GROUNDING FOR ESP LIGHTNING PROTECTION

Thomas Brinner
Subsaver, LLC

ABSTRACT

How and where ground wires are connected determines whether or not oilfield lightning protection will be effective. This is extremely evident with lightning protection of electric submersible pumps (ESP). Electric surge suppressors on the same ground wire can and will interact in a lightning storm. Instances of ESP failures due to improperly installed surge suppression are not uncommon. Understandably the value of surge suppression has been questioned. This paper proposes separate ground wires for each surge device with all wires bonded together at the wellhead. Justification for this is derived from multiple engineering reports on well site electrical installations, electrical theory and reported extended ESP runlife.

INTRODUCTION

When oil production requires high-flow from deep wells, ESPs are the most reasonable artificial lift choice. At this conference pumping units (beam, rod, sucker rod, etc.) are covered very extensively, and production personnel are very familiar with them. Although pumping units are less reliable they are much less expensive to repair and replace than an ESP. Rigs, rig crews and lost production are expenses common to both, but the major expense is the ESP. When product design specifics are considered, a multi-stage pump and a multi-rotor induction motor each less than six inches in diameter, extensive manual labor is required to build such a product, and it is not difficult to justify the expense.

Obviously minimizing production expense means keeping the ESP running as long as possible. This is the major challenge. High-power, open-prairie electric power distribution requires medium voltages (1000 to 25,000) that are prone to lightning and switching surges. Deep inside an oil well the remote ESP, typically surrounded by salt water, is exceptionally well grounded. This makes electrical insulation in the ESP power cable and motor particularly susceptible to damage from voltage impulses.

Ideally surge protection would be installed directly from the motor terminals to the housing deep inside the well. However, this is impractical because of the environment, voltage withstand requirements and available protection components. The high temperature and pressure environment comes with caustic fluids. Available surge protection devices are incapable of operating reliably in this environment. Further, connected at the motor terminals a protection device failure would appear at the surface as an ESP failure, and that is totally unacceptable. Consequently, all protection must be installed at the surface.

Historically the two major ESP manufacturers thirty years ago tried to solve this problem with lightning filters [1]. Such filters were a combination of inductors, capacitors and surge protection devises that would limit and slow impulse voltages. How to connect the filters proved to be a problem. The engineers involved tried to solve the problem by measuring the impedance of grounds and ground wires to arrive at the best connection. The problem was solved in November of 1986 when oil crashed to $8 a barrel. Any additional product like an expensive filter simply could not be justified, and all work on it ceased.

Three years after the crash the transient voltage surge suppressors (TVSS) was introduced. Although the electrical industry prefers the name surge protection device (SPD), in the oil industry surges are usually hydraulic. A transient-voltage surge makes the distinction clear.

The TVSS was simply a surge suppressor designed to protect electrical equipment running on three-phase electric power. Still, the problem of grounds and ground connections had not been solved. Worse yet connection of a TVSS at the wrong point in the well site electrical system did actually cause ESP failures. In 2005 a young petroleum engineer kept good records on ESP failures for five years, and his records showed a higher failure rate with TVSS installed than with nothing at all. At that point the effectiveness of TVSS was certainly questioned.

General principles for ESP lightning protection include a TVSS with a ground terminal, mounting the TVSS as close as possible to equipment being protected, ungrounded electrical power and wellhead grounding. However, the central issue is separate ground wires for each surge device with those wires only connected together or bonded at the wellhead.

GROUNDS AND GROUND WIRES

Grounds are electrical connections into the earth. Such connections are routinely made with copper clad steel rods, 8 or 10 feet long and 5/8 or ¾ inches in diameter. Ground rod value is determined by a resistance measurement, where a lower resistance is better. That resistance depends on soil moisture and chemistry.

Two ground rods widely separated having a resistance of 10 ohms each will have a resistance of 5 ohms when connected in parallel. Should the rods be in very close proximity the combined parallel resistance goes back up to 10 ohms, or essentially the resistance of a single rod. RULE OF THUMB. An optimum spacing between rods is 2.2 times the rod length [5], e.g. 10 foot rods should be 22 feet apart.

Electrical substations employ a grid of parallel-connected ground rods. At a well site the power drop pole always has a lightning protection ground wire running the entire length with that wire spirally wrapped around the pole end that will be buried. This is termed a “butt wrap.” If additional rods are deemed necessary one could be placed next to the butt wrap and six could be arranged in a hexagonal pattern around the one. If rods are all the same length no rod should be any closer to another than 2.2 times the rod length.

Chemical grounds have lower resistance than a single ground rod. Chemical grounds consist of a copper pipe with cross holes that is filled with salt and water and placed in an over-sized hole back filled with coke breeze. Since salt and coke breeze are conductive and the hole has a much larger diameter than a ground rod, the resistance is quite low.

Unfortunately, chemical grounds must have salt and water added periodically, i.e. they require maintenance. If this is not done the resistance increases until it is little better than a single ground rod. Maintenance of oil field equipment has never been a priority, simply because of the overwhelming number of wells that are the responsibility of each production employee. Lastly, they are expensive.

Two methods are in common use to measure ground resistance. The first uses two metal stakes with wires stretched from each stake to the test equipment. Test equipment is also connected to the grounding device being tested. Manufacturers of this equipment stress that multiple tests should be performed with the wires stretch out in different directions to account for variations of soil properties. At some point the value of such ground resistance measurements has to be weighed against the time, resources and expense to do them.

The second measurement instrument looks like a champ-on ammeter. It injects a current into a wire loop and measures the resistance. The wire loop must be stretched between a ground reference and the grounding device being tested. But where can a ground reference be easily found? Certainly, the wellhead is the closest thing to a ground reference, and for oil field measurement it should be used. Still, the resistance of the wire loop has to be subtracted from any such measurement.

At any well site the most conspicuous and important ground is the wellhead. Some argue that since the well casing is surrounded by cement, it is not a good ground. This is incorrect because cement is conductive [2]. In reality an oil well is a ground rod thousands of feet deep, and using the above stakes and wire measurement instrument, the author has never measured wellhead ground resistance greater than half an ohm.

Ground wires connect equipment to grounds. Wires have both resistance and inductance. Ohms laws, which says voltage equals resistance times current, is generally understood. Inductance is less well understood because it only comes into play when voltage and/or current are changing. A one-foot long section of solid #6 AWG copper wire has a resistance of .000395 ohms and an inductance of 0.5 μH (micro Henries). These parameters are covered in the technical calculations section. Introducing them here would detract from the purpose of this paper.

TVSS AND OTHER SURGE PROTECTION DEVICES

Early lightning arrester used to protect the power system 100 years ago where simply spark gaps. When voltage exceeded air breakdown in the gap an arc was created essentially shorting out the voltage. Obviously, this created a huge follow-on current. To avoid equipment damage reclosers briefly interrupt the current causing the flicker one sees during a thunderstorm. Some years later GE introduced a material called Thyrite in series with the gap to limit follow-on current and reduce the hazard of explosion.

In 1970 GE introduced the metal oxide varistor (variable resistor) or MOV. The metal was zinc oxide with various alloys, and the resistance changed with voltage. The MOV was a vast improvement over spark-gap arresters. While limiting the voltage, energy in the voltage impulse (volts x amps x time) was dissipated as heat in the MOV material. Further, energy was dissipated at a voltage higher than the AC voltages with no follow-on current as occurred with spark gaps. Thus, there was no interruption of the AC service. Customers seldom knew an impulse had occurred because everything kept running as usual. (Figure - 1, AC with clipped impulse)

This type of operation is analogous to pressure relief valves on a hot water heater or an oil tank, although pressure is rarely sinusoidal like the AC in Figure 1. Nothing happens until a pressure or voltage threshold is exceeded, X in Figure 2. For the MOV, X = 1.414 x MCOV (maximum continuous operating voltage or rated voltage). X is the peak value of the AC. MOVs and TVSS are tested with DC voltage, and that voltage must exceed X at 1.0 mA of current.

With a pressure relief valve X is the opening pressure. Once the impulse pressure drops below X the valve closes. Energy dissipated is fluid flow times pressure across the valve gap times the period of time the valve is open. Similar to the MOV, this takes place at pressures above tank operating pressure, and the pressure impulse can go unnoticed, save for the fluid released.

However, this analogy has a flaw. Pressure cannot be negative. The lowest pressure possible is a vacuum. On the other hand, voltage can be negative. Common AC voltages are positive half the time and negative the other half. The third quadrant in Figure 3 could be described as “Backward” operation of the MOV. An understanding of this is important to how TVSS must be installed. +/- MOV volts in Figure 3 = X in Figure 2.

TVSS construction for protection of three-phase electrical equipment requires multiple MOVs or modes. 6, 4 and 3 mode designs are possible, Figure 4. A 6-mode simply has MOVs connected 3 phase-to-phase and 3 phase-to-ground. The 4-mode TVSS has one end of each MOV all connected together and the other ends connected to the three phases and ground. Early TVSS were usually connected 4-mode because MOV technology had not advanced to the higher voltages necessary. A 3-mode TVSS can be connected either wye (Y) or delta. The wye connection has a ground terminal, but the delta connection, with no ground terminal, cannot protect electrical insulation between motor windings and the motor laminations and frame.

A ground terminal is absolutely essential to the protection of oilfield electrical equipment. It is impossible to limit impulse voltages on the three power wires without a ground. If this connection is not made the electrical insulation can quite easily be punctured and destroyed. Where this ground is connected is the central issue of this paper.

Ideally voltage on the ground terminal would be zero, the same as the ESP motor housing deep in the well. However, two conditions prevent this from happening:

1. Surge current out of the ground terminal times impedance of the ground wire.
2. Connection of the ground terminal to a single ground wire than runs from the lightning arresters atop the pole to the wellhead.

These topics are discussed in more detail in the following section.

TVSS CONNECTION POINTS

Components of an ESP system are depicted in Figure 5 below. A first consideration is the length of the TVSS ground wires. The adverse effect is best demonstrated again by using the pressure relief valve analogy, Figure 6.

A small diameter discharge tube could have an appreciable pressure drop to atmosphere. In such a case the pressure at the valve discharge would be elevated. Thus, the valve would not limit tank pressure to the actual set point but to a higher level. That level would the sum of set point plus pressure drop in the tube.

Similarly, when a MOV threshold is exceed the voltage drop across the ground wire resistance and inductance elevates the voltage at the TVSS ground terminal. This in turn raises the limiting voltage to a higher level equal to the voltage across the ground and ground wire plus the MOV threshold voltage. This is true for any length of wire. Obviously optimum TVSS connection should be as close as possible to the equipment being protected.

The more serious problem involves just a single ground wire with drive and ESP TVSS connected to it. A comparison of single ground wire and separated ground wires is shown in Fig. 7. When a small lightning bolt, 2000 A/μs, passes through the lightning arresters on the pole, the ground wire to the wellhead appears as an inductance. If the ground wire is 100 feet long and the wire has an inductance of .5 μH/foot, then the voltage at the lightning arrester common connection is 100,000 volts. (.5 x 100 x 2000)

A TVSS at the disconnect or drive input which is 70 feet from the wellhead would experience a surge of 70,000 volts minus about 850 volts across the TVSS. This is a tremendous voltage to impress into a drive running on 480 VAC, and it would certainly cause damage.

Protection of the downhole ESP is also compromised. At the junction box 30 feet from the wellhead, the surge voltage would be 30,000 volts. Subtracting the 5,660 volts across the TVSS, a surge of over 24,000 volts is still put onto the wires feeding the ESP. Although ESP insulation is typically 5,000 volts and capable of handling surges to much higher voltages, this surge is still unacceptable. Coupling all this with the simple fact that insulation is further degraded when well fluid, typically salt water, often gets into the oil in the motor, a surge of this magnitude will probably puncture the motor electrical insulation.

This problem is easily resolved simply by using separate ground wires for each TVSS and the lightning arresters, as illustrated in the lower portion of Figure 7. Since the ground terminal on the TVSS' are directly connected to the wellhead, the voltage there will be practically zero. Of course, with a surge passing through the TVSS ground terminal onto the long ground wires, there will be a slightly higher voltage, as discuss in the first part of this section.

These ground wires should only connect together, or be bonded, at the wellhead. Therefore, anything metal that a person could possibly touch would be grounded. In this way personnel safety is assured.

Obviously ensuring that the wires are indeed separate is a bigger problem at the disconnect and pole than elsewhere. One solution to this is shown in Figure 8. Here only the three power wires enter the pothead above the disconnect, and the disconnect itself is grounded to the drive components. The power system and drive system grounds are separated at the pole, but they do connect at the wellhead.

ESP WELL SITES

Figure 5 illustrates the general features of such a well site. Electric power is distributed using three power or phase wires with either an underbuilt ground wire or an overbuilt (shield) ground wire, i.e. 4 wires in total. A common line-to-line voltage is 12,470 with 7,200 volts to ground. (cf. the root 3 = 1.732 relationship). Typically, only line-to-line voltages are quoted.

Step-down transformers reduce the 12,470 down to 480 volts for variable speed drives or to the ESP voltage for switchboard operation. For nearly all ESPs over 40 horsepower drives are almost universally used. Of central importance, drives can vary the production rate of an ESP to match the productivity of a well, which can vary considerably over time. Drives are also soft starters. Starting an ESP with a switchboard that instantaneously connects rated voltage can produce starting currents as high as seven times rated amps, although three to four times is more common. Drives limit starting current to rated. For weak power systems this is a distinct advantage.

Over the years many well sites were surveyed, and engineering reports written. It is safe to say that no consensus exists as to how equipment should be wired at a well site. An attempt to do just that is the purpose of this paper.

The ESP industry has long recommended that power to the downhole should be provided by ungrounded transformer windings. Reasoning for this is that the motor will continue to run with one phase shorted to ground. Obviously, this extends ESP run time thereby reducing production costs. By ensuring that all equipment is grounded and bonded the operation is completely safe.

Another equally valid reason for not grounding ESP power is lightning protection. Why would a ground wire carrying a lightning impulse be connected directly into the power going to an ESP? Such ground wire connections are invariably made high up on the power pole to one phase wire of delta windings (corner ground, Figure 9) or to the neutral of wye connect windings, Figure 10.

ELECTRIC COMPANY RESPONSIBILITY SHOULD END AT THE PRIMARY WINDINGS OF THE STEP-DOWN TRANSFORM! IT IS THE OIL COMPANY'S RESPONSIBILITY AFTER THAT!

THIS IS NOT ROCKET SCIENCE!!

Questions?

- How are the primary windings in Fig. 5 connected?
- How are the secondary windings in Fig. 5 connected?
- Answer – see Conclusions section.

Remote, oilfield electric power distribution evolved from the Rural Electrification Act (REA) passed in the late 1940's. Consequently, electric power was usually distributed in the very least expensive way. That involves short poles and corner grounded delta windings, Figure 9. Sometimes even the UBN is omitted and power is distributed with just three wires. Check out the lightning bolt path. Do the same for Figure 10.

Another supposed good idea is the use of surge capacitors. This might help if a truly solid ground was available, but that is really not a possibility. Voltage across a capacitor does not change instantaneously. A surge on the ground wire will be conducted right onto the ESP power wires.

Electricians will frequently say that for the sake of safety a single ground wire must run from the power pole butt wrap to the wellhead connecting all equipment along the way. This is surely the least expensive way to do it, and personnel safety is the highest priority. However, protection of equipment must have some priority also. It was mentioned before that each surge protection device should be on a separate ground wire to avoid interaction. By bonding all ground wires at the wellhead complete safety is assured.

Wellhead ground connections are another point of contention. Since this connection has seldom had any priority, innumerable connection methods have been tried, most often half-heartedly. The most common is the ground clamps around a pipe near the wellhead. Experience has shown that over time clamps work loose around the pipe and wires work loose in the clamp. Thus, even this method of grounding is questionable.

The best wellhead connection discovered to date is a bronze service post. Installation requires drilling a 5/16" hole one inch deep into the lower wellhead flange between flange bolts and tapping it for 3/8"-16 treads per inch. A second tapping with a bottom tap avoids the need for a deeper drill hole. Mounting in the lower flange should make ground connection removal unnecessary during a workover. Since bronze is mostly copper and H_2S corrodes copper, it is advisable to coat the post with a sealer of some kind, cf. glyptal, etc.

Some petroleum engineers argue that drilling such a hole will void the API rating to the wellhead. Although similar holes are frequently used for other purposes, the author has not verified this claim with API. Instead a service post in a stainless-steel plate with the plate mounted under a flange bolt is considered a good option. It is better to switch than to fight.

OBJECTIONS

Safety

Having studied the national electric code (NEC) the author could not find any statement that a single ground wire had to be used. Indeed, several sections talk about separate grounds. In the case presented all ground wires are bonded to the wellhead.

Arcing Faults

With ungrounded transformer windings it is possible to have a DC voltage actually added to voltages on the windings. One phenomenon responsible for this is called an arcing fault. Years- ago many factories running ungrounded power encounter this when motor failures became intolerable. In an ESP system two features mitigate this possibility:

1. Downhole pressure and temperature sensor systems are connected between the three phase wires and ground. Usually a large three-phase reactor is used to isolate the small, virtual DC pressure/temperature signals from the AC power. These systems should prevent any DC voltage build up. Indeed, loss of these signals is indicative of a short circuit in the ESP power. Surge protection works to prevent such a short circuit.
2. Installed TVSS, being voltage-limiting devices, will prevent any large DC voltage on drive or motor leads.

Corrosion

Well casing corrosion has rarely been a problem. However, depending on soil chemistry, moisture and ground fault currents, it does occur. Ground fault currents can be either external or internal to the well casing?

Externally:

1. Leaking lightning arresters
2. Unbalanced AC voltages

A lightning arrester reaching end-of-life will being to conduct a small AC current. This current is put into the earth via the pole ground wire and could easily reach the casing. Although it is AC, electrons reaching the casing on half the cycle cannot be removed on the opposite half cycle. Similarly, with primary windings connected either grounded wye or corner grounded delta, there will be a current down the pole ground wire. Such a current can be easily measured with a clamp-on ammeter to determine the severity of the problem.

One solution to this problem is not to run the power system ground directly to the wellhead. Connecting the pole ground to a ground grid, as discussed earlier, may be the best option.

Internally:

1. Grounded AC power to ESP as discussed above. (cf. California and earthquake codes)
2. A faulted ESP motor
3. A failed TVSS

This fault current could be measured by passing all three-phase wires through a current transformer, CT. Another indication would be inability to read downhole pressure and temperature. A TVSS will restrict impulse voltages to protect downhole sensing.

Aside: The author encountered one field that employed cathodic protection but still had casing corrosion. Other modifications to surface equipment had no effect. Later it was found that the local municipality was using an old injection well to dispose of their sewage. Corrosion occurred exactly at the previous producing formation. It is unknown how prevalent this is and whether the environmentalists would approve.

Cathodic Protection

Incorporating a sacrificial anode ground operating at some positive DC voltage above the well casing will promote electron flow from the casing to ameliorate corrosion. This DC voltage source should have lightning protection also. Finally, there is no reason why the TVSS installation proposed here should in any way affect cathodic protection.

Pole Grounds

The calculations used in Figure 7 ignored the presence of butt wrap, rod or chemical grounds at the pole. A previous paper [3] presented calculations on the effectiveness of such grounds, Figure 11. Here the wellhead ground resistance was taken a 0.5 ohms and pole grounds of 5, 10 and 20 ohms were used in the calculations. Obviously a vent box mounted TVSS would prevent ESP damage; however, a switchboards mounted TVSS probably would cause ESP damage. The calculation used a 10,000 volt step-function. From this and experience it was concluded that pole grounds, necessary to protect the pole itself, were quite ineffective so far as protection of drives and the downhole ESP.

CONCLUSIONS

Principles for the installation of TVSS to protect ESP equipment were introduced at the end of the Introduction. These included:

- A TVSS with a ground terminal
- Mounting TVSS' at the drive input and at the vent or junction box.
- Using the wellhead as the main ground connection
- Ungrounded transformer windings.
- Keeping TVSS and lightning arresters on separate ground wires

Succeeding sections covered the reasoning behind each these principles from both technical and practical considerations. When these principles are meticulously followed, a significant reduction in ESP lightning damage has been observed.

This is the most complete solution we have found for protecting ESP equipment from lightning bolts carried into a well site on the power wires. Oilfield equipment needs frequent replacement and repair, and ensuring all equipment is reconnected as recommend is a true challenge. An oil company should have at least one person thoroughly trained to oversee these connections. Someone should be responsible for this in each oilfield. We believe mitigating lightning damage to ESPs greatly reduces production expenses, and in today's crude oil market production efficiency is tremendously important.

Figure 5 Quiz
Primary windings (H) are connected ungrounded wye (Y)
Secondary windings (X) are connected ungrounded delta
No ground wires are connected to either windings.

TECHNICAL CALCULATIONS

No one can disagree that lightning is random in magnitude (size), duration and time of occurrence. From the time of Benjamin Franklin, the technical community has tried diligently to measure and calculate lightning events. Before introducing these calculations, a few common notations need to be presented:

- s = seconds
- m = meters
- ft = feet
- μ = micro, 10^{-6}
- $\mu_0 = 4\pi\ 10^{-7}$ H/m, inductance (permeability of free space)
- Ω = ohms, unit of resistance or reactance
- I = current (amps, A)
- H = Henrys, unit of inductance
- L = inductance in H
- k = kilo
- Hz = Hertz (cycles per second)
- f = frequency in Hz
- c = speed of light (300,000 km/s or 186,000 miles/s)

One standard that has been established is the 8x20 μs current pulse for TVSS testing, Figure 12.
Here the current rises from zero to 50.7 kA with a rise time (10 to 90%) of 8 μs and a width to mid-point on the trailing edge of 20 μs. The voltage rises to 16.9 kV in one microsecond. Kaiser [4, p12-202] Relates this risetime (t_r) to the highest frequency of interest with the formula:

$$f = (1/(2\pi t_r)) = 1/(6.28\text{x}1\text{x}10^{-6}) = 159{,}000 \text{ Hz}$$

Consider the wavelength at this frequency compared to 60 Hz:

Lightning simulation	c/f = 300,000,000/159,000 = 1,887.8 m = 6,190 ft = wavelength
60 Hz power	c/f = 186,000/60 = 3,100 miles = 16,368,000 ft = wavelength

The most common ground wire is bare #6 AWG solid copper with a diameter of 0.162 inches and a resistance of 0.000395 Ω/ft. The inductance for 100 feet of this wire is given by the formula [4, p15-168]:

$$(\text{inductance}) = 2\text{x}10^{-7} \text{ x } l_{ng} \text{ x } (\ln (2l_{ng}/r_w) -1) = 57.4\ \mu\text{H}$$

Where l_{ng} = wire length in meters
r_w = wire radius in meters

To simplify calculations for Figure 7 an inductance value 0.5 μH/ft was used or 50 μH for the entire 100 ft ground wire. Using the slightly lower inductance introduces a small error on the conservative side and is close enough for practical purposes. Reactance is calculated as 2πf x inductance.

Lightning simulation	resistance = .0395* Ω, reactance $=2\pi$ x 159,000 x 50 x 10^{-6} = 50.0 Ω
60 Hz power	resistance = .0395 Ω, reactance = 377x50x10^{-6} = .0189 Ω

The * indicates that at a higher frequency the resistance will be somewhat higher due to skin effect. This is why the ground wires connecting lightning rods on top of barns in the country use Litzendraht (Litze) wire which has multiple strands.

The above calculation of wavelength and impedance highlight the vast different between how ground wires must be treated for lightning or power. For lightning the ground wire is overwhelmingly inductive.

In Figure 11 the current increases at a rate (di/dt) of 5,070 A/μs. For the calculations used in Fig. 7 a value of 2,000 A/μs was used. Thus the voltage at the top of the pole was calculated as $V = L(di/dt) \times 100 = .5 \times 10^{-6} \times 2000 \times 100 = 100{,}000$ volts. This is consistent with the calculation method used in reference [5]. It should be also noted that with very low wellhead ground resistance, the reflection coefficient is nearly minus one, and therefore the wellhead voltage stays near zero. All voltages along this ground wire were measured from the wellhead. Again, TVSS were installed at the VSD input and at the junction box. Although the 100,000 voltage is just a transient voltage, when delivered to live power wire through a TVSS, equipment can be damaged.

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[4] K. L. Kaiser, *Electromagnetic Compatibility Handbook*, New York: CRC Press, 2005.

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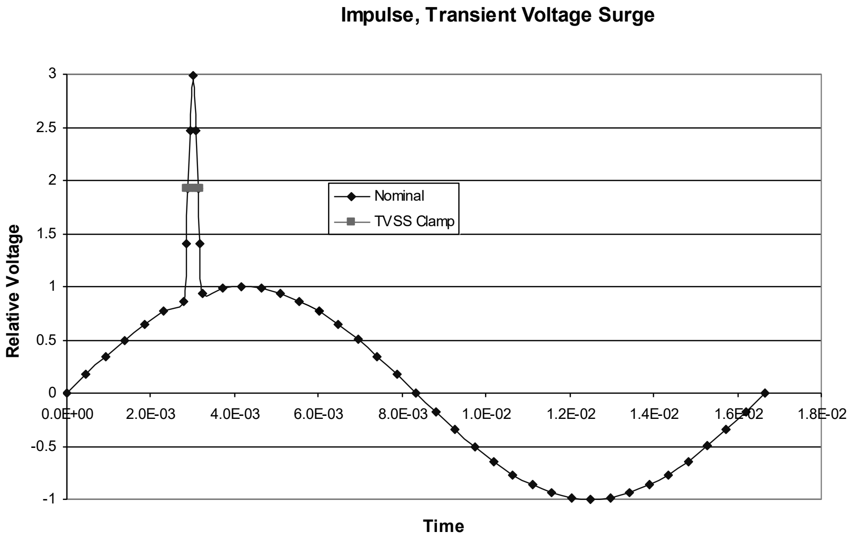


Figure 1 - Voltage Impulse Limiting

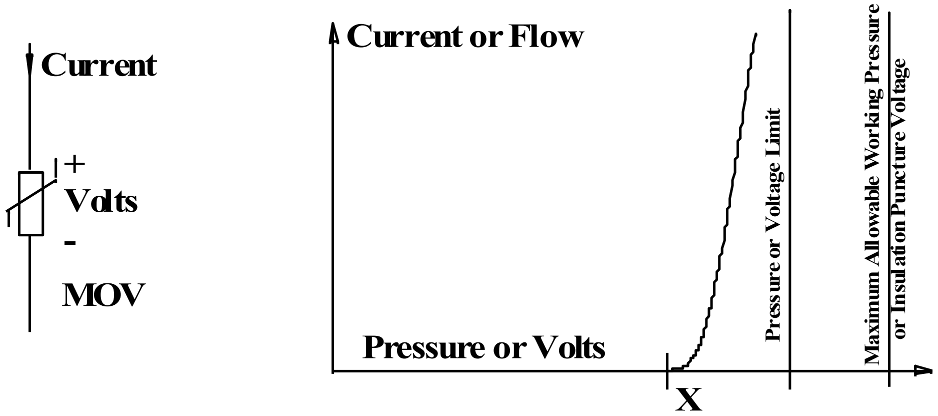


Figure 2 – Similarity of MOV and Pressure Relief Valve

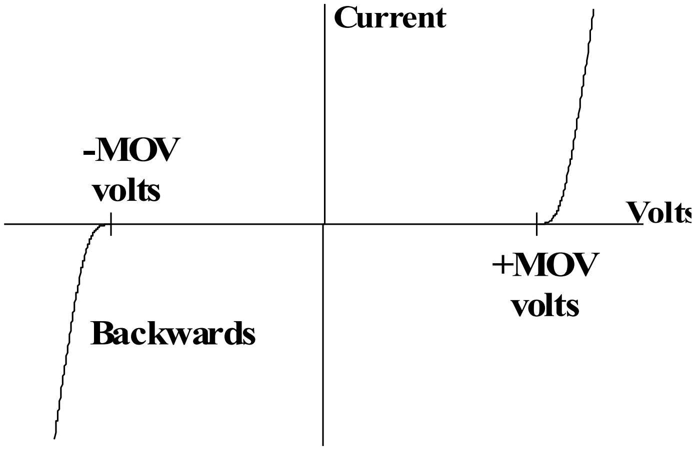


Figure 3 – Complete MOV Volt-Amp Characteristic

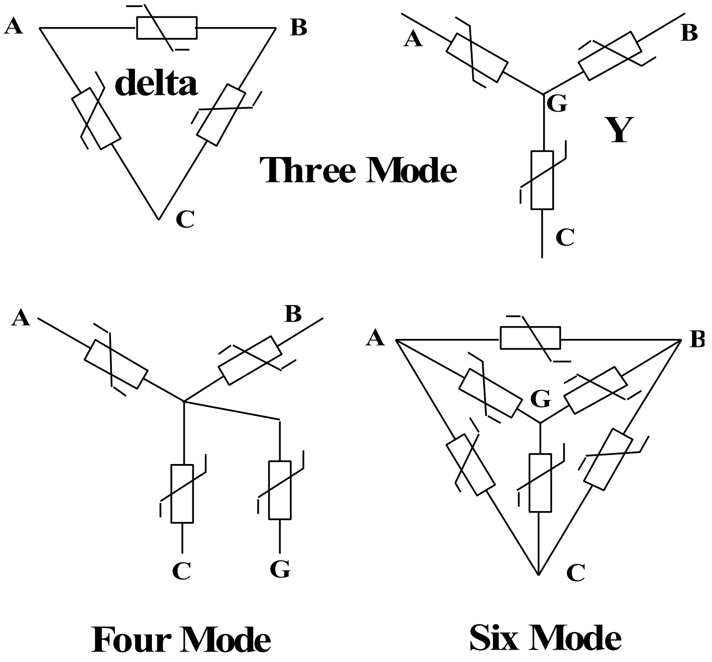


Figure 4 – TVSS Modes, Modes = Number of MOVs

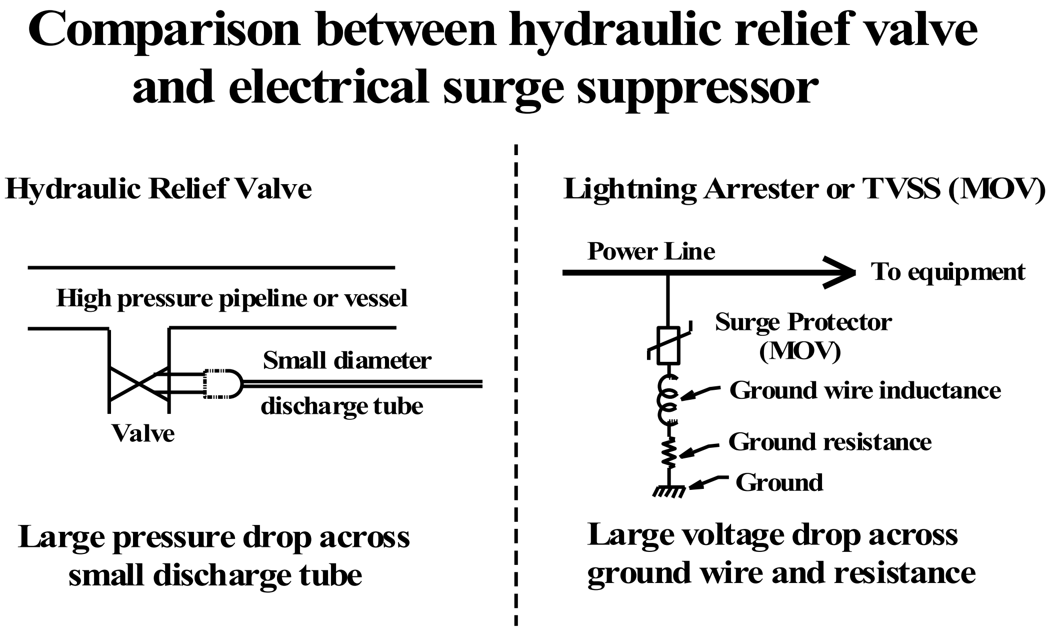


Figure 6 - Reduced Protection with long ground wires.

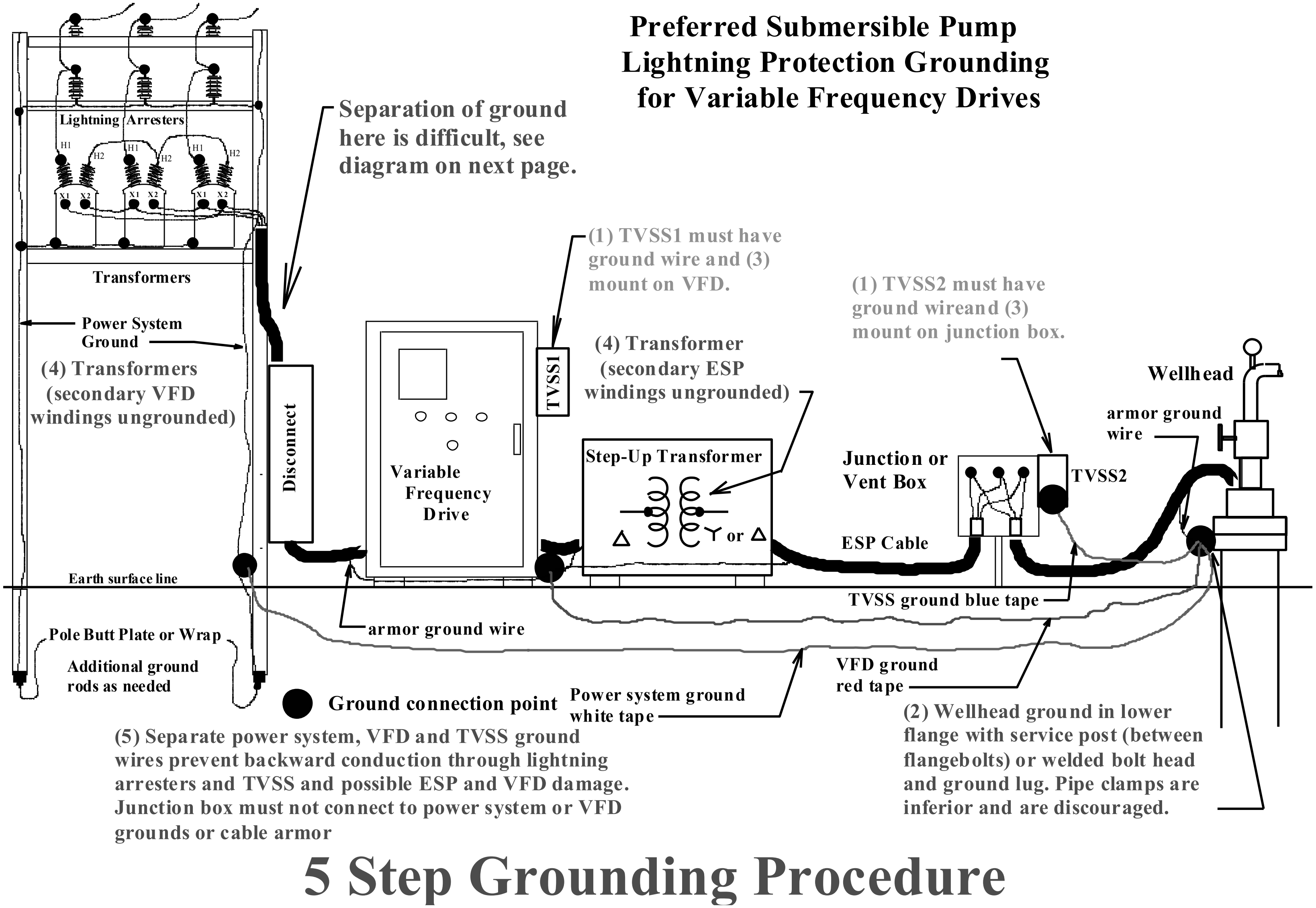


Figure 5 – Variable Frequency Drive Operation

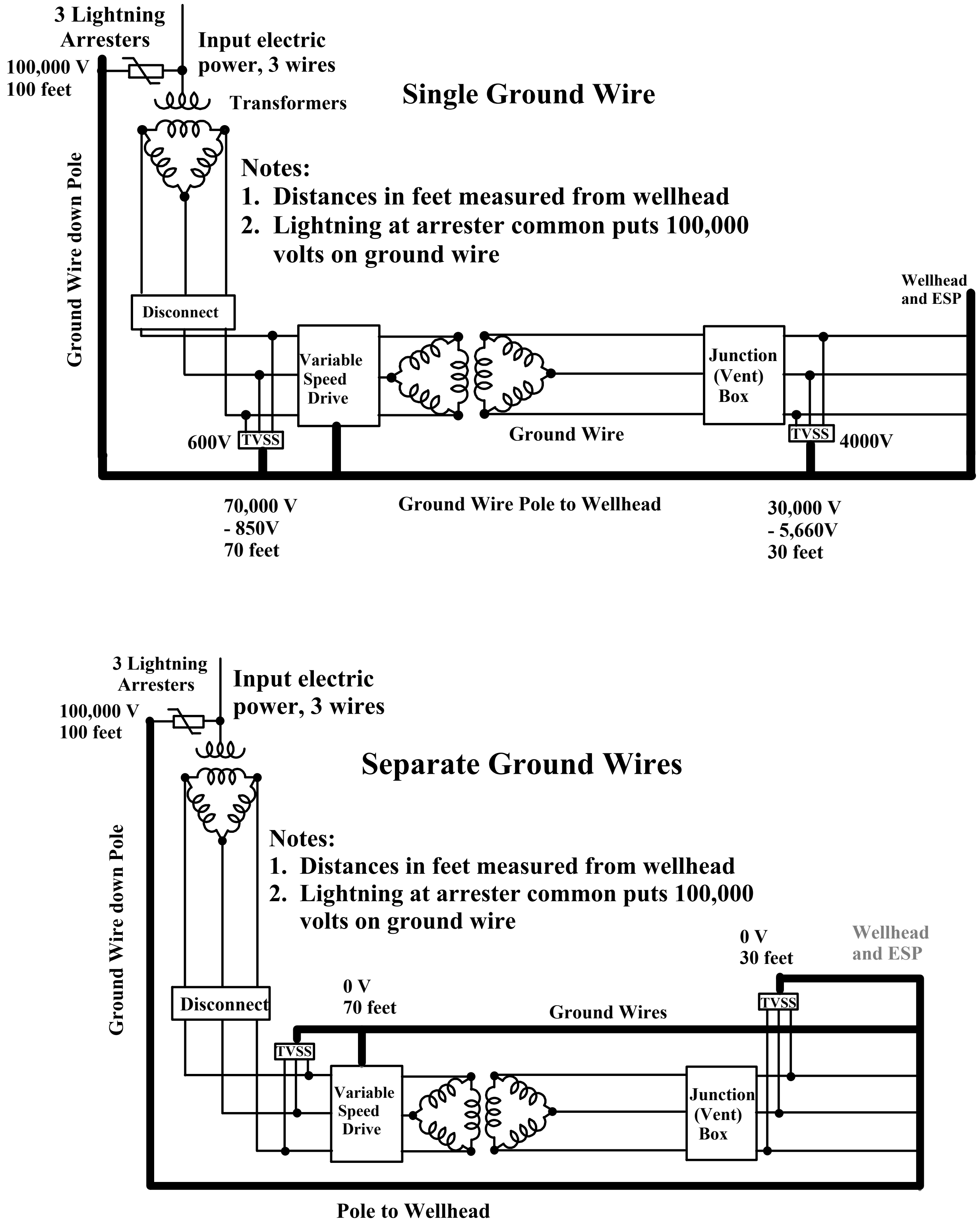


Figure 7 – Single and Separate Ground Wires

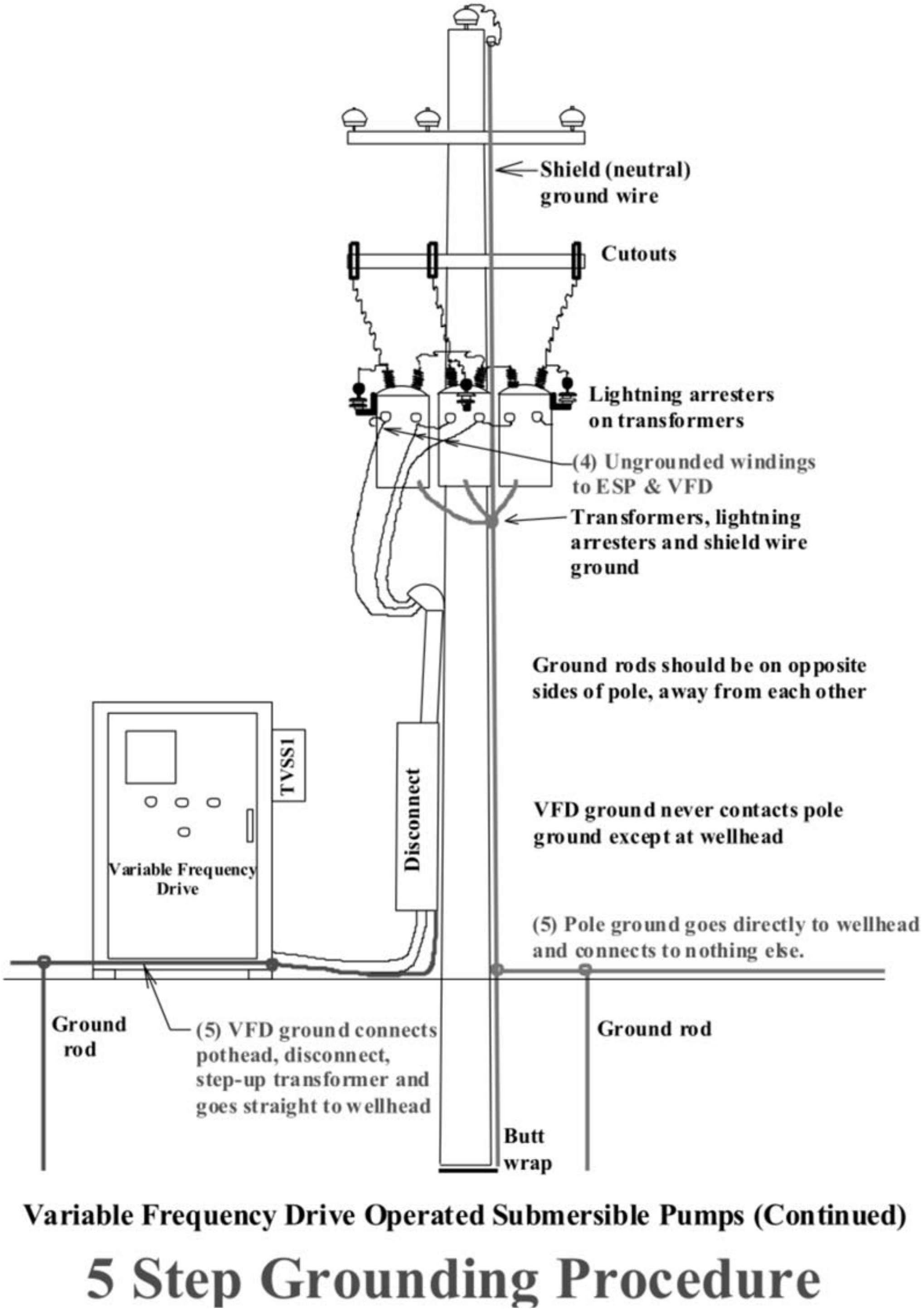


Figure 8 – Separation of Grounds at the Power Pole

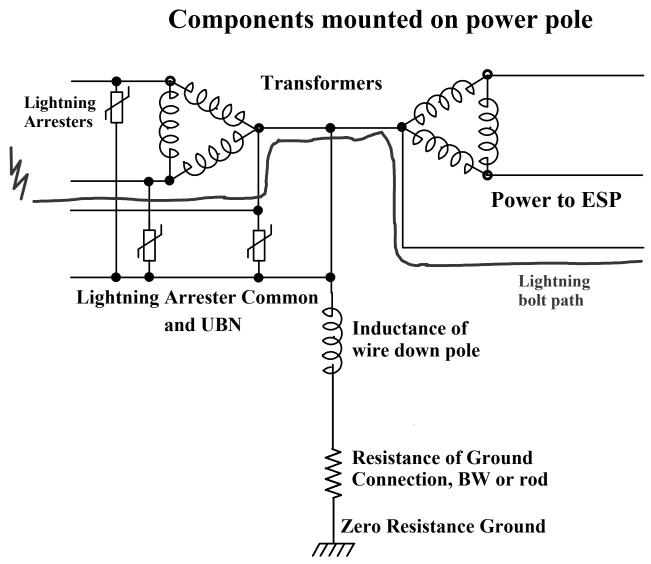

Components mounted on power pole

Figure 9 – The Corner Grounded Delta

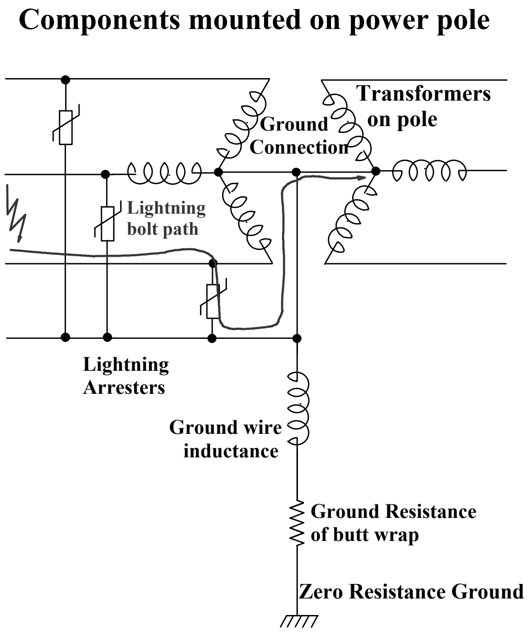

Components mounted on power pole

Figure 10 – Neutral Grounded Secondary Windings

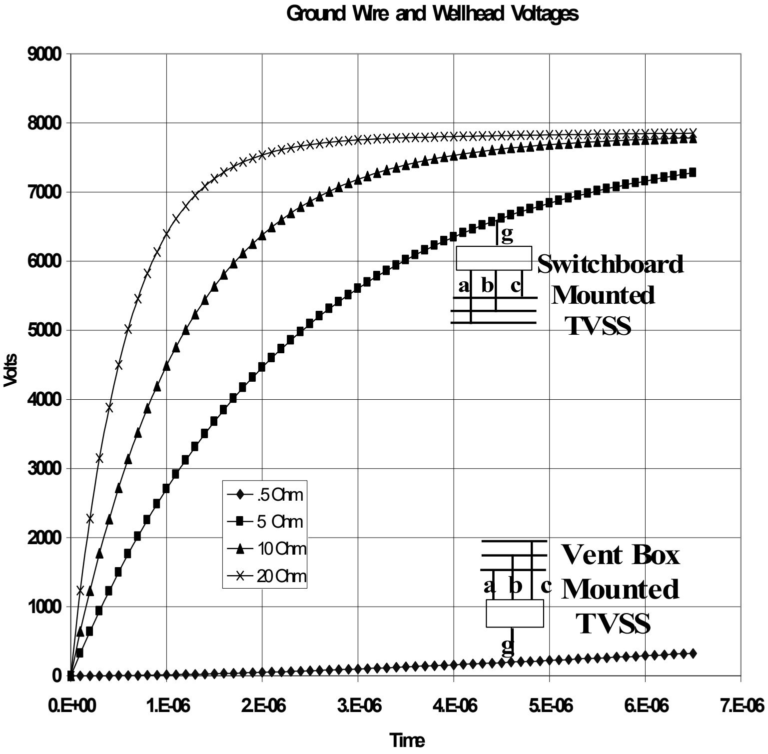
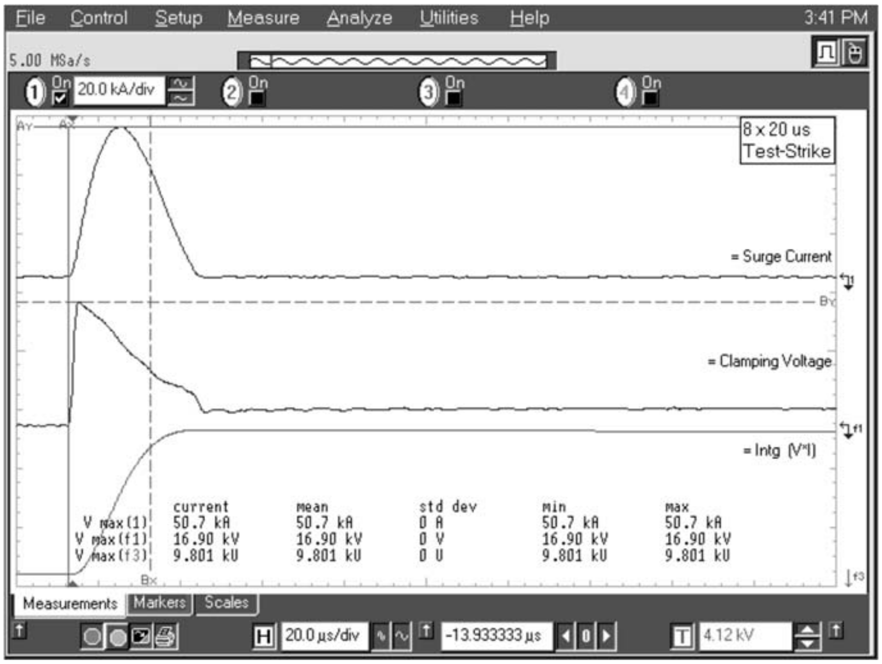


Figure 11 – Effect of Pole Grounds (copyright IEEE)



```
              current      mean         std dev      min          max
  V max(1)    50.7 kA      50.7 kA      0 A          50.7 kA      50.7 kA
 V max(f1)    16.90 kV     16.90 kV     0 V          16.90 kV     16.90 kV
 V max(f3)    9.801 kU     9.801 kU     0 U          9.801 kU     9.801 kU
```

Figure 12 – Standard TVSS Testing Waveforms