Gas-Discharge Closing Switches and Their Time Jitter

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***Abstract*—Gas-discharge closing switches are still the main option for pulsed-power systems where high hold-off voltage and high-power handling capabilities are required. One property of the switch that often is of great importance is the precision in time when the switch is to be closed. This review is a survey of existing gas-discharge closing switches, and in particular of their switching time jitter.**

***Index Terms*—Gas-discharge devices, pulse power system switches, reviews, time jitter.**

I. Introduction

HIGH-VOLTAGE CLOSING switches in pulsed-power systems are often subjected to the toughest requirements of all components in the system and a multitude of properties must be considered [1], [2]. Timing precision in the closure of the switches is vital if the system contains several sources that need to be switched in a synchronized manner either into a single load or into separate loads. This review is based on a literature survey of how precisely one can trigger externally triggered gas-discharge closing switches, which is expressed in the time jitter of the switch. The switch types that are considered in this review have a gaseous insulation medium. This means that solid and liquid dielectric closing switches are excluded, as well as solid-state switches. The survey is biased toward a hold-off voltage in the range 10–500 kV with the potential of a pulse-repetition frequency (prf) of up to 1 kHz. The literature survey is mainly performed by using the search engines at the web platform Engineering Village [3], which is linked to relevant databases of scientific and engineering journals and conference proceedings, together with the IEEE *Xplore* Digital Library [4].

The structure of the review article is as follows. Section I contains a short introduction followed by Section II where a review of the various delay times and time jitters in pulsed-power systems is presented. The main section, Section III, is where the different kinds of gas-discharge switches are concisely described and their time jitter reviewed. Section IV summarizes the switch properties, and Section V contains a review of time jitter reduction techniques. Finally, a few concluding remarks are given in Section VI.

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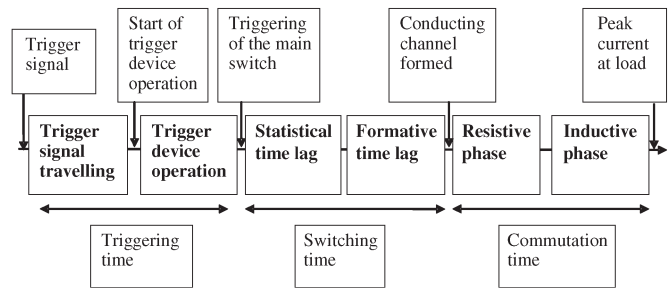

Fig. 1. Different phases that build up the delay time in a triggered gas-discharge switch. All of these phases may introduce a time jitter.

II. Time Jitter in Pulsed-Power Systems

Jitter is present in every pulsed-power system, that is, a variation of output parameters even if the initial and controllable settings are the same [5]. In particular, closing switches introduce such jitter, and all the different phases of the closing of the switch may contribute to this jitter.

The different phases of the closure of a high-voltage gas-discharge closing switch are graphically shown in Fig. 1. The process can be described as follows [5], starting from the trigger command until the peak current is achieved in the switch. When the trigger command is given, the trigger signal travels to the trigger device. The trigger device takes some time to operate before the trigger pulse is applied to the high-voltage switch. The closure of the switch comprises of the statistical time lag and the formative time lag. The statistical time lag is the time delay between the application of the trigger signal or overvoltage and the initiation of the dielectric breakdown of the gas in the switch. The formative time lag is the duration of the breakdown phenomena necessary to establish conducting path(s) or channel(s) between the main electrodes. After these time lags, a mildly conducting channel is formed between the two main electrodes of the switch. After the formation of the channel, a resistive phase takes place, which describes the heating stage of the conducting channel to a state of high conductivity. The switch behavior from then on is in most cases more aptly described by its inductance (inductive phase) rather than its resistance. These two phases determine the rise time of the current and are also strongly affected by the impedance of the external circuit.

The delay time of a switch can be defined as [5]:

- Delay Time (also called run time)—The amount of time between the application of a trigger command (for triggered switches) or overvoltage (for two-electrode switches) and the initiation of conduction. To the extent possible, the effects of the character of the trigger pulse are ignored.

Time jitter is the statistical shot-to-shot variation of the delay time and can thus be described as:

- Time Jitter—Statistical variations (usually rms or $1 - \sigma$) in the exact time of the initiation of conduction with respect to the command trigger signal or overvoltage.

The delay time of the closing of an externally triggered gas-discharge switch can be divided into three parts: The triggering time, the switching time, and the commutation time. All three parts are sources of time jitter. In this survey, the time jitter in the switching delay time (statistical and formative time lags) is considered. The switching delay time is a function of the intrinsic properties of the switch and of its operating point.

The cause of the switching time jitter is the jitter, or fluctuations, in the impedance of the electrode gap in the switch during its closure [6]. The jitter in impedance may also create a jitter in the voltage across the switch at the beginning of its closure or a jitter in the maximum current commuted to the load.

III. Gas-Discharge Closing Switch Techniques

There exist several review articles [7]–[13], journal special issues [14], and books [15], [16] dealing with the technology of high-power switches. Also, a significant part of books on pulsed power are often devoted to switches [17], [18]. The material presented in this section is derived from these sources, in particular Schaefer *et al.* [15], unless otherwise stated. These studies reveal that gas-discharge closing switches can be divided into two classes: low-pressure and high-pressure switches. The classification into low and high pressure, respectively, is related to Paschen's curve [19]. Paschen's curve relates the breakdown voltage to the product of the gas pressure and the electrode distance. There is a minimum in this curve for a certain pressure-gap distance product, and this minimum is called the Paschen minimum. On the left of the Paschen minimum, at low pressure, the mean free path of electrons is longer than the electrode distance. On the right, at high pressure, the mean free path is shorter than the electrode distance. In other words, at low pressure, it is unlikely for electrons to collide with the ambient gas molecules, whereas at high pressure, such collisions are frequent. The main low-pressure switch types found in the literature are vacuum tubes, metal vapor switches, thyratrons, cold-cathode thyratrons (pseudospark switches and backlighted thyratrons (BLTs)), and cross-field devices. For high pressure, the list consists of spark-gap switches, surface-discharge switches and corona-stabilized switches. Each of these switch types will be concisely described in this section, where also their peak performance in terms of low switching time jitter is surveyed.

A. Vacuum Tubes

In a vacuum switch, or vacuum tube, the gas is rarefied to such extent that the background gas does not take part in the discharge process. This requires a pressure of less than 0.1 mPa which implies that the switch operates on the extreme left-hand side of the Paschen curve. There are mainly three approaches for the initial supply of electrons for the closing of the switch:

- Direct electron emission from the cathode, either by thermionic emission or field emission.
- Plasma production and injection by using a third trigger electrode at the cathode.
- Irradiate the cathode with either laser or electron beam energy.

The initial plasma expands and eventually reaches the anode and thereby closes the switch.

When electrically triggered with a pin electrode, vacuum switches with a hold-off voltage of 5–20 kV and a peak current of 2–10 kA have a switching time jitter of 50–100 ns [20], [21]. For higher power, a hold-off voltage up to 50 kV and a peak current of 300 kA, the switching time jitter is of the order of 100 ns [22], [23]. A prf of up to 10 Hz has been reported for commuting up to 50 kV into 100 kA [23], [24]. For a laser-triggered vacuum switch, up to 30 kV, switching time jitter of a few nanoseconds can be achieved [25]–[27].

B. Metal Vapor Switches

In a metal vapor switch, as in the vacuum switch, the gas is rarefied to such an extent that the background gas does not take part in the discharge process. Two main versions of metal vapor switches exist, namely the ignitron and the liquid-metal plasma valve (LMPV). In the ignitron, the cathode consists of a pool of liquid mercury, and in the LMPV, the mercury is located in narrow grooves in an otherwise metal (often Molybdenum) cathode.

Ignitrons are mainly used for switching high currents (100 kA and upwards) at a voltage of around 10 kV. [28]–[31]. The LMPV can switch a higher voltage than the ignitron (above 100 kV), but the reported peak currents are lower (around 10 kA) [32]. Metal vapor switches are most often used for high-charge transfer, and discussions on time delay or time jitter are not found. It is also mentioned that the ignitron is used in situations that require a low prf.

C. Thyratrons

The thyraton is a low-pressure gaseous closing switch that operates on the left-hand side of the Paschen minimum. Many different types of thyratrons have been developed in the past, but in general, the device consists of an anode, a control grid, a baffle, a heated cathode, and a hydrogen reservoir. The hydrogen reservoir maintains the pressure in the device, which is in the region 1–100 Pa. A hot, or thermionic, cathode supplies the region between the cathode and the baffle with free electrons. The baffle has the same potential as the cathode, and its purpose is to block the line-of-sight between the cathode and the anode to prevent spurious triggering of the switch. A sufficiently intense electrical pulse applied to the grid will initiate rapid ionization of the gas between the grid and the cathode, which will subsequently cause the anode-cathode gap to break down. The grid is usually placed near the anode at a distance less than the electron mean-free path to prevent undesirable breakdown between the grid and the anode.

The hydrogen thyratron is one of the most well-developed types of the low-pressure gas switches, and Pirrie and Menown outline its development [33]. The reported operating parameters for a commercial thyratron are a working voltage from a few kV to 100 kV, a peak current up to 10 kA, a repetition rate up to 1 kHz, and a time jitter of 1–5 ns [34].

D. Cold-Cathode Tyratrons

The development of the thyratron includes the use of a cold cathode, which originates from Christiansen and Schultheiss [35]. In a cold-cathode thyratron, the plane cathode is replaced by a hollow cathode with an opening facing the plane anode. The distance between the far end of the cathode and the anode is kept at the left-hand side of Paschen minimum. During the open state of the switch, a low-current high-voltage Townsend discharge takes place in the hollow cathode. The losses balance the production of charge carriers, and the discharge is in a steady state. If the plasma density in the hollow cathode is sufficiently increased, the static electric field is distorted so much as to increase the gain over the losses inside the hollow cathode as well as in the anode-cathode gap and subsequently breakdown occurs. This transition can be achieved by injecting electrons into the hollow cathode. A distinction is made according to whether the electrons are injected by electrical or optical triggering. The former is called a *pseudospark switch* and the latter a BLT. A recent trigger version of the cold-cathode thyratron is the injection of plasma into the switch [36]. The hold-off voltage capability is increased by the development of the multistage pseudospark switch [37]. Another difference compared to the hot-cathode thyratorn is that working gases other than hydrogen have been used, such as helium, nitrogen, and argon. The general benefit of introducing a cold cathode is mainly the size and weight of the switch and not the operational parameters in particular.

Commercial pseudospark switches with the following parameters are available: Hold-off voltage 3–32 kV, peak current 2–30 kA, switching time jitter 5 ns, pulse-repetition rate 1 kHz [38]. A two-gap system with a hold-off voltage of 65 kV has been reported [39]. Bochkov *et al.* [40] reports a pesudospark switch with a hold-off voltage of 100 kV and a peak current of 5 kA with a prf of 3 kHz. The same group also presented a 30-ns switching time jitter for a switch that commutes 25 kV into 100 kA [41]. Subnanosecond jitter has been reported for the BLT with a hold-off voltage of 10 kV and a peak current of 4 kA at a prf of 10 Hz [42], and for pseudospark switches with a hold-off voltage less than 20 kV and a peak current less than 10 kA with a prf up to 100 kHz [43].

E. Cross-Field Devices

A crossed-field device works at a similar pressure range as the thyratron, which means that it operates on the left-hand side of Paschen's curve, with switching characteristics similar to thyratrons [44]. Its basic working principle is as follows. In the off-state, the gas is rarefied to such extent that the product of the pressure and the interelectrode spacing is maintained at such a low value that no breakdown occurs since the electron mean-free path is close to the electrode distance and there is a low probability that ionization collisions occur between electrons and gas molecules. By applying a magnetic field of sufficient strength and suitable orientation, the Lorentz force alters the trajectories of the electrons in such a way that the electron paths are long enough for a self-sustained discharge to form and a high current discharge can be sustained. Thus, with the application of an appropriate magnetic field, the switch closes. In effect, applying a magnetic field is equivalent to increasing the pressure. Note that the triggering magnetic field is applied for a significant time duration and is thus prone to variations which lead to an increase in the time jitter.

As a triggered closing switch, a cross-field device can have a hold-off voltage up to 100 kV and be triggered into current conduction at levels in excess of 20 kA. As a high voltage direct current interrupter, it can open an inductive circuit carrying up to 10 kA against 100 kV. At a voltage of 100 kV, this requires an internal magnetic field about 0.1 T [45]. The switching time jitter of a 60 kV/20 kA system has been reported to be 100 ns [44].

One cross-field device, called the crossatron, has been used in a 100 kV/1 kA system and a 40 kV/10 kA system with a prf in the range 1 kHz–1 MHz depending on the application [46]. The switching time jitter for a crossatron cross-field device has been studied at a voltage level 6 to 9 kV at a prf of 3.3 kHz and was reported to be 10 ns [47].

F. Spark-Gap Switches

Spark gaps are among the most widely employed switches in pulsed-power technology. They cover an impressive range of voltage and current, pulse-repetition rate, etc. A spark-gap switch is a high-pressure gaseous closing switch that operates on the right-hand side of the Paschen minimum. The pressure is of the order of atmospheric pressure or significantly higher. The breakdown mechanism of a spark gap is as follows. To initiate the breakdown, starting electron(s) must be present. There is a natural background density of free electrons in air caused by natural radioactivity and cosmic rays, but there are external means to increase this number. The free electrons are accelerated in the electric field, collide with the gas molecules and ionize them, thus forming an electron avalanche. When the electron avalanche has grown to its critical size, it develops into a streamer discharge that propagates and bridges the electrode gap. The streamer channel is at ambient temperature and is a poor conductor. The streamer is heated by the current flow and is eventually thermalized into a well-conducting spark or arc channel.

Spark-gap switches are often classified according to the trigger method used: self-triggered, electrically triggered, triggered with trigger electrode using a trigger pin (trigatron) or a field-distortion third electrode, electron beam triggered, or laser triggered. The self-triggered, the electrically triggered, and the laser triggered are two-electrode switches, whereas the other three are three-electrode switches. Only a limited range of spark gaps are available off-the-shelf because of the extremely wide range of applications and requirements, even if a few do exist [48]. All of these types are concisely described in the following subsections.

Self-Triggered Spark Gaps: A self-triggered spark gap is subjected to an overvoltage by the main voltage generator in order to close. Thus, it is the main voltage that is to be commuted into a current pulse that initiates the closure of the switch. This is the simplest possible spark-gap switch, and it is used in several applications. There are only few reports in the scientific literature that only consider the high-power self-breakdown switch and not a whole system containing such a switch. Existing works do present switches that are capable of switching megavolts with a prf of 200 Hz [49]–[51]. However, the switching time jitter is not mentioned.

In pulsed-power systems, self-triggered spark gaps can be used as the last peaking switch or as cascade breakdown switches after a main triggered switch. An example of the latter is the Marx generator. Marx generators often consist of one triggered spark gap followed by self-triggered gaps. Sack *et al.* [52] present a seven-stage Marx generator with an output voltage of 350 kV and spark gaps containing pressurized nitrogen, where the first spark gap is triggered by a superimposed voltage pulse. They measure a switching time of the Marx generator of around 200 ns with a time jitter down to 25 ns, which was sufficiently low for their application. Mayes *et al.* [53] reports on a study of a 17 stage Marx generator, 30 kV/stage, triggered via a field-distortion electrode achieving a subnanosecond time jitter from the application of the trigger pulse to the output voltage.

The Rimfire switch contains a main spark gap that is laser triggered and multistage spark gaps in series that are self-triggered once the main spark gap is triggered, much like the trigger sequence in a Marx generator [54], [55]. Such a switch has been shown to switch 5 MV into 0.5 MA with a delay time of 20 ns and a jitter of 0.4 ns [54], and to switch 6.1 MV into 0.79 MA with a delay time of 50 ns and a jitter of 6 ns [56]. Both these switches contain SF_6 at a pressure of about 0.3 MPa, and their main spark gap was triggered by a laser pulse. This time jitter includes both the time jitter of the main, triggered switch and the time jitter of the cascade breakdown of self-triggered spark gaps. For the latter switch, 1 ns of the time jitter is attributed to the laser-triggered section, and the remaining time jitter is attributed to the cascade section, in particular the first spark gap of the cascade.

Examples of using a self-triggered spark gap as a last peaking switch are the following. The Russian RADAN generators include high-pressure, self-triggered spark gaps that transform long (2–5 ns) pulses to shorter ones (150–200 ps) [57]. They operate in nitrogen or hydrogen at 4 MPa and at around 100 kV, stable operation up to 100 Hz, and are reported to have a time jitter of around 0.3 ns. A pulse-repetition rate of 3.5 kHz was achieved using hydrogen at a pressure of 10 MPa [58]. A similar system was presented by Pécastaing *et al.* [59] with a hydrogen pressure of 5.5 MPa, generating 2-kV pulses with 70-ps rise time up to 900 Hz. The jitter is claimed to be low, but is not quantified other than that the output pulse reproducibility was better than 5%.

Electrically Triggered Spark Gaps: The closure of the self-triggered spark gap is determined by the application of the main voltage. To separate the application of the main voltage and the triggering of the switch, a second high-voltage circuit can be connected to the main electrodes. By superimposing an overvoltage by this second circuit onto the main voltage, the closure of the switch can be triggered independently of the main charging voltage, and thus allows a triggering at a range of main voltage. He *et al.* [60] presents a switch with a hold-off voltage of 23 kV and a peak current of 320 kA that is triggered with a 120-kV Marx generator. The rise time of the trigger pulse is 20 ns, but the authors do not discuss the time delay and time jitter of the switch. This triggering technique is often used in Marx generators, where the trigger pulse is applied to the first spark gap, whereas the following spark gaps are self-triggered as, for instance, is described by Sack *et al.* [52]. They present a seven-stage Marx generator with an output voltage of 350 kV, spark gaps with pressurized nitrogen with a switching time of the Marx generator of around 200 ns with a time jitter of down to 25 ns, which was a sufficient jitter for their application.

Trigatrons: In a trigatron, a third electrode is introduced in proximity to one of the main electrodes. In a typical trigatron, the spark gap consists of two main electrodes with a trigger pin electrode placed coaxially inside a hole on one of the main electrodes and insulated from it. During operation, the main gap is charged to a voltage somewhat less than the static, self-breakdown voltage. The switch is closed by applying a fast-rising trigger pulse to the trigger electrode, which thereby initiates the breakdown of the main gap. The preferred operation is that the trigger electrode initiates a breakdown to the opposite electrode and later a breakdown to the adjacent electrode. The most efficient polarity configuration for jitter reduction is when the anode is the main electrode with the adjacent trigger electrode, the cathode is the opposite main electrode, and the trigger pulse has positive polarity, which can result in subnanosecond switching time jitter [61].

McPhee *et al.* [62] introduce a trigatron with a hold-off voltage of 500 kV that operates with a prf of 50 Hz and a switching time jitter of about 1 ns. The spark gap contained SF_6 at a pressure of 0.8 MPa. Minimal or no flow of the gas was required to achieve the repetition rate. They used a pre-ionization corona source (needle; separate from the trigger electrode) to reduce statistical time lag.

Beverly and Campbell [63] present a switch with a hold-off voltage of up to 50 kV that commutes a current of 6 kA at a prf of 100 Hz. The gas in the switch was dry air at pressure of 0.25 MPa. The switch uses transverse gas flow with a mass rate of 0.5–8 g/s to maintain the repetition rate. A switching time jitter of 0.60 ns for a hold-off voltage of 30 kV was reported.

Boyko *et al.* [64], [65] reveal a four-channel trigatron with hold-off voltage of 400 kV for commuting a peak current of 280 kA for each channel. The operating gas is SF_6 at a pressure up to 1 MPa. The switching delay time is less than 40 ns and its jitter less than 1 ns.

Lehr *et al.* [66] present a hermetically sealed trigatron with a 50-kV self-breakdown in hydrogen at 1.03 MPa. They increased the pressure to allow triggering and a prf of 600 Hz. The switching time jitter was of secondary importance for intended application; however, voltage jitter was considered important. The voltage jitter was not quantified, but a graph shows good reproducibility of the amplitude of the switched voltage. The jitter of the time delay was measured to be 20 μs, sufficient for the intended application.

Farr *et al.* [67]–[70] introduce a ferroelectric ceramic material in the trigger pin. When subjected to the trigger pulse, the ferroelectric ceramic emits electrons which thereby support the closure of the gap. They have managed to switch a hold-off voltage of 2.5 kV with a switching time jitter of 63 ps at a prf of 1 Hz in nitrogen, and to switch a hold-off voltage of 10 kV with a switching time jitter of 175 ps.

Ron *et al.* [71] discuss the possibility having a trigger electrode at both main electrodes, and their findings are that the double-trigger mode is superior. They managed to switch a hold-off voltage of up to 30 kV in atmospheric air with a switching time jitter of less than 4 ns [72].

Niedbalski [73], [74] reports on a trigger method where capacitively coupled (pulsed corona) discharge inside of the one of the main electrodes acts as a UV source and thereby trigger the closure of the switch. The author reports the performance of commuting 17 kV into 6 kA in nitrogen at atmospheric pressure. The typical delay between the application of the high-voltage pulse to the corona assembly and the closure current was about 170 ns for a gap voltage close to self-breakdown, with a time jitter of about 25 ns.

Gerasimov [75] displays a multiple-channel trigatron spark-gap switch. It contains a flat-topped trigger electrode and an opposite main electrode with an annual groove. The working gas is a mixture of SF_6 of N_2 in the proportions 4 : 6 at a pressure in the region 0.5–1.0 MPa. When the trigger pulse is applied, the critical electric field strength is reached at the trigger electrode and at the surface of the opposite main. At the trigger electrode, several streamers are launched toward the opposite electrode. The breakdown is accelerated by the discharges at the groove of the opposite electrode. Performance of a switch include a hold-off voltage of 100 kV commuted into a peak current of 250 kA with a switching time jitter within 3 ns (relative to the start of the application of the trigger pulse).

Field-Distortion Three-Electrode Gaps: In the field-distortion three-electrode gap switch, a third electrode is introduced in the spacing between the two main electrodes, essentially creating two spark gaps in series. The third, trigger, electrode is arranged in such a way that it does not significantly affect the electric field distribution before applying a trigger voltage to the trigger electrode. There are basically two modes of operation of a closing switch with field-distortion electrode: Cascade breakdown and simultaneous breakdown of the two spark gaps in series. In cascade breakdown, the application of the trigger pulse makes the gap between the trigger electrode and one of the main electrodes break down. After this breakdown, the potential of the main electrode is commuted to the trigger electrode, and breakdown occurs between the trigger electrode and the other main electrode. In simultaneous breakdown, the switch is arranged in such a way that both gaps break down simultaneously. Schaefer [76] gives a comprehensive table of operating characteristics of field-distortion closing switches from the time period of 1960–90 which include switches that handle a hold-off voltage of hundreds of kilovolts with a switching time jitter of the order of nanosecond, but he does not report on the prf.

Chen *et al.* [77], [78] moved the field-distortion electrode closer to one of the main electrodes in such a way that the switch rather operated as a trigatron, but with the trigger electrode surrounding one of the main electrodes. They tested various gases and gas mixtures at a pressure up to 2.6 MPa. The hold-off voltage was up to 50 kV with a pulse-repetition rate of up to 100 Hz. They reported subnanosecond time jitter of the switching delay time for several gas mixtures, but hydrogen and hydrogen/nitrogen mixtures appear to give the best jitter performance.

One measure to reduce the inductance of the switch is to have several arc channels in the same spark gap. Gerasimov [75] provides one solution by letting the midplane trigger electrode consist of several thin plates, symmetrically arranged around the main gap. The trigger potential is simultaneously applied to all plates, and the field enhancement at each tip of the edge causes streamers to be launched to one of the main electrodes, and each plate triggers a cascade breakdown. He reviews multichannel low-inductance ($\sim$1 nH) gas-filled spark gaps with several tens of channels each designed for an hold-off voltage of up to 100 kV, and a peak current of up to 400 kA. The requirement, which was fulfilled, was that the spread of its operational time delay was within 3 ns. In some cases, they report subnanosecond time jitter. The working gas is nitrogen at a pressure up to 0.5 MPa.

A similar approach is the so-called V/n switch [79]. In such a switch, a mushroom-shaped trigger electrode emanates from the centre axis of one of the main electrodes, like in the trigatron, but extends into the gap in such a way that the ratio of the voltage across the whole switch to that of the trigger electrode is the given number n. The basic idea is that the trigger electrode should take a potential in such a way that it does not distort the electric field distribution in the main gap during hold-off. One of the advantages of the V/n trigger scheme is that the trigger voltage can be lower than if the trigger electrode had been located midgap. Carboni *et al.* [80] present a pulsed-power supply based upon such a switch. The pulsed-power supply had a V/n switch in a transfer stage in series with a self-breakdown switch. The V/n had hold-off voltage of 300 kV in nitrogen at a pressure of 8–10 MPa, with a switching time jitter of at best 30 ps.

Another way of achieving a multichannel spark gap is the rail switch, where the main electrodes consist of two parallel bars, or rails. When a midplane field-distortion trigger electrode with a sharp edge is placed into the main electrode gap, multiple channels can be initiated. They are used in systems that are intended to switch a high current with low impedance, typically a hold-off voltage of around 100 kV with a peak current of hundreds of kiloampere [81]–[83]. The reported switching time jitter is around a nanosecond or below. One improvement of the rail switch is to include an acoustic standing wave along the rails and the trigger electrode [84]. The standing wave modifies the pressure along the trigger electrode so that arc channels are created in the noughts.

Electron-Beam-Triggered Spark Gaps: In an electron-beam-triggered switch, the transition from insulating to conducting state is triggered by the injection of an electron beam into the electrode gap. These electrons serve two functions. First, they constitute a large supply of initial electrons, thus reducing the statistical time lag. Second, the passage of the beam generates a space-charge distribution as a result of impact ionization of the working gas in the gap which has a considerable effect on the development of the transition. Yalandin *et al.* [85] introduce electron beam triggering into the RADAN-303 pulse generator [86], where they achieved a time jitter of less than 25 ps when switching some tens of kilovolts.

Laser-Triggered Spark Gaps: In a laser-triggered spark gap, the optical energy of a laser pulse triggers the breakdown of the gap. There are essentially three techniques that are used. First, the laser beam is focused on the surface of one of the electrodes to create a small volume with a high degree of ionization close to the surface. This perturbation creates initial electrons and field distortion to trigger the closure of the switch. Second, the laser beam is focused midgap, creating a small volume of ionization midgap, together with a thin filament of substantial ionization which spans much of the gap. Third, which applies to rail gaps, the laser beam is directed parallel to the rail electrodes and transverse to the gap axis, where it creates a low-ionization density but sufficient to supply the rail gap with initial electrons along the rail electrodes. For a midgap-triggered spark gap, three different physical mechanisms can be used [87]: Nonresonant multiphoton ionization, resonant enhanced multiphoton ionization (REMPI), and electron tunneling. The first two typically use ns-laser pulses whereas the last one use fs-laser pulses.

Laser-triggered switches are generally considered to have potentially the lowest switching time jitter due to the precise deposition of laser energy in the spark gap. In a review made in 1978, Guenther and Bettis [8] found that demonstrated capabilities of laser-triggered switching included a switched voltage above 3.5 MV, repetition rate of 50 Hz, switching delay time of much less than 1 ns, and a switching time jitter below 0.01 ns, even if it is not stated that these operation performances have been achieved together.

Luther *et al.* [88] report the use of a Ti:Sapphire laser (50 fs pulse @ 800 nm with a prf of 10 Hz). The hold-off voltage was 10 kV, and the spark gap was filled with dry air at a pressure between 0.15 MPa and 0.27 MPa. They studied two cases, with similar results, laser focused midgap or focused at the anode. Their best switching time jitter reported was 37 ps with a laser pulse energy of less than 1 mJ. Brussaard *et al.* [89]–[91] also used a Ti:Sapphire laser. They focused the laser beam by a cylindrical lens to get a line-shaped focus, thereby bridge the whole gap with laser plasma. They studied a switch with hold-off voltage of 4.5 kV (90% of self-breakdown) at atmospheric air. 15 min operation with 10 Hz resulted in a switching time jitter less than 15 ps (better than the resolution of the measuring equipment).

Glover *et al.* [92] used a Nd:YAG laser and varied the wavelength of the laser pulse: 266 nm and 532 nm. The hold-off voltage used was 16–17 kV (20 kV was the self-breakdown voltage), and their gap contained 10% SF_6 and 90% N_2 at a pressure slightly below ambient pressure. For a 70 μJ laser pulse a switching time jitter of less than 1 ns was achieved with a laser radiation wavelength of 266 nm and around 1 ns for 532 nm.

The Rimfire switch is a combination of a main laser-triggered spark gap in series with several self-triggered spark gaps [54], [55]. The arrangement is made to allow switching several megavolts into several hundreds of kiloamperes with low inductance and switching time jitter, using multichannelling. The Rimfire switch contains a main spark gap that is laser triggered and multistage spark gaps in series that are self-triggered once the main spark gap is triggered, much like the trigger sequence in a Marx generator. Such a switch is shown to switch 5 MV into 0.5 MA with a delay time of 20 ns with a jitter of 0.4 ns [54], and to switch 6.1 MV into 0.79 MA with a delay time of 50 ns with a jitter of 6 ns [56]. Both these switched contained SF_6 at a pressure of about 0.3 MPa. This time jitter includes the time jitter of the cascade breakdown of self-triggered spark gaps. The delay time and its jitter are measured from laser beam arrival at switch-to-switch conduction. The switching time jitter of only the laser-triggered main switch of the Rimfire switch is around 1 ns [56], [93], [94].

The studies above using ns-laser pulses used nonresonant multiphoton ionization. Miles *et al.* [95] have studied a switch based on REMPI, where they switched 10 kV with a switching time jitter of about 1 ns.

G. Surface-Discharge Switches

A surface-discharge switch is mainly realized as two parallel electrodes mounted on a surface with a guiding electrode mounted below the surface and connected to one of the surface-mounted electrodes. Such a switch can be triggered in several ways, like the spark-gap switch: self-triggered, triggered by a field-distortion electrode, laser triggered, etc. One advantage with the surface-discharge switch is that multichannelling is easy to achieve. Thus, such a switch is good for usage where a high voltage (over 100 kV) shall commute a very high current (several MA) with low impedance. For such applications, the switching time jitter is not primarily discussed [96]; however, a switching time jitter of as low as 50 ps has been reported when switching 30 kV using a nitrogen laser (337 nm) [97]. Frescaline *et al.* [98] switches 50 kV into 700 kA with a switching time jitter of less than 2 ns using a trigger electrode. Nunnally *et al.* [99] report subnanosecond jitter for uv-laser-triggered surface-discharge switch, but they do not state other relevant electrical parameters.

H. Corona-Stabilized Switches

A corona-stabilized closing switch uses the phenomenon of corona stabilization, which occurs in an electronegative gas subject to a strongly nonuniform electric field distribution. A typical electrode configuration is a rod-plane electrode gap. With these operating conditions and under slow rising and dc voltage, there is a range of pressure where breakdown is preceded by a corona discharge from the pointed electrode. This discharge generates a space charge between the electrodes which has the effect of redistributing the electric field such that the nonuniform electrode is shielded from the rest of the gap. It results in a maximum in the dc breakdown voltage versus pressure curve, and this dc breakdown voltage exceeds the impulse breakdown voltage. This phenomenon can be used to reduce the recovery time of the withstand voltage of a spark gap and thereby an increased prf [100]–[102]. MacGregor *et al.* [103] presents a system where a triggered corona-stabilized switch closes 100 kV into 1 kA with a prf of 1 kHz. Beverdige *et al.* [104] introduce a cascade switch in dry air at a pressure of 0.1–0.2 MPa with an operating voltage in the range 40–100 kV, which in a single-shot mode produces a switching time jitter less than 2 ns.

Sarkar *et al.* [105], [106] present a self-breakdown, needle-to-plane switch in SF_6 at ambient pressure. The self-breakdown voltage is 18 kV, and a voltage jitter of $\pm 4.9\%$ was achieved at a prf of 2 kHz. For the intended application, the switching time jitter was not a concern.

Focia and Frost [107] present a first prototype of a 1-kHz Marx generator with four stages, where each stage contained a corona-stabilized switch. The switches have pin-plane geometry, and the first stage has a trigger-able corona stabilized spark-gap switch to allow for precision triggering of the pulse. The insulating gas was dry air at a pressure about 0.3 MPa and the charging voltage below 10 kV. They measured a time jitter of 0.5 ns in the delay time between the closing of the first spark gap and the output voltage.

IV. Summary of Switch Properties

A compilation of selected properties of the gas-discharge switches surveyed is found in Tables I and II. Table I contains all switch types except the spark-gap switches, whereas the spark-gap switches are found in Table II. The properties listed are the main voltage, the prf and the switching time jitter $(\Delta\tau)$. Table III contains a summary of Tables I and II which indicates if the different switch types have confirmed performance in respect to the switching time jitter, hold-off voltage, and prf capability as outlined in the introduction. All spark-gap switches, regardless of trigger technique, the corona-stabilized switch and the cold-cathode thyratron appear to be capable of switching a high voltage with a small switching time jitter at a high pulse-repetition frequency. One should, however, be aware of the fact that the peak performances in the different parameters are not necessarily proven in the same experiment. The reader should also bear in mind that the quoted figures in several cases are from experimental switches or without any consideration of other parameters such as stressed time, lifetime, and reliability.

TABLE I
Compilation of Switch Performance. U_0 is the Hold-Off Voltage, PRF is the Pulse-Repetition Frequency, and $\Delta\tau$ is the Switching Time Jitter

Switch type	U_0	**prf**	$\Delta\tau$	**Ref.**
Vacuum Tube				
- trigger pin	50 kV	10 Hz	100 ns	[20-24]
- laser-triggered	30 kV	-	Few ns	[25-27]
Metal vapour switch				
- ignitron	30 kV	-	-	[28-31]
- liquid-plasma metal valve	100 kV	-	-	[32]
Thyratron	≤ 100 kV	≤ 1 kHz	1-5 ns	[34]
Cold-cathode tyratrons				
- pseudospark switch	32 kV	1 kHz	5 ns	[41]
- pseudospark switch	100 kV	3 kHz	-	[40]
- pseudospark switch	< 20 kV	100 kHz	< 1 ns	[43]
- backlighted thyratron	10 kV	10 Hz	< 1 ns	[42]
Cross-field device	< 10 kV	3.3 kHz	10 ns	[46-47]
Surface-discharge switch	30 kV	-	50 ps	[97]
Surface-discharge switch	50 kV	-	< 2 ns	[98]
Corona-stabilized switch	100 kV	1 kHz	-	[103]
Corona-stabilized switch	100 kV	-	< 2 ns	[104]
Corona-stabilized switch	< 10 kV	1 kHz	0.5 ns	[107]

V. Switching Time Jitter and its Reduction

All trigger techniques are in principle jitter-reduction techniques, since they aim at controlling and reducing the switching time and thereby also reduce the jitter of the switching time. As mentioned in Section II, the switching time comprises of two parts: statistical and formative time lags. The former is reduced by making initial electrons available and the latter by supporting the formation a conducting channel between the electrodes.

The statistical time lag is the time between the external event producing an overvolted gap and the appearance of initial electrons suitable positioned to start electron avalanches. This time lag can be reduced or even eliminated by externally generating electrons before or during the trigger pulse [76]. Several techniques are at disposal, such as UV-pre-ionization, field emission, radioactive species, ferroelectric material in the trigger electrode, and injection of an electron beam.

In *UV-pre-ionization*, the main electrode gap is illuminated by ionizing radiation in order to produce free electrons. This can be achieved by an electrical discharge in separate electrode gap or by an UV lamp. As an example, in the system of Carboni *et al.* [80], their peaking spark gap is illuminated by a UV illuminator gap in series. In Marx generators, it is common to have line-of-sight between the cascade spark gaps so the discharge in the first spark gap illuminates the rest of the spark gaps [19], which may result in subnanosecond switching time jitter [53], [108].

Free electrons provided by *field emission* require a very high electric field strength at the surface of the electrode that serves as a cathode, for instance at sharp edges at trigger electrodes [76].

The use of a *radioactive isotope* to provide free electrons is another traditional way of reducing the statistical time lag [19]. This can be done by an isotope that emits β particles directly or emits ionizing γ rays. Chen *et al.* [109] introduced the β-emitting radioactive isotope Kr^{85} as a component in the working gas. They measured the time jitter for N_2 and

TABLE II
COMPILATION OF SWITCH PERFORMANCE FOR SPARK-GAP SWITCHES

Trigger type	U_0	prf	$\Delta\tau$	Ref.
Self-triggered	> MV	200 Hz	-	[49-51]
Self-triggered	100 kV	3.5 kHz	0.3 ns	[58]
Trigatron	500 kV	50 Hz	< 1 ns	[62]
Field-distorted three-electrode gap	50 kV	100 Hz	< 1 ns	[77-78]
Field-distorted three-electrode gap	100 kV	-	< 1 ns	[75]
Field-distorted three-electrode gap	300 kV	-	30 ps	[80]
Electron-beam triggered	10 kV	-	25 ps	[85]
Laser-triggered	4.5 kV		< 15 ps	[89-91]
Laser-triggered	6.1 MV	-	6 ns	[56]

TABLE III
SUMMARY OF TABLES I AND II

Switch type	Sub-ns-jitter reported?	Hold-off voltage of 100 (500) kV reported?	Prf of 100 Hz (1 kHz) reported?
Vacuum Tube	No	No	No
Metal vapour switch	No	Yes (No)	No
Thyratron	No	Yes (No)	Yes
Cold-cathode thyratron	Yes	Yes (No)	Yes
Crossed-field device	No	Yes (No)	Yes
Surface-discharge switch	Yes	No	No
Corona-stabilized switch	Yes	Yes (No)	Yes
Spark-gap switch			
- Self-triggered	Yes	Yes (Yes)	Yes (Yes)
- Trigatron	Yes	Yes (Yes)	Yes (No)
- Field-distorted three-electrode gap	Yes	Yes (No)	Yes (No)
- Laser-triggered	Yes	Yes (Yes)	No

$N_2 - Ar - Kr^{85}$ gas mixtures and found a slight but clear reduction in the time jitter by adding Kr^{85}. Their conclusion was that a more radioactive source than the one they used is needed for a more significant reduction of the time jitter.

Ferroelectric materials can be used as electron emitters [110], [111], and thereby also as providers of initial electrons in spark gaps. Farr *et al.* [67]–[70] introduced a ferroelectric material in their trigatron trigger electrode and achieved subnanosecond jitter in the switching time.

With an *electron beam*, one can directly provide the spark gap with initial electrons [112]. Yalandin *et al.* [85] introduce an electron beam triggering into the RADAN-303 pulse generator [86], where they achieved a time jitter of less than 25 ps when switching some tens of kilovolts. Triggering a spark gap with an electron beam does not only provide the gap of the switch with initial electrons, it also starts the cascade ionization directly.

Other means of reducing switching time jitter includes multichannelling and the use of corona-stabilized plasma. Multichannelling provides several paths for the switch current with the objective of lower the inductance of the switch [75], [81]–[83], [113], but it is also reported to reduce the time jitter of the switching delay time resulting in subnanosecond time jitter [75], [80]. The use of a corona-stabilized plasma in a switch was mainly to increase the recovery time and thereby increase the pulse-repetition frequency of the switch [102], but is also reported to be able to support subnanosecond switching time jitter [104], [114].

The spark-gap switches that have the lowest switching time jitter are of the laser-triggered type, where the lowest time jitter was less than the resolution of the measurement system (15 ps) [91]. The latest advances in laser triggering is the use of optics to create a line plasma that covers the whole electrode gap [90], [115] or a linear array of discrete foci along the spark gap axis [116]. The laser systems used for laser triggering (typically Nd:YAG lasers or Ti:Sapphire-lasers) suffers from two limitations: they are complex and bulky, and a pulse-repetition frequency of above 15 Hz is complicated to achieve. However, promising development is under way, including actively Q-switched microchip lasers, pumped with a 0.5-W diode laser that can produce pulses as short as 115 ps with pulse energy of several microjoules, and passively Q-switched, pumped with a 10-W diode laser that can produce pulses as short as 380 ps with peak power in excess of 560 kW at pulse-repetition rates up to 1 kHz [117].

To increase the hold-off voltage of a spark-gap switch, the normal procedure is to increase the pressure of the gas in the spark gap. Spark-gap switches with a pressure of up to 10 MPa have been reported [58], [80].

To increase the pulse-repetition frequency of the switch, the gas in the switch must recover after its closure and commuting of the current to a state where it can withstand the hold-off value. The recovery times are about 10 ms for most gases such as air, nitrogen, and SF_6, whereas hydrogen, with its high thermal diffusivity, has a recovery time an order of magnitude faster, or about 1 ms [118]. The recovery time can also be increased by replenishing the spark gap volume with new gas after each discharge by the introduction of a gas flow, and it also may have a stabilizing effect on the discharge [63], [119], even if cases have been reported where the switching time jitter has increased with the presence of a gas flow [78]. Another means of reducing the recovery time is to use corona-stabilized plasma [102] as mentioned above.

One important issue to address is if the switch is to be pulsed/fast charged or dc/slowly charged, which might determine the choice of switch type and implementation [102]. For instance, a self-triggered spark gap could be the simplest solution if the switch is pulsed charged [57]–[59], [80], while the corona-stabilized discharge does only work for slowly charged systems [102].

VI. Concluding Remark

Gas-discharge closing switches are still the main option for pulsed-power systems where high hold-off voltage and high-power handling capabilities are required even if semiconducting switches are replacing gas-discharge switches in several other applications [13]. Thus, these switches will continue to be used in pulsed-power system for years to come. This review will assist the reader in choosing the closing switch for his or her pulsed-power system, in particular when precision in the closure time of the switch is an important system parameter.

The rationale for performing the review presented in this article was to identify the types of gas-discharge closing switches that would be useful for switching several sources at well-defined instances, as indicated in the introduction. Four types were identified to have interesting properties in this respect, and they are:

- Laser-triggered spark-gap switch.
- Field-distortion three-electrode switch.
- Corona-stabilized discharge switch.
- Pseudospark switch.

The first three are high-pressure switches, whereas the last one is a low-pressure switch. Laser-triggered spark-gap switches have the smallest reported switching time jitter. Disadvantages with the laser-triggered system used today are that they are bulky and have a poor pulse-repetition frequency. However, the development in laser technology, both regarding miniaturization and increase in pulse-repetition frequency, is exciting. Another direction of research is to explore the possibilities of increased switch performance by the use of REMPI.

Switches with a third field-distortion trigger electrode are the most mature of the selected types where low values of time jitter with a high hold-off voltage at a decent pulse-repetition frequency have been reported.

The switch based on a corona-stabilized discharge is the least developed type but has a great potential for use in systems where a high pulse-repetition frequency is required.

The pseudospark switch has an excellent pulse-repetition frequency capability, but uncertain voltage scalability.

Following the review, studies of a corona-stabilized switch, a field-distortion three-electrode switch, and a laser-triggered spark-gap switch have been initiated [120]–[122].

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