Piezoelectric-Transformer Inverter with Maximum-Efficiency Tracking and Dimming Control

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Abstract

This paper provides a solution for the problem of efficiency decrease caused by load variation and environmental temperature change. A novel control scheme of tracking the PT's operation frequency for the maximum efficiency is proposed. As a result, a high efficiency over 80% has been achieved even under the output current decrease down to 10% of the maximum, and under the resonant-frequency variation by environmental temperature change of -10 to +70 centigrade.

I. INTRODUCTION

In recent years, piezoelectric transformers(PTs) have been widely used as electronic ballasts for cold cathode fluorescent lamps(CCFLs) in liquid crystal displays for portable electronic equipments. The application of PT yielded the development of low-profile and energy-saving electronic equipments. Concerning the dimming control of a CCFL, the conventional method is to vary the operating frequency of PT to control the output current of the electronic ballast[1]. However, the power efficiency of PT depends on the operating frequency, and so the large frequency deviation from its resonant frequency causes the efficiency deterioration. In the previous paper[2], the electronic ballast with dimming control at a fixed-frequency operation has been reported, and the high power efficiency has been confirmed even for a deep dimming level. However, the resonant-frequency variation of PT is caused by load variation and environmental temperature change, and then the power efficiency can be more improved.

This paper provides a solution for the above-mentioned problem, and presents the more improvement of efficiency by a novel control scheme. Namely, for tracking of the maximum efficiency, a method of controlling the PT's operation frequency is proposed. As a result, in the experiment, a high efficiency over 80% has been achieved for the output current decreased down to 10% of the full load, and under the resonant-frequency variation by environmental temperature change of –10 to +70 centigrade.

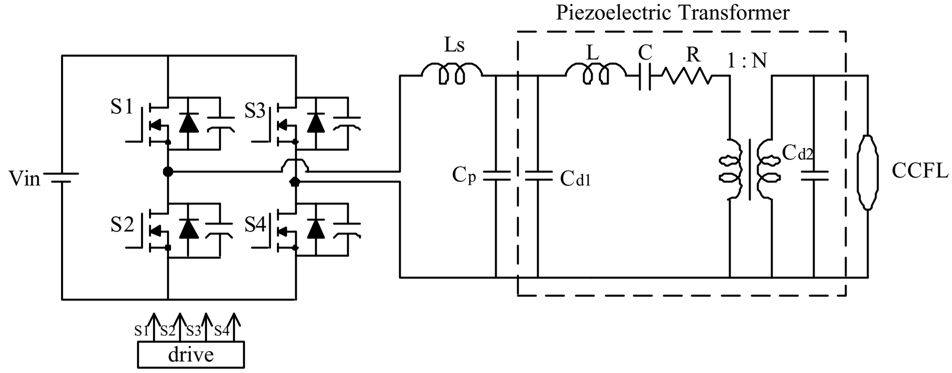


Fig.1. Piezoelectric-Transformer Inverter using Full-Bridge Circuit.

II. CIRCUIT AND CONTROL OPERATION

Figures 1 and 2 show an inverter circuit configuration, and its waveforms to describe the mechanism of the phase-shift control in a full-bridge inverter. As seen from the time chart of gate signals for four switches, the input voltage Vr of the parallel-resonant circuit equals +Vin while both the switches S1 and S4 are kept ON. The voltage Vr becomes zero while both the switches S2 and S4 are ON. Therefore, the duration of voltage occurrence for Vr decreases oppositely when the phase difference f between S1 and S4 increases. During the negative half-cycle, the duration when the voltage Vr keeps -Vin decreases with the increase in the phase difference f between S2 and S3. Consequently, the pulse width of the voltage Vr varies with the phase difference of these switches. As a result, the input voltage of PT can be varied, and then the lamp current can be controlled at a fixed switching frequency.

This full-bridge inverter has a prominent feature of achieving the ZVS operation easily. The condition for ZVS is discussed. Figure 3 shows the detailed waveforms of gate signals for switches, where the dead time Td is inserted between S1 and S2, and between S3 and S4. The current flow just after S1 is turned off is shown by dotted lines in Fig.4, where the capacitance Cds across S1 is charged and the capacitance Cds across S2 is discharged. Here, since the dead time is short enough, the inductor Ls is assumed to be a constant current source, and then the equivalent circuit during the dead time is derived as shown in Fig.5. When the voltage Vds across S2 reached zero during the dead time Td, the ZVS of S2 is achieved.

Therefore, from the circuit analysis of Fig. 5, the ZVS condition is derived as follows:

$$I_{Ls} > \frac{2C_{ds}V_{in}}{T_d}$$

From the above relationship, the ZVS region is calculated for several values of inductance Ls, and is shown in Fig.6, where the load resistance denotes the actual load of PT.

The ZVS operations of other switches are achieved under the same condition.

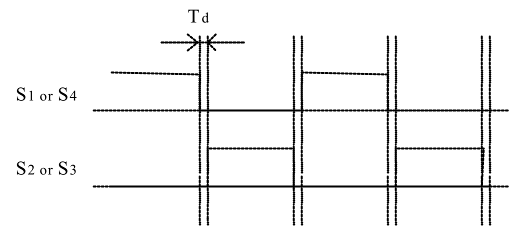


Fig.3. Waveforms of gate signals with dead time Td.

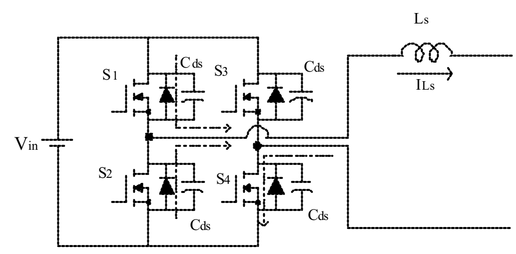


Fig.4. Current flow just after S1 is turned off.

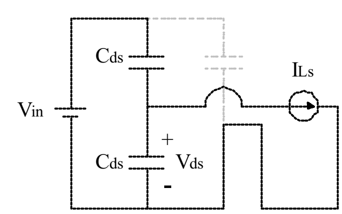


Fig.5. Equivalent circuit during dead time.

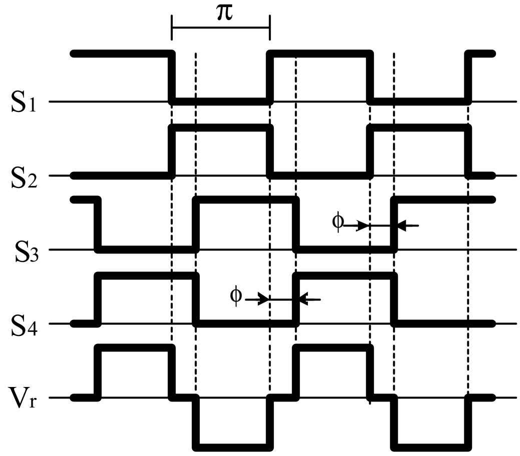


Fig.2. Time chart of gate-driving signals for phase-shift control.

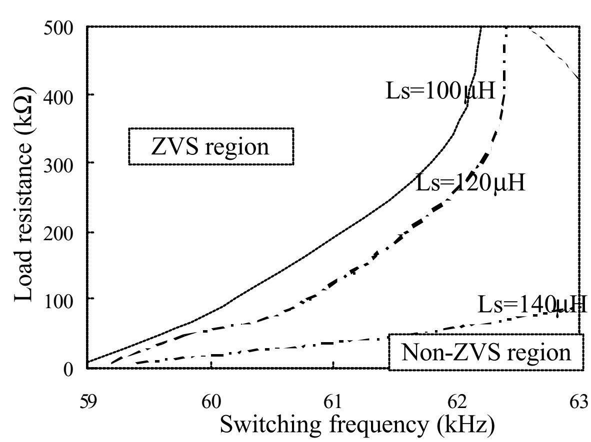


Fig.6. ZVS region.

III. PT RESONANT CHARACTERISTICS

A PT has the resonance peak in the frequency response of voltage boost ratio and efficiency. The frequency variation from the resonant frequency for dimming causes the efficiency deterioration. The operation near the resonant frequency is required to obtain the high efficiency. Therefore, as mentioned above, the scheme of controlling the phase difference of the full-bridge inverter at a fixed switching frequency is effective in order to improve the efficiency for dimming.

However, the PT's resonant characteristics depend on the load impedance and the temperature change[3]. When the lamp is dimmed, the equivalent impedance of CCFL becomes larger than at the full-load condition, and therefore the PT's resonant frequency increases. As seen from Fig.7 where the simulated frequency characteristics of the PT inverter efficiency are shown for three values of load impedance, the switching frequency where the maximum efficiency is obtained shifts to the higher side as shown by black circles on the curves. Furthermore, the phase difference between input and output voltages of the PT is also shown in Fig 7. As seen from this result, the switching frequency where the phase difference is about 110 degrees also moves to the higher side. Therefore, by varying the switching frequency so as to keep the phase difference constant, the tracking control for a higher efficiency can be obtained, though it does not completely coincide with the maximum efficiency.

Figure 8 shows the experimental frequency responses of voltage ratio, efficiency, and PT's phase difference, and compares them with the simulated results. It is evident from these results that the higher-efficiency tracking can be obtained by keeping the PT's phase difference to be 110 degrees.

IV. TRACKING CONTROL SCHEME

Based on the above discussion, a block diagram of the quasi-maximum-efficiency tracking controller is proposed as shown in Fig.9. The input and output voltages of PT are detected, and their phase difference is converted to a voltage signal. The minor feedback loop of frequency control by VCO maintains the PT's phase difference of 110 degrees. Hence, the switching frequency is shifted at the frequency near the resonance peak. The dimming control is achieved by the phase-shift control of the full-bridge inverter. Consequently, the quasi-maximum efficiency can be obtained at any conditions.

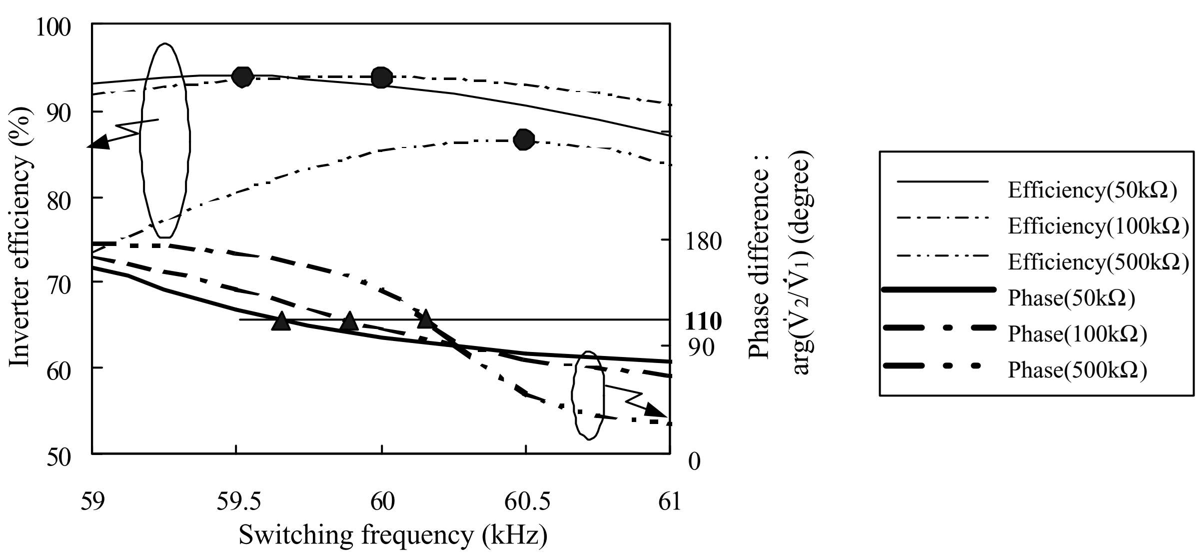
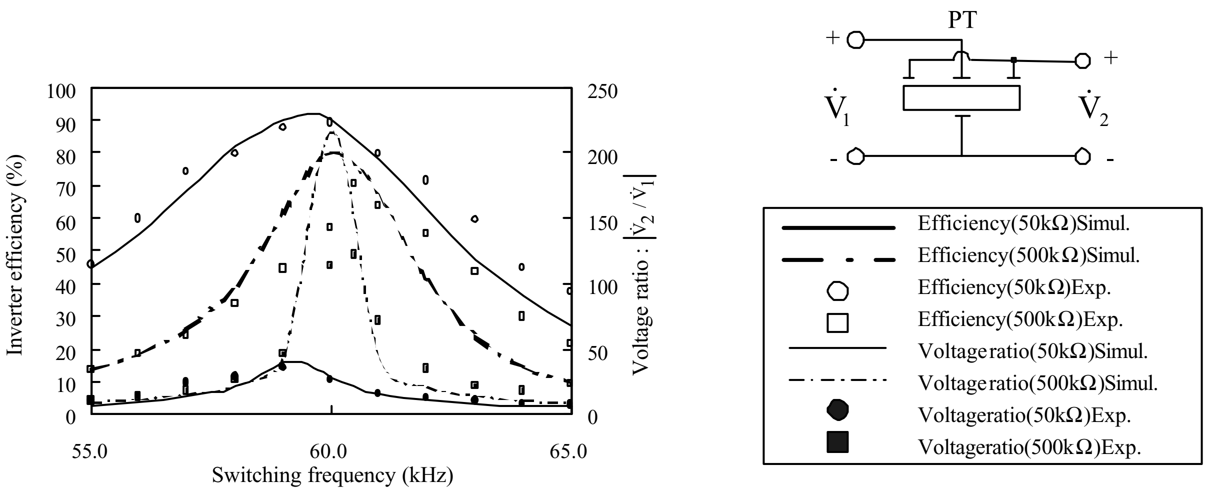
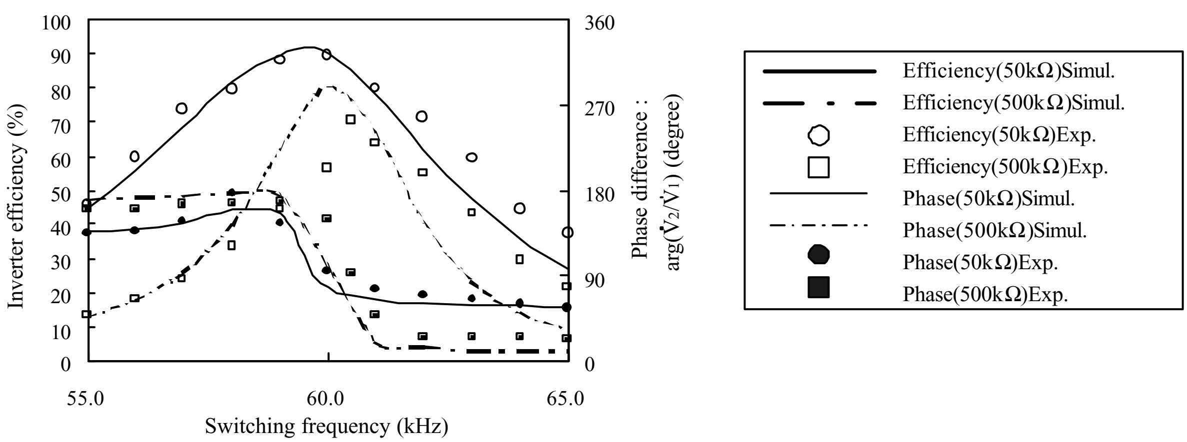


Fig.7. Frequency response of phase difference and inverter efficiency by simulation



(a)Frequency response of voltage boost ratio and inverter efficiency



(b)Frequency response of phase difference and inverter efficiency

Fig.8. Resonant characteristics of PT inverter

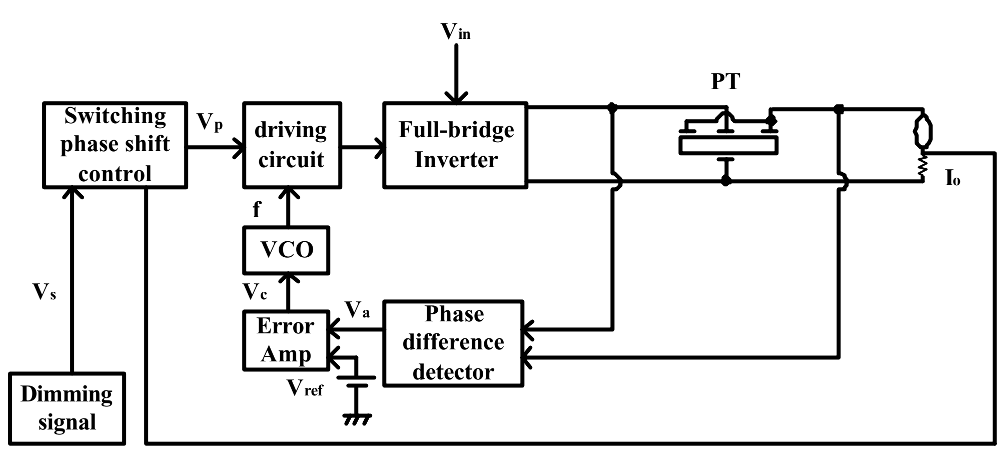


Fig.9. Block diagram of controller for dimming and maximum-efficiency tracking

V. EXPERIMENTAL RESULTS

In the experiment, a CCFL (3W rated) made in Matsushita, Inc., Japan, a PT (3W rated) made in Hitachi Metals, Inc., Japan, were used. In this case, a full-load lighting state was achieved at the output current of 10mA, and the power efficiency of the PT inverter was 88%. Figure 10 shows the efficiency characteristics for output-current variation, i.e. dimming control. It is evident from this result that a higher efficiency than 80% was maintained over a wide range of 10% to 100% of the maximum rating, and that the efficiency improvement of 8% was obtained at the dimming condition of 10% by this novel control scheme when compared with the fixed-frequency operation reported previously.

Moreover, the resonant frequency is changed also by environmental temperature change of a PT. Figure 11 shows the experimental frequency characteristics of the PT inverter efficiency for three values of environmental temperature. As seen from this result, the switching frequency corresponding to the maximum efficiency changes as shown by black circles on the curves. Furthermore, the phase difference between input and output voltages of the PT is also shown in Fig. 11, and then the switching frequency where the phase difference is about 110 degrees also moves in the same manner.

Therefore, by varying the switching frequency so as to keep the phase difference constant at 110 degrees, the tracking control for a higher efficiency can be obtained, though it does not completely coincide with the maximum efficiency.

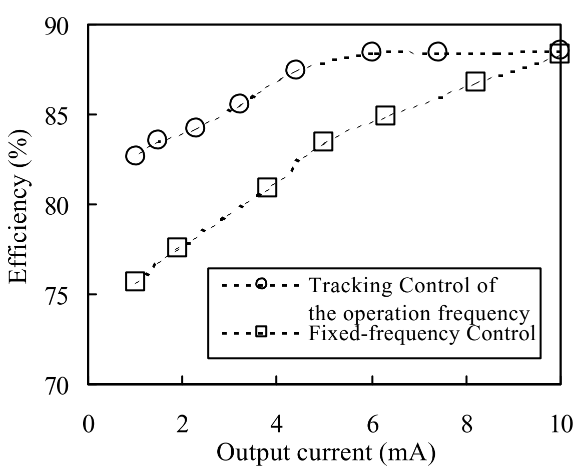


Fig.10. Efficiency for dimming control operation

Figure 12 shows the experimental result of power-efficiency variation for temperature change. The above-mentioned tracking system also has the ability of obtaining the quasi-maximum efficiency for environmental temperature change. For the environmental temperature change of –10 to +70 centigrade, the proposed control system maintained the high efficiency by the tracking control of switching frequency, and its power efficiency was 3% higher than by the previous method of fixed-frequency operation.

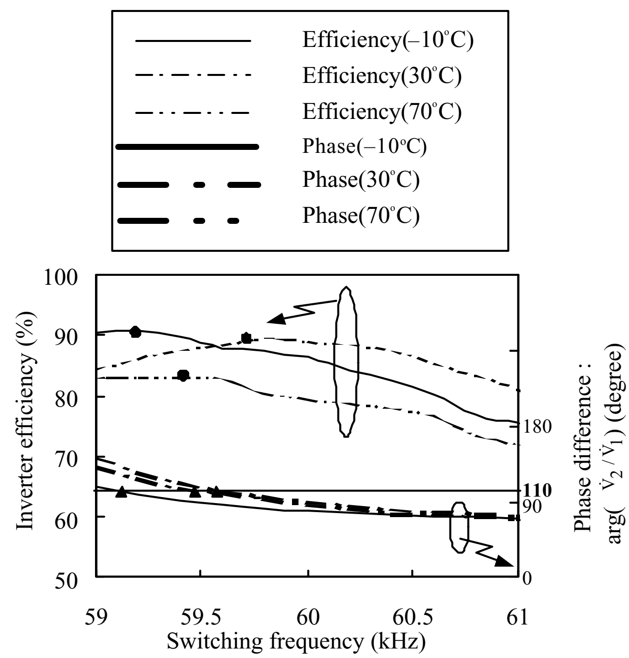


Fig. 11. Frequency-response variation of PT inverter for environmental temperature changes

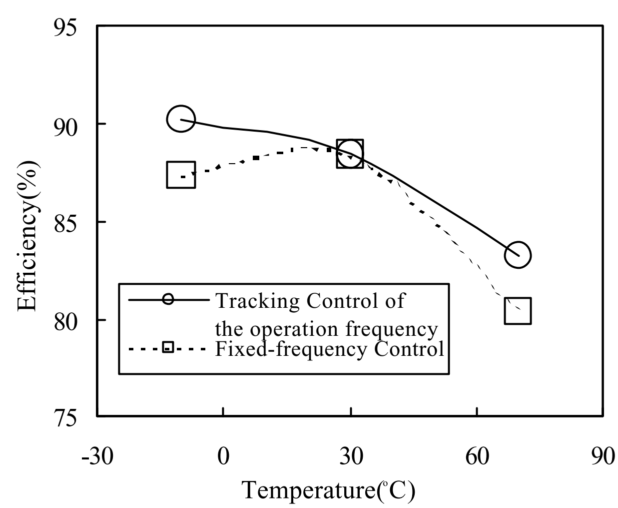


Fig.12. Thermal effects on Efficiency

VI. CONCLUSION

A tracking control system has been proposed for achieving the maximum efficiency of the PT inverter, and the experimental confirmation has been shown. This control system varies the inverter's switching frequency with the variation of PT's resonant frequency for the load and the temperature changes.

As a result, in case of an inverter composed of a 3W-rated PT and a load of a 3W-rated CCFL, a high efficiency over 80% was achieved over a wide range of the load variation of 10% to full load and the temperature change of –10 to +70 centigrade. This proposed inverter has a higher efficiency than the fixed-frequency inverter reported before.

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