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Technologies for Protecting Critical Electrical and Control Systems on Movable Structures

W. Michael Sutton, PE Project Sales Engineer
Dick March, Sr. Business Development Manager
Phoenix Contact USA

TAMPA MARRIOTT WATERSIDE HOTEL AND MARINA
TAMPA, FLORIDA

Introduction

The technologies behind the control of our movable structures continue to advance and increase in sophistication. While relay logic is a mainstay in the control of these structures, Programmable Logic Controllers (PLCs) and other sensors are increasingly being used to monitor and in some cases control the operation of the bridge. Many of these movable structures are located in the Southeast region of the United States where the power and electronics are exposed to more frequent and higher levels of surges. This paper will examine the different technologies that can be used to protect against surges and transients and how these technologies can be applied to provide a holistic approach in protecting critical electrical and control systems on movable structures.

Need for Surge Protection

Definition of a Surge

The International Electrical Commission (IEC) defines a surge voltage as a "transient voltage wave propagating along a line or a circuit and characterized by rapid increase followed by a slower decrease of the voltage". In simpler terms, a surge event is a rapid rise in current along a circuit that occurs in a very short period of time. Depending on the type of event, the current will typically rise to a maximum value on the order of 8-10 microseconds and dissipate over a period of twenty to several hundreds of microseconds. The two main causes of surge events can be attributed to lightning discharges and switching operations. The third main type is electrostatic discharges but because we are looking at a heavy industrial application, we will focus on lightning and switching transients. The following graph shows the typical discharge waveforms that surge protection devices are tested against. These waveforms are approximate representations of the two main types of surge events:

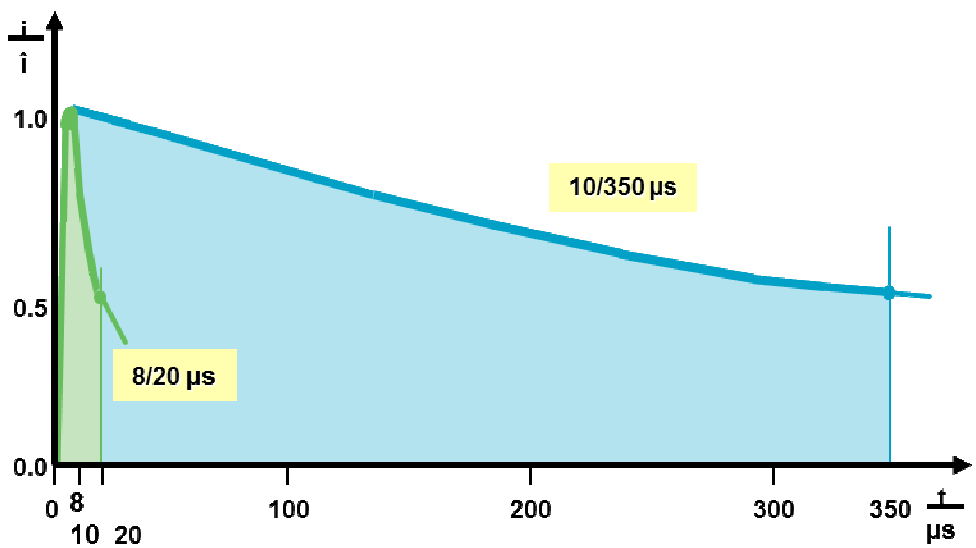
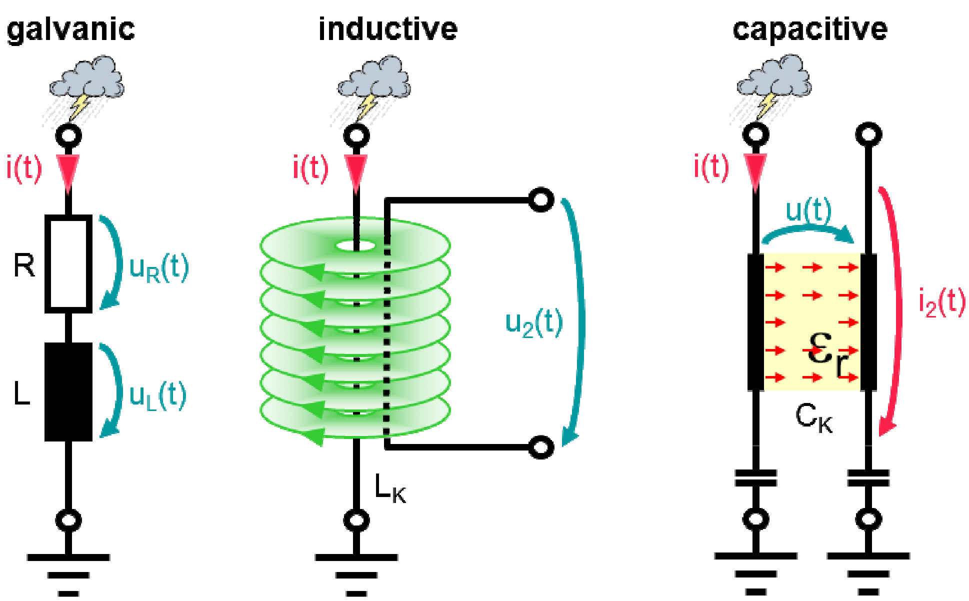


Figure 1: Waveforms used in Testing Surge Protective Devices

The graph represents two different waveforms with the first number representing the time to rise to maximum surge or current (8 or 10 µs) and the decay time to half value of the surge event (20 or 350 µs). The area under the curve represents the amount of energy. The 10/350 µs waveform on the graph attempts to represent the two main currents of lightning strokes, impulses with short duration of less than two milliseconds and long strokes with durations greater than two milliseconds. This waveform is part of the IEC 62305 standard.[1] As can be seen from the graph, lightning results in a tremendous amount of energy that can be very damaging to electrical and control systems. The other type of surge or transient event is a switching event and examples of these include switching in the power grid, starting of large AC/DC motors, and starting of generators. They are more closely approximated on the graph by the 8/20 µs waveform. All of these types of switching events could be possible when one is looking at a movable structure.

The way in which these types of events can affect circuits is multiple. Lightning currents can couple into electrical and electronic systems either directly or galvanically, inductively or through capacitive means. The following diagram provides a pictorial representation of the different types of coupling mechanisms.



Lightning surges seek multiple paths to ground so galvanic coupling is the surge current being directly applied on to the circuit as it seeks to go to ground. Lightning surges create intense magnetic fields and as such can induce voltages across wires that are in the magnetic field. As much as 70 V per meter of cable can be induced on a cable from a lightning strike that is a three-dimensional mile away. These strikes do not have to be cloud-to-ground strikes; induced coupling can occur from cloud-to-cloud lightning. Capacitive coupling is derived from positively and negatively charged ions passing over conductors due to the potential differences between the wires. Capacitive coupling can create significant noise on analog circuits disrupting the signal to a control system.

Switching transients affect circuits through inductive coupling. When equipment is turned on or off or when switching operations are being performed by the local power company, the currents in those lines will increase thereby creating surge voltages that can be induced on nearby cables and wires. These types of transients occur much more frequently and thus need to be considered when developing surge protection scheme.

Need for Surge

There are approximately 845 movable bridges in the United States. Of those 845 movable bridges, close to 300 of them are in Louisiana or Florida, which are areas with high densities of lightning strikes. The following map of the USA shows the average number of lightning ground strikes or flashes per year per square kilometer. From this map, one can see that Florida has certain areas that experience 14 flashes or greater per sq km per year.

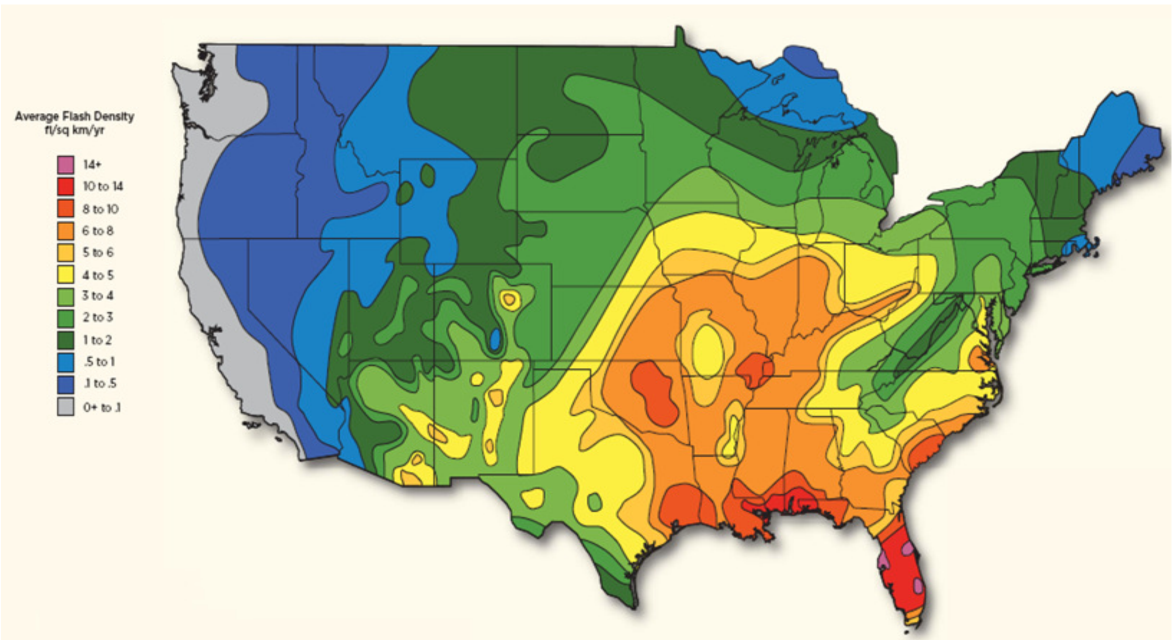


Figure 2: 1997-2007 Average US Lightning Flash Density Map, Insurance Institute for Business and Home Safety, 2012.

However, this graph does not represent cloud to cloud lightning strikes which are the more prevalent types of events. Also, -t is just not lightning that can create problems for electrical and control systems. We also have to be concerned with switching transients and surges that can occur on a daily basis. Eighty percent (80%) of equipment failures can be attributed to switching events although it is harder to correlate because these types of transients are typically not monitored and recorded.

Damage to the electrical and control systems of a movable bridge due to surge events is costly from a replacement and maintenance standpoint but it also render the bridge inoperable until it is repaired which has far more reaching economic impacts, particularly in waterways used for the transport of freight. Thus, it is imperative to consider surge protection as part of a reliable design of any movable bridge.

Surge Protection Technologies

Surge protection devices (SPDs) are designed to divert the higher voltages and currents away from sensitive equipment without interruption of the circuit. There are four main types of surge protection technologies used in SPDs by most manufacturers. These technologies can be split into two categories, voltage switching and voltage limiting. Within voltage switching technologies, there are gas discharge tubes (GDTs) and spark gap technologies. Voltage limiting technologies include metal oxide varistors (MOVs) and suppressor diodes.

Voltage Switching Technologies - General

Voltage switching technologies are more coarse protection elements that are characterized by an ignition voltage at which the device switches on. In the order of nanoseconds following the ignition voltage, the device changes to a low-resistance state and discharges current over a low voltage (10-30 V) known as the burning or arc voltage. One of the things to recognize is that the ignition voltage is not constant and will vary within 20% depending on the rate of rise of the surge voltage. The following graphs depict the characteristic curves of GDTs and spark gap technologies, with U_z representing the ignition voltage and U_B representing the burning voltage.

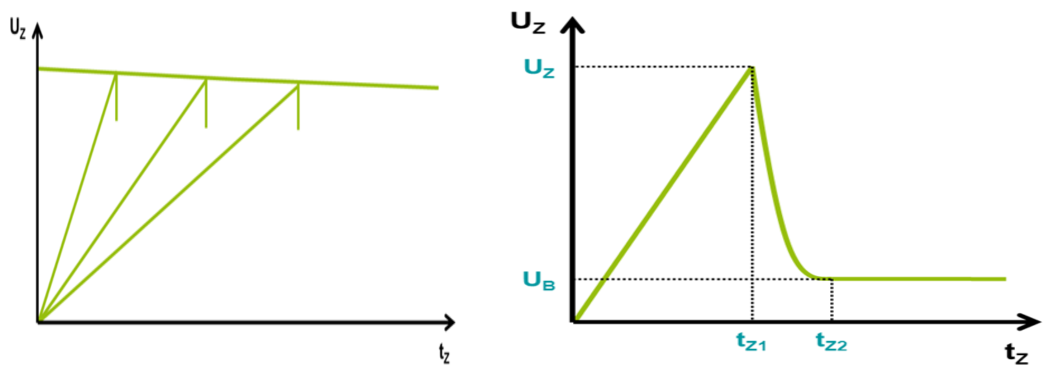
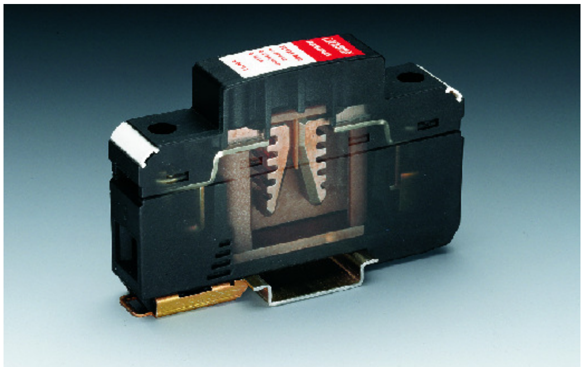


Figure 3: Characteristic Curves of Spark Gaps and Gas Discharge Tubes

Voltage Switching Technologies - Spark Gaps

Traditional spark gap devices have been around for many years and have often been used by electric utilities in high voltage applications. However, some of the older types of devices have not been used on the secondary side of the transformer because of the difficulty in extinguishing the arc and the potential for line follow currents. Thus, the device may "turn on" and actually not "turn off". The result is a short circuit on the system that will trip upstream circuit protection devices and limit the reliability of the system. To prevent tripping of upstream circuits, properly sized fuses need to be installed upstream of the SPD.

Advances in surge protection have led to the development of arc chopping spark gaps, which have the ability to eliminate line follow currents making them ideal as lightning arresters for power applications. These spark gaps have tremendous energy capabilities of up to 50 kA (10/350 µs) and are used as lightning arresters. The unique feature of these devices is the quenching and baffle plates arranged around the spark horns that help to quench the arc and the associated line follow currents. Because of its capability to quench and dissipate the surge energy, arc chopping spark gaps can take multiple strikes before reaching end of life. The following is a picture of an ARC spark gap with quenching plates and the associated symbol used in circuit diagrams:



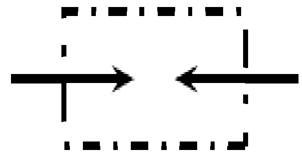
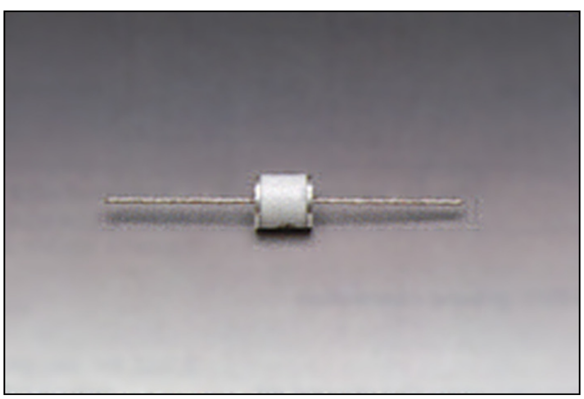


Figure 4: ARC Spark Gap Surge Protection Device and Symbol

Voltage Switching Technologies – Gas Discharge Tubes

The other type of voltage switching technology is gas discharge tubes. GDTs consist of an electrode arrangement in a ceramic or glass tube. Between the electrodes is some type of inert gas such as neon or argon. Once the ignition voltage is reached, an arc voltage between 10 and 30 V typically occurs. . The most commonly used GDTs can discharge transient currents in the range of 10 kA – 100 kA (8/20 µs) and are typically used in conjunction with suppressor diodes to protect low voltage signal circuits. The following is a picture of a typical GDT and the symbol utilized to represent these devices in circuits.



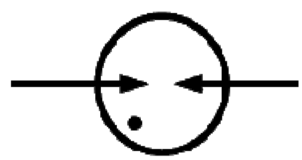


Figure 5: Gas Discharge Tube Surge Protection Device and Symbol

Voltage Limiting Technologies - General

Voltage limiting technologies such as suppressor diodes and metal-oxide varistors (MOVs) are used in both power and signal applications. These devices are voltage dependent and have very specific turn-on voltages with rapid response times in the nano and pico second range. The following shows typical characteristic curves for voltage limiting devices:

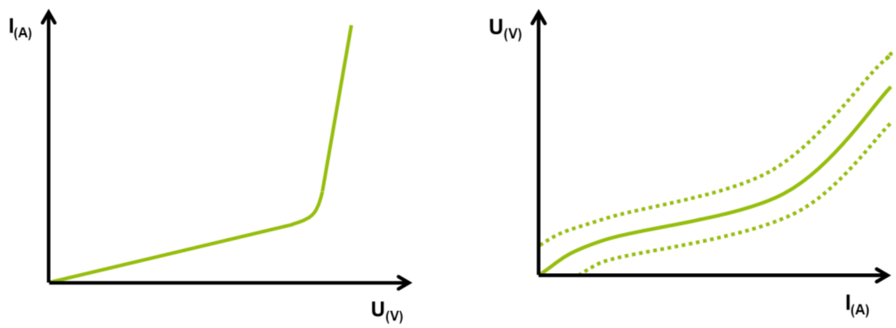


Figure 6: Characteristic Curves of Suppressor Diodes and Metal Oxide Varistors

Voltage Limiting Technologies – MOVs

As their name implies, MOVs consist of a matrix of metal oxides squeezed between two metal plates or electrodes. Depending on the size of the MOVs, they have the capability to handle large surge currents of up to 35 kA for 10/350 waveform. While having the advantage of fast response times and fairly large surge capabilities, MOVs do have some disadvantages and must be properly applied. For one, MOVs degrade over time and will start to draw leakage current over time. The amount of leakage current can be significant as the MOV ages, which can lead to disruptions in analog signal circuits. The high capacitance of the varistors can lead to attenuation of signals in high frequency application so they are not used in data transmission lines with high frequencies. For frequencies up to approximately 30 kHZ, the attenuation is almost insignificant. The following are pictures of small MOVs and the symbol utilized to represent these devices in circuits.

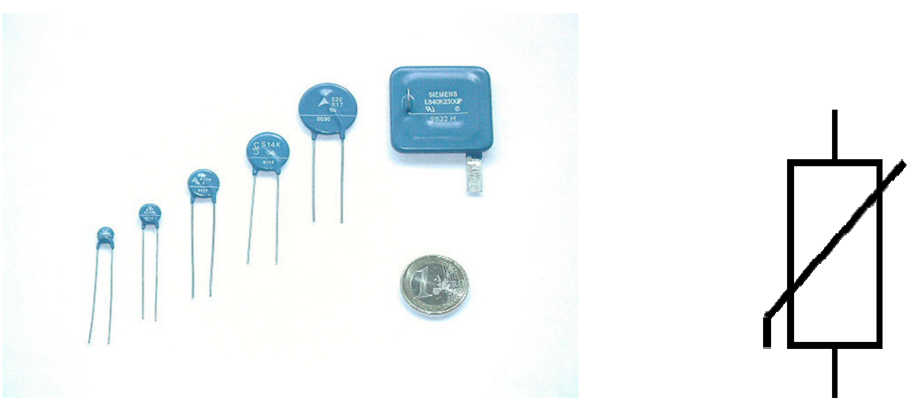


Figure 7: Metal Oxide Varistor Surge Protection Device and Symbol

Voltage Limiting Technologies – Suppressor Diodes

Suppressor diodes or silicon avalanche diodes (SADs) are diodes that are made of silicon, have extremely fast response times and very specific turn-on voltages. SADs are used in conjunction with other surge protection technologies, such as GDTs, in signal circuit protection since they have lower energy handling capabilities. One disadvantage to SADs is similar to varistors in that the capacitance of the device can lead to attenuation of signals in high frequency applications. The following is a picture of a typical SAD and the symbol utilized to represent these devices in circuits.

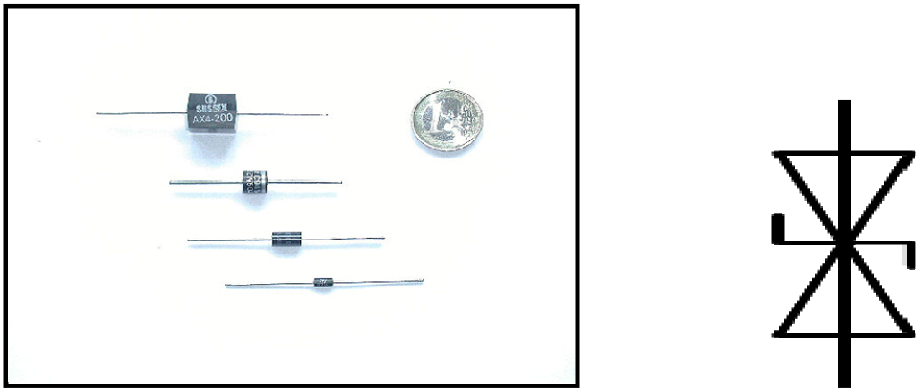


Figure 8: Suppressor Diode Surge Protection Device and Symbol

Classification of Surge Protection Devices

Before we look at how to apply surge protection devices and technologies, it is important to understand how they are classified by two of the most important standards organizations: Underwriter's Laboratory (UL) and the IEC. The UL standards are predominantly followed in North America whereas the IEC standards are more European centric.

In 2009, UL released the 3rd edition of their standard for surge protection titled UL Standard for Safety for Surge Protective Devices, UL 1449[1]. There are a number of significant modifications between UL 1449, 2nd edition to UL 1449, 3rd edition. The nomenclature for referring to surge suppressors was modified from Transient Voltage Surge Suppressor (TVSS) to Surge Protection Devices (SPDs). UL 1449 now applies to devices used to repeatedly limit transient voltages on 50/60 Hz circuits 1000 volts and below. This is an increase in voltage from 2nd Edition, which covered devices 600 volts and below. One of the most important factors that differentiate UL standards from IEC standards is the classification. UL 1449 3rd Edition gives four designations to surge protective devices depending on where in the electrical system the device is connected.

- **Type 1** - Permanently connected device installed before the service disconnect overcurrent device and intended to be installed with no external overcurrent protective device. This type of SPD most closely relates to devices that were called secondary surge arrestors prior to 3rd Edition.
- **Type 2** - Permanently connected device installed after the service disconnect overcurrent device. This type of SPD most closely relates to devices that were called transient voltage surge suppressors prior to 3rd Edition.
- **Type 3** - Point of use SPDs that are installed with a *minimum* of 30 feet of conductor length from the service panel. The 30 feet of conductor length does not include conductors used to attach the

SPD. Some examples of Type 3 SPDs are cord connected, direct plug-in and receptacle type SPDs.
- **Type 4-** Component SPDs and component assemblies.

The IEC product standard is 61643-11[3] and the devices are split into three categories based on their surge capability rather than location within the electrical system. The three categories are as follows:

- **Type 1:** Protection level < 4 kV, Lightning arresters are for the effects caused by direct or close-up strikes designed to protect the installation and equipment at the interfaces for the main incoming power. Type 1 arresters are always recommended if the building has an external lightning protection system.
- **Type 2:** Protection level < 2.5 kV, Surge arresters for the effects caused by remote strikes, inductive or capacitive coupling, and switching surge voltages designed to protect the installation, equipment, and termination devices typically in the sub-distribution level.
- **Type 3:** Protection level < 1.5 kV, Device arresters are designed to protect particularly sensitive termination devices to further reduce the voltage level. These may include devices for permanent installation in distributions or portable protective devices in the socket area directly before the termination device that is to be protected.

Effective Surge Protection Principle

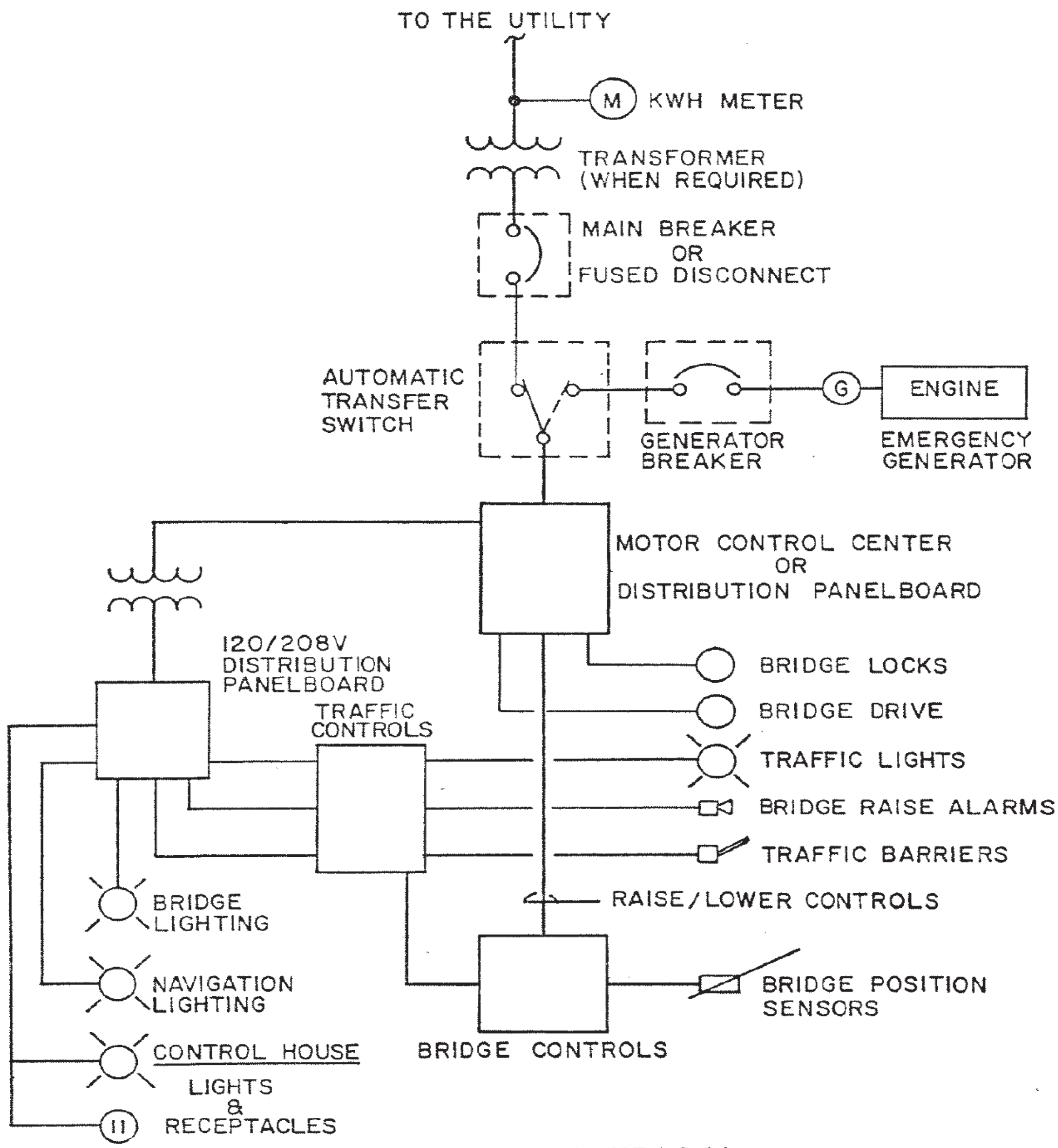
When applying surge protection technologies to any electrical or control system, one should always take a big picture approach and look at the overall facility. If the incoming power is not properly protected, then the downstream surge protection will not be properly coordinated to protect the lower voltage electronics. Similarly, even if the power is properly protected, surges can still enter the system and damage sensitive electronic equipment such as Programmable Logic Controllers (PLCs) and Human-Machine Interface (HMI) devices. The best surge protection scheme encompasses a cascade or step approach that protects all circuits going in and out of the facility including power, control and measurement signals, data/communication lines and transceiver/antenna connections.

In addition to taking a cascade approach in properly protecting a facility, the other key factor is ensuring that the surge protection and equipment within the facility are effectively grounded and bonded. Surge protection works essentially as a switch; when a surge event occurs, the SPDs switch on and divert the additional current to ground. Without effective grounding and bonding, surge protection will not properly protect the facility and the end user will have a false sense of security.

Movable Bridge Example

Movable bridges are an important component of our transportation infrastructure in the United States. Thus, it is important to design our bridges with the ability to withstand many different factors for increased operational availability and uptime. Obviously, availability needs to be balanced against financial constraints but a good surge protection scheme can provide significant increases in uptime at a relatively low cost.

Let's examine a typical movable bridge electrical schematic. The preferred voltage for powering most movable bridges is 480 VAC, 3 phase 60 Hz power. Most likely a transformer will be needed to step down the voltage from the local power utility. Most movable bridges are also equipped with standby generation system(s) to provide a backup source of power in the event the utility service fails. The following is a typical electrical block diagram for a movable bridge[4]:



BRIDGE ELECTRICAL BLOCK DIAGRAM

Using the diagram above as a basis, the first point at which surge protection should be installed is after the Automatic Transfer Switch (ATS) on the incoming power to the Motor Control Center (MCC) or Distribution Panelboard. For the purposes of this discussion, we will refer to device by Type # according to IEC standards. The type of device that should be installed downstream of the ATS is a Type 1 Lightning Arrester device. It is recommended that the device be capable of handling a surge of 25 kA for L-N connections and up to 100 kA for N-GND. One important factor to note is that the device should be tested to the typical lightning transient waveform of 10/350 µs to insure a quality product. One option to a Type 1 device is a combination Type 1/Type 2 device that coordinates both lightning and transient protection in a single panel or enclosure. As noted in the discussion about surge technologies for voltage switching devices, it is imperative that properly sized fuses are provided upstream of the SPD and there are manufacturers on the market that build in fusing to the surge protection solutions.

The next point of surge protection is to protect critical components downstream of the motor control center. For critical motors and drives, a Type 2 style surge arrester rated at 40 kA would be appropriate at an 8/20 waveform.

For the 120 VAC distribution panel board, a Type 2 SPD rated at 20 kA for L-N and N-GND and a max discharge current of 40 kA should be installed in front of the panel board to protect the downstream power and components. Depending on the distance between the panel board and the control panels, a Type 2 or Type 3 SPD may be warranted for the incoming power to the control panel. A rough rule of thumb is that for distances less than ten feet, a SPD should not be necessary. Over ten feet, one needs to consider the distance and the potential for induced surges on the wires and design a Type 2 or Type 3 SPD for protecting the power.

For signals entering the control panel, SPDs should be installed to protect the PLC and other electronics within the control enclosure. Depending on the application, there are SPDs designed for 24 VDC analog circuits and 24 VDC and 120 VAC discrete circuits that can handle total surge currents of 5 kA to 20 kA depending on the voltage.

Operation and Maintenance of SPDs

While surge protective devices do protect electrical and control system components from failure resulting in reduced maintenance costs for these components, the SPDs will eventually reach an end of life and require maintenance and replacement particularly in areas prone to high levels of surges. Thus, it is important that ease of maintenance of these devices is a feature set when selecting SPDs to not only reduce replacement time costs but to insure increased system availability. There are a number of manufacturers on the market that have maintenance friendly devices. When considering SPDs, we recommend a number of features be included as part of the specification to insure ease of maintenance:

- Pluggable – many manufacturers have two piece SPDs in which the actual surge components are housed in a pluggable element that inserts in a base element. The wires to the SPD are terminated on the base element. When the device reaches end of life, the pluggable element is hot swappable and can be easily removed with standard tools and replaced with a new plug. Unless there is significant damage to the base element, many hours of labor can be saved from disconnecting and re-terminating wires on the SPD. However, a properly coordinated surge protection strategy should eliminate significant damages to base elements. Pluggable SPDs come in all IEC styles from Type 1 Lightning Arresters to Type 3 Device Protection as well as signal circuit SPDs.
- Remote Indication – to reduce routine maintenance hours, many SPDs come with a remote indication dry contact that can be wired to a PLC or indicating light to note when the device has reached its end of life. Remote indication can be found on both power (Type 1 -3) and signal circuit SPDs.

  There are other options for large banks of signal circuit SPDs protecting multiple analog and discrete input/output points. One option is to jumper the contact to common the alarm to the control system. Another option that is specific to one manufacturer is a head end controller that monitors the status of each SPD through a T-bus connector along the DIN rail. The head end controller has the same form factor as the SPDs and provides two contacts, one for performance level nearly reached and one for end of life. The controller requires 24 VDC power and can be used for analog, 24 VDC discrete and certain communication signals.

- Visual Indication – if a routine spot check of panels and electrical components is a part of the maintenance program, visual indication of end of life either through a LED light or red-flag is useful for quickly determining which SPDs require replacement. It is recommended that the SPD source the power for the LED indications separate from the circuit that it is protecting to avoid any possible interference with the circuit.

- Testable – many manufacturers have the ability to test their SPDs with some type of proprietary testing device. This can be useful as part of a routine maintenance check on an annual or semi-annual basis. One manufacturer utilizes a testing device that allows you to determine if the SPD has certain elements that have been compromised or reached its end of life. The tests can be stored in memory or printed to keep an official record. One key point is to insure that the SPD is hot swappable and can be tested without affecting the circuit or signal.

Summary

In summary, movable bridges are a very important part of our nation's infrastructure. To protect these structures and to expedite operation of the bridges, they are increasingly being monitored and controlled through sensors and analyzers that are connected to PLCs. To maximize availability of movable bridges and to protect the power and sensitive electronic equipment used to monitor and control the bridge, it is crucial to employ an effective and encompassing surge protection scheme.

REFERENCES

[1] International Electrotechnical Commissions 62305-1: Protection against lightning - Part 1: General principles. 2013.

[2] Underwriter's Laboratory (UL) 1449 3rd Edition: Standard for Safety for Surge Protective Devices. 2009.

[3] International Electrotechnical Commissions 61643-11: Low-voltage surge protective devices - Part 11: Surge protective devices connected to low-voltage power systems - Requirements and tests. 2011.

[4] Richardson, Robert A., *1St HMS Symposium*. "Movable Bridge Electrification" November 1985.