Application Information
for
SG-Series Spark-Gap Switches

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Application Information for SG-Series Spark-Gap Switches

SG-series spark-gap switches are engineered for dependable service with minimal maintenance. This guide gives recommended installation guidance for representative applications. Electrical circuitry is the primary emphasis of this application guide; please refer to our Application Notes for information on maintenance, gas supply systems, and other specialized topics. Useful references are also given at the end of this document. Please consult us for advice on applications not discussed here. We provide complete engineering and design services, including turn-key construction of customized pulsed power systems, on a contract basis.

IMPORTANT SAFETY ADVICE

Please observe all prudent safety precautions with high-voltage circuitry. Careful grounding and shielding will minimize hazards and safety interlocks should be employed at all times. Remember that a capacitor can re-acquire a LETHAL charge following discharge because of dielectric relaxation. Use shorting straps when servicing high-voltage equipment and assume nothing is at ground potential!

Introduction

Gas-filled spark gaps satisfy a range of plasma-closure switching requirements involving capacitive discharge circuits. Series SG switches manufactured by R. E. Beverly III and Associates are designed for use in low-inductance (e.g., strip-line), fast-pulse systems where large peak currents (~1–500 kA) and high voltages (2.5–75 kV) are commuted. Although nominally designed for single-pulse operation, repetition rates in excess of 100 Hz are possible for decreased charge-transfer rates. Modular construction allows different configurations to be rapidly assembled from off-the-shelf components. Three basic switch types are available: (i) passive, (ii) electrically triggered, and (iii) laser triggered. Passive switches have only two electrodes and operate spontaneously when the applied voltage exceeds the self-breakdown voltage. Electrically triggered switches utilize three electrodes and employ an external trigger generator to initiate breakdown— we manufacture both *trigatron* and field-distortion switches. Laser triggered switches consist of two electrodes and a lens that focuses laser radiation onto an on-axis, mid-plane point between these electrodes; the laser-generated spark initiates breakdown.

Trigatron switches are the simplest design to install and offer the lowest cost. For those applications that demand a very compact and low-inductance design, the field-distortion switch is the optimum choice. Laser triggered switches consist of two electrodes and a lens that focuses laser radiation onto an on-axis, mid-plane point between these electrodes; the laser-generated spark initiates breakdown. This trigger method offers the fastest turn-on and lowest jitter of all of our switches.

Pulsed-power applications for SG-series switches generally fall into two broad categories:

1. Series switches, where stored energy is discharged rapidly into a load. Typical loads include flashlamps, gas lasers, accelerators, exploding wires, plasma pinches, x-ray generators, etc.

2. Protective switches, where the gap is used to short circuit or *crowbar* energy-storage devices thereby protecting other circuit elements from damage due to over-voltage and/or over-current.

Although they are simple in design, spark-gap switches must be installed and operated properly for best results. This application guide gives information on switch construction, operating characteristics, electrical connections, gas-supply requirements, replacement parts, and our warranty. Detailed switch specifications and ratings are given in a separate brochure. For further technical information, please consult the bibliography at the end of this document.

Construction

Series SG switches are designed for reliability and durability. Sintered tungsten-alloy electrodes ensure long life and low probability for misfire or prefire. The translucent polycarbonate or polyetherimide insulator makes firing easily and safely visible without UV hazard. The top and bottom plates are brass or aluminum alloy; the bolt circles are identically dimensioned and located for easy attachment of conductors. Buna-N (Nitrile Elastomer) O-rings seal the top and bottom plates and trigger plug (trigatron models). For the field-distortion models, the trigger ring is self-locating and self-centering using either plastic dowel pins or ceramic standoffs, and a brass rod serves as electrical feed-through. The gas fittings are made of nylon or polypropylene, depending upon the model, and all fasteners are nylon or stainless steel. All models employ metric fasteners (-M suffix). All components, including the trigger plug for the trigatron models, the trigger ring for the field-distortion models, and the lens for the laser triggered models, are readily replaceable and the entire switch can be disassembled for inspection and cleaning using ordinary tools.

Operating Characteristics

Trigatron. The trigatron has found wide application in the pulsed power community as a demand-triggered, high-voltage switch whose self-breakdown voltage can be easily changed over a wide range by adjustment of the internal gas pressure. These simple devices employ two main discharge electrodes, called the opposite (O) and adjacent (A) electrodes, and an insulated trigger pin (T) that is usually flush with or slightly recessed below the surface of the adjacent electrode. The internal gas acts as an insulator until an external trigger pulse initiates breakdown between the trigger pin, adjacent electrode, and/or opposite electrode. The two main electrodes carry the current once the main gap becomes fully conductive. There is no trigger pin in the passive models and self-breakdown occurs when the gap voltage exceeds the self-breakdown voltage. Trigatron switches are the least expensive models to purchase and the simplest to install and operate.

Field-Distortion Switches. Both main electrodes (M) in the field-distortion switch are identical and a trigger ring is suspended at the mid-plane between these electrodes. Proper biasing of the trigger ring ensures that the static potential of this electrode is exactly one half of the potential across the main gap, i.e., prior to triggering. When a fast-rise trigger pulse is applied to this ring, the local electric field is severely distorted which induces avalanche ionization of the gas and electrical breakdown of the main gap. Although more complicated to configure and install, field-distortion switches offer the fastest breakdown time and lowest jitter for our electrically triggered models.

Laser Triggered Switches. These models rely upon a laser-generated spark to initiate breakdown. A spark is produced when the local electric field within the focal volume exceeds the minimum required for avalanche ionization. Streamers from the main electrodes to this spark cause complete breakdown of the gas within the gap and closure of the switch. Laser trigger switches offer very precise triggering and the lowest jitter of all of our models.

The important parameters in this discussion are defined as follows:

I_p — **Peak Discharge Current**, the maximum discharge current that flows through the main gap. The maximum peak current is limited by the structural characteristics of the switch and its ability to manage the combined electromotive and overpressure forces.

Q — **Charge Transfer**, the total charge transferred by the switch; for a series-discharge circuit (non-oscillatory) with capacitive energy storage, $Q = CV_g$.; otherwise it is defined by

$$Q = C\int i(t)dt$$

where *i(t)* is the time-dependent current.

t_{bd} — **Breakdown Time**, the time between arrival of the voltage pulse at the trigger electrode and main gap conduction, often defined as the time at which the instantaneous current $I(t)$ is a small fraction of the peak current in the main circuit, e.g, $I(t_{bd}) = 0.1I_p$; minimum breakdown time is obtained when the switch is operated in the heteropolar mode, when the main-gap voltage V_g is close to the self-breakdown voltage V_{sb}, and when a fast rising trigger pulse is used. For over-volted passive gaps, t_{bd} depends primarily upon dV_g/dt. For laser triggered switches, t_{bd} is defined by the time between arrival of the laser pulse at the switch and main gap conduction. For electrically triggered switches, $t_{bd} \approx 100$ ns at the lowest operating voltage and decreases rapidly to ≤ 20 ns as $V_g \rightarrow V_{sb}$. For laser triggered switches $t_{bd} \leq 10$ ns.

E_{laser} — **Laser Energy**, for laser triggering, the minimum energy required to reliably initiate breakdown.

τ_{laser} — **Laser Pulse Width**, for laser triggering, the maximum pulse width recommended to achieve the specified jitter.

σ_{bd} — **Jitter**, the statistical pulse-to-pulse difference in t_{bd}, defined here as one standard deviation.

V_g — **Main Gap Voltage**, the potential between the two main electrodes prior to breakdown.

V_{min} — **Minimum Operating Voltage**, the minimum voltage across the main gap that assures firing using a standard triggering arrangement; operation below this voltage is unreliable and is not recommended.

V_{op} — **Recommended Operating Voltage**, the value of V_g recommended for most reliable operation with minimum delay time and jitter, typically 60-80% of V_{sb}; operating at a higher voltage increases the statistical likelihood of a prefire or misfire, especially during repetitive operation, while operating with $V_g << V_{op}$ will result in excessively long breakdown times.

V_{sb} — **Self-Breakdown Voltage**, the voltage across the main gap at which there is a 50% probability that self breakdown will occur; the gas fill, internal pressure, and electrode separation determine this value. The self-breakdown voltage will be strongly influenced by the time between discharges (see the discussion below on **Recovery Time**). Passive gaps operated in a repetitive mode, in particular, will exhibit premature breakdown at $V_g < V_{sb}$.

V_t — **Trigger Voltage**, peak voltage appearing on the trigger electrode just prior to breakdown.

V_t^* — **Critical Trigger Voltage** (trigatron switches only), trigger voltage that produces simultaneous breakdown to the adjacent and opposite electrodes, which concomitantly minimizes breakdown time and jitter. The critical trigger voltage depends upon the main gap voltage and switch geometry as discussed below.

Electrically triggered spark gaps are generally characterized by an arc resistance of ~1 mΩ, a breakdown time ~10–100 ns, a jitter ~1–10 ns, a self-inductance <20–45 nH, and a life expectancy of ~10^3–10^6 shots. Significant improvements in t_{bd} and σ_{bd} are possible with laser triggered switches. R. E. Beverly III and Associates manufactures trigatron, field-distortion, and laser switches that offer working voltage ranges from 2.5 to 75 kV, peak current ranges from ~1 to >500 kA, and repetition rates to 100 Hz. Current pulse widths are dependent upon the user's circuit and are typically in the range of 100 ns to ~10 μs. Custom switch development is available upon request.

Triggering of Trigatron Switches. In the conventional trigatron circuit and as recommended here, the opposite electrode is at high potential and the adjacent electrode is at ground potential. A trigger pulse with peak voltage V_t is applied to this pin in the presence of the main gap voltage V_g. Switch closure involves two gaps, the trigger gap d_t between the trigger pin and the adjacent electrode, and the main gap d_g between the opposite and adjacent electrodes. For heteropolar operation, i.e., V_t and V_g are of

opposite polarity, the mean electric field between the trigger pin and adjacent electrode and between the high-potential opposite electrode and the trigger pin are

$$E_t = V_t / d_t \qquad \textbf{(1a)}$$

and

$$E_g = \left(V_g - V_t\right) / \left(d_g + h\right), \qquad \textbf{(1b)}$$

where h is the pin recess distance. Two discharge initiation and switch closure mechanisms are possible: (i) if $|E_t| > |E_g|$, then the trigger pulse first causes breakdown to the adjacent electrode (BAE) and the resulting UV radiation and plasma provide a source of ionization leading to discharge across the main gap, or (ii) if $|E_t| < |E_g|$, then the trigger pulse first forms breakdown streamers directly to the opposite electrode (BOE) and the resulting ionization density, which is driven by the applied field, avalanches until the arc channel forms, the resistance across the main gap drops abruptly, and the switch closes. There is general agreement in the literature that operation in the purely BAE mode results in a longer breakdown time and excessive jitter.

Optimal results are obtained with simultaneous BAE and BOE initiation using the critical trigger voltage V_t^*, given by

$$V_t^* / V_g \;=\; -d_t / (d_g + h - d_t) \qquad \textbf{(2)}$$

for heteropolar operation. Hence, for $|V_t| > |V_t^*|$, BAE operation will occur first while for $|V_t| < |V_t^*|$, BOE will happen first.

An in-depth discussion of breakdown time and the associated jitter are beyond the scope of the present application guide since these parameters are highly dependent upon the user's circuit and operating parameters. In general, however, σ_{bd} is minimized by

- Circuits with the opposite electrode initially at negative high potential and the adjacent electrode initially at zero potential,
- Charging the capacitor such that $V_g \geq 0.85 V_{sb}$,
- Operating in the combined BAE-BOE mode as discussed above, and
- Utilizing a fast rising and accurately timed trigger pulse.

Triggering of Field-Distortion Switches. Prior to triggering, the trigger ring must not be allowed to float at some uncontrolled potential but rather must be at a potential that is exactly one half of the voltage difference between the main electrodes. The polarity of the trigger pulse must be chosen to induce the maximum field gradient, e.g., if the high-voltage side of the switch is at positive potential and the other side is at ground potential, then the trigger pulse should be negative potential. The trigger circuit must be properly decoupled and biased as described below in **Representative Circuits**.

Triggering of Laser Switches. Using excimer or nitrogen lasers, for example, a peak intensity at focus $>10^{12}$ W/cm^2 is required to initiate a laser generated spark and trigger breakdown. Light enters the switch through an on-axis aperture of 0.670 inches (17 mm). The focusing lens (supplied) is integral with the switch and is selected for use with the customer's laser. To protect the lens from discharge vapor, the focusing chamber is pressurized and gas flows from this chamber through the hole in the main electrode, into the switch interior, and then exits through two tube fittings in the insulator. Generally speaking, visible or UV lasers with a pulse energy ~1 mJ and a pulse width ≤30 ns will reliably trigger these switches. For extremely short-pulse lasers such as those operating in the femotosecond regime, the switch can be triggered with an extremely small energy: $\tau_{laser} \sim 10^{-15}$ s, $E_{laser} \sim 1$ μJ.

Trigger Generator Requirements. Triggering requirements for the electrically initiated models demand a fast pulse having a peak voltage >|V_g|/3, a rise time ~1–10 kV/ns (field-distortion) or ~0.1 kV/ns (trigatron), and an energy >5 mJ.

Our model PG-103D trigger generator is specifically designed for trigatron switches and can be configured to simultaneously control up to four switches with programmable delays. One trigger head is utilized with each switch and the control unit may be located up to 1000 m away. Any channel may be disconnected without harm to the unit. The peak voltage is set at the factory and is optimized for the particular switch model ordered, although it may be readjusted using an internal potentiometer. Single pulse or repetitive operation (externally or internally clocked) is possible. A recharge command signal is provided for synchronizing and controlling an external constant-power charging supply. An adjustable delay allows time for the switch to recover before voltage is reapplied to the energy-storage capacitors during the subsequent recharge cycle. This feature is particularly important during repetitive operation at high frequencies.

The PG-103D generator may also be used with smaller field-distortion switches, but a custom trigger generator is recommended for optimum results, especially for the larger models.

Voltage Drop. The resistive voltage drop is typically 130-370 V and is dependent upon Q and the gas fill. For a fixed value of Q, the voltage drop is independent of I_p, provided that there is sufficient current to sustain conduction (>10 A).

Recovery Time. The gap recovery time depends upon I_p, Q, and the gas type, pressure, and flow rate. Minimum recovery times are only obtained when the discharge waveform is critically damped or overdamped; recovery will be prolonged for discharges with significant voltage reversal. Recharging of the energy-storage capacitor should occur slowly, preferably by means of an inductive or resonant L-C charging system. For repetitive operation, best results are obtained using a command charging source that delays recharging for a few milliseconds following each discharge. Constant power supplies are available from several vendors that satisfy these requirements. These HV supplies should be connected directly to the energy-storage capacitor(s) through special protective networks (see our Application Note AN-102 for an example). A fully discharged capacitor represents a short circuit to a constant-power supply and the supply begins the charge cycle in constant-current mode. As charge flows to the capacitor, the supply senses when the current drops below the limiting value and changes to constant-voltage mode. The set-point charging voltage is maintained until the subsequent switch closure-capacitor discharge and the charge cycle begins afresh.

Life Expectancy. Energy losses in the switch are due to three mechanisms: (i) plasma sheath dissipation including various electrode sputtering phenomena, (ii) heating of the gas column in the spark and associated radiative losses, and (iii) resistive (Joule) heating in the bulk electrode material. There is unfortunately no precise method for predicting life expectancy since operating conditions vary widely. Under maximum rated operating conditions, typical life expectancies are 5,000 to 20,000 shots. Life expectancies in excess of 100,000 shots can be realized under derated operating conditions. Periodic maintenance by the user is necessary to achieve these limits. Although we can provide estimates for user-specific conditions, we recommend that the user perform lifetime tests for critical applications.

Life expectancy is primarily limited by erosion of the main electrodes due to mechanism (i) and is therefore dependent upon total accumulated charge transfer. For the trigatron models, erosion of the trigger pin will lead to erratic operation. In most circumstances, the life of the trigger plug will be shorter than the life of the main electrodes; however, the trigger plug can be easily replaced in the field without disassembly of the entire switch. Intense radiation from the spark [mechanism (ii)] causes ablation of insulator material. Sputtering of the electrodes also adds impurities to the internal gas. Subsequent plasma-chemical reactions in the spark discharge produce contaminants that are adsorbed onto internal surfaces thereby reducing V_{sb} and causing intermittent prefires and misfires. Proper preventative maintenance of the switches can prolong their useful life. For repetitively pulsed applications, average heating due to mechanism (iii) may also be an important factor, especially if the temperature of the bulk

electrode material is allowed to increase well above ambient. Series SG switches are cooled primarily by the internal gas flow and maximum life expectancy will only be obtained using the recommended flow rate. For extreme duty, we offer a finned heat sink (model HEX-101) that bolts directly to the top aluminum plate.

Minimum lifetimes can be expected when the load impedance is comparable to the resistance of the spark-gap switch itself. This occurs, for example, when a capacitive discharge system drives a low-impedance load such as a spark. Under these conditions, a large fraction of the stored energy is dissipated within the switch with concomitantly higher erosion rates. In conclusion, there is no firm rule-of-thumb to determine life expectancy as each pulsed power system places different demands upon the switchgear. Electrodes are rated for the total charge transfer accumulated over the lifetime of the switch, Q_{tot}.

Maintenance. Please refer to our Application Note AN-101, *Care and Feeding of Spark-Gap Switches* for information on routine maintenance and cleaning. Our switches can be refurbished at the factory for approximately one-third the cost of a new unit. This procedure involves cleaning the switch and replacing both main electrodes and the trigger electrode. Standard-duty switches can also be upgraded for heavy-duty operation by replacing the used electrodes with our -75C series electrodes. Please inquire for further information and a quotation.

Mounting

Gas-flow switches must be mounted with the axis of the switch VERTICAL, not horizontal, to prevent accumulation of discharge debris on the inner wall of the insulator and increased probability of surface tracking. This is especially important for high charge-transfer switches such as our SG-171M, SG-172M, and SG-173M models. Horizontal orientation of the switch axis also induces excessive lateral stresses on the fasteners and, for these reasons, will void the warranty.

Electrical Connections

Trigger Mode. For trigatron switches, the trigger mode is defined by the relative polarities of the trigger (T), adjacent (A) and opposite (O) electrodes. As depicted in Figure 1, there are two heteropolar and two homopolar modes. In general, mode A offers the widest operating range with smallest breakdown time and jitter. Homopolar operation (modes C and D) is strongly discouraged.

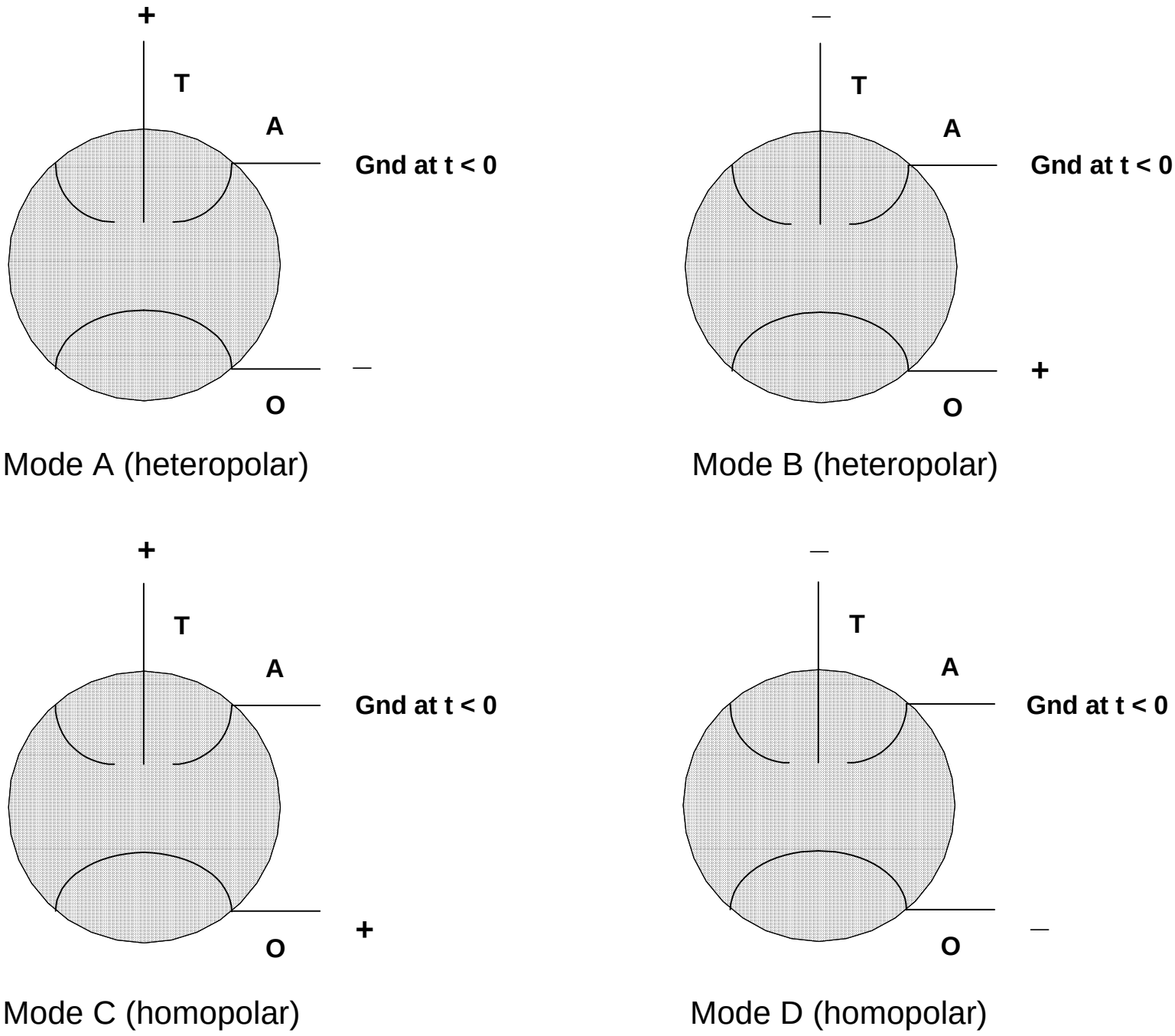


Figure 1. Trigger-mode designations

Representative Circuits. Representative circuit diagrams for capacitive-discharge applications using spark-gap switches are shown in Figures 2 through 5. C_s is the energy-storage capacitor, Z_L is the load (characterized by resistive and/or reactive components), and the heavy lines denote high-current paths. VS is the high-voltage power supply. D_p is a high-voltage diode or several diodes in series and L_p is an inductor; these components protect the power supply from discharge transients. Consult your power supply manufacturer for specific recommendations. **FAILURE TO PROTECT THE POWER SUPPLY MAY RESULT IN CATASTROPHIC DAMAGE.** Trigatron circuits labeled *(a)* employ negative charging and operate in heteropolar mode A while circuits labeled *(b)* employ positive charging and operate in heteropolar mode B. PG is a pulse source (trigger generator), TL is the output coaxial cable, and D_s and R_s together form a snubber circuit to protect PG from discharge transients. TR is the trigger transformer. For the circuits shown here, the transformer must have isolated primary and secondary windings, i.e., do not use an automotive type autotransformer. R_t (≈5 kΩ, 5-10 W, high-voltage type) and C_b (≈500–1000 pF, ≥40-kV "doorknob" ceramic type) decouple the secondary winding from the trigger pin and protect the primary circuit from dangerous transients. The trigger transformer (TR) should be placed in close physical proximity to the switch and all leads should be kept as short as practicable on the secondary side. Never bundled secondary leads together or allow them to touch metal surfaces. A crimp-type spark-plug connector is supplied with our trigatron switches.

In all examples, the primary current paths are denoted by heavy lines and these conductors should be designed for low self-inductance (e.g., strip lines). A robust, single-point earthen ground is essential for any high-voltage, high-current discharge circuit. Utilize a "tree" topology when connecting individual ground lines ("branches") to the earthen ground ("trunk" terminus) otherwise ground loops (eddy currents) will cause excessive EMI/RFI and may even destroy electronic equipment including the trigger generator. The case or enclosure of the trigger transformer enclosure, if metallic, **must** be grounded. Keep the "branch" lengths as short as possible. The building's electrical safety should **never** be used to ground a discharge circuit.

The circuits shown yield the fastest turn-on, lowest jitter, and maximum repetition rate over the widest range of charging voltage, however, they represent only a small selection of possibilities. Only one lead from the trigger transformer requires decoupling for the series circuits shown in Figure 2. The load floats at high potential during the charging phase. If it is absolutely necessary that the load remain at zero potential prior to discharge, then it may be placed between the adjacent electrode and ground as shown by the circuits in Figure 3. An additional resistor, R_d (≈2–10 MΩ, ≥20-kV thick-film type), is needed to drain accumulate charge from the trigger pin. Both secondary leads from the trigger transformer must be decoupled using doorknob capacitors.

The primary-secondary DC isolation rating for typical trigger transformers is only 20 kV. Failure to follow these recommendations regarding isolation of the trigger transformer may lead to its destruction or to damage to the trigger generator. The polarities indicated should be carefully observed, otherwise switch operation will be erratic or incomplete.

If you purchase any of our trigatron switches together with a THD-series trigger head and custom Z18/147/148 transformer, then we will configure the secondary circuit according to your requirements. In particular, our transformers are certified to an isolation value of 50 kV and do not require the decoupling capacitors C_b and drain resistor R_d under usual operating conditions. These trigger transformers should never be used in the series-injection mode, i.e., with the primary discharge current from C_s flowing through the transformer secondary winding.

LC-inversion circuits are depicted in Figure 4. $C_{s1} = C_{s2}$ are the energy storage capacitors and R_c is a high-voltage resistor enabling charging of C_{s2} by VS. Both capacitors charge to voltage V_c as determined by VS. When switch SG fires, the instantaneous voltage applied across Z_L is then $-2V_c$. Hence, these circuits are useful for generating pulse voltages greater than allowed by operation in laboratory air without resorting to dielectric gases or fluids. For negative charging [Figure 4(a)], the load will initially experience a positive pulse. Conversely, the load in Figure 4(b) will initially experience a negative pulse for positive charging.

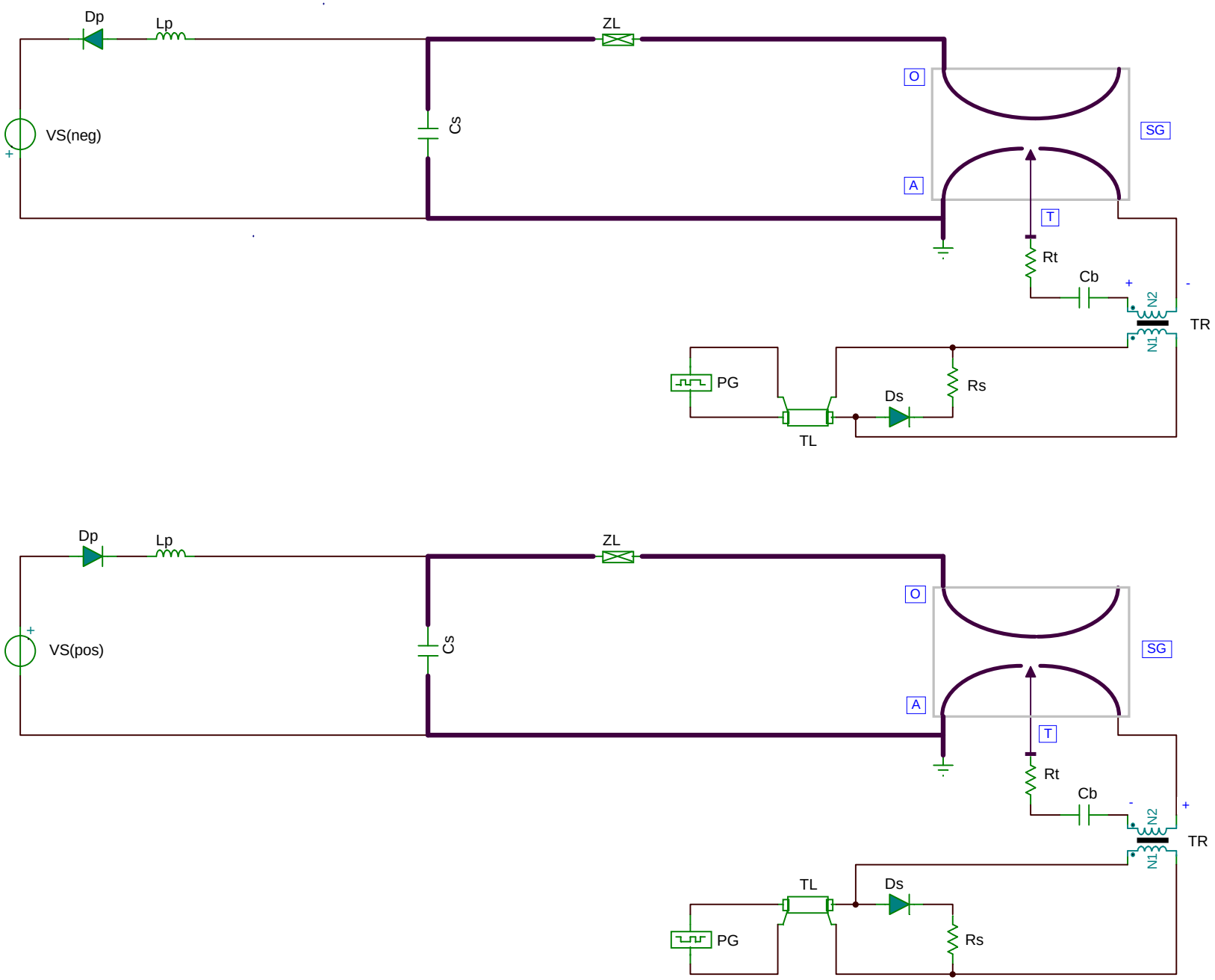


FIGURE 2. Typical series circuits.

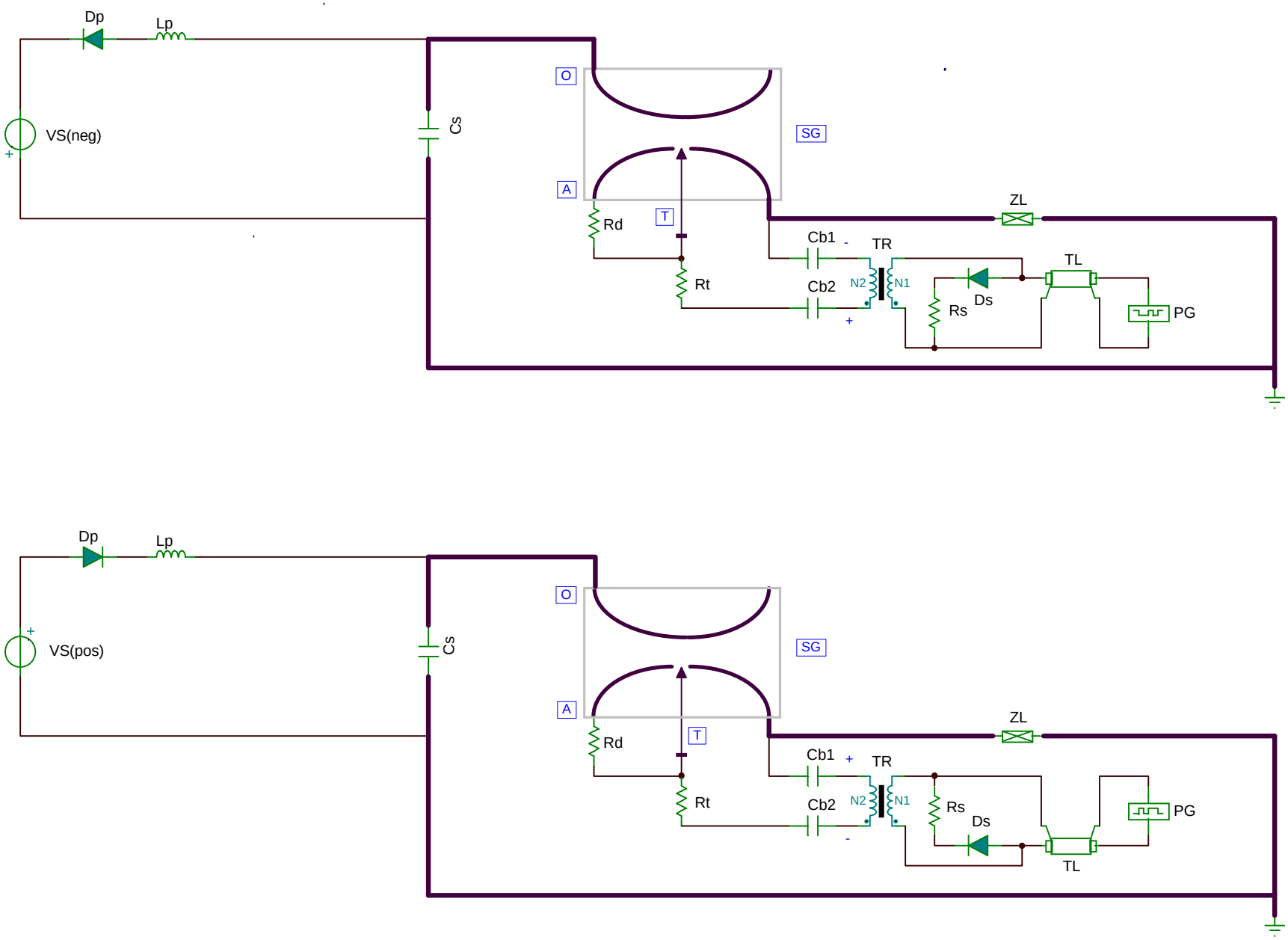


FIGURE 3. Isolated-load series circuits.

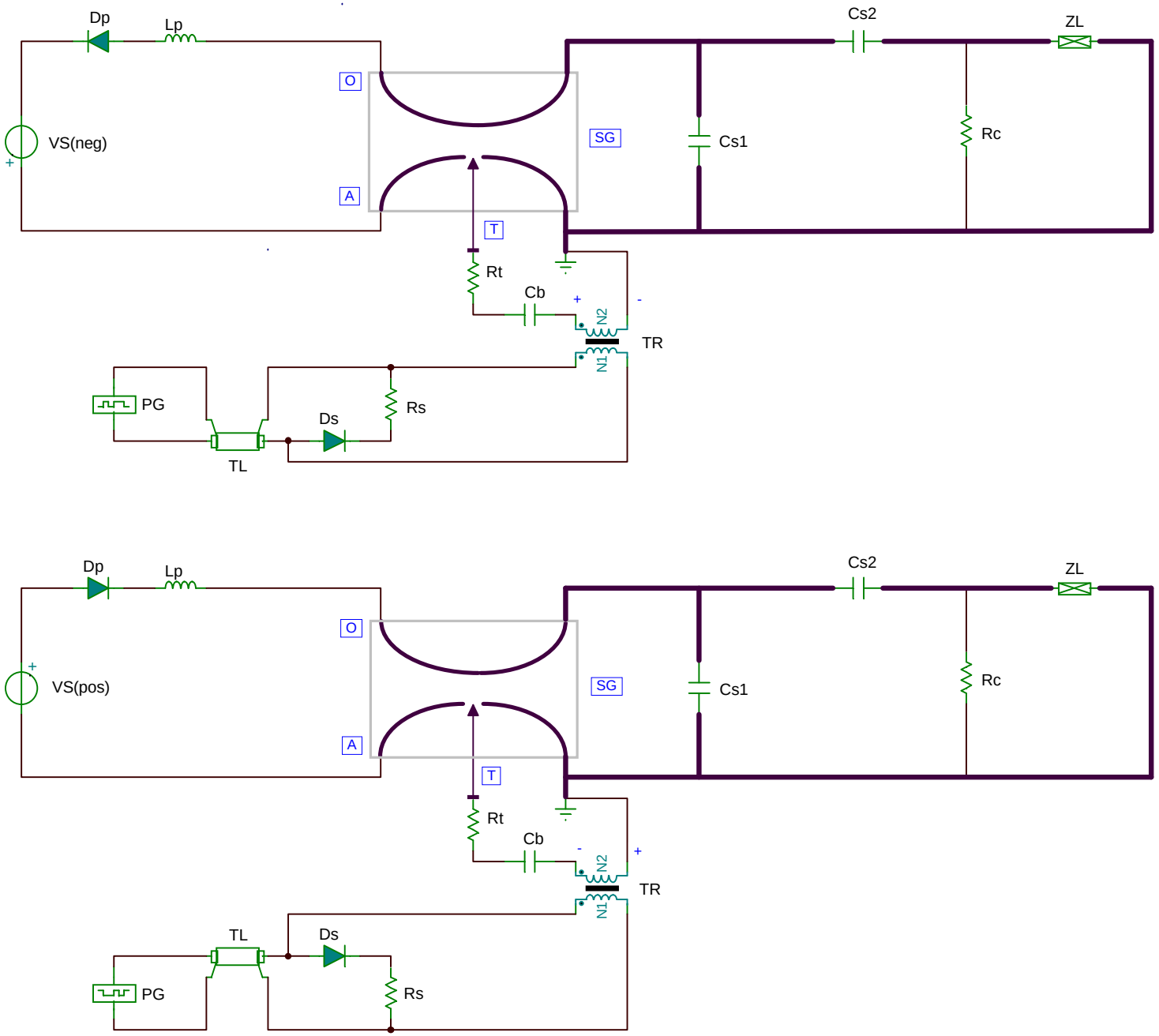


FIGURE 4. LC-inversion circuits.

Field-distortion switches require triggering arrangements as shown in Figure 5. For mid-field trigger ring configurations such as our model SG-124M switch, two high-voltage resistors of equal value, $R_{b1} = R_{b2} \approx 50–200$ MΩ, ensure that the static potential of the trigger ring is one-half the potential difference across the main gap. Decoupling capacitors C_{b1} and C_{b2} prevent inadvertent damage to the trigger transformer. Again, the trigger transformer (TR) should be placed in close physical proximity to the switch to achieve a fast rise-time trigger pulse. R_p is a parallel resistor for use with loads that are initially at high impedance (e.g., gas-discharge loads); choose R_p to give 1-5 A of switch current before load conduction. This resistor is not necessary for loads with a resistive component. Electrical connection to the trigger ring is by means of 0.25-inch (6.4-mm) brass rod with jack. This rod penetrates the insulator and is sealed using a plastic compression fitting. A mating banana plug is supplied. It is imperative that the polarity shown in these schematic diagrams is observed to assure reliable triggering.

Large field-distortion switches such as our model SG-184M require a fast trigger pulse and custom trigger generator. A transformer based trigger generator does not provide either the requisite voltage or rise time for reliable triggering of these switches. Specific recommendations are given in the respective data sheets.

The circuits shown here are examples only and do not represent all possibilities. For more complex systems, including Marx generators and crowbar circuits, we provide complete engineering assistance on a contract basis. If you purchase our PG-103D trigger generator along with a trigatron switch, then we will configure and wire the trigger circuit depending upon your operating polarity and mode. Due to the large number of possible secondary transformer circuits, additional components may be needed and must be purchased separately. Please consult our Links page for suppliers of high-voltage resistors and door-knob capacitors. We generally maintain stocks of these items in smaller quantities.

The entire switch may be immersed in transformer oil or dielectric gas (e.g., SF_6). We recommend Exxon (Esso) Univolt 51, Mobil Mobilect 44, or Shell Diala-A oil for optimum high-voltage service. For $V_{op} \leq 30$ kV, all switches may be operated in the ambient environment depending upon altitude and relative humidity.

Conductors for High Charge-Transfer Switches. Current feed to the switch, via strip-line (sheet) conductors, should be radially uniform. At very high currents and non-uniform current flow, the magnetic pressure on the arc is sufficiently strong to “blow” the arc off axis. This in turn promotes uneven electrode ablation and shortens the switch lifetime. Please refer to our Application Note AN-105, *Transmission Lines —A Basic Primer on Strip Lines* for more details.

Parallel Operation of Switches. Parallel circuits, with two or more switches discharging into a common load, allow larger currents to be commuted while reducing the total circuit inductance. Use of a common trigger transformer is not recommended; each switch should be triggered by a separate, fast-rise-time transformer. For systems with more than 4 switches in parallel, development of a custom trigger generator is usually recommended and cost-effective. If each subsystem consists of a capacitor, switch, and trigger transformer, then the individual capacitors must remain electrically isolated during the charging cycle. This is best accomplished using separate charging inductors or resistors, or for repetitively pulsed systems, separate constant-power supplies. Please refer to our Application Note AN-102, *Massively Paralleled Systems* for further information.

IMPORTANT ADVICE

Proper grounding and shielding protect not only the pulsed power system but also operating and maintenance personnel. An inadequate or poorly designed grounding system will cause unexpectedly large transient voltages in regions of the circuit thought to be at ground potential, resulting in significant safety hazards, copious EMI/RFI generation, and possible damage to associated electronic equipment.

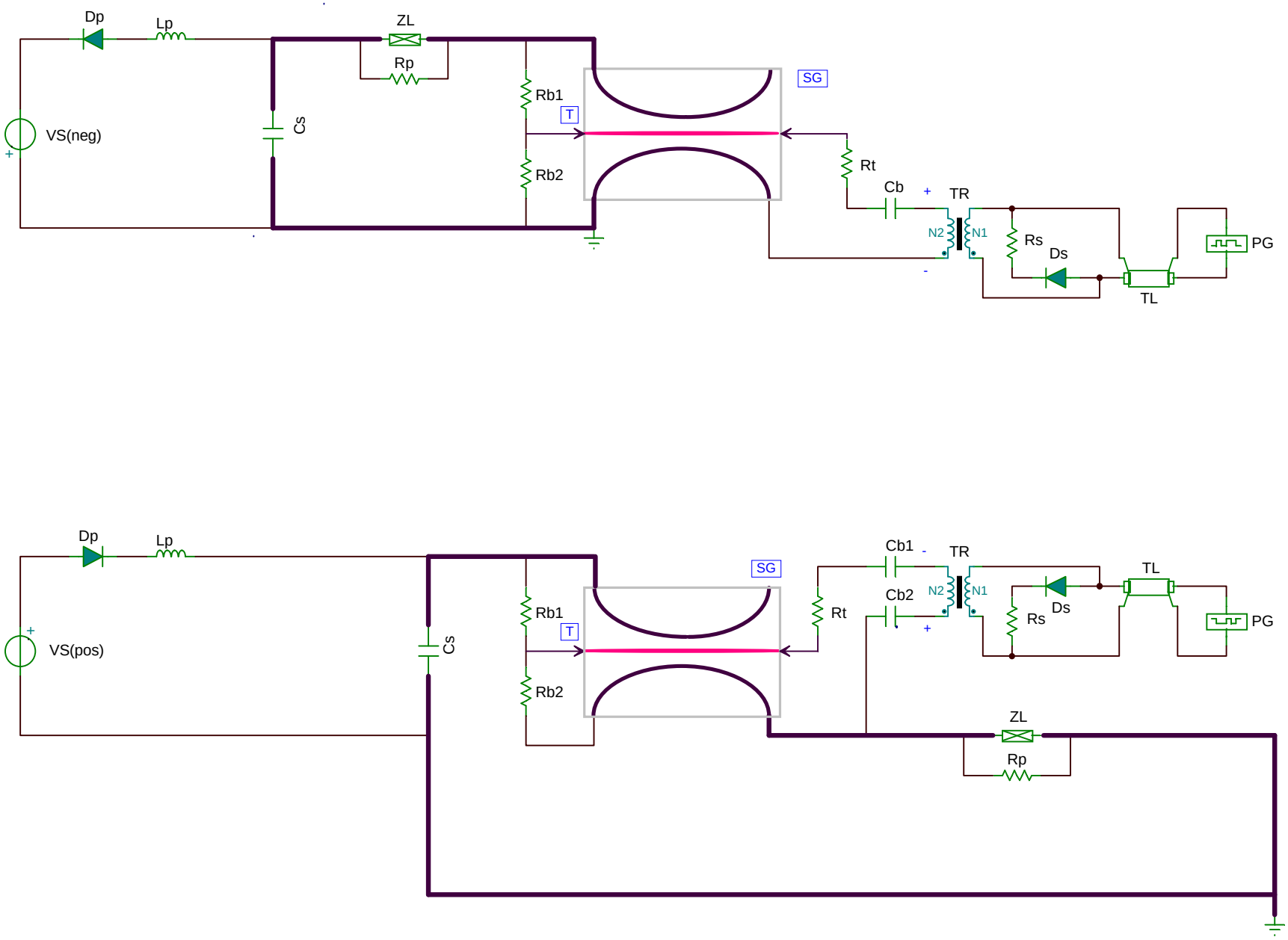


FIGURE 5. Typical series circuits using field-distortion switches.

Gas-Supply Requirements

A pressurized gas supply [typically N_2, synthetic air (21% O_2, 79% N_2), or dry air] is required for operation. We recommend a minimum gas purity of 99.995% and the total hydrocarbon plus water vapor content should be <10 ppm. The presence of water vapor and low-ionization potential hydrocarbons can significantly reduce the breakdown potential. Under no circumstances should *welding grade* gases or unpurified, unfiltered compressed air from the ambient environment be used. In addition to degrading the spark-gap hold-off potentials (both static and repetitive), hydrocarbon impurities undergo various plasma chemical reactions in the discharge and are adsorbed onto the insulator, further degrading performance and life expectancy. Under extremely contaminated conditions, surface tracking along the interior surface of the insulator will result in highly erratic operation and serious damage to the switch. Periodic disassembly, inspection, and cleaning of the switch are recommended. High charge-transfer switches ($Q \geq 5$ Coulombs) should be inspected after the first 50 shots and then periodically after each group of 100-200 shots thereafter. Smaller switches ($Q \leq 1$ Coulomb) should be inspected after the first 500 shots and then periodically after each group of 1000-5000 shots.

Our switches are gas-flow devices rather than hermetically sealed units. Prolonged operation without flow, even during de-rated conditions, will damage the switch and void the warranty. The maximum recommended flow rate as specified on each data sheet is determined by the internal gas volume ϑ (cm^3), repetition frequency f (pulses per second), and exchange fraction E. An exchange fraction $\mathrm{E} = 1$ corresponds to one complete internal gas volume replacement per pulse and this is the criterion for maximum rated operating conditions for our smaller switches. During repetitive switch closure, the **recommended** gas flow rate is

$$\dot{V}_{gas} = 0.06\, f\, \mathrm{E}\, \vartheta \text{ (LPM)}$$

where LPM denotes liters per minute. This flow rate may be reduced for less stringent discharge conditions. however, for high-charge transfer switches ($Q > 1$ Coulomb), we recommend $\mathrm{E} = 3$–5. Use polyethylene, polypropylene or nylon tubing. For shipments to countries on the Imperial system, we supply the switches with ¼" or 5/16" tube fittings; for metric countries, M6 or M8 tube fittings are provided.. The ends should be cut squarely and inserted fully into the Parker fittings. Our fittings utilize either a capture ring and O-ring (Parker fittings) or a double-ferrule system (Swagelok® fittings). The former fitting is fully connected by finger tightening only; the latter fitting should be tightened 1-1/4 turns beyond finger-tight. The gas pressure regulator should be installed on the supply-line side while the internal pressure gauge and flow meter should be installed on the outlet-line side. High charge-transfer switches should be equipped with a gas expansion tank and pressure relief valve for safety. Please refer to our Application Note AN-101, *Care and Feeding of Spark-Gap Switches* for more information on gas supply systems.

Other gases may be utilized for special-purpose operation. For example, argon will allow the switch to operate at much lower voltages, but runaway (self-triggering) will occur for $f \geq 30$–50 pulses per second (pps) unless sulfur hexafluoride (SF_6) is added. A 10% SF_6:N_2 mixture will permit the switch to operate at higher voltages. All gas mixtures must be pre-mixed and allowed to equilibrate, i.e., do not attempt to combine the constituents during flow through the switch because the heavy minority gas (sulfur hexafluoride) will not adequately mix with the carrier gas (argon or nitrogen). Most gas vendors worldwide will provide custom gas mixtures of SF_6 with Ar or N_2. The highest repetition rate and smallest electrode-erosion rate are obtained with hydrogen, but safety precautions are advised. Switches using hydrogen demonstrate the lowest insertion loss due to Ohmic resistance and give the fastest turn-on compared with other pure gases and their mixtures.

IMPORTANT: Please read the data sheet for your particular model for additional information regarding allowable operating gases, pressures and flow rates. Operating voltage-pressure curves for the recommended gases are also given there. To prevent mechanical failure, the maximum recommended operating pressure should never be exceeded.

Replacement Parts

User-replaceable parts are available from the manufacturer. The Buna-N O-rings are standard sizes (AS568A Imperial standard) and are widely available. The trigger plugs for the trigatron switches, however, are specially modified for this application. Replacement field-distortion electrodes are also usually in-stock. Please contact us for prices and availability.

Warranty

All SG-series switches are covered by a manufacturer's limited warranty for a period of one (1) year after purchase. Any defective unit will be repaired or replaced at our option with no additional charge for materials or labor. This warranty is void if the switch was not installed or operated in accordance with our instructions, or if it has been modified or subjected to deliberate misuse. For warranty service, please provide an explanation of the problem and contact us to obtain a return authorization:

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P. O. Box 198
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Return instructions will be provided with the Return Material Authorization (RMA). Unauthorized returns will not be accepted. The switch will be repaired or exchanged and returned within one week after receipt. The switch can be refurbished at the factory after the warranty period for a nominal charge. The switch is cleaned, both main electrodes are replaced, and a new trigger plug or field-distortion ring is installed. Please call for a quotation.

The manufacturer's sole obligation under this warranty shall be repair or replacement of a defective switch. Since these switches are to be incorporated into a pulsed-power system of the customer's own design, we bear no responsibility for the proper engineering of these systems or for their safe operation. Under no conditions will the manufacturer be liable for incidental or consequential damages arising from use of this product.

Other Products and Services

Please inquire about other products and services:

Low-inductance, high-voltage, aqueous-electrolyte resistors
Surface-discharge light sources
Surface-discharge switches
Complete pulsed-power systems
Laboratory data acquisition software
Gas-discharge laser development
Specialized diagnostics for plasma-physics research

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Massively Paralleled Systems, Application Note AN-102, R. E. Beverly III and Associates.

Installation of Switch Couplers, Application Note AN-103, R. E. Beverly III and Associates.

Poco-Graphite Trigger Electrodes, Application Note AN-104, R. E. Beverly III and Associates.

Transmission Lines – A Basic Primer on Strip Lines, Application Note AN-105, R. E. Beverly III and Associates.

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