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Design and Development of High Voltage Scheme for a Crowbar in RF Heating

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Abstract— **Plasma is a mixture of freely moving charged particles. To sustain these particles in ionic state, very high temperature is essential. RF heating systems are utilized for obtaining high temperatures. Arching phenomenon in these systems can cause enormous damage to the RF tube. Fast switching circuit breakers are used to cutoff the load from the supply in cases of arcing. The crowbar interrupts the connection between the high voltage power supply (HVPS) and the RF tube for a temporary period during which the series switch has to open.**

This paper presents the design and development of Crowbar based on fiber optic triggering for the protection of RF heating system. The importance of optical triggering and utilization of fiber optic has been justified. Protection techniques other than crowbar are briefly discussed. The design of Crowbar is well supported with the experimental results.

Keywords— RF Heating, Fiber Optic Triggering, Arcing, Crow Bar, Time Delay

I. INTRODUCTION

Plasma is a collection of freely moving charged particles mainly in the form of electrons and ions. High temperature is required to sustain these charges in their ionic forms, which is provided by RF heating systems. The RF heating systems operate at High Voltage DC (HVDC) and so the probability of the occurrence of arcing phenomenon is very high. The cost of the RF tube is very high and therefore damage to the tube is not affordable. The maximum charge that can be sustained across A-K junction of the tube ranges from 10 C to 50 C. During the arcing phenomenon, approx. 250 C of charge is released across the tube. This high current needs to be suppressed within 10 µs for the safety of the tube.

The circuit breaker or the series switch is normally closed (ON state). When triggered it opens (OFF state), cutting off the load from the HVPS. The OFF-time for a switching device is generally much higher than the ON-time. Thus, a commonly used series switch requires 100 ms to clear the fault. The requirement of the protection system is to suppress the current within 10 µs, so the load should be shunted (bypassed) till the series circuit breaker network opens. The function of shunting the current across the load is achieved using a crowbar. The turn-ON time being less, the current can be satisfactorily suppressed using a shunt network or a crowbar. The schematic diagram of the project is shown in figure 1. When an arc is produced in the RF tube, an arc detector detects it and sends a signal to the feedback card. The feedback card produces two pulsed signals, one each for the trigger network of the series switch and the crowbar.

The crowbar is turned ON first, shunting the current across the load. This bypass of the load leads to short-circuiting of the HVPS. If this persists, it may damage the power supply. Thus, a combination of series switch and crowbar is generally preferred.

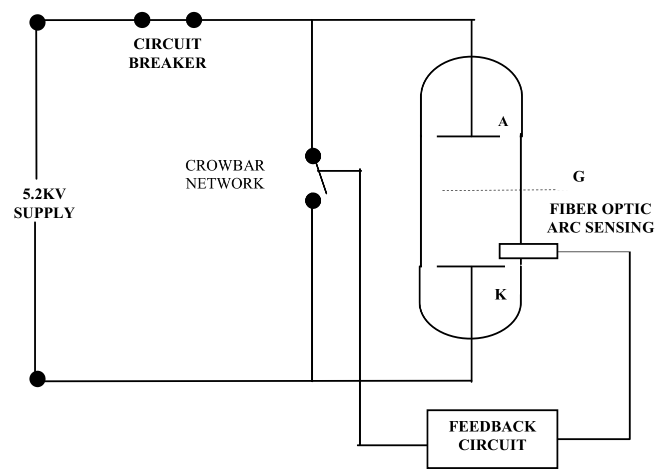

Figure 1. Schematic diagram of the project.

Within few milliseconds the series switch opens, cutting of the load from the HVPS. Thus, along with the load (RF tube), the HVPS is also protected.

II. EVOLUTION OF CROWBAR

Rail Gap: This setup contains a nitrogen filled vacuum chamber and two parallel rails. The rails are made up of tungsten alloy that can sustain high voltage arcs. When triggered, an arc is established between the rails in the gap. This causes a short circuit and shunts the energy across the load.

Ignitron: The ignitron consists of a vacuum tube with an anode and cathode. The cathode contains a vessel filled with mercury. The cathode triggering is in the form of heat. This leads to formation of mercury vapors that rise up to the anode causing a short circuit.

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Solid-state crowbar: In solid-state crowbar, a single semiconductor switch or a combination of these is connected across the load as a shunt. The switching device can be transistors, MOSFET, IGBT or thyristors.

III. COMPONENT SELECTION

The series switch was obtained using an array of transistors in series. While, the crowbar is designed using SCR 51RIA 100 as the switching device. The selection of a thyristor-based design over a transistor was made because of the following reasons:

Here, the HVPS is short-circuited using crowbar hence heavy current flows through the loop. The current rating of thyristor is much higher than that of a transistor.

The switching time for a SCR is much lower than that of a transistor. In this case, the limitation of fast switching has to be met with and so a faster switching device – SCR – is chosen.

A. SCR Connection

The total voltage applied across the switch is 5.2 kV. The voltage rating of 5.2 kV is very high for a single thyristor to handle, so series connection of thyristors was used to obtain the same. The voltage rating of a single 51 RIA is 1.2 kV hence 10 such thyristors were connected in series to achieve a 5.2 kV rating.

B. Equalizing Network

The electrical characteristics of no two SCR are exactly same, but differ in one aspect or the other. This may lead to a miss match and the whole system may fail due to unequal distribution of voltage. An equalizing network is required when operating a series connection of SCRs.

IV. GATE TRIGGERING SCHEME

The crowbar is designed using 10 SCRs in series connected scheme. As mentioned above, all the SCRs are to be switched simultaneously to avoid unequal distribution of voltage, which may lead to the failure of the whole system. Even the gate trigger scheme for SCR is based on fiber optic triggering due to the following inherent advantages over other triggering scheme:

(1) Isolation
(2) Fast Switching Speed

The arc in the RF tube is detected using an arc detector, which sends a signal to a feedback card. The feedback card multiplies this signal into two, one is transmitted to the base-triggering network for series switch, while the other to the gate triggering network for crowbar. This signal acts as the input to the gate-triggering network.

The triggering network can be divided into three sections:
(i)Transmitter Section
(ii)Signal Multiplier Section
(iii) Receiver Section

Component Selection:
Agilent Technologies' HFBR-X521 fiber optic connection has been utilized to establish the link between transmitter and the receiver sections. Fairchild Semiconductors' 7407 and IRF 840 power MOSFET are used for the purpose of buffering and logic inversion, respectively.

(i) Transmitter Section: The signal from the arc-detector serves as the input to the transmitter at node 1 in figure 2. The signal triggers the transmitter to send an optical pulse to the fiber optic receiver of the signal multiplier, embedded in the same card.

(ii) Signal Multiplier Section: There are 10 different receiver cards, one for each SCR. All the receiver cards must receive the trigger signal simultaneously so as to trigger the SCRs at the same instant. Thus, the signal from the transmitter has to be multiplied and sent to each receiver card.

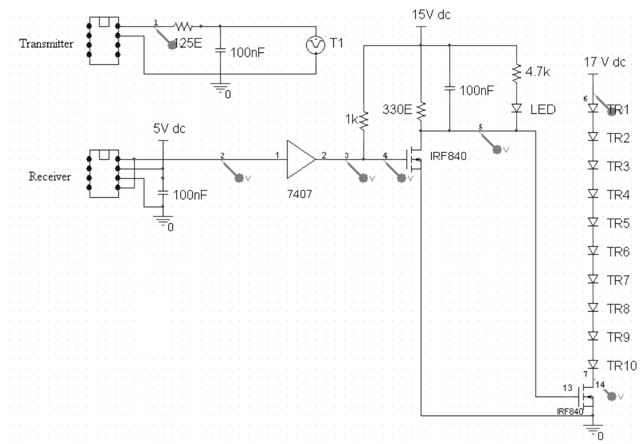


Figure 2. Circuit diagram of the transmitter and signal multiplication sections.

TABLE I. TIME DELAY MEASUREMENT

	First Probe	Second Probe	Time
1	Input from function generator (1)	Input of Transmitter	0 μs
	Signal Multiplier Segment		
2	Input from function generator (1)	Output of Receiver	1.2 μs
3	Input from function generator (1)	Buffer 1 input (2)	1.2 μs
4	Input from function generator (1)	Buffer 1 output (3)	1.2 μs
5	Input from function generator (1)	Gate of MOSFET 1 (4)	1.2 μs
6	Input from function generator (1)	Drain of MOSFET 1(5)	1.8 μs
7	Input from function generator (1)	Transmitter 5 input (6)	3.0 μs
8	Input from function generator (1)	Transmitter 10 input (7)	3.5 μs
9	Input from function generator (1)	Gate of MOSFET 2 ()	1.8 μs
10	Input from function generator (1)	Drain of MOSFER 2 ()	3.5 μs
	Receiver Segment		
11	Input from function generator (1)	Output of Receiver ()	4.5 μs
12	Input from function generator (1)	Buffer input ()	4.5 μs
13	Input from function generator (1)	Buffer output ()	4.5 μs
14	Input from function generator (1)	Gate of MOSFET ()	4.5 μs
15	Input from function generator (1)	Drain of MOSFET ()	4.8 μs
	Switch		
16	Input from function generator (1)	Gate of SCR	5 μs
17	Input from function generator (1)	Anode of SCR	5 μs

The signal multiplication stage starts with a fiber optic receiver. The output of the receiver is given to a MOSFET1 through a buffer. The output current of the receiver is of the order of 5µA to 250µA, which is not sufficient to trigger the MOSFET, so external current needs to be sourced. This is done with the help of a buffer. The pull-up resistance of the buffer is supplied with 15 V dc. The series connection is superior over the parallel connection and the same has been utilized for the gate trigger scheme for crowbar also.

Here, 10 transmitters are connected in a series connection to produce 10 simultaneous pulse trigger signals. The first transmitter is directly supplied with 17 V dc. The cathode of the tenth transmitter is connected to the drain of the MOSFET2. The output of MOSFET1 serves as the triggering signal for MOSFET2. Table 1 gives the node-to-node time delay measurement results.

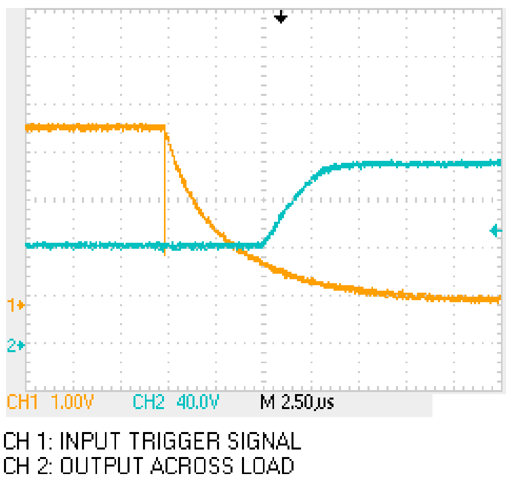


Figure 3. The final time delay measurement waveform

(iii) Receiver Section

The receiver section provides final trigger pulses to the crowbar switch. The triggering of 10 transmitters in the signal multiplier section produce optical pulses that would trigger 10 receiver cards, one for each transistor in the series switch. To conserve the significance of isolation, each receiver card has its own dedicated 5 V and 12 V power supplies.

The receiver card being void of transmitters does not have any high voltage (high current) requirement hence a 12 V dc is enough to drive the receiver section. The circuit design of the receiver section is similar to the transmitter card. The circuit design is shown in fig. 4. Apart from this, the equalizing network for transistor is also mounted on the receiver card, and has already been discussed before.

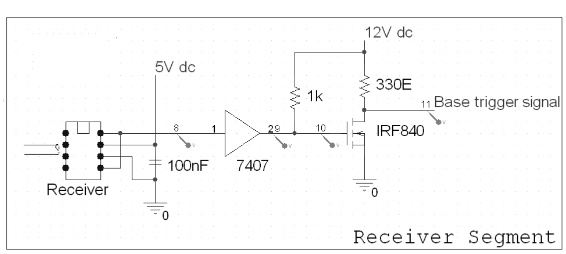


Figure 4. Circuit diagram of the receiver segment

The total time delay as mention above and shown in Fig.3 was found to be 5 µs, which is quite within our specified range. The switching time is of primary importance, but it is very important to test the switch at various voltage levels before it is implemented for high voltage applications.

The testing of the crowbar was done by charging the capacitor through the transformer. The primary side of the transformer was supplied through the variac. The input trigger to the transmitter was given only when the switch of the variac was turned off. All the tests were performed using this method.

V. TASTE RESULTS

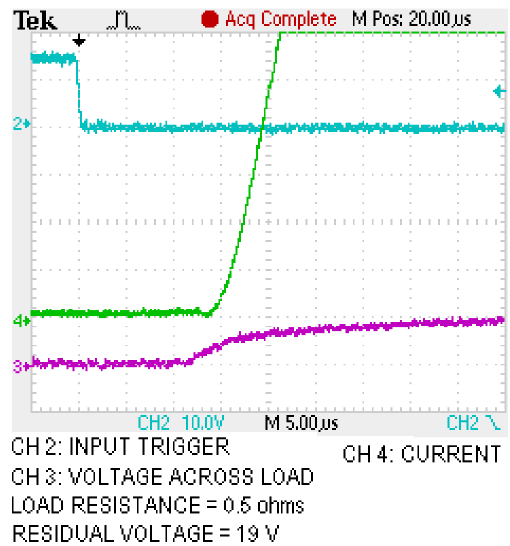


Figure 5. The waveform at 320 V

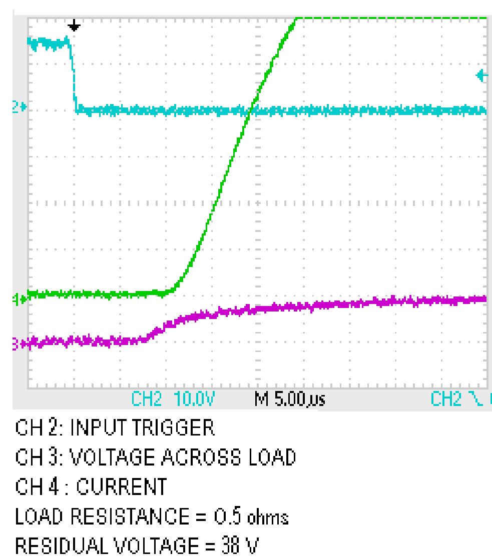
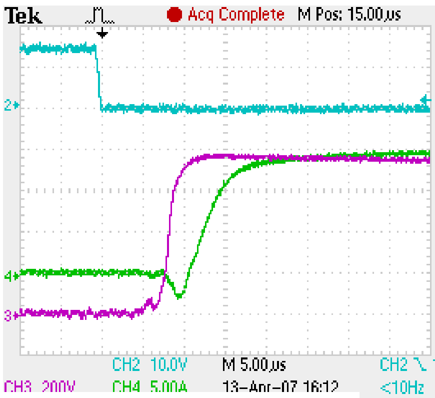
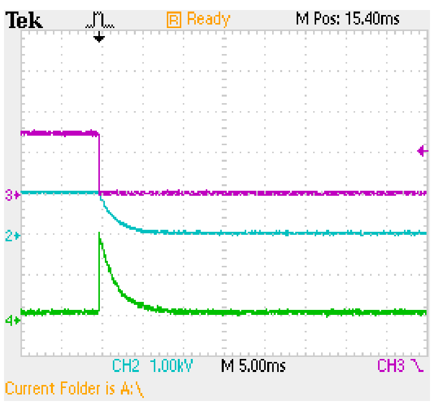


Figure 6. The waveform at 600 V



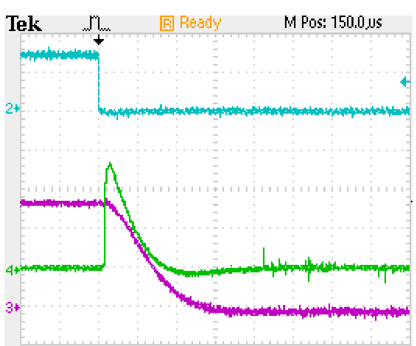
CH 2 : INPUT TRIGGER
CH 3 : VOLTAGE ACROSS CAPACITOR
CH 4 : CURRENT
RESIDUAL VOLTAGE = 35 V

Figure 7. The waveform at 800 V



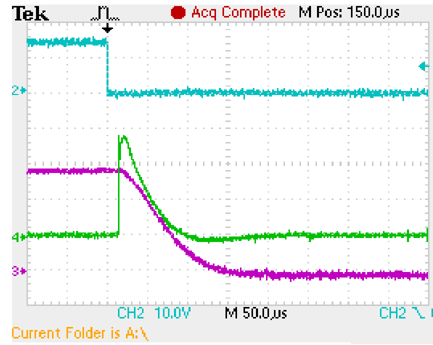
CH 2: VOLTAGE ACROSS THE CAPACITOR
CH 3: INPUT TRIGGER
CH 4 : CURRENT

Figure 8. The waveform at 1KV



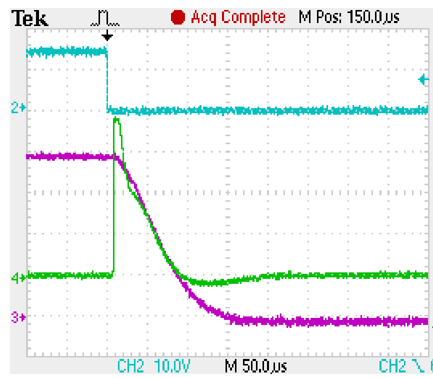
CH 2 : INPUT TRIGGER
CH 3 : VOLTAGE ACORSS CAPACITOR
CH 4: VOLTAGE ACROSS SHUNT
VOLTAGE ACROSS SHUNT = 10 V
CAPACITOR = 80 uF
RESISTANCE OF SHUNT = 3 milliohms.

Figure 9. The waveform at 1.3KV



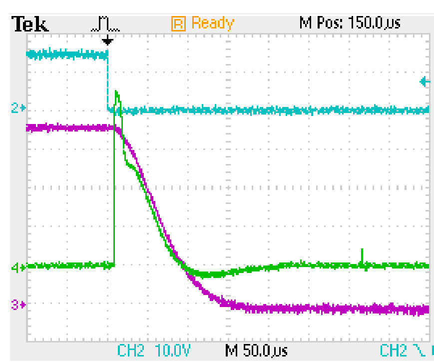
CH 2: INPUT TRIGGER
CH 3 : VOLTAGE ACROSS CAPACITOR
CH 4 : VOLTAGE ACROSS SHUNT
VOLTAGE ACROSS SHUNT = 20 V
CAPACITOR = 80 uF
RESISTANCE OF SHUNT = 3 milliohms

Figure 10. The waveform at 1.4KV



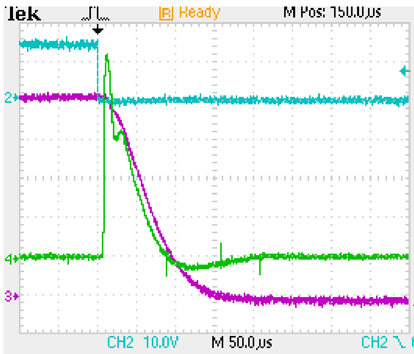
CH 2 : INPUT TRIGGER
CH 3: VOLTAGE ACROSS CAPACITOR
CH 4: VOLTAGE ACROSS SHUNT
VOLTAGE ACROSS SHUNT = 20 V
RESISTANCE OF SHUNT = 3 milliohms

Figure 11. The waveform at 2 KV



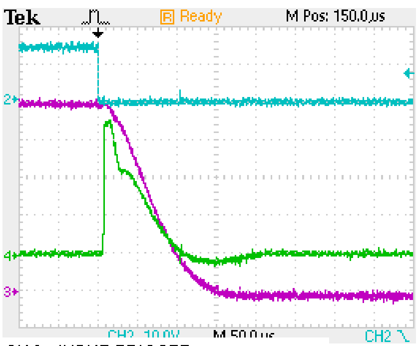
CH 2 : INPUT TRIGGER
CH 3: VOLTAGE ACORSS CAPACITOR
CH 4: VOLTAGE ACROSS SHUNT
VOLTAGE ACROSS SHUNT = 18 V
CAPACITOR = 80 uF
RESISTANCE OF SHUNT = 3 milliohms

Figure 12. The waveform at 2.35 KV



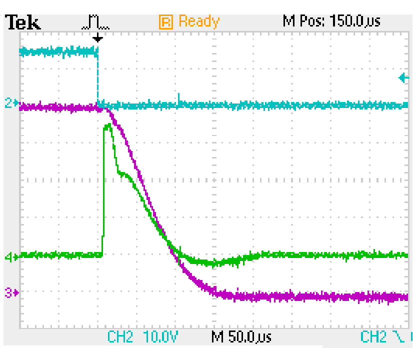
CH 2 : INPUT TRIGGER
CH 3 : VOLTAGE ACROSS CAPACITOR
CH 4 : VOLTAGE ACROSS SHUNT
CAPACITOR = 80 uF
RESISTANCE OF SHUNT = 3milliohms

Figure 13. The waveform at 2.5 kV



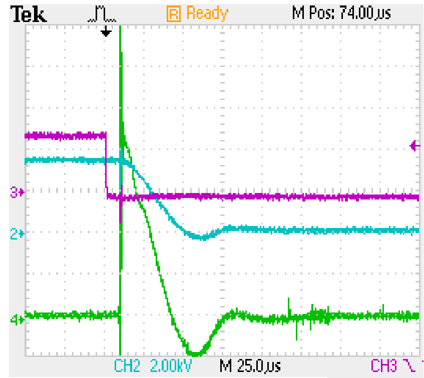
CH 2 : INPUT TRIGGER
CH 3: VOLTAGE ACROSS CAPACITOR
CH 4: VOLTAGE ACROSS SHUNT
CAPACITOR = 80 uF
INDUCTOR = 3 millihenry
RESISTANCE OF SHUNT = 3 milliohm

Figure 14. The waveform at 2.4 kV (with inductor)



CH 2 : INPUT TRIGGER
CH 3 : VOLTAGE ACROSS CAPACITOR
CH 4 : VOLTAGE ACROSS SHUNT
CAPACITOR = 80 uF
INDUCTOR = 3 millihenry
RESISTANCE OF SHUNT = 3 milliohms

Figure 15. The waveform at 2.5 kV(with inductor)



CH 2 : VOLTAGE ACROSS CAPACITOR
CH 3: INPUT TRIGGER
CH 4 : CURRENT
CAPACITOR = 20 uF

Figure 16. The waveform at 3 kV

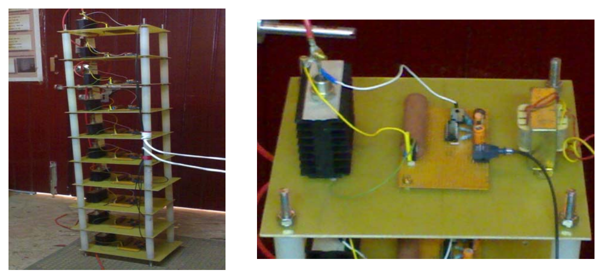


Figure 17. Photograph of the crow bar circuit and the receiver section

VI. OBSERVATIONS

(i) Gate triggering scheme:

As earlier mentioned, the output current of the receiver is not enough to drive the MOSFET. Hence, a buffer was introduced to source greater current. Also, LED (transmitter) being a current driven device requires adequate current for proper intensity. Hence, 15 V as MOSFET supply was not enough to light up the LEDs in the transmitter. The minimum voltage level was 15.5 V (each LED drops 1.54 V). Appropriate intensity of the LEDs was obtained at 17 V.

Also, the time delay between the transmitter and receiver (light propagation period) is a direct function of the intensity of light (current through the LEDs). Connecting the MOSFET at the end (configuration 2) of the transmitter series helped to increase the current at lower voltage levels.

(ii) High voltage test:

From the above waveforms (figure 4.1 to figure 4.13) it can be observed that the two waveforms are in phase with each other. In more precise words it can be said that the switch will close (short-circuit) when the trigger signal is transmitted by the arc detection system. Hence, a logic inversion stage is to be placed as a part of feedback card.

Also, we can observe that the ground line of the output waveform has been lifted above 0 V level. This indicates the presence of some leakage current when the switch is in off state.

VII. Conclusion

(i) Base trigger scheme:

From the experimental observations it can be said that to bring the switching periods in the stipulated time limits, it is very important to drive the transmitters with adequate current. This can be achieved by using two MOSFETs in configuration 2. With this configuration the total triggering period was measured to be 4.8 µs, quite within the stipulated limits.

(ii) High voltage test:

The total time delay observed between the instant the input trigger was given to the input to the transmitter and the closing of the switch was found to be 5 µs.

The time delay using the thyristor 51 RIA was satisfactory, but it can be still improved by using the thyristors of better rating. Great maturity can be observed in the design of the trigger circuit and the time delay results are encouraging.

Acknowledgment

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