SOLID STATE SPARK GAP REPLACEMENT SWITCHES

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Abstract

Improvements in solid state high voltage switching technology now make it feasible to replace triggered spark gap switches, used in many medical and commercial applications to switch tens of kilovolts and thousands of amperes, with compact solid state switches. We have developed a multi-stage high voltage solid state switch that is triggered by a single 10 V isolated trigger pulse to only one stage thereby reducing the size and decreasing the triggering complexity of the switch. The switch uses small 5300 V thyristors capable of 14 kA peak currents and > 25 kA/µs rate of current risetimes. The short turn-on delay, less than 200 ns, makes the switch suitable for crowbar applications.

This paper will include a description of the solid state switch and triggering system as well as show data from a 24 kV system using both the spark gap and the solid state replacement switch to discharge a 0.15 µF capacitor at 1.5 pps. The switch current has a ringing discharge with a peak forward value of 10kA and a quarter cycle time of 500 ns. The overall size of the solid state switch, including the fins required for convective cooling at several pps operation, is 2" x 4" 6.5".

These switches are used commercially in Lithotripters, a medical system that effectively treats renal and urinary calculus by fragmentation of kidney and ureteral stones.

INTRODUCTION

Triggered spark gap switches and thyratrons are used in many applications, including medical linacs, lithotripters, and lasers. These switches suffer from short lifetimes and expensive replacement costs and are therefore being phased out in favor of solid state replacements. However, these solid state replacements have been larger and more difficult to utilize than the triggered spark gap switches they replace. We have developed a triggering technique which reduces the size of the solid state switches as well as their complexity.

Because existing commercial thyristors cannot operate at tens of kilovolts, multiple devices in series are required. In many cases a snubber circuit, comprised of a capacitor in series with a resistor, connected in parallel with the thyristor is also required for proper operation. A snubber circuit may be used to ensure equal voltage distribution between the multiple devices in series as the voltage across the switch changes. Triggering the individual devices can be a complicated task, since each device is floating at a different voltage.

This paper describes a low cost method for triggering a high voltage solid state switch comprised of a set of thyristors connected in series. The thyristors all have snubber circuits. Initiating switch turn-on requires command triggering of only one thyristor. This causes the voltage drop across the other devices to rise, resulting in current flowing through the snubber circuits to charge the snubber capacitors. This current flows from the external circuit which supplies the required energy. Because the capacitance of the snubber capacitors is small, this energy is a very small fraction of the total switched energy. Using a transformer, a portion of the snubber current is coupled to the gates of the thyristors, triggering the thyristors. The thyristor stages are connected in series and experience the same snubber current, resulting in simultaneous turn-on of all stages. The components used to initiate triggering of each stage are at the potential of that stage so that no high voltage isolation is required. This makes for a compact, inexpensive triggering system enabling thyristor stages to be stacked in series to create very high voltage switches.

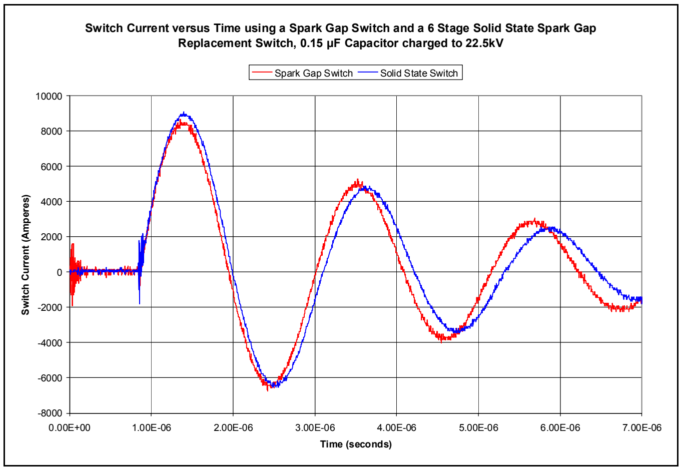

Fig. 1. Comparison of Switch Currents for a Solid State and a Spark Gap Switch

Fig. 1 shows a comparison of load current from the discharge of a 0.15µF capacitor switched by either a spark gap or the solid state switch. The size of the switch, shown in Fig. 2 attached to the capacitor, is 2" x 4" x 6.5". Testing was done at 2 pps with the capacitor charged to 22.5 kV.

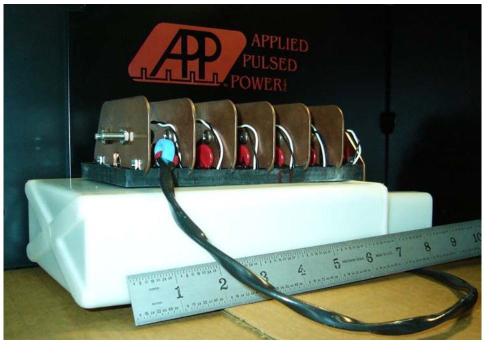

Fig 2. 24 kV, 10 kA Switch installed on 0.15µF Capacitor

SWITCH DESCRIPTION AND PERFORMANCE

A block diagram of the switch in a typical application is shown in Fig. 3. The switch consists of a command triggered stage in series with several auto triggered stages. A gate drive unit is used to trigger the command triggered stage. In Fig. 3 the command triggered stage is shown located at one end of the switch, convenient if this end of the switch is at ground potential. However, the command triggered stage can be located anywhere in the switch stack and the switch performance will be unaltered.

A schematic for one implementation of the auto triggered stage is shown in Fig. 4. The thyristor has a voltage hold-off greater than 5kV and can conduct greater than 10 kA for 10µs pulses at rates of current risetime of > 30kA/µs. R1, which typically has a resistance of equal to or greater than 10 megaohms, is in parallel with the thyristor and helps insure equal voltage sharing between the series connected switch stages. Snubber capacitor C1 and resistor R2 have several functions. One function is to help maintain equal voltage sharing between the series connected switch stages during turn-on and turn-off of each stage. Also, the energy stored in C1 is discharged through the thyristor as the thyristor begins to turn on. This can increase the rate of turn-on.

Trigger transformer T1 has a small saturable magnetic core. The one turn primary of the transformer is connected in series with the thyristor. The secondary is connected in a full wave center-tapped rectifier configuration. Diodes D1 and D2 are 400V fast recover rectifiers. Resistor R3 limits the peak gate current to the thyristor gate.

The command triggered stage is triggered and the voltage across this stage begins to fall. Because the remaining switch stages are still in the off state and the total voltage across the switch remains the same, the voltage across these stages begins to increase. As an example, if there are N identical auto triggered stages, then the voltage across each auto triggered stage rises from $(V_{switch}-V_{comand\ triggered\ stage})/N$ to V_{switch}/N. For fast switching thyristors the auto trigger stages will start to turn on well before the V_{switch}/N voltage is reached. In order for the voltage across each stage to increase, current must flow through the snubber resistor to charge the snubber capacitor. The magnitude of the current is proportional to the product of the snubber capacitance and the rate of increase of the stage voltage. The peak current can be tens of amperes or more if the command stage turns on rapidly, as is usually required for high current switches. This current flows from the external power supply or energy storage network and through the switch.

As can be seen in Fig. 4, this current flows through the primary of transformer T1, resulting in a current through the secondary, gate resistor R3, and thyristor gate which turns on the thyristor. The volt second product of the saturable magnetic core transformer is selected based on the turn-on characteristics of the thyristor. As the switch begins to turn-on, the transformer saturates and the primary inductance falls to a value of a few nanoHenries, the voltage drop across the primary becomes very small. The transformer secondary has multiple turns so that even after saturation there is still sufficient voltage across the secondary to provide positive gate current as long as the switch is conducting. The full wave rectifier configuration ensures positive gate current regardless of the direction of current flow through the thyristor. Fig. 5 shows the gate current at one auto triggered stage for a six stage switch with one command triggered stage discharging a 15 kV, 0.15µF capacitor into a 0.25 Ω inductive load.

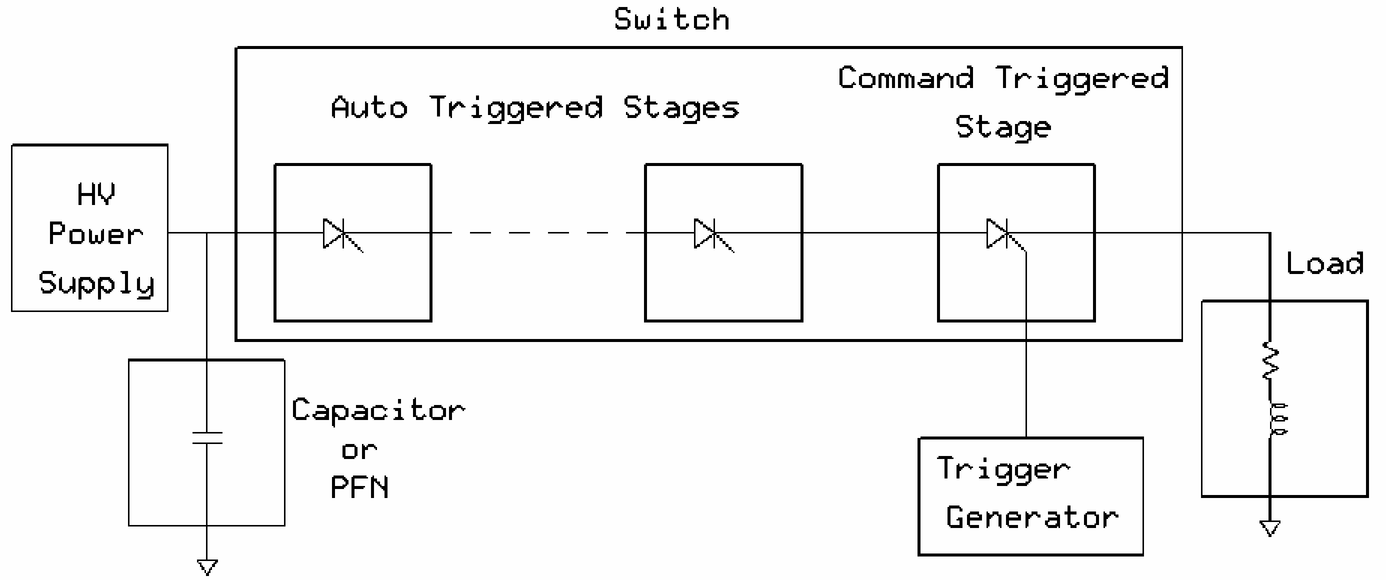

Fig. 3. Block diagram of the Switch in a Typical Circuit Configuration

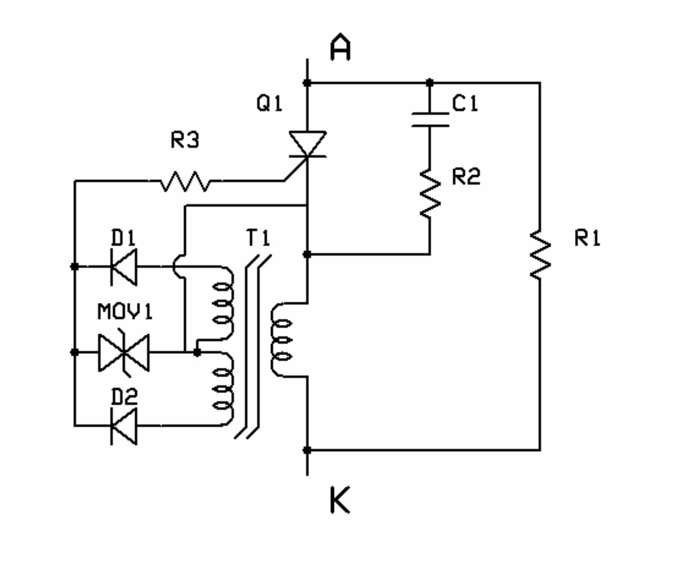

Fig. 4. Schematic of the Auto Triggered Stage

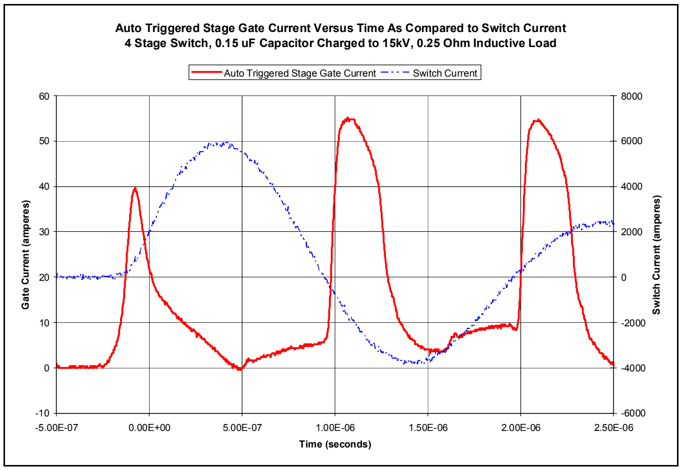

Fig. 5. Load and Gate Current for an Auto-Triggered Stage

The primary inductance adds to the total inductance of the switch. However, for fast turn-on thyristors, a one turn primary winding can be made by routing the cathode lead of the thyristor through a small toroidal ferrite core. Then the inductance of this winding, when the core saturates, can be small compared to the total stage inductance.

The rate of change of the voltage (dv/dt) across the switch when the energy storage network is charged must be much smaller than the dv/dt during the initial turn-on phase in order to keep the snubber current below that required to initiate turn-on of the thyristor. This is usually the case for high-peak power low-duty cycle applications. For example, a switch operating at 24 kV and discharging 100 times a second will experience a dv/dt of ~ 3 V/µs during the charging phase and > 1000 V/µs during the initial turn-on phase. The value of the snubber capacitance and the design of the trigger transformer must be selected to avoid auto triggering of the switch during the charging phase. The auto triggered stages are connected in series and experience the same snubber current, resulting in simultaneous turn-on of all these stages. For switches requiring a large number of stages, it may be desirable to use several command triggered stages to increase the dv/dt across the auto triggered stages in order to increase the snubber current.

During the initial turn-on phase, the voltage across the auto triggered stages increases. Some of this increased voltage is dropped across the trigger transformer until it saturates while the rest is added to the initial voltage drop across the thyristor. Because thyristors typically should be operated at no more than 60-75% of their maximum hold-off voltage to prevent spurious triggering, this increase in voltage, present for < 1 µs, will not exceed the hold-off rating of the thyristor. For most applications, this means no more stages are required than would be for a switch in which all stages are command triggered. Measurements of the voltage across an auto triggered stage of a 6 stage switch blocking 22.5 kV show the stage voltage increasing to a peak of 4.1 kV from 3.75 kV. Only a portion of this voltage increase is seen by the thyristor. Within 100 ns from the command triggered stage starting to turn on, the stage voltage on the auto triggered stage described above has fallen below 3.75 kV.

The result of this method is a small increase in turn-on time and in switch inductance. For example, turn-on times may increase from 60ns to 100ns and inductance from 10nH per device to 15nH per device. Fig. 6 shows the temporal relationship between the gate currents for the command and auto triggered stages and the switch current for a 6 stage switch operating at 15 kV.

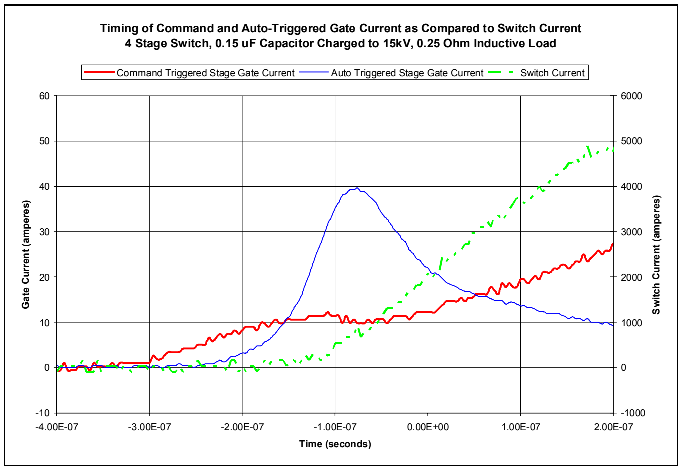

Fig. 6. Timing of Gate Currents in Command and Auto-Triggered Stages versus Switch Current

Several alternate implementations of the auto triggered stage are possible. One example is shown in Fig. 7. In this circuit the primary of the trigger transformer is in series with the snubber capacitor but not with the thyristor. When the command triggered stage begins to turn on, the resulting increase in snubber current through the primary of the transformer produces a current pulse in the secondary, triggering the thyristor as in the previously described approach. However it is not necessary for the transformer to saturate. When the thyristor turns on, the snubber current reverses direction as the snubber capacitor is discharged through the thyristor. The full wave rectifier configuration couples some of this current to the gate, ensuring positive gate current during the high di/dt phase of current conduction through the thyristor. Gate and switch current waveforms for an auto triggered stage switching a 1.68 µF PFN are shown in Fig. 8. The advantage of this configuration is the removal of the transformer from the main current path which eliminates the inductance penalty. One disadvantage of this approach is the fact that when the switch is on and the snubber capacitors have discharged, there is no gate current, which prevents this configuration from being used for applications where there is a substantial delay between switch closure and the start of high di/dt current through the switch.

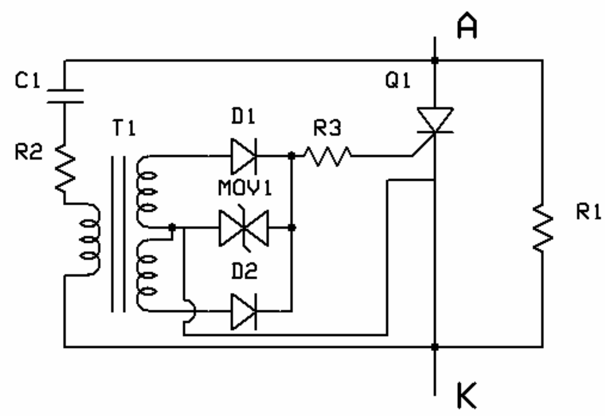

Fig. 7. An Example Schematic of an Alternate Implementation of the Auto Triggered Stage

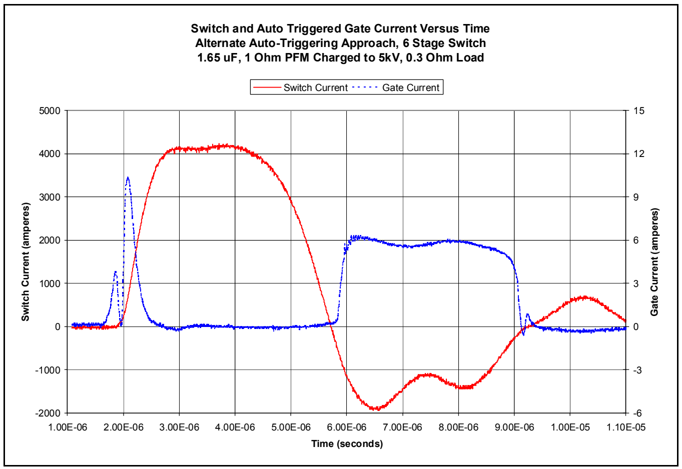

Fig. 8. Switch and Auto Triggered Gate Current using an Alternate Auto-Triggering Approach

APPLICATIONS

A current use of this switch is to replace 24 kV spark gap switches used in Lithotripters. The load for this application is a water insulated spark gap that produces shockwaves in the water when the gap breaks down. The shockwaves are focused and used to shatter kidney stones. This application requires a fast closing switch to produce a rapidly rising voltage pulse at the water gap. A high di/dt current pulse through the water gap is also required, but the start of this current does not occur for up to several microseconds after the switch closes. Fig. 9 shows load voltage and current waveforms for a Lithotripter using the solid state switch. This switch, shown in Fig. 2, has operated at up to 2 pps with a maximum peak current of 9kA at 22.5 kV using convective cooling.

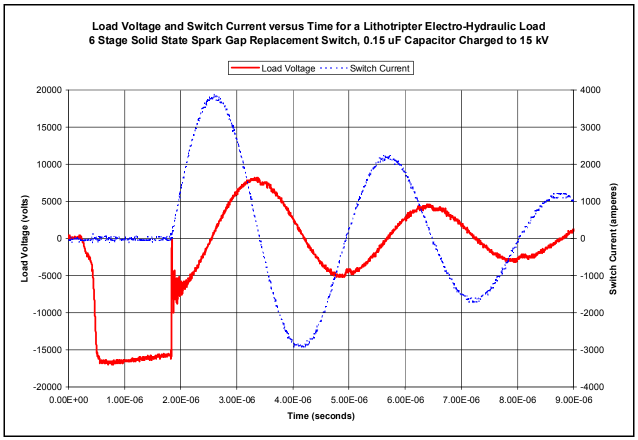

Fig. 9. Load Voltage and Switch Current of the Switch in a Lithotripter

Applications requiring greater repetition rates can be accomplished by using forced air cooling and/or larger fins or water cooling. Other configurations of the switch can be used to meet different voltage and current requirements.