Designing an Ignitor for Short-Arc Xenon Lamps

Chin S. Moo   Tsai F. Lin

Power Electronics Laboratory
Department of Electrical Engineering
National Sun Yat-Sen University
Kaohsiung Taiwan R. O. C.
Tel: +886-7-5252000 EXT-4150
Fax: +886-7-5254199
e-mail: mooxx@ee.nsysu.edu.tw

Ying C. Chuang

Department of Electrical Engineering
Kung-Shan Institute of Technology
949 Da Wan Rd. Yung Kang City
Tainan Hsien Taiwan R. O. C
Tel: +886-6-2720801
Fax: +886-6-2734126
e-mail: chuang@ksitcc.ksit.edu.tw

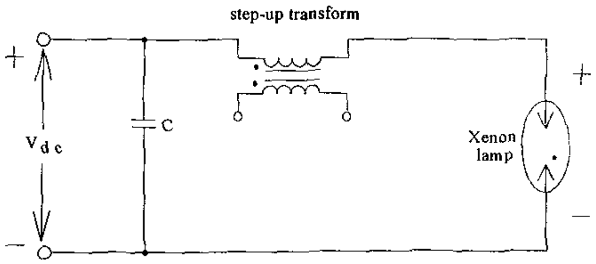
Abstract- **A compact ignitor is designed for short-arc xenon lamps which require high ignition voltage and fast transition. The ignitor employs two stages of step-up circuits with two small sized transformers. A capacitor with an intermediate voltage is used for storing the energy converted from the dc power supply by the first-stage step-up circuit. The impact voltage necessary for igniting the xenon lamp is generated by the second-stage step-up circuit which is connected in series with the lamp and the dc power supply. The design of the ignitor for a short-arc xenon lamp of 350W is discussed as an illustrative example.**

I. INTRODUCTION

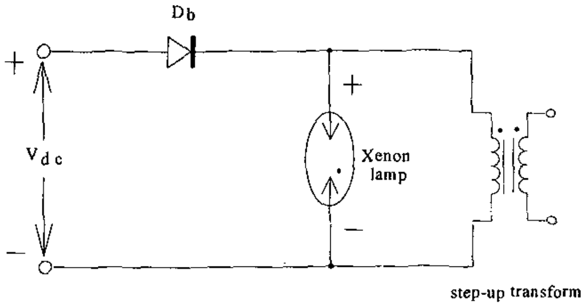
The short-arc xenon lamp is a xenon-filled discharge lamp for dc operation. As compared with other discharge lamps, the short-arc xenon lamp requires a relatively high ignition voltage to ionize the insulating gas between the electrodes gap. After the ignition spark, the dc power supply should be able to provide the discharge current quickly enough to establish the lamp arc[1,2]. Therefore, an ignitor incorporating with a dc power supply has to be carefully designed to ensure successful ignition and smooth transition from the high-voltage, low-current spark to the low-voltage, high-current arc [3].

Conventionally, the ignition voltage is generated by a step-up transformer. This step-up transformer can be connected in either series or parallel with the xenon lamp and the dc power supply as shown in Fig. 1. With series connection, a step-up transformer is interposed between the dc power supply and the lamp. The secondary winding of the transformer is with a great number of turns to generate the required high ignition voltage. This winding carries the large lamp current at the steady state, and therefore has to be with a thick wire. As a result, a bulky step-up transformer has to be used. On the other hand, the ignition circuit in parallel connection allows for the use of a step-up transformer with a smaller wire. However, a costly diode rated at very high voltage and large current is necessary for blocking the high ignition voltage generated from the step-up transformer. This blocking diode, being with a high forward voltage drop, carries the large lamp current at the steady state, leading to considerable losses.

In order to reduce the volume and weight of the step-up transformer and exclude the use of the blocking diode, an ignitor with two stages of step-up circuits is proposed. Each stage of the step-up circuit consists of a small sized transformer. By using a bi-directional diode thyristor and a spark gap as the energy transfer switches, the ignitor can be automatically switched on when the dc power has been supplied and switched off once the lamp current has been established. The size of the first-stage step-up circuit is further reduced by multiple switching actions of transferring energy. The design of the ignition circuit is illustrated by an example for a short-arc xenon lamp of 350W.



(a) series connection



(b) parallel connection

Fig. 1 Wiring diagrams of ignition circuits

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II. CIRCUIT CONFIGURATION AND OPERATION

Fig. 2 shows the circuit configuration of the ignitor. The ignitor consists of two stages of step-up circuits with two step-up transformers, T_1 and T_2. The first stage is connected in parallel with the dc power supply. At beginning, when the dc power supply is turned on and the lamp is ready for the ignition, an open circuit voltage applies to the first-stage step-up circuit. This open circuit voltage is typically greater than the rated lamp voltage by a factor of 3 or 4. Then, the capacitor, C_1, is charged by the dc power supply through a current limiting resistor, R_1.

A bi-directional diode thyristor(SIDAC), S_1, is used as an energy transfer switch. The breakdown voltage of S_1 should be lower than the open circuit voltage of the dc power supply. When C_1 is charged up to break down S_1, C_1 is discharged and energy is transferred into C_2 through T_1. This small amount of energy is then temporarily stored in a capacitor, C_2. Once C_1 is completely discharged, S_1 is switched off until the following breakdown. The diode, D_1, is used for clamping the voltage on C_2, V_{C2}, at the positive peak induced from T_1 for each switching-on of S_1. By repeatedly switching S_1 on and off, the energy transferred from C_1, is accumulated in C_2. Then, V_{C2} can be gradually charged up step by step to a required intermediate high voltage.

The step-up transformer in the second-stage, T_2, is connected in series with the xenon lamp. This transformer converts the intermediate voltage on C_2 into a sufficiently high peak voltage by one shoot action of the switch, S_2. S_2 can be realized by a spark gap. The breakdown voltage of the spark gap is specified by the air gap distance[4]. When V_{C2} reaches the specified voltage, S_2 is broken down. Then, V_{C2} is applied on the primary winding of T_2, inducing an impact voltage on the secondary winding. This impact voltage and the voltage of the dc power supply are superimposed on the lamp electrodes for the ignition.

After the ignition, the lamp arc current is set up. At this time, the dc power supply provides the lamp voltage which is much lower than the breakdown voltage of S_1. Therefore, S_1 stays at the state of open-circuit, and hence stops the switching action and the operation of the ignition circuit.

Since the first-stage transformer carries only a small current, it allows for using small windings. Moreover, the total energy is transferred through T_1 by a number of switchings. In other words, T_1 delivers only a small amount of energy in each switching period, and can thus be smaller. On the other hand, with a relatively high voltage applied to the primary winding, much less turns ratio can be adopted for T_2. This leads to a much smaller second-stage transformer even though the secondary winding carries the large lamp current at the steady state. Therefore, a compact design for the ignition circuit with two small transformers can be achieved.

III. DESIGN EXAMPLE

An ignition circuit is designed for a short-arc xenon lamp of 350W. The xenon lamp is rated at an arc voltage of 22V and an arc current of 16A. The open circuit voltage of the dc power supply is 150V. The breakdown voltage of S_1 is selected at 120V, which is lower than the open circuit but higher than the rated lamp voltage. The breakdown and ionization mechanisms between electrodes are very complicated. In fact, the breakdown voltage depends largely on the ambient conditions and the lamp lifetime, and thus can be different time by time. The test results indicate that this ignition voltage may vary from 15kV to 20kV. Therefore, the ignitor should be designed to have a minimum impact voltage of 20kV for ensuring a successful ignition.

Since the secondary winding of T_2 must withstand the high ignition voltage and the large lamp arc current, a transformer with a bar core and well insulated windings is used. The primary and the secondary windings of T_2, are 3 turns and 30

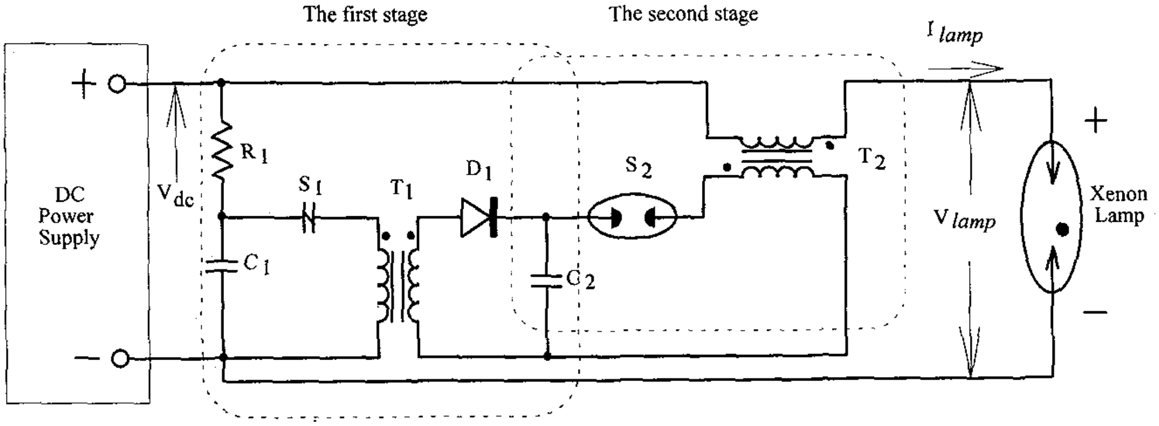


Fig. 2 Proposed circuit configuration

turns, respectively. When the turns ratio of a step-up transformer is specified, a higher output voltage can be obtained by increasing the mutual coupling factor. Unfortunately, for such a transformer with a bar core and loosely coupled windings, the mutual coupling factor, k, lies only in a range about between 0.3 to 0.4[5]. To ensure a successful ignition, the mutual coupling factor is estimated at the worst case, 0.3.

Fig. 3 shows the equivalent circuit of the second-stage step-up circuit. For the transformer with such few turns, the winding resistances of both primary and secondary windings can be ignored. However, the breakdown of the spark gap, S_2, results in considerable loss. This loss is treated as an equivalent resistance, R_{S2}. The stray capacitance, C_{m2}, at the output terminals should be as small as possible because it will cause the loading effect resulting in a lower output voltage. R_{S2} and C_{m2} can be estimated from experimental tests, in this design case are, 5.6Ω and 46pF, respectively.

From the equivalent circuit in Fig. 3 with the parameters listed in Table I, the voltage at the output terminals of T_2 can be obtained. Fig. 4 shows a simulated voltage waveform when the lamp is open-circuited. The voltage reaches its peak at the first half cycle then decays rapidly. The lamp is ignited at the first pulse. Fig. 5 depicts the output peak voltages, V_{T22}, for different values of C_2 with different initial discharging voltages. Obviously, the output peak voltage is almost proportional to the initial voltage on C_2. On the other hand, the increase in capacitance also results in a higher output peak voltage. This effect becomes insignificant when the capacitance is greater than 2nF.

The capacitance and the minimum intermediate voltage of C_2 can be figured out from Fig. 5. Since a higher V_{C2} requires higher ratings of C_2 and D_1, C_2 is chosen to be 2.5 nF with a rated voltage of 4kV. In other words, the breakdown voltage of the spark gap is set at 4kV.

TABLE I
Parameters Of The Second Stage Step-Up Circuit

Mutual Coupling Factor k	0.3
Turns Ratio $N_{21}:N_{22}$	3:30
Magnetizing inductance L_{m2}	0.38μH
Leakage inductance of the primary L_{21}	0.24μH
Leakage inductance of the secondary L_{22}	2.4μH
Stray capacitance C_{m2}	46pF

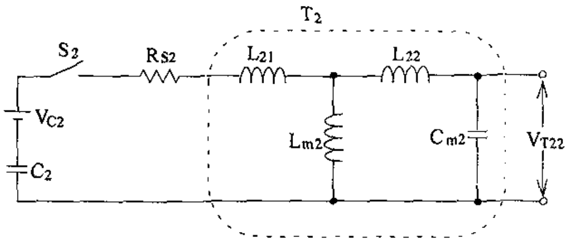


Fig. 3 Equivalent circuit of the second-stage step-up circuit

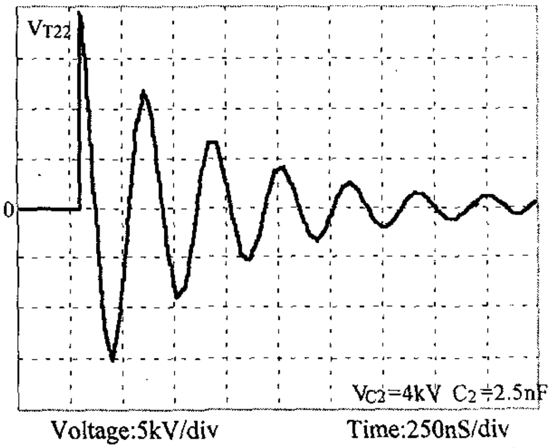


Fig. 4 Simulated waveform of output voltage of T_2

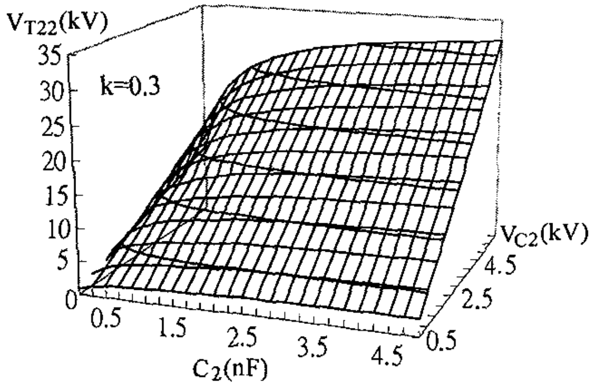


Fig. 5 Output peak voltage of T_2

In the first-stage step-up circuit, the transformer is with tightly coupled windings to generate a voltage high enough for charging up C_2. The turns ratio of T_1 is 100 with 15 turns and 1500 turns for the primary and secondary windings, respectively. The mutual coupling factor is 0.85. The equivalent circuit is shown in Fig. 6. The stray capacitance, C_{m1}, as well as the winding resistances, R_{11} and R_{12}, have significant effects on circuit performance, and thus can not be neglected. The circuit parameters for the equivalent circuit are listed in Table II. Fig. 7 illustrates the output voltage waveform of T_1, the charging current and the voltage of C_2 for the first switching period. The output voltage of T_1 can reach a level of 9 kV at the first peak and then decays rapidly. The charging current presents only when the output voltage of T_1 is greater than the voltage of C_2. The voltage on C_2 will be gradually increased by repeatedly switching S_1 and charging C_2 as shown in Fig 8. As illustrated in Fig. 9, using a larger C_1 can significantly reduce the number of switching actions of S_1, while slightly decrease the time required for charging C_2 up to 4kV. In this design, C_1 is chosen to be 0.5 uF to have charging time of 60 ms by 21 times of switching actions.

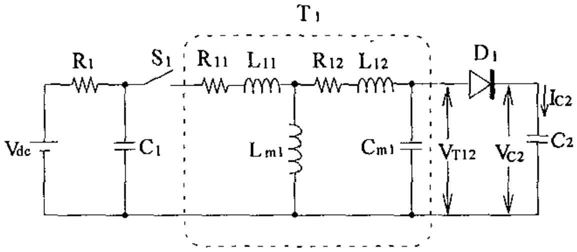
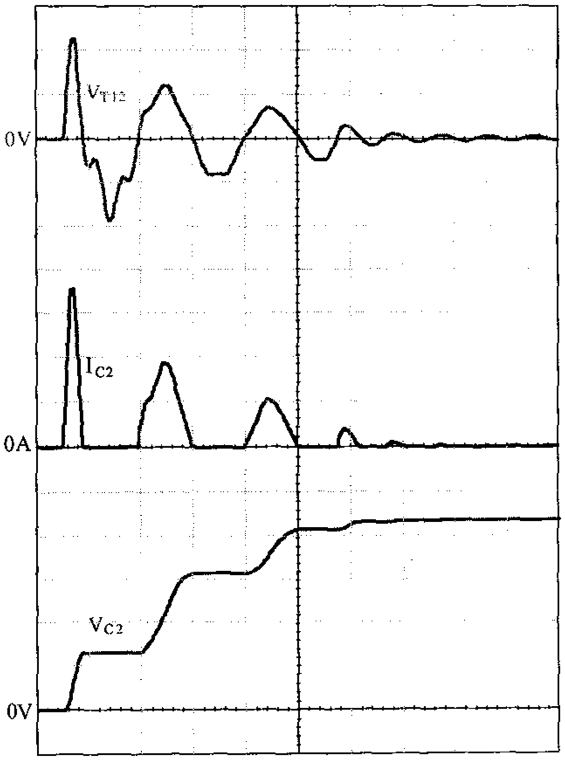


Fig. 6 Equivalent circuit of the first-stage step-up circuit

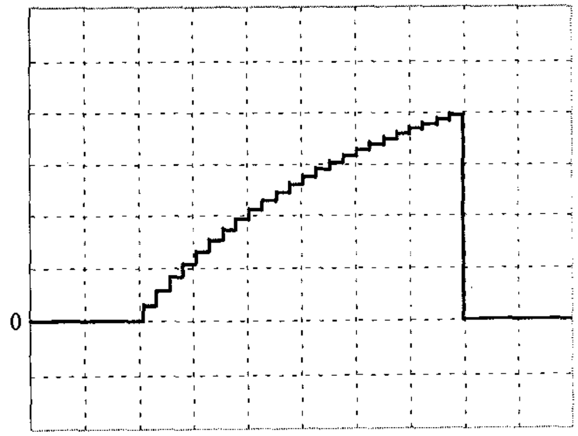
TABLE II
PARAMETERS OF THE FIRST STAGE STEP-UP CIRCUIT

Mutual Coupling Factor k	0.85
Turns Ratio N_{11}:N_{12}	15:1500
Magnetizing inductance L_{m1}	44μH
Leakage inductance of the primary L_{11}	8μH
Leakage inductance of the secondary L_{12}	8μH
Stray capacitance C_{m1}	140μF
Resistance of the primary R_{11}	0.05Ω
Resistance of the secondary R_{12}	0.6Ω



V_{C2}:50V/div V_{T12}:4kV/div I_{C2}:10mA/div
Time:20μS/div.

Fig. 7 Simulated waveforms of first-stage step-up circuit



Voltage:1kV/div Time:10ms/div

Fig. 8 Simulated waveform of V_{C2}

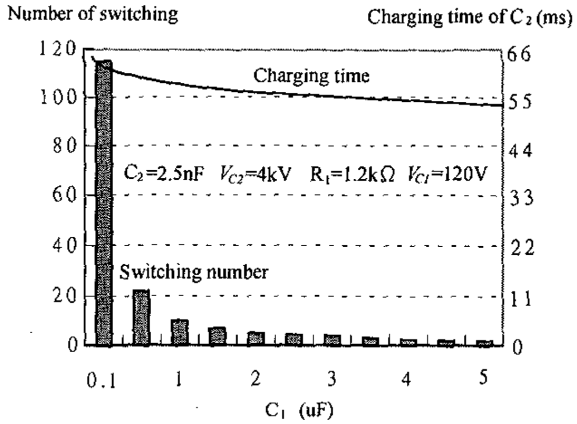
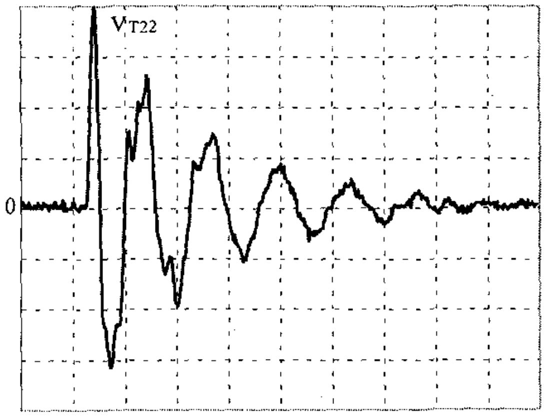


Fig. 9 Charging time and switching number versus C_1

IV. EXPERIMENTAL RESULTS

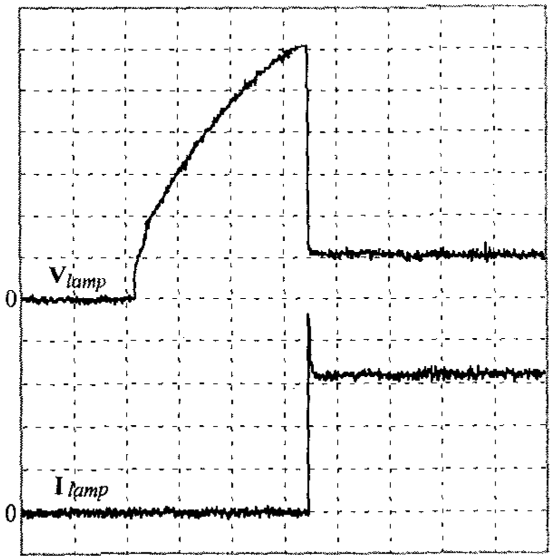
A laboratory circuit of the ignitor with above designed parameters was built for experimental tests. Fig. 10 shows the impact voltage on the lamp when the lamp is removed. A higher frequency oscillation is found to be superimposed on the simulated waveform. This is due to the complicated discharging mechanism of the spark gap. However, as compared with Fig. 4, the peak voltage at the first pulse is very close to the predicted value. The lamp voltage and current waveforms of one complete transition from ignition to steady state operation is shown in Fig. 11. After switching on, the output voltage of the dc power supply goes up gradually. Before ignition, the output voltage is applied on the ignition circuit. Since the voltage drop on the secondary winding of T_2 is very small in this period, the voltage on the lamp electrodes is nearly the same as the output voltage of the dc power supply. When this voltage reaches to the breakdown voltage of S_1, 120V, the voltage of C_2 is built up to the intermediate voltage and then the lamp is ignited within a very short period.



Voltage:5kV/div Time:250nS/div

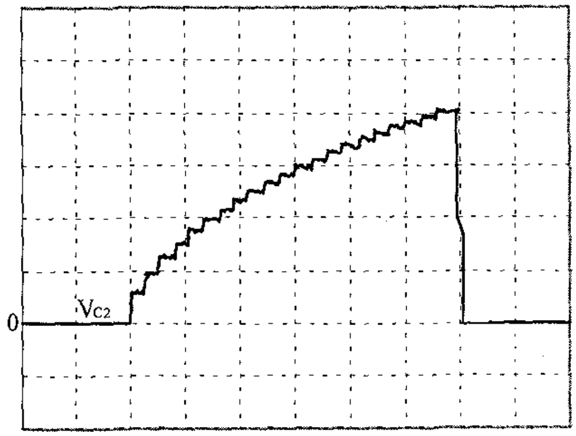
Fig. 10 Measured output voltage of T_2

After ignition, the lamp voltage drops and the lamp current rises up immediately to their rated values. The duration of the ignition is too short to present in this figure. The measured voltage waveform on C_2 is shown in Fig. 12. As predicted in Fig. 8, the voltage is increased up step by step. After 21 times of switching action, the voltage reaches a level of 4kV. At this instant, S_2 breaks down, and an impact voltage is generated on the lamp electrodes. The transient waveforms during ignition are shown in Fig. 13. The lamp electrodes are broken down at about 16kV, at which a flash current with a peak of 36A occurs to ignite the lamp.



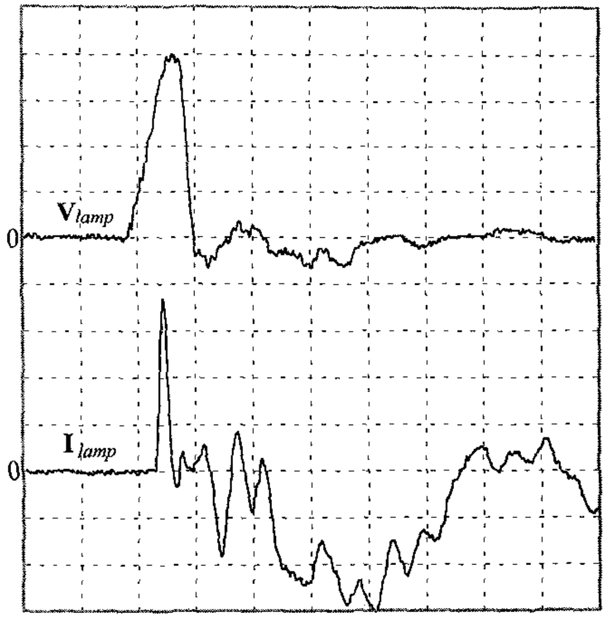
Voltage:20V/div Current:5A/div
Time:200mS/div

Fig. 11 Lamp voltage and current waveforms for transition from ignition to steady state



Voltage:1kV/div Time:10ms/div

Fig. 12 Measured waveform of V_{C2}



Voltage:5kV/div Current:10A/div Time:25ns/div

Fig. 13 Measured waveforms of lamp voltage and current during ignition

V. CONCLUSIONS

A compact design of the ignition circuit for xenon lamps has been presented. The size and weight of the ignition circuit can be effectively reduced since it mainly consists of two small size step-up transformers. With only few turns of the secondary winding of the second stage transformer, the copper loss due to the lamp current is much less than those in the conventional designs. The two energy transfer switches are accomplished by a bi-directional diode thyristor and a spark gap, respectively, which can be automatically switched at the specified voltages. Therefore, no additional control circuit is needed. Experimental results show that the proposed ignition circuit has satisfied performances.

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