Surge Management

RobustDC Application Note #18

Quick Index:

• What is a Surge?

Hmm ... what is a surge? More important, how to understand the phenomena of surge well enough to properly protect my equipment? No doubt there are super-scientific explanations around, but these won't help the average engineer or technician protect our equipment. So let's see if we can discuss surges as they relate to our goal of protecting our equipment.

> **Electricity** (î-lèk-trîs´î-tê, ê´lèk-) noun - The physical phenomena arising from the behavior of electrons and protons that is caused by the attraction of particles with opposite charges and the repulsion of particles with the same charge.
>
> **Ground** (ground) noun - A large conducting body, such as the earth or an electric circuit connected to the earth, used as an arbitrary zero of potential.
>
> **Surge** (sûrj) noun - A sudden, transient increase or oscillation in electric current or voltage.
>
> *The American Heritage® Dictionary of the English Language, 3rd Edition © 1992 by Houghton Mifflin Co. Electronic version licensed from INSO Corp. All rights reserved.*

So, what is a surge? The definition above mentions "a sudden transient increase" ... that means we have an unexpected, higher-than-normal flow of electricity. Worse, not only did we not expect it, but our equipment didn't either and the result is damage ... and repair ... and down-time ... and lost $$$. But why does electricity flow anyway? A stupidly simple question, but perhaps so simple it is often overlooked. Well, when you connect a material with more free electrons to a material with less free electrons, electrons will flow from the more to the less. This flow crosses physical space and takes finite time - admittedly a very, very small time, but it does take time.

So back to that surge and our damaged equipment. Our equipment is damaged because it finds itself in the middle of this unexpected flow of electricity. On one side of our equipment is too many free electrons, and on the other side of our equipment is where they naturally want to go. Analogies would be a fence flattened by a cattle stampede or a small river dam suddenly overwhelmed by a flood of water. But the concept of a flow from more to less is critical for understanding surge damage and how to prevent it. Surges are not a sub-atomic mountaineer who damages equipment "because it is there"; ***surges damage***

equipment because it is in the way! Either move your equipment out of the way - or offer a safer by-pass around your equipment.

A surge is a transient increase in electric flow, which is the result of the repulsion of many electrons seeking roomier quarters, which brings us to the concept of the perfect ground. As we all know, the best place for excess electrons to flow is into the Earth. But it is not so simple - 50% of the time free electrons flow *into* our equipment *from* the Earth! First lets discuss 3 background issues.

1. The definition of ground mentions that wonderful word ***arbitrary*** - "arbitrary zero of potential".
2. Soil has a fairly high resistance, making it a very poor and unpredictable conductor.
3. During a really big surge condition (ie: lightning) excess electrons are just as likely to enter your equipment from the Earth as they are to exit your equipment into the Earth.

• The Mythical Concept of the "Perfect Ground"

I say the perfect ground is mythical because most engineers and technicians maintain strong faith in a pure concept of ground that approaches religious dogma. This faith is implanted in technical schools were grounding issues must be over simplified and generalized to allow the solution of problems. The faith includes the idea of the Earth/soil as a good conductor and if systems are done right, a perfect ground can be created with an infinite ability to absorb current instantaneously. Designs that approach the prefect ground with good connections (rods, mats, tapes) will solve all surge problems. Drop a watt of power - !*poof*! it's gone. Drop a few billion watts of lightning energy - !*poof*! it's gone.

But it doesn't work that way. The earth is a conductor and energy storage medium just like wires and capacitors and inductors. All the rules, like V = I*R still apply, but the non-homogeneous nature of soil make them hopelessly complex to calculate. Here are some excerpts from ***Grounding & Noise Reduction Practices for Instrumentation Systems***. It was written by Xerox Corporation under contract to the U.S. Air Force (but unfortunately the copy I have is old & damaged - parts are missing).

> ***2.1.4 Ground Currents (on page 2-8 to 2-9)***
>
> *Generally speaking, ground currents can be any current flow in the neutral or common conductor of any circuit, whether it is directly connected or not. ...*
>
> *In addition to ground currents associated with an individual circuit, there also may exist considerable earth ground currents which flow below the earth's surface. Earth current is often detrimental to instrumentation systems because of the potential that exists at different points in the earth. Potential differences between two earth grounding rods have been theoretically calculated at well above 10V peak-to-peak.*
>
> *To date, a satisfactory method of measurement has not been developed which can be used to quantitatively determine the magnitude in amperes of earth current. ...*
>
> *However, to measure the amount of stray earth current from one point to another is a very complex matter involving soil resistivity, moisture, weather conditions, and depth of electrode. ...*

So I hope this helps to show that there is no dead, immovable 0V ground sink. If you could see current flow like water, you'd often see a wonderful rippling of current flowing (or fluxing) around your site. On a sunny day the ground potential between 2 earth rods can be as high at 10 volts - and during a lightning storm it can be 100's of thousands of volts.

Understanding the misconception of the perfect ground is critical to designing robust industrial systems. Too many engineers believe that having good ground rods will eliminate surge problems. Instead, a more robust and workable concept of grounding is to assume each ground rod and each metal structure that contacts the soil is a new and potentially different “ground” - a different arbitrary zero of potential. It can be done - properly designed systems still work fine with such dynamic ground assumptions. Engineers must just design proper grounding, isolation, and surge management into their system.

Do you want to design a fragile system that requires near-perfect ground?

Do you want to design a robust system that works with dynamic ground quality?

It boils down to an analysis of errors and consequences. A system designed to assume near-perfect grounds will fail repeatedly if there are any flaws in the design or the maintenance of the system. ***The resulting system is fragile.***

On the other hand, if a system is designed assuming imperfect grounds, then proper isolation is placed between sub-systems. The overall system works whether the grounds are perfect or not. Design or maintenance flaws have little or no impact on the system. ***The resulting system is robust.***

• The Role of Soil

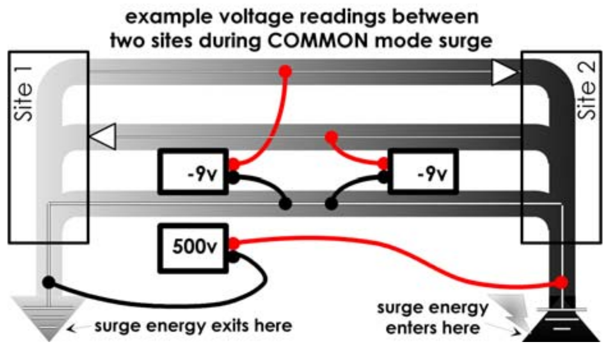
In order for the Earth to be a "perfect ground" which absorbs unwanted energy ASAP, it requires a very low resistance to maximize current flow. Unfortunately, this is far from the truth. In an appendix to the Xerox book are many tables on Earth resistivity based on various criteria. The following example shows resistance (in ohms) of various types of soil in 5/8in x 5 ft rods:

Soil Type	***Min***	***Avg***	***Max***
Fills: Ashes, cinders, brine waste	3.5	14	41
Clay, shale, gumbo, loam	2	24	98
Same with varying proportions of sand & gravel	6	93	800
Gravel, sand, stones, with little clay or loam	35	554	2700

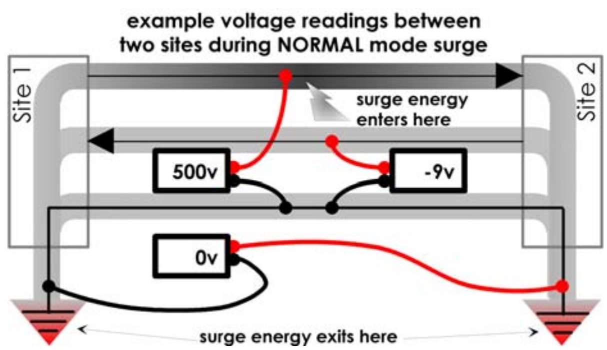
Just look at the last row - sand has an average of 554 ohms per 5 linear feet of distance. Imagine trying to design a ground system using wire with 360 ohms of resistance per meter! Imagine the problems if your AC neutral wire had 360 ohms of resistance per meter! Yes, yes, I know that is not really what this table means - the Earth is a 3-dimensional conductor and a wire a 1-dimensional conductor, so the comparison is not directly valid. But I hope this points out that the Earth (meaning "soil") cannot an ideal ground system. That is why power system engineers spend time & money adding chemicals & ground mats to improve the nature of their site ground. *That is why your equipment and your wires will always make a preferred path for surge energy.* That is why “surge management” - which assumes surges are a natural part of any system - is a safer philosophy than treating surges as pesky leftovers from bad designs.

• Common vs Normal Mode Surges

There are 2 main surge patterns industrial people have to plan for. A ***common mode surge*** is present on all wires of the interface, while a ***normal mode surge*** is present on only one or some wires of the interface. This is the same concept as common/normal mode noise. In industrial settings, 99% of surge damage is caused by Common Mode surges. This is unfortunate, because most industrial people expect and plan only for Normal Mode surges. They incorrectly apply surge solutions and their equipment is still damaged!



A ***common mode surge*** is present on all wires of the interface - that mean it is *common* to all wires. The usual cause of a common mode surge is a ground potential shift due to lightning, bad ground design, faulty machinery, or the return current of arc welding. This causes a remote site to see all wires as having a high voltage. In the example here, a 500v ground potential shift causes our problems - a common mode surge enters the ground of the right-hand device, travels across the data communications wires, and exits the ground of the left-hand device. The surge *enters* by one ground connection and *exits* the other - 50/50! Notice the voltage potential between wires is as expected - in this example only -9v. The problem is when all 3 wires are referenced to the local ground at the left; the 3 wires are "coming in" as 491v, 491v, and 500v respectively. These voltages are obviously not supported by the EIA/RS-232 standard!



A ***normal mode surge*** is present on only one or some wires of the interface - it is not common to all wires. The usual cause of a normal mode surge is strong electrical noise that induces an energy spike on a transmission wire. This noise can be caused by lightning, arc welding, proximity to noisy equipment, radio units, or vehicle ignition systems. This causes the integrated circuits (IC or chip) at each end to see one pin having a high voltage. In this example, a 500v noise spike was induced on one wire and travels outwards towards both remote grounds.

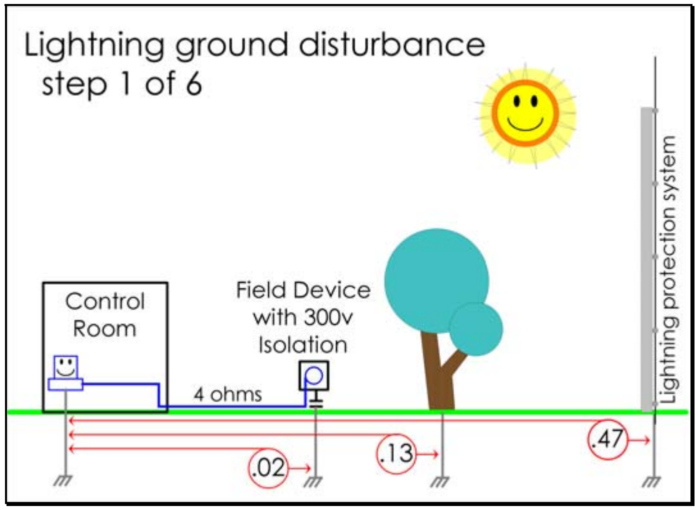
Common mode surges tend to be high-energy surges where hundreds (or thousands) of Amps of current flows within only a few tens of microseconds. It takes gas discharge tubes and spark arrestors to handle this much power. By contrast, normal mode surges tend to be very low energy surges - and easily handled by simple transient surge diodes.

• Anatomy of a Ground Potential Disturbance Caused by Lightning

Step 1) An Average Sunny Day

Here we see a ground potential situation on an average sunny day. Due to the high variability in soil conditions, the large variety of equipment leaking current to the earth, natures preparation for and the aftermath of lightning storms, any industrial site can have a flux of ground currents moving here and there through the earth. Yet even if we accept that the Earth is always 0v on a sunny day, lightning activity will cause large energy charges to move through the Earth - both in response to the charges drawn from the earth to charge the clouds & as a result of lightning discharges themselves. For example, Singapore has officially 230 days of lightning activity each year. So on 230 of 365 days (63%) it is safest to assume ground potential differences and ground current fluxes will exist.

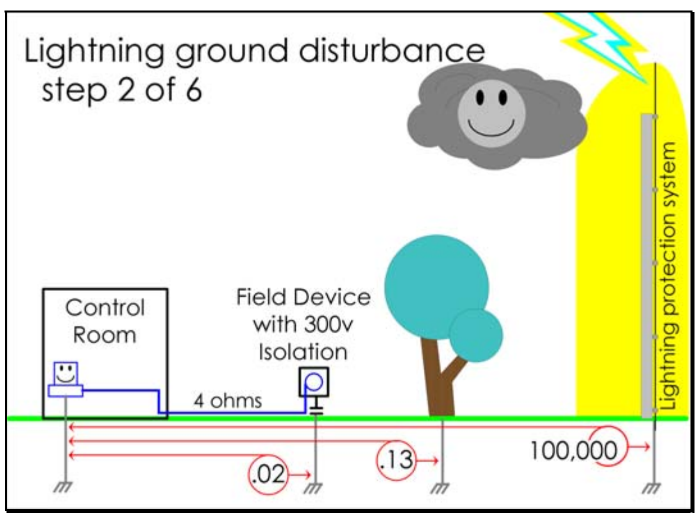
The drawing "Step 1 of 6" show one possible set of Ground Potential Differences measured with reference to the Physical Earth at the Control Room building. In this case we see 0.02v with respect to the field device physical earth, 0.13v with respect to a neighboring tree, and 0.47v with respect to a distant tower with a good quality lightning protection system installed. If we have a communication cable (like RS-232) with 4 ohms of resistance between the computer and field device, then at this moment we could potentially have about 5mA of ground current flowing from the field device to the computer through the RS-232 port. This would be known as a "ground loop" and is why most 4-20mA loop devices (like pressure or temperature transmitters) are carefully isolated. It must be stressed that the actual values during ground potential disturbances are in a constant state of flux. This is just a simple, non-destructive example.



We can assume that the computer has no isolation from the control room ground - I have yet to see any standard computer with more than 1 ohm of resistance between it's RS-232 ground and it's chassis & AC Physical Earth (PE) pin. The field device - if professionally designed & installed - may be isolated from it's local earth by at least 300 volts. This prevents any minor ground loop current.

Step 2) Lightning Strikes

Now the sunny day is replaced by a lightning storm. An average lightning bolt hits an average tower or high building with an average, safety-code-approved lightning protection system. Things work just as expected and no harm is done - so far. While the ground potential difference with respect to the field device & tree have not changed yet, we now have a 100,000 volt ground potential difference between our control room and the distant tower. This potential may be 30,000 or 850,000 volts or any big value. The

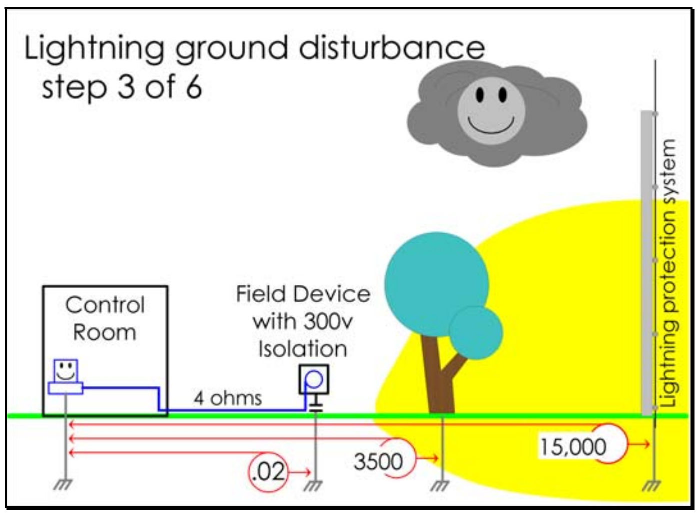


exact number is not important, other than it's more than you want. The background shading in this drawing and the following ones represents visually the voltage potential movement.

But what happens to the energy inherent within the lighting strike? Does it magically dissipate like a puff of vapor once it hits the Earth? Of course not. It just charges the soil in the immediate vicinity like a big battery. An analogy is a pail of water. If you have very fast eyes, when it is poured out only the ground you start with a pile of water, which spreads out and soaks into the ground. Now you won't see a pile of energy on the ground, but the concentrated charge at the site of the strike is like a "pile of energy". This energy then dissipates OVER TIME out and down into the Earth. Simple concepts of physics like resistance and geometric reduction interact with the local soil conditions in hopelessly complex way to eventually (*OVER TIME*) dissipate the energy charge throughout the local soil. *OVER TIME*, the local ground potential are once more returned to the common, every-day flux of minor ground currents.

Step 3) Energy Dissipates Through the Earth

Now the real "inconvenience" of lightning begins to unfold. As the energy dissipates, it creates something like a "wave" of voltage potential that moves out from the tower. At the moment shown here, this wave has just passed our neighborhood tree. But the tree is not damaged, and neither are the birds sitting in it hurt because they all rise to this potential almost instantly with only micro-currents involved. While our tree is now 3500v higher in ground potential than our control room, the field device and our data communications is still not affected by the lightning.

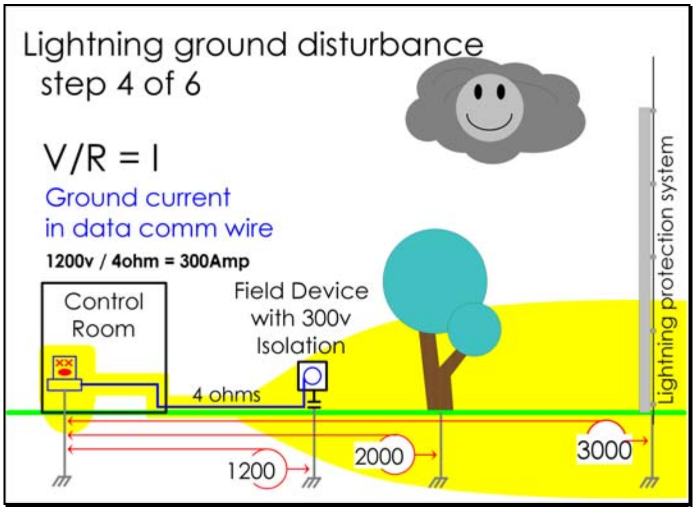


This whole concept of how the Energy moves out over the landscape is called "voltage step potentials" and one of the reasons you're not supposed stand under a tree during a lightning storm. The voltage step potentials could cause there to be a few thousand volts difference between your right and left leg, with painful consequences. See documentation from your favorite "Lightning Protection Unit" vendor for more formal details about this phenomenon. Remember how this ground potential disturbance is taking place over time. The movement is fast, but it still takes a finite time. The actual voltage values shown are not important - it is just the magnitude of difference that matters.

Step 4) Energy Reaches Your Outstation

So the Energy moves out across the landscape like a ripple on a pond. At from 10 to 100 ohms per meter, this movement is a minor battle. As it spreads, the voltage potential naturally reduces. In this picture, the energy has now reached our outstation (the field device). Now the damage starts. If the field device were a stand-alone unit like a sundial or tree, then there would be no damage. But our field devices offer the

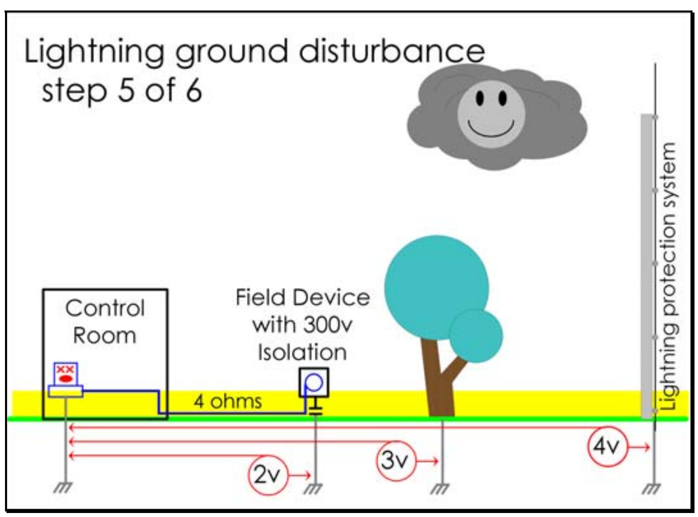
Energy something quite useful - a good, ***lower-resistance*** alternative path to a lower ground potential than is offered by the high-resistance soil. While most of the energy will continue moving through the soil, some of it will chose the easier path. Our 300-volt galvanic isolation is not enough to prevent a high potential surge from entering the field device and rushing toward the lower ground potential of the control room. It will surge into our field device and leapfrog ahead via our average data communications line into our average RS-232 port on our average computer. This energy surging into our RS-232 port will in effect start to raise the potential of our entire control room to the same potential as the earth at the field device. Do a little math - in this example a 1200 volt potential across a 4 ohm wire causes 300 AMPS of surge current for a tiny fraction of a second. These numbers are just examples - what if the voltage potential is 200 or 8000 volts, and the resistance only 0.3 ohms or 25 ohms? You know the math. Is it any wonder integrated circuits can explode as if tiny mines where inside? Or that wires can unsolder themselves? These are all damages seen at customer sites.



Just to review surges a moment. Before we discussed the difference between a ***normal mode surge*** and a ***common modes surge***. This example shows a common mode surge - and you can see why lightning protection units are rated at 6500 or even 10,000 Amps! Normal mode surges, where energy is induced within 1 wire of a multi-core cable will never have such high energy.

Step 5) Energy Reaches Your Control Room

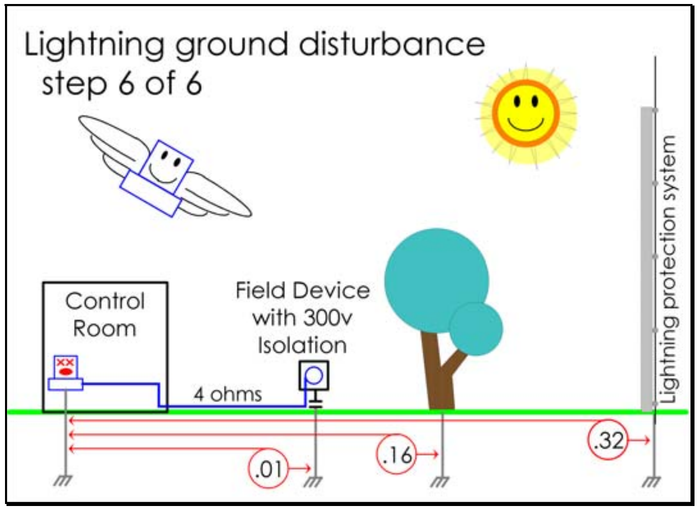
Now things start to return to normal. The Energy has reached our control room and the damaging surge currents have stopped flowing. The entire site is probably still at a raised ground potential - say 50 volts - with reference to some remote external system like the telecommunications authority or electric utility. But within our site the ground potential differences are returning to normal. Eventually the Energy contained within the lightning strike spreads itself so far and so thin that we pretend it has disappeared. But we all know



vaguely that the law of Conservation of Energy says it cannot disappear. It will eventually be attracted to some remote location to due to the creation of lightning-causing potentials. In fact, the ground charges are to lightning much like water is to rain.

Step 6) The Sun Shines Again

Need we say more? The sun is shining again. The local ground currents are fluxing quietly as they like to do*. **The repair man cometh to repair our computer and/or our field device.*** Was the surge demonic in it's behavior? Of course not. It was merely doing what all voltage potentials seek to do - flow towards a lower voltage potential; millimeter-by-millimeter; atom-by-atom. Due to our system design, we provided a better path - we marched the surge right through our expensive equipment! We rolled out the red carpet for the surge.

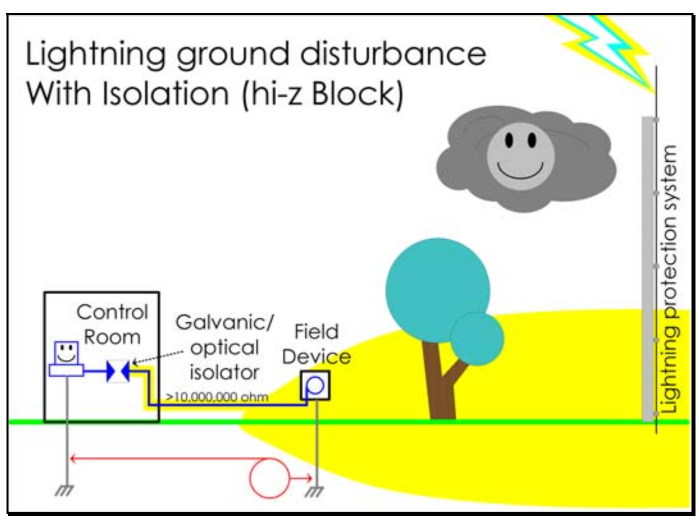


- ## Proper Surge Management Design

I like to compare a surge to a wild elephant that sees wonderful ripe bananas on the other side of your carefully cultivated field. Is the elephant demonic to smash through your fence and trample your crops to get to the banana? We cannot STOP the elephant from going for the bananas once they are seen. However, we can 1) prevent the elephant from seeing the banana in the first place - or 2) provide an "easier" path to the bananas that spares our fence and our crops. These 2 options relate to 1) isolation and 2) surge devices. Read on for more information. Keep in mind that you cannot “stop” the surge energy. It will still eventually reach a lower ground potential. That is why traditional surge “protection” is a misleading concept. A better term is “Surge Management” - you manage the inevitable surges & get them to move by non-destructive paths.

- ## Isolation During Ground Potential Difference

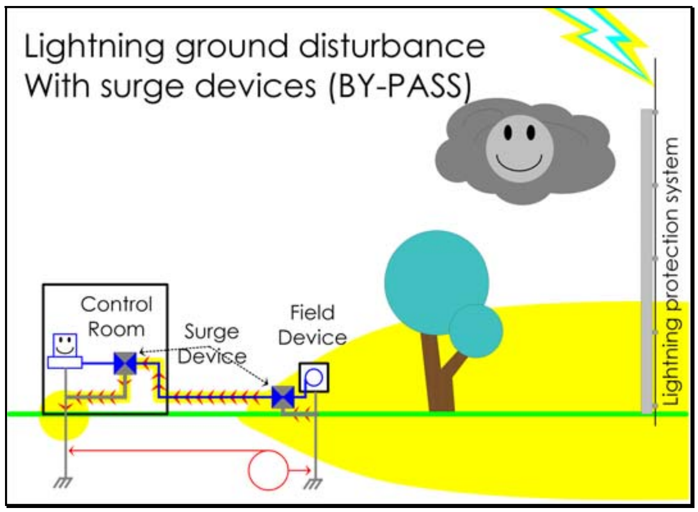
Isolation is like not letting the elephant see the bananas across your field - or creating a ditch so deep it must search for another path to reach the bananas. Isolation prevents surges by making the data communication line look like a floating dead-end instead of a path to a lower potential ground.



The galvanic/optical isolator effectively increases the resistance of the data communications wire to over 10,000,000 ohms. Remember the I = V/R equation? Even at ground potential differences of thousands of volts, there will be no surge current and no damage. The demonic surge finds the isolated data communications line unappealing and seeks to travel elsewhere. But the voltage potential *will* enter with only micro-currents and raise the potential of 1/2 of your isolator. In the case shown before, you will have a short-lived 1200 volt potential across your isolator. Therefore thought must be given to the insulation level of your cabling, cable routing, and placement of the isolator and wires.

Isolation is ideal for day-to-day ground potential shifts due to large machinery operation, arc welding, AC mains failures, or to connect floating-earth systems to grounded systems.

• Good Lightning Protection During Ground Potential Difference



This is analogous to providing the wild elephant an easier path to the bananas around your field. Surge devices encourage surges by making the data communication line look like a good path to a lower potential ground, but then provides the surge with a safe bypass around your devices to/from ground.

To perform this magic, surge devices must be quick-change artists. When low-voltage data signals are present, they must appear as high impedance paths to ground so the data signals function normally. When over-voltage conditions exist, the surge device must rapidly "break-down" and appear as a low-impedance path to ground. They effectively short the wire to ground to discharge the surge (or allow the ground surge to enter!) The first concern is of course the speed of this change, and the second is that if your device already offers a low-impedance path to ground, then a surge device cannot provide a lower one and will not work.

Surge devices are ideal for the occasional large and short-lived ground potential shifts due to lightning. Surge devices work very poorly for low-voltage ground potential shifts caused by day-to-day ground potential fluxes.

• Comparison of Isolation and Surge Devices

Isolation and surge devices are two different concepts. Each is best applied to specific situations - and with very sensitive or expensive devices, they can be applied together for best protection.

Issue	Isolation	Surge Devices
Completeness of Solution	You do not need to isolate both ends - isolating one end of a comm line helps both ends. With isolation, every bit helps.	You must install surge protection at both ends. Surge devices are “All-or-Nothing” solutions - a little hurts more than it helps.
Low Voltage Protection	Isolation works as well at a 20 volt surge as it does at a 1000 volt. Ideal for day-to-day low-level ground potential shifts.	Surge devices work better farther from data signal voltage. A 300v surge is handled better than a 20v surge. Ideal for occasional large ground potential shifts.
Effect of Failure	Isolators generally are active components, so failure generally halts data communications & is obvious.	Surge devices generally are passive and just “disappear” with little or no impact on communications - this means failures are difficult to detect and routine testing is required.
Effect of Installation	Fairly straight forward to install - but proper ground wires are critical to long-term robustness.	Improper installation is not obvious to users. Placement of ground wires is critical or the device does nothing.
Protection Levels	Generally 250v, 1000v, or 2500v. There are no current flows to worry about.	Any level from 5v to 10,000v or higher, but maximum short-term and long-term current limits are critical to selection.
Protection of “Floating Earth” systems	Perfect application	Complicates design

• For More Information

Robust DataComm can truly make your data flow like water - safely, sanely, and silently.

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