

Synchronous Triggering of Multiple Spark Gap Switches

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Abstract: This paper presents Fiber optics based technique for synchronizing the operation of two or more spark gaps. The aim of this work is to configure a pulse power system where various gas filled spark gap switches can be synchronized for simultaneous operation or with a preset delay with accuracy better than 50ns to achieve higher pulse currents. Use of fiber optic allows the various high voltage circuits to be electrically isolated from each other and thus offering simplicity in trigger control. Power for trigger system can be derived from the electrical fields near the trigger, so all electrical cables to the trigger system are eliminated and replaced with a fiber cable that triggers the system. We have used commercially available fiber optical transmitter HFBR1404 and receiver HFBR 2402 to configure the optical interface. The delay between the transmitted pulses is generated electrically and thus can be precisely adjusted to attain desired value. A TTL high speed high current driver is used to generate an electrical pulse which is converted to optical trigger pulse by fiber optic transmitter. The leading edge of the pulse is used for timing reference and pulse width is not important. fiber optic receiver converts the optical signal back to electrical signal which is further used to trigger gas filled spark gap.

Key words: SPARK GAP, SYNCHRONOUS TRIGGERING, FIBER OPTIC TRIGGER, SYNCHRONIZATION OF SPARK GAP, TRIGGERING PULSE POWER SWITCHES.

1. INTRODUCTION

Most of the time, in Electrical systems, pulsed power is generated by first storing the energy for a long duration both feasible and desired for an application. High energy storage capacitor or a Marx bank usually needs a shorting (Closing) switch for transferring the stored energy in a capacitor or in an inductor and then releasing it over a comparatively short period of time as may be technologically feasible into the load, while an opening type of switch is required to commute inductively stored energy. Switches are most critical part of pulse

power technology and their operating characteristics like breakdown voltage, peak current discharge, jitter, switch on time etc influence the overall design, capability and performance of the system. Usage of different kinds of switches like magnetic switch, semiconductor switch i.e. Thyristors/ MOSFET/ IGBT, pseudo spark gap switches etc. are reported in research papers. Use of spark gap switches is worldwide accounted as a controlled switch [1, 2].

There are various applications in pulse power technology which require i) high peak current through a single load, ii) pulsed current through isolated loads simultaneously or iii) operation of two or more pulsed currents with a certain amount of time delay between them. For case (i), either a single circuit may be used with component ratings good enough to meet the requirement, or else two or more circuits with similar ratings, may be simultaneously fired to accomplish the desired results when components with higher ratings are not easily available. For case (ii) and (iii), two or more circuits need to be accurately synchronized for desired results. When two or more high energy electrical circuits are fired, several issues like spurious triggering due to noise, ground isolation, synchronization etc. need to be taken care of for proper functioning. Pulse discharge circuits are always accompanied with fast changing electromagnetic fields and large ground currents. They induce noise spikes in other electrical circuits or their own circuits. When digital circuits are used to control and synchronize timings, this noise which has peak value several times the magnitude of supply voltage, if not taken care of properly, can not only lead to false triggering but also cause failure of components in many cases. Filters can be employed to reduce the noise to some extent but cannot be eliminated completely. Since pulse discharge circuits are accompanied with high magnitude fast rising and

falling currents and voltages, operating two or more pulsed circuits require careful grounding to ensure proper operation. Variation in device characteristics like propagation delay and jitter in switches can lead to synchronization issues if synchronization timing requirements are high.

To achieve a high output current beyond the capability of a single switch, various topologies for simultaneously triggering the switches have been followed. Figure 1 shows some of topologies in common use for synchronizing multiple pulses discharge circuits. Usage of Marx generator [3] for the voltage addition, where multiple switches are synchronized automatically by the overvoltage forces generated by closing of first switch, are very well documented and used for the industrial and defence applications. Figure 1 shows various options for multiple switch topologies.

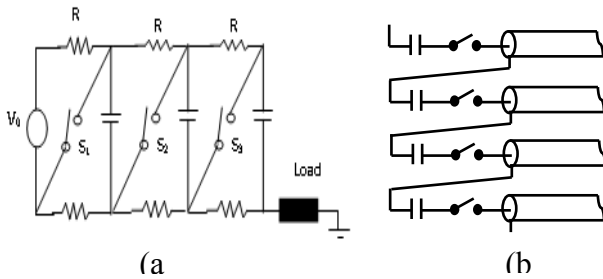


Fig 1. a) Schematic of Marx generator with three switches b) TLT based approach for multiple switching

Another recent approach listed in literature and as shown in figure 1(b) for triggering multiple spark gap switches is based on transmission line transformer (TLT) technique where the capability of switching multiple spark gap either in series (for high voltage generation) or in parallel (for current multiplication) are utilized. However this technique has limitation of number of spark gap that can be synchronized because of overvoltage requirement of closing the switch [4, 5, 6]. Moreover, in general, as number of discharging circuits increase, coupling of noise to electrical cables increases. This may result in false triggering and synchronization mismatch. Solution to this problem is optical isolation of the control operation of switch from discharge circuits through fiber optic links which provides several advantages in circuit implementation. Lasers have been used to trigger spark gaps through fiber optic links directly [7] for isolation and controllable switching delay. Fiber optically controlled trigger generators based on conductive semiconductor switches (PCSS) have been used to trigger the high

voltage switches in pulsed power systems where they control the timing synchronization and amplitude variation of multiple pulse forming lines that combine to produce the total system output [8, 9]. As rise time and pulse widths get shorter, the requirements for synchronization increase. Furthermore, applications with specific or controllable pulse shape requirements demand modules that can be independently triggered to deliver their energy packets. This work is different and unique from earlier works based on fiber optic links as we are using fiber optic links for transmission of trigger pulse only. Generation and control of timing is based on electrical circuitry which makes it very simple to implement trigger control. Optical trigger pulse after reception is converted back to electrical trigger pulse and standard trigger circuit is used to generate electrical trigger for spark gap. The overall circuitry is very simple and can be implemented easily. As trigger control is electrical, it offers very high flexibility and versatility in triggering requirements of different applications.

2. THEORY OF OPERATION

This paper describes the implementation of Fiber optic based technique using spark gap to synchronize two pulse discharging circuits. Spark gap switches are most commonly used as closing switches for controlled release of energy into the load over a short duration. We have selected spark gap switches for this study for their suitability of performance in required voltage and current range and easy availability. A schematic of capacitor discharge circuit using a spark gap is shown in figure 2.

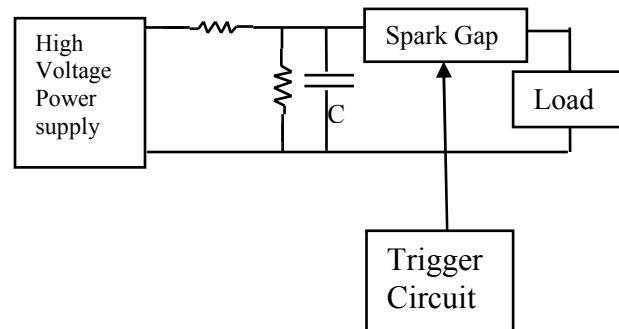


Fig 2. Schematic for the discharge of the capacitor through load with the spark gap switch on triggering through external trigger circuit.

Capacitor C is first charged to required voltage. When trigger pulse is applied by trigger circuit, the spark gap switch closes and energy is released in the

load. For synchronous operation, two or more such circuits are to be synchronized. For this, trigger pulse is generated for each circuit and required delay is provided in the trigger pulses. To electrically isolate the trigger circuits, the trigger pulses are converted to optical pulses and sent on fiber optic links of equal lengths so that they do not introduce additional delay. An optical to electrical converter near the trigger circuit converts back the optical

pulse to electrical pulse, and operates the trigger circuit which fires the individual spark gap switch.

3. EXPERIMENTAL RESULTS & DISCUSSION

A. Synchronous triggering without delay

Block diagram of the system shown in figure 3(a). Schematic of spark gap switching circuit of experimental set up is shown in figure 3(b). For our experimentation we have synchronized two

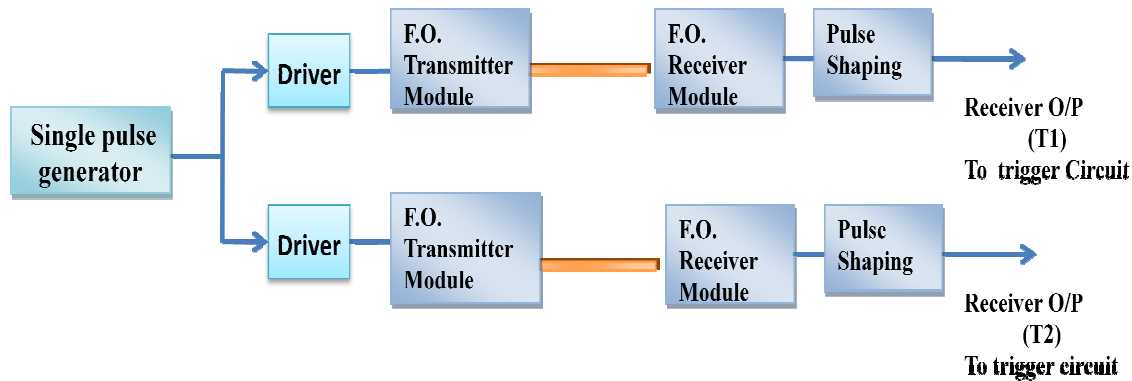


Fig 3a. Block diagram showing circuit connected through fiber optic link

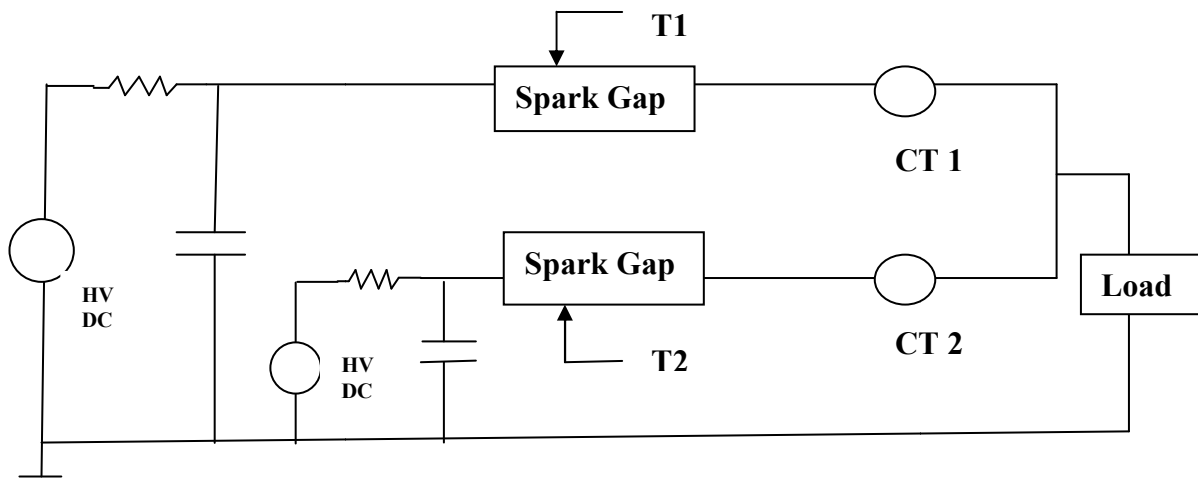


Fig 3b. Circuit Diagram of experimental set up showing the switching circuit.

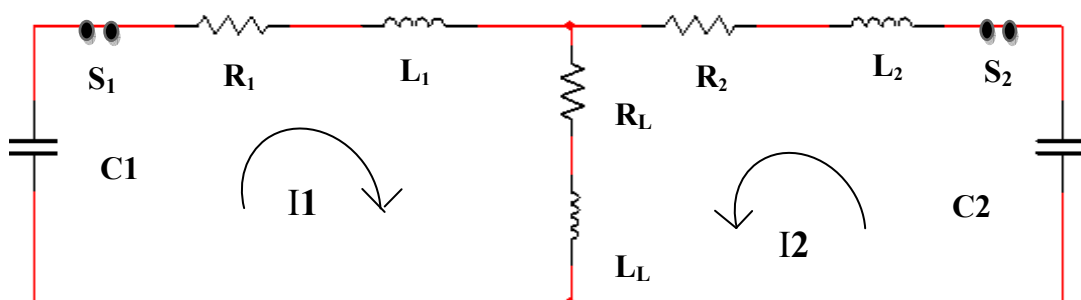


Fig 3c Equivalent circuit Diagram for the main configuration

circuits discharging into a common load simultaneously and with varying delays. The circuits were first individually charged to 3kV supply. Inductive load of 1.35 μ H was used. Capacitor of value 1 μ F was used for storing initial energy. Spark gap used has self breakdown voltage of 5kV. Equivalent circuit diagram is shown in the figure 3c. Initially two identical capacitors C1 and C2 are charged up to the voltage V_0 . High voltage fast rising pulse is fed between trigger pin and corresponding electrode of spark gap switch [10,11], it will start conducting get closed. Current starts to flow in the two separate circuits and get accumulated at load with the direction shown in the figure 3c. R1, L1 and R2, L2 represents the circuit lead resistance & inductance respectively of the two loops and load is represented by its RL and LL value. When both switches (S1 and S2) are closed, from the equivalent circuit figure, one can write the following equation

$$V_0 - \frac{1}{C_1} \int I_1(t) dt - I_1(t) * R_1 - L_1 * \frac{dI_1}{dt} - (I_1 + I_2) * R_L - L_L * \frac{d(I_1 + I_2)}{dt} = 0 \quad (1)$$

$$V_0 - \frac{1}{C_2} \int I_2(t) dt - I_2(t) * R_2 - L_2 * \frac{dI_2}{dt} - (I_1 + I_2) * R_L - L_L * \frac{d(I_1 + I_2)}{dt} = 0 \quad (2)$$

In the above equation, $I_1(t)$ and $I_2(t)$ are the currents through switches S1 and S2 respectively. For simplicity sake, we can consider that both the circuits are identical i.e. $C_1 = C_2$ and $L_1 = L_2$ and neglecting lead resistance and inductance as compared to load resistance and inductance, we can obtain the following expression for $I_1(t)$ and $I_2(t)$

$$I_1(t) = I_2(t)$$

$$I(t) = I_1(t) + I_2(t)$$

$$I(t) = \frac{V_0}{\omega_n L} * \exp(-\alpha t) * \sin(\omega_n * t) \quad (3)$$

Where

$$\alpha = \frac{R}{2L}$$

$$\omega_n = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}$$

$$C = C_1 + C_2$$

V_0 = charging voltage

R = load resistance

L = load Inductance

Photograph of experimental set up is shown in figure 4. Easily available commercial components were chosen for design of transmitter and receiver circuits since synchronization timing requirement was about 50ns. For transmitter circuit, 74AC14 was used as driver and HP 1404 was used as optical transmitter. Transmitter 7414 has propagation delay of 10 ns and HP 1404 has a typical rise time of 4 ns. The receiver 2402 has a typical propagation delay of 60 ns.

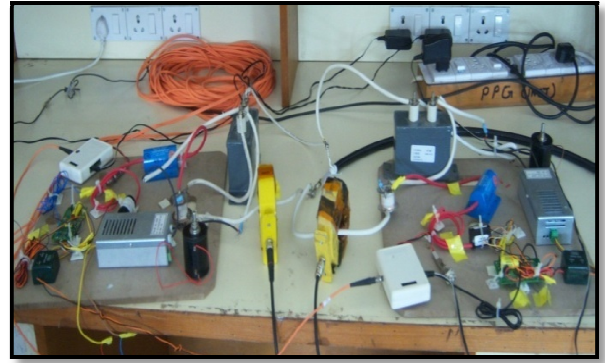


Fig4. Photograph of configured pulse power system

This electrical pulse was fed to a MOSFET circuitry which generates trigger pulse for spark gap switch. This has a typical turn on delay of 13 ns and rise time of 7 ns. Since the same delays are occurring in both the channels, both channels will be delayed by approximately same time. Usually, the variation in delay will be much less than 10ns.

Further, this delay will not vary much with time as this delay is on account of variation in individual component fabrication. This variation in total delay from electrical pulse at transmitter end to the trigger pulse for MOSFET can be precisely adjusted by introducing additional electrical delay in one of the channel. The delay introduced due to fiber optic cable was same for both the channels since the same cable length was chosen for both channels as 50m.

The peak current and the time for current to obtain peak value come to about 4.3 kA and 1.6 μ s respectively for individual channel which can be obtained using the discharge equation(3). Records obtained for the simultaneous triggering of above circuit into a common load is shown in figure 5.

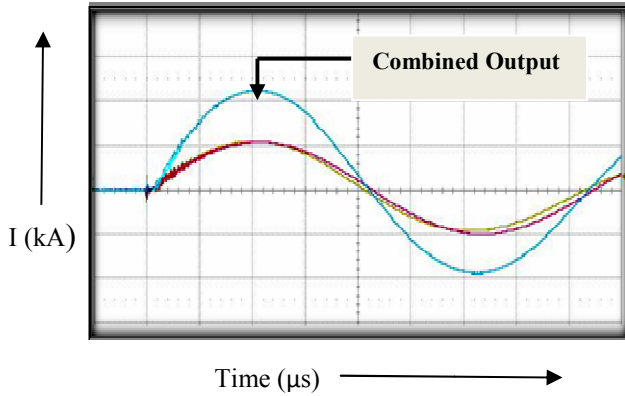


Fig 5. Output current waveform when two spark gap switches triggered simultaneously into a common load. Y-axis represents 2 kA/div and X-axis represents 1 μ s/div

Figure 6 shows record of trigger voltage at MOSFET. Synchronization mismatch delay of about 10 ns was observed which is well within the synchronous timing requirement of 50ns. This was tolerable for simultaneous discharge of two current waveforms. The slight mismatch of triggering does not affect much the total added up current for the case when peak current requirements through a single load are high as the sinusoidal wave is almost flat near the peak value. To get tighter tolerances on delay, faster driver ICs like 74F3703, transmitters and receivers should be used. The variation in delay can be reduced to less than 10ns by using these faster devices.

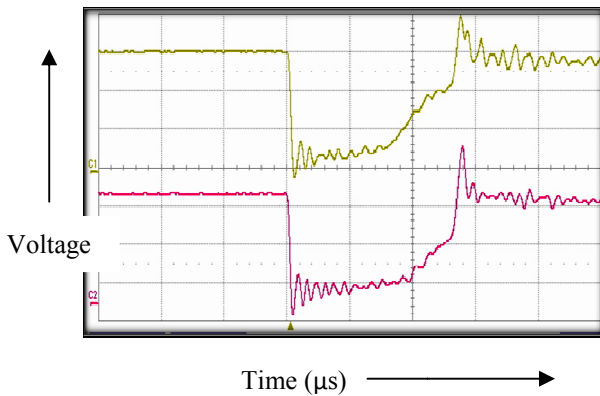


Fig 6. Trigger waveform at the MOSFET drain of two simultaneous fired channels. Y-axis represents 100V/div and X-axis represents 200 ns/div.

B. Delayed Synchronous triggering

Delayed triggering can simply be achieved by electrically delaying one transmitter pulse channel with the required delay using commercially available ICs. A delay of 200ns was introduced in one of the channels. The delay was monitored at the drain of MOSFETs of both the channels and is shown in figure 7. Again the variation in delay observed was less than 10ns. Another delay of 600ns was introduced in one of the channels. The current waveforms were monitored on the oscilloscope and are shown in figure 8. The observed delay in current was 611ns.

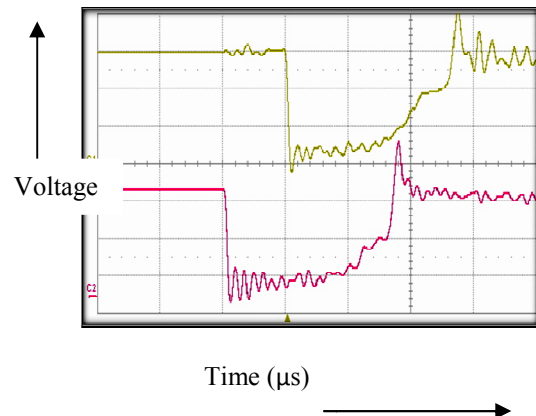


Fig7. Voltage waveform at the drain of two MOSFETs which is used to fire two spark gap switches. A delay of 200ns is given to trigger pulse of channel 1. Y-axis represents 100V/div, X-axis represents 200ns/div

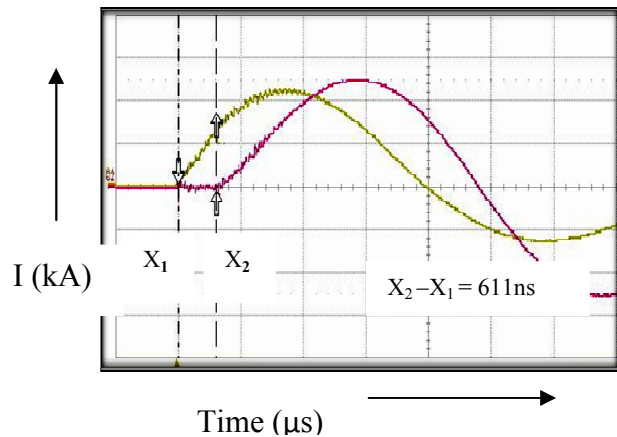


Fig 8. Output Current waveform record when two spark gap switches are triggered with delay of 600ns given to trigger pulse of channel 2. Y-axis represents 1 kA/div, X-axis represents 1 μ s/div.

4. Conclusion

Two or more pulse power systems can be very effectively synchronized using fiber optic based technique. This technique not only provides

electrical isolation which is inherent to fiber optic based system, but also allows complete control of delays between two pulse power systems by the use of easily available electronic components. The trigger electronics is electrically isolated from the high voltage switching circuits which provides immunity from high voltage transients and can easily be controlled from a large distance. Several pulse power systems can be connected through fiber optic link and synchronized easily. The delay between the transmitted pulses is generated electrically and thus can be precisely controlled as per requirement. Two or more pulsed power systems may also be synchronized for zero delay to increase the peak current through a single load. Any delay mismatch between the components can also be catered for by adding/subtracting additional delays. The whole scheme is extremely versatile and can be implemented using easily available components.

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