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Comparative Study of Different High Voltage Switches Used in Pulsed High Voltage Application

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Abstract

High-voltage switches play a crucial role in pulsed power applications, where the efficient and reliable control of high-voltage pulses is required. This study aims to compare different types of high-voltage switches commonly used in pulsed power systems including electromechanical switches, vacuum switches, gas-filled switches, triggered spark gaps and solid-state switches. The comparison study focuses on key performance parameters such as voltage handling capability, current carrying capacity, turn-on time, and repetition rates are considered to provide a comprehensive study and analysis of the switch's suitability for different pulsed power applications. Gas-filled switches such as spark gaps, thyratrons and ignitrons have been used in pulsed power systems due to their high voltage handling capability and low switching losses. However, they suffer from a limited lifetime and require maintenance and periodic replacement. Solid-state switches, i.e. Silicon-Controlled Rectifiers (SCRs), Insulated Gate Bipolar Transistors (IGBTs) and Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) offer advantages in terms of longevity, reliability, and reduced maintenance. However, they have limitations in high-voltage applications and exhibit higher switching losses. The findings of this comparison study will assist researchers, engineers, and system designers in selecting the most appropriate high-voltage switch for pulsed power applications, considering the specific requirements and constraints of the system. This will ultimately contribute to the advancement and optimization of pulsed power technologies across a wide range of scientific, industrial, and strategic applications.

Keywords: High Voltage, High Voltage Switches, Pulsed Power, Solid State Switches

1. Introduction

A Pulsed power system stores energy over an extended duration and releases it in intense bursts which allows the high-power generation in levels of gigawatts in terms of short pulses of nanoseconds (ns) to microseconds (μs) of duration which may not be achievable with continuous power source[1].

A pulsed power system consists of several components like energy storage elements, like capacitors and inductors which store electrical energy for a long period Pulse Forming Networks (PFN) are used for sharpening the pulses which consists of capacitors and inductors and high voltage switches in specific configuration[2].

High voltage and high-power switches are also important components in this pulsed power system because they govern and transfer stored energy from energy storage devices to load quickly. High power and high voltage switches are divided into two primary types based on their operation closing switches and opening switches. "Terms such as 'opening' or 'closing' are used to describe which transitional state of the switch is controlled to achieve the desired circuit function"[3]. In comparison, opening switches are less common than closing switches. They are frequently employed in the inductive system.

The parameters used to evaluate the performance of the pulsed power switch are very similar, while the terminology for pulsed power switches might be

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dissimilar, the switch parameters are generally described and defined as follows[4]:

Hold-off voltage – The voltage also known as gap voltage, self-breakdown voltage, or blocking voltage, is the upper limit of voltage applicable across switch electrodes without causing its breakdown; typically measured in volts (V) or kilovolts (kV).

Peak current – The highest current carrying capability of the switch. Which is typically measured in ampere (A), or kilo ampere (kA).

dI/dt rating– The permissible rate of current change to be applied without causing damage to the device, which is measured in amperes per second (A/s).

dV/dt rating – The permissible voltage change rate, usually quantified in volts per second (V/s).

Turn-on time –The time it takes for the switch to transition from the off state to the fully conducting or closed state, allowing the flow of current through the switch.

Delay time – The duration between activating a trigger command and the initiation of switching conduction, often measured in seconds (s), microseconds (μs), or nanoseconds (ns).

Rise time – The time taken by the signal or waveform to make the transition from a 10% level to a 90% level of the signal's amplitude.

Fall time – The time taken by the signal or waveform to make the transition from a 90% level to a 10% level of the signal's amplitude.

Jitter – Statistical variation in latency. This duration is usually measured in nanoseconds (ns) or microseconds (μs). Sufficient energy is needed to accelerate charge carriers and move them into the gap, leading to "turn-on" and sustained conduction.

Recovery time – The time it takes for the dielectric properties of the switch to recover and allow the voltage to be reapplied at the specified rate (dV/dt).

Forward drop – while transitioning into the "turn-on" phase, the voltage dips across the switch impedance.

Repetition rate – The Frequency at which the switch can be activated without deterioration of properties which is commonly measured in Hertz (Hz) or kilohertz (kHz).

Lifetime – This refers to the duration during which it can reliably and efficiently perform its intended function.

Full-width half modulation - Represents the distance between two points on the curve where the intensity, amplitude, or power drops to half of its maximum value.

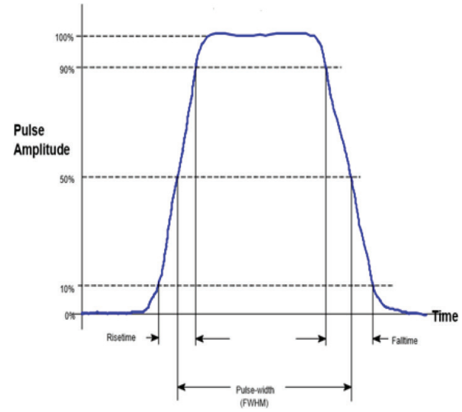

Figure 1. Pulse wave shape.

2. Electromechanical Switches

These switches use a combination of mechanical and electrical principles to establish or disrupt the current channel. These switches as opposed to electronic switches physically open or close a circuit by moving mechanical components. The voltage and current ratings of the switch as indicated in Table 1 but disadvantages are as large as jitter and poor as an opening switch and low repetition rate due to low recovery time[4].

3. Vacuum Switches

These switches are opposite to standard electromechanical switches and work by using the principles of gas discharge within a sealed enclosure to create a low-pressure environment or vacuum. Because of this distinguishing feature, vacuum switches provide various advantages over traditional switches, including greater insulating qualities, increased dependability, and improved performance in high-voltage or high-frequency applications. The voltage and current ratings are as indicated in Table 1 but these switches are high-cost compared to conventional switches.

4. Gas Filled Switches

Gas-filled switches are specialized electrical devices that control the flow of electric current by using ionized gas. To build and break electrical connections, these switches make use of the unique qualities of gas discharge[3,4]. Because of its capacity to tolerate high voltages, large currents, and quick switching speeds, gas-filled switches are suited for a wide range of applications.

4.1 Spark Gap Switches

These switches are used as closing switches which are used to control the flow of current by creating and extinguishing electrical arcs over a small gap. These switches work by ionizing a medium, commonly air, to create a conductive route and then rapidly extinguishing the arc to interrupt the current. The gap itself, which is often the smallest distance between two conductive electrodes, is the most important component of a spark gap switch[2-4].

By applying high voltage across the electrodes, the electric field intensifies enough to ionize the surrounding medium, forming a conductive route for current to flow[4]. This ionization process produces a bright electrical arc, which is frequently followed by a characteristic spark or discharge. Spark gap switches are known for their ability to handle high voltage and high-power levels (as indicated in Table 1). They are commonly used in applications that require fast and reliable switching, for pulsed power systems, minimal jitter spans from nanoseconds (ns) in triggered gaps to hundreds of microseconds (μs) for self-breaking overvoltage gaps and repetition rates usually single shot but low kHz is possible. These switches have disadvantages like low lifetime due to erosion of electrodes.

4.2 Thyratrons

A cathode and anode configuration enclosed within a chamber filled with a specific gas or gas mixture is at the heart of a thyratron. When a control voltage is applied, electrons are emitted from the cathode. This emission causes an avalanche of ionization, ionizing the gas and generating a conductive plasma channel between the cathode and anode. Once the plasma channel is constructed, the thyratron acts as a closed switch, enabling current to flow with only a few voltage drops. The control voltage is decreased or withdrawn to turn off the thyratron and interrupt the current[1-3]. This action closes the plasma channel, causing the thyratron to revert to its non-conductive state, thus acting as an open switch. These switches have voltage range, and peak current as indicated in Table 1, these switches have low jitter, and high repetition rate switches but their lifetime is usually limited by cathode depletion[1-3].

4.3 Ignitron

A cathode and anode arrangement encased within a gas-filled chamber is the basic component of an ignitron. The conducting medium is commonly mercury vapour or a combination of inert gases. Electrons are emitted from the cathode, by applying a control voltage to the ignitron. The gas ionizes during the ionization process, resulting in the development of a conductive plasma channel between the cathode and anode. Once the plasma channel is constructed, the ignitron acts as a closed switch, allowing current to pass with a low voltage drop. This enables effective regulation of high currents in the circuit. This is a high voltage, high current (as indicated in Table 1) switch which is simple with many operational issues such as jitter and turn-on delay issues and switch should be mounted vertically and has repetition rates limited[1-3].

While gas-filled switches have advantages in terms of high-voltage handling and fast switching, they do have limitations, such as the need for appropriate gas selection, limited lifespan due to electrode erosion, etc., however, gas-filled switches remain useful components in a variety of industries where their unique properties fulfil specific switching requirements[1-3].

5. Solid State Switches

Solid-state switches are electronic devices that employ mechanical components to control the flow of electric current. Solid-state switches are useful for applications that demand high-frequency switching or precise control[5,6].

5.1 Diodes

Diodes are employed as switches because of their simplicity, unidirectional conduction feature, and dependability, making them suited for quick switching. These switches have high voltage and current specifications as indicated in Table 1. These switches have a low jitter and a high repetition rate of several kHz, but it is important to consider the limitations of diodes, as they are not useful for bidirectional switching and have a forward voltage drop during conduction, which affects system efficiency[4,5].

5.2 Thyristors

The Silicon Control Rectifier (SCR) is a three-terminal power semiconductor device with anode, cathode, and gate terminals that are used as a switch in electrical circuits and have special features in controlling current flow in high voltage systems[2]. To activate these switches, a little gate current is applied to the gate terminal, allowing the "latching" function to take place. These SCRs are capable of handling higher voltage currents and repetition rates (as indicated in Table 1) these switches have low jitter, but they require gate control to operate, which increases the complexity of the switch as the voltage levels of the circuit increase. Switches in the thyristor family include GTO and TRIAC[1-3,5,6].

5.3 Power IGBT

The Insulated Gate Bipolar Transistor (IGBT) is a power semiconductor device consisting of three main regions: the collector, the emitter, and the gate. The collector and emitter regions are composed of N-type and P-type semiconductor layers, while the gate region is an insulated layer. The operation of an IGBT as a switch is based on the control of a small gate current to regulate a larger current flow between the collector and emitter terminals. These switches have low voltage and current ratings (as shown in Table 1) as compared to thyristors which is a major disadvantage, but these have higher repetition rates and low voltage drop compared to thyristors[1-3,5,6].

5.4 Power MOSFET

The Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) is a popular power semiconductor device that works well as a switch in high-voltage and high-power applications. A voltage provided to the gate terminal controls the flow of current between the source and drain terminals. Power MOSFET's quick switching capability is one of its primary advantages. Because of their fundamental design, they may rapidly transition between the on and off states, allowing for high-frequency operation; However, as indicated in the table, the high conduction resistance limits these switches to have low voltage and current ratings. Recently, a new family of SiC discrete MOSFETs began to appear with very low conduction resistance, with increasing currents up to 100s and voltage hold-off up to 1700 V[1-3,5,6].

5.5 PCSS

Photoconductive Semiconductor Switches (PCSS) are semiconductor devices that respond to incident light by changing their electrical conductivity. The operation of a photoconductive semiconductor switch is based on the phenomena of photoconductivity, which occurs when a semiconductor material's conductivity rises due to photon absorption. A photosensitive semiconductor material, such as Gallium Arsenide (GaAs) or Silicon (Si), with photoconductive characteristics, is commonly used in the PCSS. One of the primary benefits of PCSS devices is their extremely quick switching speed. They can switch between high- and low-resistance states in nanoseconds or even picoseconds, making them useful for high-speed switching applications. Furthermore, PCSS devices have a high sensitivity to incident light, but they, like other switches, have limitations such as light dependency, a short recovery period, and a high cost[1-3,9-11].

Table 1. Summary of properties of high voltage switches used in pulsed power applications

Type of Switch	Electro mechanical Switches	Vacuum Switches	Gas-Filled Switches			Solid State Switches				
			Spark Gaps	Thyratron	Ignitrons	Diodes	Thyristor	Power IGBT	Power MOSFET	PCSS
Model Number	GW 7	3AH 47	ZHS/ 001/055	TDI1- 100k/150	GL-6228	FDA 640-300	HTS-1200- 2400 SCR	HTS 361- 200-FI	HTS 120- 15-UF	-
Voltage handling capability	800 kV	25 kV	0.1 MV	150 kV	60 kV	64 kV	120 kV	36 kV	12 kV	75 kV
Current carrying capacity	6 kA	25 kA	100 kA	100 kA	8.6 kA	3 kA	24 kA	2 kA	0.15 kA	1 kA
Turn-on time	> 1 ms	<1 ms	< 1 ns	< 20 ns	< 50 ns	< 1 µs	35 µs	0.3 µs	200 ns	500 ps
Repetition rate (Hz)	10	25	10	5 k	10	1 k	1 k	10 k	100 k	1 M

6. Experimental Verification

A test was conducted experimentally to confirm the turn-on time property of a switch with theoretical claims using an input voltage source, resistors, a capacitor as a form of energy storage, and a switch with one gas-filled spark gap switch as shown in Figure 2 and one solid-state as thyristor switch as shown in Figure 3 as a result short negative voltage pulses are generated by the circuit as shown in Figures 4 and 5 respectively.

However, the distance between the two conducting electrodes, which is set to 1 mm, is the most crucial circuit parameter for the spark gap switch as addressed in Section 4.1. The circuit parameter values for the spark gap switch and thyristor switch as shown in Table 2 and Table 3 respectively.

Table 2. The circuit parameters for the spark gap switch

Parameter	Value
V_{in}	2.2kV
R_1	10kΩ
R_2	10kΩ
C	40nF
R_L	100Ω

Table 3. The circuit parameters for the thyristor switch

Parameter	Value
V_{in}	4kV
R_1	10kΩ
R_2	10kΩ
C	40nF
R_L	100Ω

However, by adding a small amount of voltage to the RC circuit as depicted in Figures 2 and 3, the capacitor will begin to charge within the circuit's time constant of "τ," which is given as τ = Req.Ceq. When using a spark gap switch, the breakdown is caused by ionizing the medium between the electrodes at a specific moment. However, when using a thyristor as a switch, a triggering pulse is delivered between the gate and cathode terminals of the thyristor after the circuit's time constant.

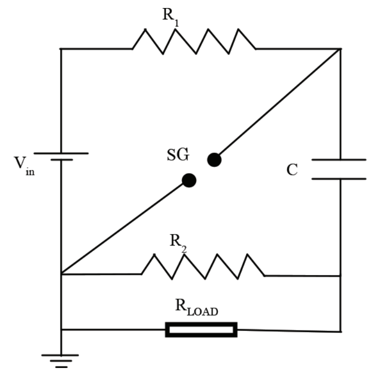

Figure 2. RC circuit with Spark Gap (SG) as a switch.

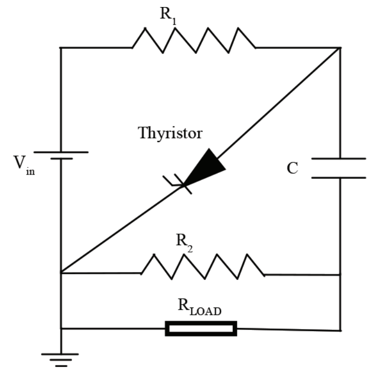

Figure 3. RC Circuit with thyristor as a switch

As a result, a negative voltage pulse appears across the load with the turn-on time of the spark gap switch is less than 1ns, the rise time of the negative pulse is 50 ns, and output voltages as 2 kV as shown in Figure 4. However, to turn on the thyristor a separate gate pulse must be applied between the gate and cathode terminals of the thyristor, which is set to 5 v for 100 µs of time. This results in the turn-on time being less than 50 µs, the rise time of the negative pulse being 250 ns and the output voltage being 3.2 kV as correspondingly shown in Figure 5.

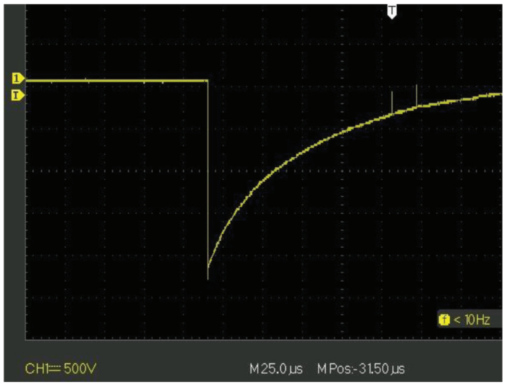

Figure 4. Pulse of RC circuit with spark gap as a switch.

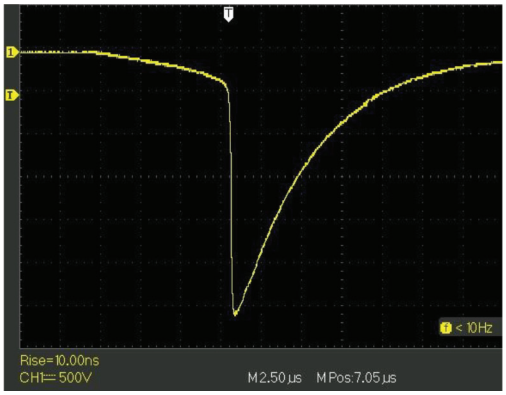

Figure 5. Pulse of RC circuit with thyristor as a switch.

Turn-on times were measured for all switch types, including all other electromechanical switches and solid-state switches, to support the theoretical assertions. It was discovered that every switch complied with Table 1's discussion of its turn-on time features.

7. Conclusion

In conclusion, high-voltage switches employed in pulsed power applications have a variety of advantages and disadvantages, each with its own set of characteristics. These switches are critical for delivering efficient and controlled power in high-energy applications. Their ability to handle high voltage and current levels while offering fast switching speeds enables precise control over energy transfer and the generation of intense electrical pulses. High-voltage switch technology must constantly evolve for fields like high-power lasers, particle physics, and electromagnetic research to advance further.

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