, steady-state compensation of the resonant DC-DC converter and the fluctuation compensation of input voltage are controlled to make the same practical tube voltage waveform with a desired tube voltage waveform. Fluctuation compensation of input voltage is processed by using a new input $u(i)$, which is derived by detecting inverter input voltage $V_{in}(i)$ and calculating fluctuation difference to perform the compensation. Making the use of the characteristics that the steady-state tube voltage is almost cosine function of phase-shift ϕ , introducing $\cos^{-1}$ function into a control system to get the non-linear characteristics of the phase-shift ϕ vs. the tube voltage become linear characteristics so as to realize steady-state compensation of resonant DC-DC converter.

The feedback control system is evaluated according to the computer simulation results. Fig.10 shows the simulating results at $y_{set}(0.6), \lambda(0.5, 5.0)$, respectively. It is obvious that the desired tube voltage is not influenced upon by the fluctuation of input voltage, Therefore, stable tube voltage waveform can be obtained at extremely wide load ranges.

6. SIMULATION AND EXPERIMENTAL RESULTS

The experimental results of this converter system are shown in Figs.11 and 12.

A rising time of desired tube voltage is 400 μ s. In this case, repetitive learning times is 30 times. Fig.11 shows the results under heavy and light load conditions at the same tube voltage.

Fig.12 shows the results when desired tube voltage is changed at the same load condition.

Observing the Figs.11 and 12, it is understood that the simulated results are compared with the experimented results, and better tube voltage waveform can be obtained in spite of different load conditions and setting-values of input voltage.

CONCLUSIONS: This paper has discussed the application of repetitive learning control scheme for this transformer resonant DC-DC converter used as x-ray power generator by both of computer simulation analysis and experiments. It was shown that stablized tube-voltage waveforms could be obtained by this feedback control implementation treated here. As this adjusting method of optimum control parameters, repetitive learning control scheme which is able to automatically get given-ideal operating-form according to repetitive learning procedure was more suitable for acquiring desirable stable tube-voltage output of X-ray power generator by using feedback control under conditions of wide load ranges.

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高周波高電圧トランスの漏れﾊﾟﾗﾒｰﾀを用いた繰り返し学習制御方式トランス共振位相シフトPWM　DC-DCコンバータ

孫　俊明　ラクナース.ガマゲ　中岡　睦雄

インバータを用いた高出力Ｘ線高電圧電源装置は、出力電流が大きい時、即ち、負荷としてのＸ線管のインピーダンスが小さい重負荷のときにも十分な出力が得られる直列共振回路トポロージを取り入れたトランス共振タンク高周波インバータ型ＤＣ－ＤＣコンバータが採用されている。また、高電圧トランスの一次側に換算した二次巻線の寄生浮遊容量は巻数比の二乗倍の値になり、巻数比が非常に大きい高電圧トランス浮遊容量がその漏れインダクタンスとの組み合わせで並列共振回路を形成し、回路動作や特性に強い影響を与える。このため、高出力のトランス共振高周波インバータ式Ｘ線高電圧装置は、直列共振形コンバータとしての動作特性と、並列共振形コンバータとしての動作特性を兼ね備え、負荷抵抗によっては過渡応答特性と定常特性が回路特有の非線型性をもっている。そこで、学習制御法をX-線発生用電源としてのトランス共振インバータ方式ＤＣ－ＤＣコンバータへ適用し、幅広い負荷に対して管電圧波形の動特性と静特性の改善を自動的に行う新方式を提示している。本論文では、医療Ｘ線発生トランス共振インバータ方式ＤＣ－ＤＣコンバータシステムとしてその学習制御の適用時の性能評価と検討を加え、提案した学習則が本方式に有効となることを試作実験により検証している。