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A Protection Circuit for the Power Supply of a Gas Discharge Lamp

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Abstract

In order to drive gas discharge lamps, DC-AC converters with a LCC resonant tank, whose output voltage is adjusted by a variable frequency control are frequently used. However, when they are activated by varying the operating frequency, converters are frequently damaged by unstable operation, due to the rising and falling of the operating frequency near the resonant frequency. To solve this problem, a simple protection circuit for the power supply of a gas discharge lamp is proposed in this paper. This circuit senses the primary current of the main transformer. Using this protection circuit, the operating frequency of the lamp driving inverter system is kept close to and on the right side of the resonant frequency and the inverter is always operated in the ZVS condition. The resulting stable variable frequency operation allows various gas discharge lamps to be tested without the risk of damaging the main switches, because the protection circuit can protect the power MOSFETs of bridge converters from abnormal conditions. The validity and effectiveness of the proposed protection circuit are verified through the experimental results.

Key Words: Gas discharge lamp, LCC resonant converter, Protection circuit, Variable frequency control, ZVS operation

I. INTRODUCTION

Recently, due to an enlarged display market, the usage of gas discharge lamps such as CCFLs (cold cathode fluorescent lamps) and EEFLs (external electrode fluorescent lamps) has been increasing year by year [1]-[2]. However, even if gas discharge lamps are produced with the same manufacturing processes, their characteristics are not the same. Their ignition frequency, voltage, and current vary due to the different types and rating powers of the lamps. Thus, the design of a resonant LC tank is extremely important for driving various types of lamps.

In order to drive gas discharge lamps, variable frequency operation is chiefly used. Subjecting them to variable frequency control is the best way to determine the operating characteristics, such as operating frequency and ignition voltage, of unknown lamps. Using the optimal operating frequency and voltage helps to extend the lifetime of a gas discharge lamp. If a lamp designer wants to know the characteristics of a new lamp, a scanning method using variable frequency can provide them with the necessary information. Generally, when designing circuits using variable frequency control, the operating frequency will not be lower than the resonant frequency for minimizing the turn-on loss through zero-voltage switching (ZVS). In other words, when lamp driving circuits operate at the required voltage gain, the lowest operating frequency is the resonant frequency [3].

Owing to the high equivalent lamp resistance before ignition, the initial resonant gain is very high at the resonant frequency. If a lamp is ignited at the resonant frequency, its main switches may be destroyed, because the temperature of the MOSFETs increases rapidly due to the large inductor current [4]. Therefore, when a driving discharge lamp uses variable frequency control, the lamp operating frequency must always be kept close to and on the right side of the resonant frequency to insure the efficiency and stability of the main circuit. For the stable operation of discharge lamps, phase-locked loop (PLL) techniques [3],[5],[6], self-oscillation circuits [7],[8], and digital phase control methods [9]–[12] have been developed. When a circuit designer already knows the operation characteristics of a lamp, these techniques enable better performance when driving it. However, when determining the operating characteristics of an unknown lamp, it is difficult to use a scanning method with a variable frequency, because the circuits are designed to operate at the optimal operating frequency. Thus, arbitrary frequency operation is not applicable. Furthermore, a general lamp drive IC does not eliminate the cause of an over-current, it only acts to protect operation after the occurrence of an over-current [13]. If this operation is frequently repeated, a converter may be damaged by over-current or unstable operation.

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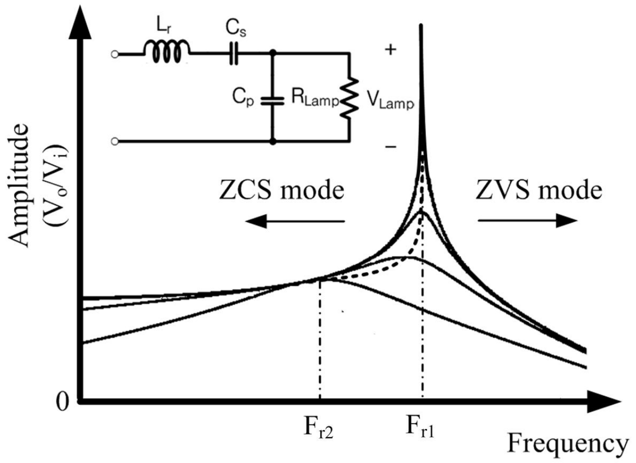


Fig. 1. DC gain of LCC resonant tank as a function of the frequency.

In this paper, a simple protection circuit for the power supply of a gas discharge lamp is proposed. This circuit only senses the primary current of the main transformer. The operating frequency is kept close to and on the right side of the resonant frequency. In addition, stable arbitrary frequency operation is possible, due to this protection technique which keeps the operating frequency below the resonant frequency. Because the protection circuit prevents the transition from the right side of the resonant frequency to the left side under variable frequency operation, the resulting stable variable frequency operation allows a variety of gas discharge lamps to be tested without the risk of damaging the main switches.

II. THE PROPOSED PROTECTION CIRCUIT

Actually, the resonant gain of a gas discharge lamp is changed by adjusting the equivalent resistance, (R_{Lamp}), which leads to a change in the voltage gain of the resonant tank. Due to the resistance change before and after ignition, LCC resonant tanks are mainly used for driving gas discharge lamps. Fig. 1 shows the DC gain of a LCC resonant tank as a function of the frequency and R_{Lamp}.

The resonant frequency of a LCC resonant converter is determined by an inductor, L_r, two capacitors (C_s, and C_p), and R_{Lamp}. In the general design of resonant converters, the resonant tank is fixed. Thus, the resonant frequency and the DC gain are mainly affected by R_{Lamp}. When R_{Lamp} is very high, the resonant frequency is close to F_{r1}. However, if R_{Lamp} is decreased, the resonant frequency moves closer to F_{r2}. In other words, before ignition, the initial resonant frequency of a gas discharge lamp is close to F_{r1}. After ignition, the resonant frequency is located between F_{r1} and F_{r2} in the steady state.

Varying the output voltage of LCC resonant converters can be achieved by providing them with variable frequency control. However, when they are activated by varying the operating frequency, the converters are frequently damaged by their unstable operation due to the rising and falling of the operating frequency in the vicinity of the resonant frequency. It is very dangerous for the main MOSFETs when the operating frequency of the circuit is close to the resonant frequency before ignition, because of the resulting very high DC gain.

Generally, the ZVS technique is used to improve the efficiency of the power supply for new lamps or ballasts, because it does not contribute to power loss or dissipation in the switch. The DC gain of a LCC resonant converter can be divided into the ZVS region and the ZCS region. When the DC gain slope is negative, the converter operates under ZVS conditions. For safe variable frequency operation, the bridge converter using MOSFETs must be operated under ZVS conditions. Thus, the operating region is always on the right side of the resonant frequency. When using arbitrary frequency operation, it is possible for the operating frequency to be lower than the resonant frequency, in which case the resonant converter is not operated under ZVS conditions.

The conventional PLL control method can always track the resonant frequency. However, for the phase detection in this method, more sensing circuits are needed. These sensing circuits of the converter result in power loss, noise interference, and increasing cost. When the operating frequency is close to Fr1, the PLL control ICs need additional external circuits to decrease the high DC gain. In addition, it is difficult to apply arbitrary frequency operation to control circuits using PLL ICs, because the ICs are always operated at their designed operating frequency.

To overcome this drawback, a simple protection circuit is proposed in this paper. The proposed circuit only senses the primary current of the transformer. This circuit increases the operating frequency before it approaches the resonant frequency. Therefore, the resonant converter always operates in the stable region under ZVS conditions.

Fig. 2 shows a DC-AC inverter using the proposed protection circuit. The primary side of the inverter system uses a full-bridge converter to enhance the efficiency of the system. The proposed circuit can also be used in half-bridge converters. Fig. 3 shows a block diagram of the proposed circuit. The circuit consists of current sensing, processing, and phase comparison parts. The sensing part only senses the primary current (I_P) of the main transformer. The processing part transforms the previously sensed current into a new current signal (I_T) which depends on the polarity of the sensed current. At this time, a generated voltage signal (V_T) is estimated from the gate driving signal (V_S). The proposed circuit needs one gate signal for making V_T. Any gate signal can be chosen for V_S. In the prototype converter, the gate signal of SW4 is used for V_S. For the phase margin, V_T has a slight delay time (T_d). Due to the phase margin, the ZVS condition will always be maintained. The phase comparison part compares I_T with V_T using a D-flip flop. When V_T is the rising edge, the D-flip flop checks the phase of I_T. The phase angle between I_T and V_T is zero near the resonant frequency. If the phase of I_T is the same or leading the phase of V_T, the output signal of the D-flip flop (Q) will be changed to the high state. At this time, the operating frequency will be increased by the control part. Fig. 3 shows the key waveform of the proposed circuit.

Fig. 4 (a) shows the operating waveforms under ZVS conditions. Fig. 4 (b) shows the operation of the protection circuit when the operating frequency is near the resonant frequency. If Q is high, the operating frequency increases before the ZVS operation fails. Therefore, stable ZVS operation is always

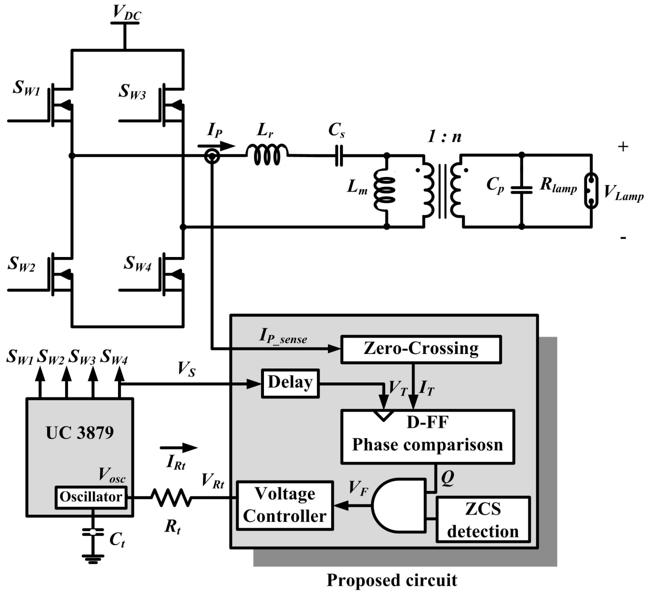


Fig. 2. DC-AC Inverter system using proposed circuit.

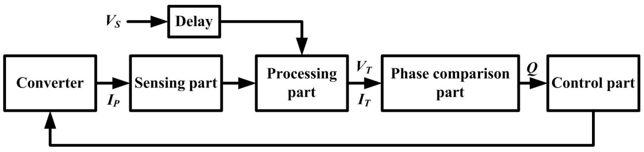


Fig. 3. Block diagram of the proposed circuit.

possible.

III. CONTROL ALGORITHMS OF PROPOSED CIRCUIT

In general, the resonant tank of a LCC resonant converter using a transformer can be simplified, as shown in Fig. 5. The magnetizing inductance (L_m) does not affect the resonant frequency within the lamp's operating range. This inverter has two resonant frequencies, due to the LCC resonant tank. As shown in Fig. 1, the two resonant frequencies are:

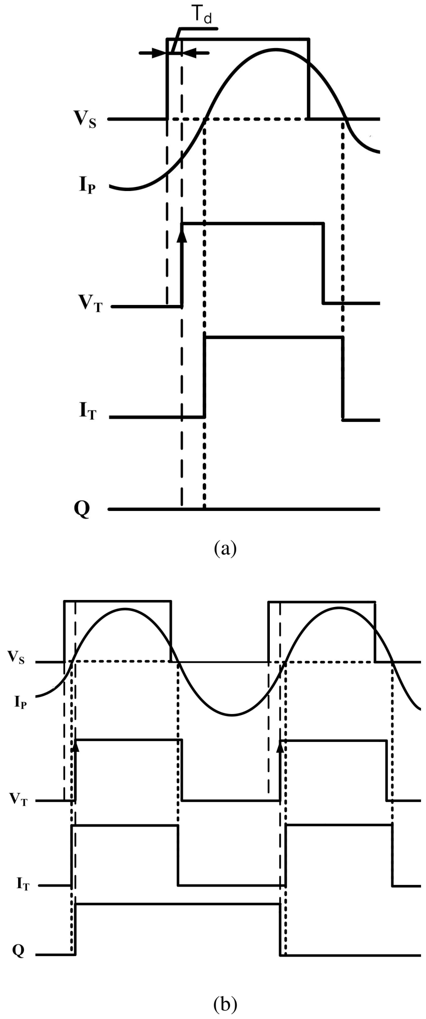
$$F_{r1} = \frac{1}{2\pi\sqrt{L_r(C_s//n^2C_p)}} \tag{1}$$

$$F_{r2} = \frac{1}{2\pi\sqrt{L_rC_s}}. \tag{2}$$

With the proper design of a resonant tank, the inverter can be kept in the ZVS region by varying R_{Lamp} and the input voltage. On the primary side, a square wave with a 50% duty cycle is produced by the PWM IC (as shown in Fig. 2). The operating frequency of a general PWM IC is determined by connecting a resistor from $R_t$to ground (GND) and a capacitor from C_t to GND. The current (I_{Rt}) flowing at R_t determines the operating frequency. Thus, if I_{Rt} can be controlled, variable frequency control is possible. The R_t pin of a typical PWM IC is internally set to a fixed reference voltage (V_{osc}). The value of I_{Rt}, the charging current of C_t, is calculated as:

$$I_{Rt} = \frac{(V_{OSC} - V_{Rt})}{Rt}. \tag{3}$$

When the value of R_t is large, the operating frequency is decreased by the resulting small I_{Rt}. Conversely, a small R_t increases the operating frequency. However, it is not easy to adjust the value of R_t in actual control circuits. Thus, in the proposed circuit, I_{Rt} is controlled by adjusting the value of V_{Rt}. The zero current switching (ZCS) detection circuit detects failures in ZVS operation. If ZVS operation does not occur, the output signal of the D-flip flop (Q) will be changed to the high state and the ZCS detection circuit will detect a ZVS failure. At this time, the voltage controller decreases V_{Rt}. As a result, the PWM IC increases the operating frequency and maintains ZVS operation.



(a)

(b)

Fig. 4. Key-waveform of the proposed circuit.

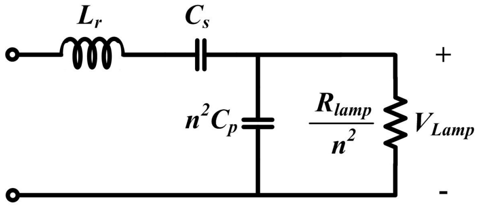
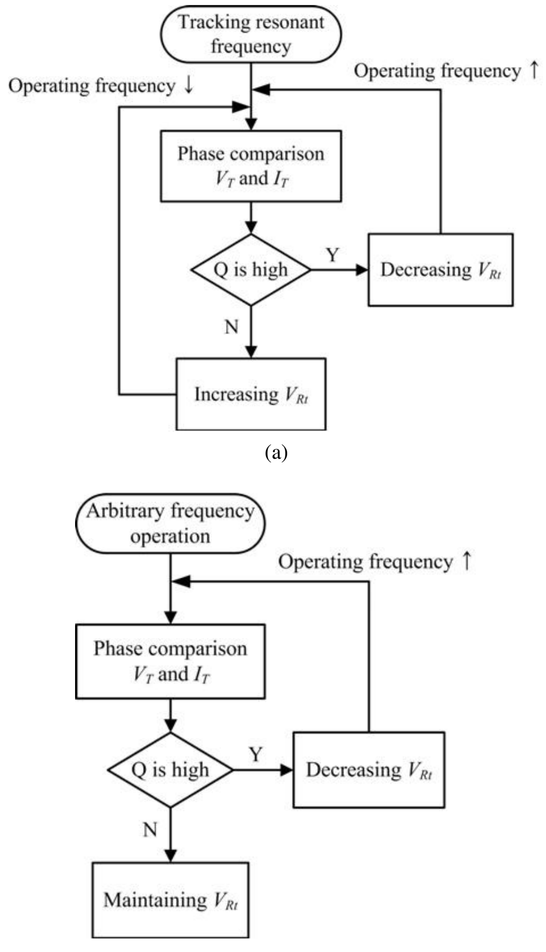


Fig. 5. The equivalent circuit of the resonant tank.

Fig. 6 (a) shows the resonant frequency tracking algorithm for the proposed protection circuit. In this condition, the phase comparison part always compares I_T with V_T using a D-flip flop. Using the proposed circuit, the operating frequency



(a)

(b)

Fig. 6. Operating algorithm of the proposed circuit.

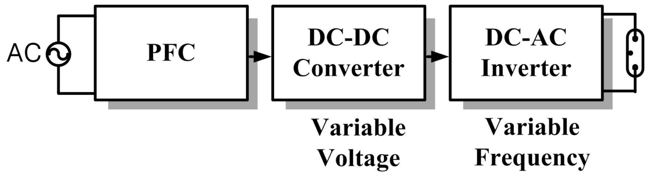


Fig. 7. Power supply system for driving gas discharge lamps.

can be controlled by adjusting the state of Q. The operating frequency is kept close to and on the right side of the resonant frequency with a phase margin T_d. Thus, the ZVS condition is always maintained. Fig. 6 (b) shows the algorithm for the arbitrary frequency operation mode. Due to the arbitrary modulation of V_{Rt}, the operating frequency is easily controlled. In this case, if Q is high, decreasing the operating frequency below the resonant frequency is not possible. In other words, the protection circuit prevents the transition from the right side of the resonant frequency to the left side under arbitrary frequency operation. Thus, a variety of gas discharge lamps can be easily tested without the risk of damaging the main switches.

IV. EXPERIMENTAL RESULTS

Fig. 7 shows the proposed power supply system used for driving gas discharge lamps. Compared with an actual lamp ballast, the proposed power supply system includes a DC-DC converter situated between the PFC and the DC-AC inverter, in order to vary the output voltage. In actual lamp ballasts, the role of the DC-DC converter is included in the operation of the DC-AC inverter, because variable frequency control can easily change the resonant gain. However, if the DC gain at the resonant frequency is less than the desired voltage gain in the steady state, using the fixed DC input voltage, the resonant tank should be redesigned. Because the equivalent resistance of most lamps is not the same after ignition, a variable voltage system using a DC-DC converter is more advantageous. Using this power supply system, the lamp operating characteristics can easily be determined and the lamp ballast can be designed simply.

TABLE I
THE DESIGN SPECIFICATIONS OF THE LAMP DRIVING SYSTEM WITH THE PROPOSED CIRCUIT

Specifications	Values
System Input voltage (rms)	220V (AC) 60Hz
DC-DC converter output voltage	10 – 100V (DC)
Transformer turns ratio ($n = N_1/N_2$)	13 : 1
Rated lamp power	32W
Lamp ignition voltage (rms)	500V
Steady-state lamp voltage (rms)	230V
Steady-state lamp current (rms)	140mA
Initial ignition frequency	88kHz
Steady-state operating frequency	64kHz
Steady-state R_{Lamp}	1650Ω
L_r	150μH
C_s	47nF
C_p	360pF
Resonant frequency	$F_{r1} = 80$kHz , $F_{r2} = 61$kHz

The design specifications and the circuit parameters of a lamp driving system with the proposed circuit are shown in Table 1. The electronic ballast must have a power factor correction (PFC) stage. A boost converter is employed in the PFC stage and the system input voltage (AC 220V 60Hz) is converted to DC 380V with a power factor of more than 0.95. The DC-DC converter is composed of a phase shift full-bridge converter. Using this DC-DC converter, it is easy to obtain the desired input voltage of a DC-AC inverter by varying the input voltage (10-100).

The DC-AC inverter is controlled by a PWM IC and the proposed protection circuit. Fig. 8 shows the resonant frequency and the DC gain of the proposed inverter system. The resonant frequencies are calculated from equations (1) and (2) to be $F_{r1} = 80$kHz and $F_{r2} = 61$kHz.

Fig. 9 shows the waveforms of the proposed circuit at the initial ignition stage. The input voltage of the DC-AC inverter is set to DC 20V. The initial ignition voltage must be at least 500V (rms). Due to the high DC gain before ignition, the lamp must be ignited before F_{r1} is reached. Hence, the lamp's ignition frequency is 88kHz and the DC gain is 1.9 when R_{Lamp} is 1MΩ. At this time, the phase angle is 19°. Due to this phase margin, the main switches can be protected from the high DC gain.

Fig. 10 shows the waveforms of the proposed circuit at the steady-state. The primary equivalent resistance is 9.8 Ω in the steady-state based on the calculation of R_{Lamp}/n^2. The operating frequency, F_{steady}, is set to 64kHz for stable ZVS

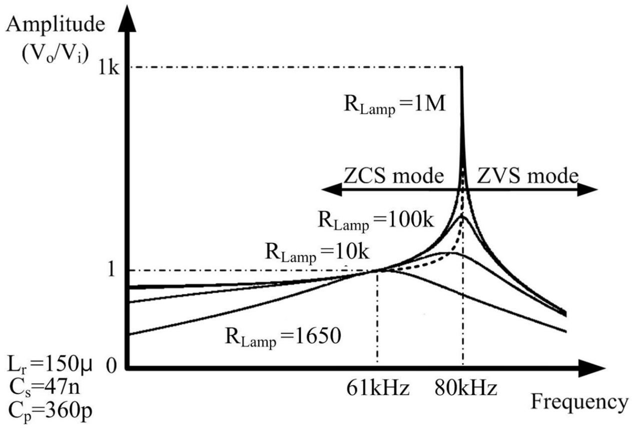


Fig. 8. Resonant frequency and DC gain under variable frequency operation.

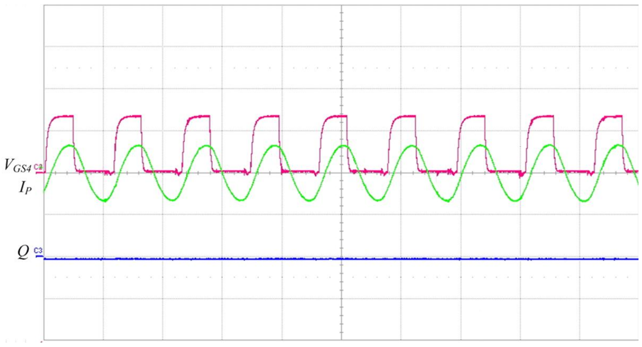


Fig. 9. Waveforms for V_{GS4}, I_P, and Q at initial ignition; Switching frequency = 88kHz, V_{GS4} (10V/div.), I_P (2A/div.), Q (20V/div.), Time base (10μs/div.), Phase margin = 19°.

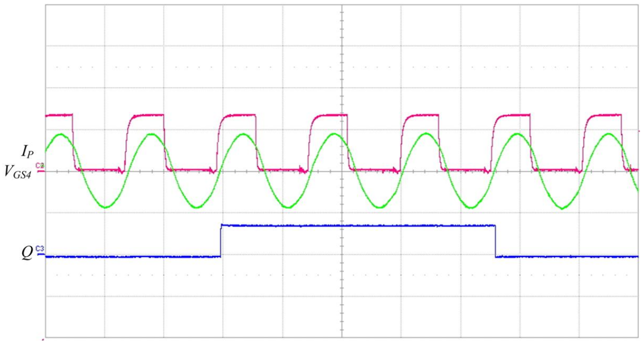


Fig. 10. Waveforms for V_{GS4}, I_P, and Q at steady state; Switching frequency = 64kHz, V_{GS4} (10V/div.), I_P (2A/div.), Q (20V/div.), Time base (10μs/div.), Phase margin = 6°.

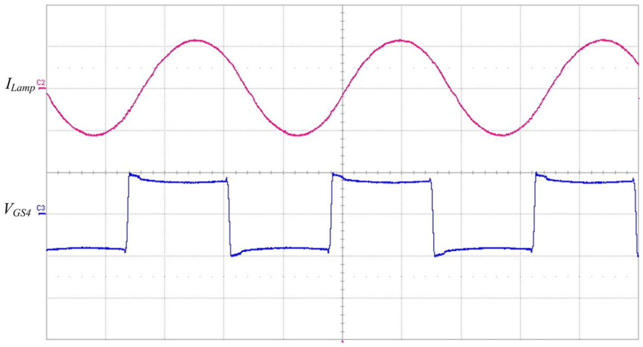


Fig. 11. Waveforms of adjusting phase margin 20° in steady state (32W); V_{GS4} (10V/div.), I_{Lamp} (200mA/div.), Time base (5μs/div.).

operation in the steady-state. At this time, the phase margin is 6° and the DC gain is 0.9. Due to this phase margin, the ZVS condition will always be maintained. If the phase angle between I_T and V_T is less than 6°, Q will be changed to the high state and the operating frequency will increase.

The phase margin is related to the inverter efficiency and stability. If the inverter system has a high phase margin, the ZVS operation will be more stable but the inverter efficiency will be decreased. It is easy to adjust the proper phase margin using the proposed circuit with a delay circuit. Fig. 11 and 12 show the waveforms of the phase margin at the same operating frequency. Using a delay circuit, the phase difference between the input and output waveforms of the resonant tank can also be controlled.

Fig. 13 shows the process of lamp ignition using the proposed circuit. Through the control algorithm of the proposed circuit, the operating frequency continuously tracks the resonant frequency as it decreases from a high frequency to a low frequency. Using the proposed circuit, the inverter operates under the soft lamp ignition conditions. Before ignition, the preheating time is sufficient to warm the filament in order to ignite the lamp. During the ignition period, the stress on the inverter switches decreases, because the proposed circuit can maintain the ZVS operation of the inverter under a light load. After ignition, the lamp voltage and current are controlled by the proposed circuit. In the steady state, the lamp voltage and current are kept close to and on the right side of the resonant frequency.

V. CONCLUSIONS

In this paper, a simple protection circuit for the resonant power converter of a gas discharge lamp was proposed. The proposed protection circuit only senses the primary current of the transformer. This circuit increases the operating frequency before it reaches the resonant frequency. Therefore, the resonant converter always operates in the stable region under ZVS conditions. In addition, stable arbitrary frequency operation is possible, due to the protection technique which keeps the operating frequency below the resonant frequency.

Through experiments using a 32W fluorescent lamp, the validity and effectiveness of the proposed circuit were verified. Due to the control algorithms of the proposed circuit, the phase angle between I_T and V_T is maintained at 19° before ignition and at 6° in the steady-state. If Q is changed to the high state, the operating frequency is increased by the protection circuit.

The proposed protection circuit has the merit of improving the reliability of the power supply. Thus, a variety of gas discharge lamps can be easily tested without the risk of damaging the main switches. Also, the proposed circuit is suitable for the protection circuits of resonant converters using half-bridge or full-bridge converters.

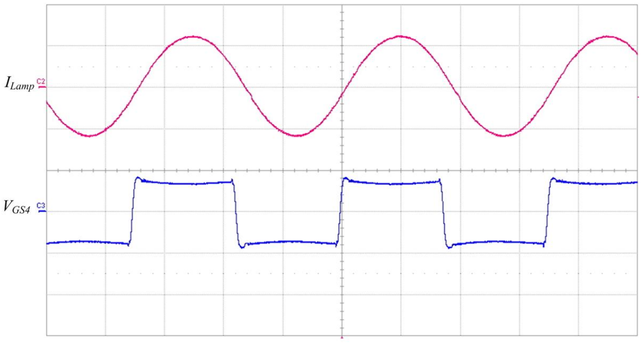


Fig. 12. Waveforms of adjusting phase margin 9° in steady state (32W); V_{GS4} (10V/div.), I_{Lamp} (200mA/div.), Time base (5μs/div.).

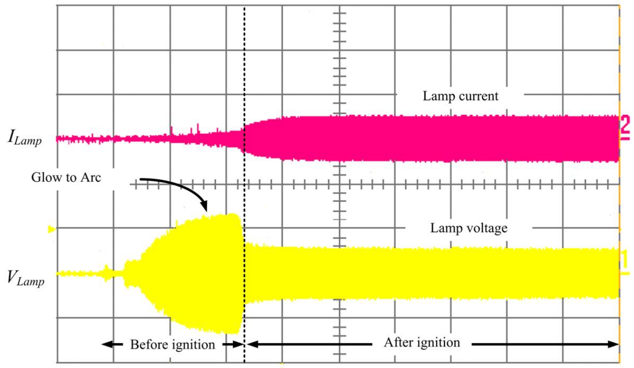


Fig. 13. The process of lamp ignition using the proposed circuit; I_{Lamp} (0.5A/div.), V_{Lamp} (500V/div.), Time base (10ms/div.), Phase margin = 9°.

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