Transient-Voltage Aspects of Grounding

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***Abstract*—Lightning damages millions of dollars of electrical equipment each year. With the protective devices currently available, this should not happen. Unfortunately, in most cases, little consideration is given to the effects of grounding on the effectiveness of surge suppression. When the surge suppression device cannot be directly connected at the terminals of the equipment to be protected, the impedance of the connecting means must be examined. High ground resistance and lead inductance greatly diminish the effectiveness of surge suppression. This paper describes a circuit approach to lightning protection starting with a discussion of infinite ground, ground resistance, and lead inductance. These concepts are then applied to various types of pole-top grounding. Normally, the grounding terminal of transformer secondary windings connects to the common terminal of the lightning arresters. This is demonstrated to be a central cause for much of the ensuing damage. Usually, several surge suppression devices are connected to a single ground wire, and the transient voltages on that wire not only reduce the effectiveness of the devices but, because of their bilateral characteristics, can also actually cause damage. Multiple ground wires terminating on a primary low-resistance ground have proven very effective in minimizing equipment damage. The integrity of ground bonding for personnel safety is still preserved. The only alteration is how and where ground wires are connected. This solution greatly increases the efficacy of lightning protection, without sacrificing safety or code compliance.**

***Index Terms*—Electric submersible pumping (ESP), lightning protection, medium-voltage lightning protection, metal–oxide varistors (MOVs), oil-field lightning, power system lightning protection, surge protective devices (SPDs), transient-voltage surge suppressors (TVSSs).**

I. Introduction

TOO OFTEN, the design of grounding systems stops when safety standards have been met and personnel safety has been ensured. Protection of electrical equipment from injurious transient voltages, lightning, and switching surges is often an afterthought. If grounding and protection are ignored, equipment failure can cost the owners millions of dollars in replacement equipment and service charges. Additionally, disruption of continuous processes results in lost revenue, which is frequently more costly than the equipment and service charges combined.

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Modern transient-voltage surge suppressors (TVSS) utilize metal–oxide varistors (MOVs) and do an excellent job of limiting transient voltages and dissipating the related energy. Unfortunately, these devices are frequently not utilized, or they are installed improperly. In either case, the result is damaged equipment.

For residential and commercial properties, the most common voltages are 240/120 V. Most people use a TVSS built into a power strip to protect their computers and other important electronic devices. At such low voltages, the failure of the TVSS is a minor incident because the amount of energy involved is relatively small.

For common industrial plants, most of the energy consumed is three-phase at 480 V. In these applications, the TVSS can consist of multiple MOVs connected phase-to-phase and phase-to-ground. At these much higher energy levels, the failure of a TVSS is far more dramatic. Catastrophic failure of devices is the rule rather than the exception.

In an effort to reduce such failures, MOV manufacturers have introduced thermally protected MOVs. These devices are designed to address one typical failure mode, i.e., the degradation of the threshold voltage from the absorption of multiple high-energy transients over time. This degradation involves a lowering of the threshold voltage to the point where the ac voltage produces increasingly significant current and heating in the MOV. As heat in the MOV builds up, the threshold voltage decreases even more, leading to a thermal runaway condition just prior to failure.

The thermally protected designs rely on the melting and clearing of a solder connection before explosion occurs. Such designs have led to wider usage of MOV-based TVSS products; however, the question of effectiveness still remains.

Two factors contribute to the perception that a TVSS is not effective. Often, a TVSS is degraded or has completely failed, and there is no indication of this condition. A consequence of this is failure of the protected equipment despite installation of a TVSS. In order to combat this, means must be provided to alert the customer to the deterioration or outright failure of the TVSS.

The second factor, i.e., improper installation, is the central topic of this paper. Ideally, the TVSS should be connected directly across the terminals of the equipment being protected. In practice, such a connection is often impossible. Grounds are imperfect, and ground wires are often long. In general, these problems are more pronounced in rural rather than in urban areas.

Electric submersible pumping (ESP) systems for petroleum production provide an excellent avenue to explore the installation issue. A wellhead is an excellent ground. Distribution lines feeding these installations are frequently long, poorly

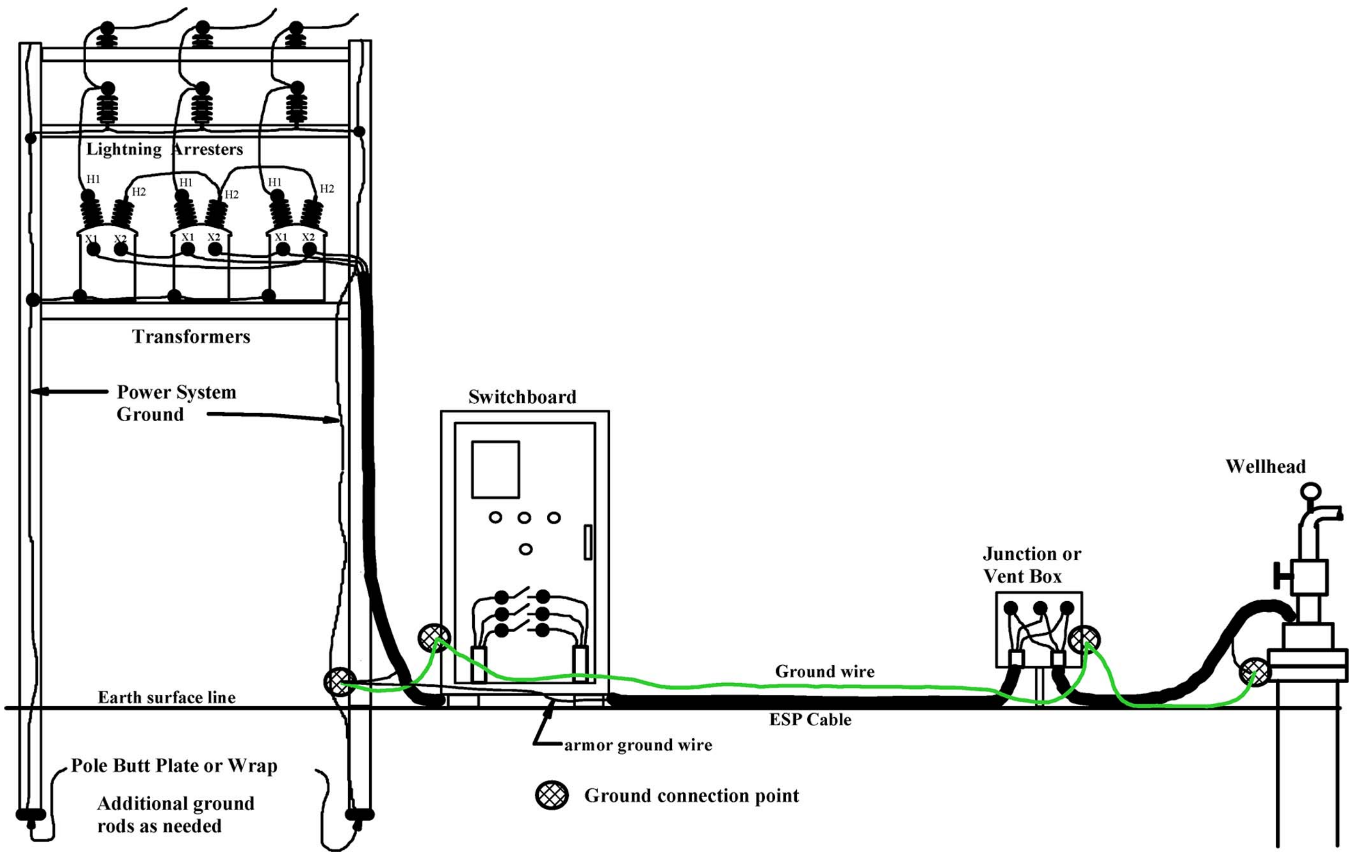

Fig. 1. Typical ESP surface equipment and ground connections.

grounded in arid regions, and prone to lightning strikes. The ESP is located near the bottom of the well. To transmit adequate power to it, a long power cable operated at medium voltages is required. Due to space limitations, ESP electrical insulation is minimal. Since the ESP often runs in salt water, it is exceptionally grounded. The preferred path for lightning discharge, then, is usually the pump itself, making damage a major problem. Surface equipment for a common installation is shown in Fig. 1.

II. Distributed or Discrete

When analyzing the characteristics of a power distribution system, it is important to determine the analytical approach that is most appropriate to the application. The two methods examined are distributed or traveling-wave analysis and discrete component analysis.

Distributed or traveling-wave analysis involve characteristic impedances and reflection coefficients. If the transmission medium is terminated in the characteristic impedance, there are no reflected waves and all the power is absorbed in the impedance. Except for minor losses due to conductor resistance and insulation losses, the waveforms at the receiving end are identical to the waveforms at the sending end.

For terminating impedances larger than the characteristic impedance, the reflection coefficient is positive, voltage waveforms are increased, and current waveforms are decreased. Terminating impedances smaller than the characteristic impedance produce just the opposite effect.

In contrast with the traveling-wave method, discrete resistors, inductors, and capacitors are used for the 60-Hz analysis of power circuits. Whereas sinusoidal voltages produce leading or lagging sinusoidal currents, the analyses with pulse and digital waveforms typically produce exponential or ringing waveforms with energy stored in the capacitors and inductors.

The suitability of an analysis method depends on the length of the conducting medium relative to the wavelength of the excitation voltage. For the ESP system in Fig. 1, the conducting medium includes the distribution feeder, ESP cable, and ground wires.

Determining the wavelength of a lightning impulse requires an assessment of voltage and current waveforms. From studies conducted early in the 20th century, a standard voltage waveform with a 1.2-μs rise time and a 50-μs pulsewidth down to the 50% point on the tail was specified. The associated current waveform had an 8-μs rise time and a 20-μs pulsewidth, also to 50% [1], [2]. More recent studies with higher speed measurement equipment indicate a current waveform with a rise time in nanoseconds [3], [4].

A Fourier series analysis of either waveform cannot have a highest frequency component that has a slope greater than the slope of the waveform voltage during the rise-time period

$$T \approx 2\pi t_r \qquad (1)$$

where T is the period of the highest frequency component and t_r is the waveform rise time. Using a 1.2-μs rise time, the period is $\approx 7.54\ \mu$s, and assuming propagation at the free-space

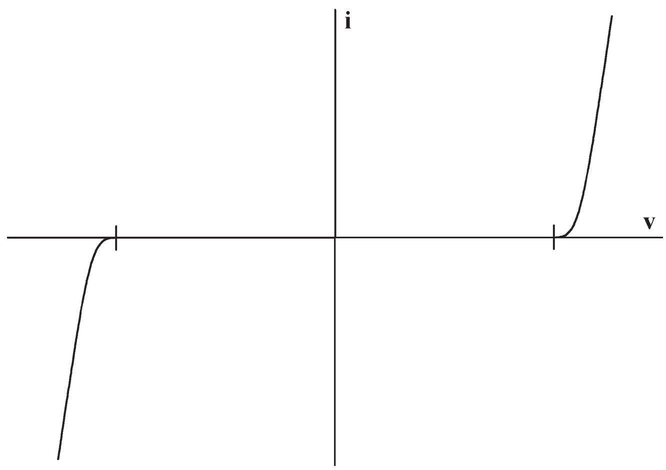

Fig. 2. General MOV volt–ampere characteristic.

speed of light, this wave would occupy about 2.26 km on a transmission line or distribution feeder.

In a power cable having an insulation relative permittivity of 2.5, the same period would only occupy 1.43 km. Thus, for both power lines and ESP cables, distributed network analyses are appropriate.

On the other extreme, power system grounds, extending from the pole top to ground, are very short compared to the period wavelength. Consequently, analyses using discrete components are more suitable and should be applied to the grounding structure and ground wires.

III. MOV Basics

MOVs are the main elements in all modern lightning arresters and TVSS. The volt–ampere characteristic of an MOV is shown in Fig. 2. Varistor, as the name implies, is a voltage-sensitive variable resistor.

The peak value of voltage sine waves applied across the MOV must be less than the threshold voltage at which significant conduction begins. The maximum continuous operating voltage (MCOV) defines this threshold. For a dc current of 1 mA, the applied voltage must be greater than $\sqrt{2}$ times the MCOV. Typically, the thickness of the MOV material relates to the MCOV, and the cross-sectional area relates to the current capacity.

Voltage impulses above the threshold are limited in magnitude. Since the threshold is well above the ac voltage, and impulses are of very short duration, there is no significant fault current. Consequently, reclosers do not operate, and the lightning event normally goes unnoticed. Energy at voltage levels above the threshold is dissipated as heat in the MOV.

An MOV is a bilateral device, i.e., its volt–ampere characteristic is the same in the third quadrant as it is in the first quadrant. A negative voltage threshold exists, which is nearly equal to the positive threshold. When lightning protection devices are installed, this bilateral characteristic has great importance. Improperly installed arresters and TVSS can actually increase the risk of damage to equipment.

Last, the electrical characteristics of transformers must be considered. For fast voltage transients, the capacitive couplings between windings and from the windings to the core play an important role in transferring impulses from primary to secondary. Magnetic coupling still exists, but the initial impulse transfer is practically independent of the presence or absence of the iron core. A thorough analysis of transformer transient-voltage behavior [3] is beyond the scope of this paper, but it must be acknowledged that voltage impulses do propagate through transformers.

IV. Grounds and Connections

The most common and one of the least effective grounding systems is the rod. The ground resistance of a single rod [7] is calculated from

$$R = \frac{\rho \ln(4L/r - 1)}{2\pi L} \tag{2}$$

where

- R grounding resistance (in ohms);
- ρ resistivity of the surrounding medium (in ohms–centimeter);
- L is the rod length (in centimeters);
- r the rod radius (in centimeters).

Additional rods can be added to reduce ground resistance, and the general rule is that they should be separated by at least $2.2L$. Assuming $2.2L$ spacing, the effective resistance of multiple rods is shown in [8]

$$R_n = (R/n) * \left(2 - e^{-0.17(n-1)}\right). \tag{3}$$

Connection of two isolated widely separated rods would effectively put the rods in parallel, producing half the resistance of an individual rod. At very close spacing, the ground resistance of paralleled rods approaches that of just an individual rod. The $2.2L$ value was chosen because, at that spacing, the parallel combination is less than 10% above the minimum parallel resistance [4].

Distribution power poles should all have a pole ground wire. A common practice for such wires is to spirally wind them on the bottom of the pole before the pole is set in the earth. This is commonly referred to as a butt wrap. Butt wrap grounding is less effective than a single driven ground rod. The purpose of the pole ground is not only to provide the power system ground but also to prevent damage to a pole from a lightning discharge.

Other than the parallel connection of rods forming a grid, single rods, pole butt wraps, chemical grounds and Ufer grounds are frequently used in arid and rocky terrains. The chemical ground requires periodic maintenance and can cause corrosion problems when attached to other buried metal structures such as well casings and storage tanks.

The concept of an "infinite ground" was proposed some years ago [5] as a potentially useful concept for power system analyses. It was compared to the widely accepted notion of an "infinite bus" or ideal voltage source. By comparison, an infinite or ideal ground would be a terminal that has zero resistance and can accept an infinite amount of current with no increase in voltage. The ground resistances calculated above are assumed to terminate on an infinite ground.

TABLE I
GROUND WIRE EXTERNAL INDUCTANCE (IN MICROHENRYS PER FOOT)

AWG	20ft	30ft	50ft	100ft
6	0.47	0.49	0.52	0.57
4	0.45	0.48	0.51	0.55
2	0.44	0.47	0.50	0.54

The ramification of this for the analysis of lightning protection circuits is easily understood. Lightning protection is intimately concerned with keeping voltage impulses to levels below the basic insulation impulse limitation (BIIL) of electrical machinery and to proportionally lower levels for the protection of power electronics and controls. An infinite ground becomes the reference point for all lightning simulation calculations.

At the top of a power pole, the common terminal of all lightning arresters connects to the pole ground wire; therefore, the impedance of this wire, between arresters and the ground, is extremely important. That impedance can be expressed as the sum of internal and external impedances

$$Z = Z_i + Z_e \quad (4)$$
$$Z_i = a + b\sqrt{\pi f} + jb\sqrt{\pi f} \quad (5)$$
$$a = r_{\mathrm{dc}} = \frac{l_{\mathrm{th}}}{(\sigma \pi r_w^2)} \quad (6)$$
$$b = \left(\frac{l_{\mathrm{th}}}{2\pi r_w}\right)\sqrt{\frac{\mu}{\sigma}} \quad (7)$$

where
- l_{th} wire length (in meters);
- σ wire conductivity (in meters per ohm);
- r_w wire radius (in meters);
- μ permeability of free space ($4\pi \times 10^{-7}$ H/m);
- r_{dc} dc resistance of the wire (in ohms);
- f frequency (in hertz).

In order from the left, the components in (5) represent the dc resistance of the wire, the skin-effect correction, and the internal inductance.

The external impedance is

$$Z_e = j(2\pi f)(2 \times 10^{-7}) l_{\mathrm{th}} \left[\ln\left(2\frac{l_{\mathrm{th}}}{r_w} - 1\right)\right]. \quad (8)$$

For all practical purposes, the external impedance completely dominates in (4). In fact, the external inductance per foot does not vary significantly with wire gauge or length, as shown in Table I. For simplicity, with little loss of accuracy, ground wire inductance can be taken as 0.5 μH/ft.

For circuit analysis purposes, the impedance of the downcomer wire is added to the impedance of the ground contact resistance in parallel with other impedances to determine the impedance of the entire ground path.

V. WELLHEAD GROUNDING

The most successful grounding connection technique noted so far has been the installation of a service post in the lower wellhead flange. The lower flange was chosen because it is not removed for a workover. A hole must be drilled and tapped between flange bolts to accommodate the bolt end of the service post. This may require a "hot work" permit. Ground wires are clamped in the opposite split-bolt end, as shown in Fig. 3. The wellbore provides an effective ground connection with minimal contact resistance.

Fig. 3. Service post wellhead ground connection.

Two alternative wellhead connection techniques, namely, exothermal welds and ground clamps, are discouraged. Welding in a potential explosive environment is hazardous. Furthermore, a weld to the casing reduces casing strength.

Ground clamps work loosely around a pipe, producing a questionable electrical connection. The ground wire frequently works loosely inside the clamp. Workover crews must remove the clamps and pipes to do their work, and often, the clamp is not reconnected.

Sometimes, wellhead grounding is prohibited because a cathodic protection system is in use to minimize casing corrosion. The engineer must then choose between the potential of repairing a casing leak or replacing an ESP, which are two nearly equal expenditures. Just how much dc current is diverted to the power system grounds is highly speculative. Some suggest that the dc current need only to be increased to ensure casing protection. A cathodic protection evaluation tool is available to make actual measurements of the protection.

VI. GROUND CIRCUIT

In rural areas, distribution feeders are rarely constructed with an overhead neutral (OHN) to shield the phase wires against a direct lightning strike. Typical construction includes four wires, including an underbuilt neutral. Three-wire construction still exists in many oil fields. Consequently, in these locations, lightning strikes to phase wires are the rule rather than the exception.

For the single ground wire shown in Fig. 1, such a strike could be modeled as the circuit shown in Fig. 4. The assumptions are that the ground wire down the pole is 30 ft long, the wire from the pole and switchboard to the wellhead is 100 ft long, and the wellhead has a ground contact resistance of 0.5 Ω.

The ground wires are thus 15 and 50 μH, respectively. Of most concern is the ground resistance of the butt wrap or rod at

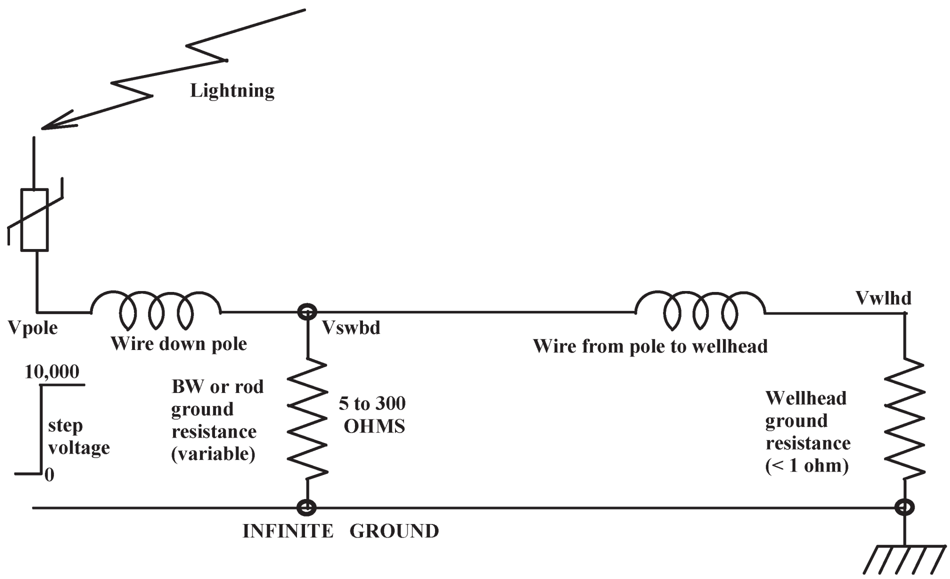

Fig. 4. Single-ground-wire circuit model.

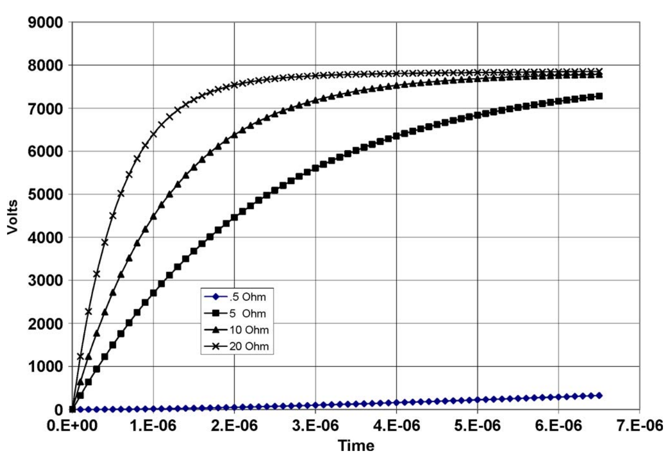

Fig. 5. Switchboard and wellhead voltages.

the pole. Since soil moisture can change substantially over the course of a year, ground resistance values of 5, 10, and 20 Ω are examined. These are minimal values for ground rods or butt wraps. Experience has shown these to be as high as 1000 Ω or greater.

Lightning on the ground side of the arresters is modeled as a 10 000-V step function. The calculated voltages at the switchboard, essentially the same as the pole ground connection, and at the wellhead are shown in Fig. 5.

Seldom is the quality of a ground connection questioned; however, lightning can elevate the voltage on a ground wire. If a TVSS ground terminal is connected to this ground wire at the switchboard beneath the pole, as shown in Fig. 6, the TVSS can actually do damage.

Referring back to the bilateral characteristics of an MOV, as shown in Fig. 2, the TVSS is, in effect, conducting backward or in the negative-voltage quadrant. The voltage injected onto the ESP cable wires is the switchboard voltage V_{swbd} minus the voltage drop across the TVSS MOVs, Fig. 6. Depending on the actual magnitude of the lightning strike, this voltage can easily puncture the electrical insulation in the ESP or the cable.

To make matters worse, the ESP cable must be treated as a distributed network. A very short rise-time impulse encountering the inductance of the ESP motor has a nearly $+1$ reflection coefficient. As a result, the impulse voltage practically doubles at the motor. Since the motor lead extension and pothead are the weakest points in the insulation system, failures often occur at those points.

A very simple solution is to mount the TVSS on the junction box instead of the switchboard. A separate ground wire connection to the wellhead is used for the TVSS ground so that the main surge voltage from the lightning arresters is on a completely separate but bonded ground wire. The TVSS ground wire only carries the TVSS surge current. Because wellhead ground resistance is so low, the voltage rise there is likewise low, as shown in Fig. 5. Furthermore, the wellhead is in direct electrical contact with the ESP motor housing. The TVSS installation shown in Fig. 7 places the TVSS as close as possible to the equipment being protected and provides the best limiting of phase-to-ground impulses.

The most common objection to this grounding arrangement is that there is not one single ground wire from the power pole to the wellhead with all equipment grounds connected to it. This is not a requirement of the National Electric Code (NEC). The NEC simply states that all equipment must be bonded. This application meets that requirement.

Junction box mounting is frequently viewed as removing protection from the equipment in the switchboard. Once the TVSS threshold is exceeded, the reflection coefficient becomes negative. A reflected negative wave subtracts from the incident wave, thereby reducing the impulse voltage at the switchboard. This same technique is used to eliminate similar end-of-line problems on feeders. A pole equipped with lightning arresters and a good ground is set beyond the existing end pole to reflect a negative wave and reduce the actual impulse voltage magnitude at the site [8].

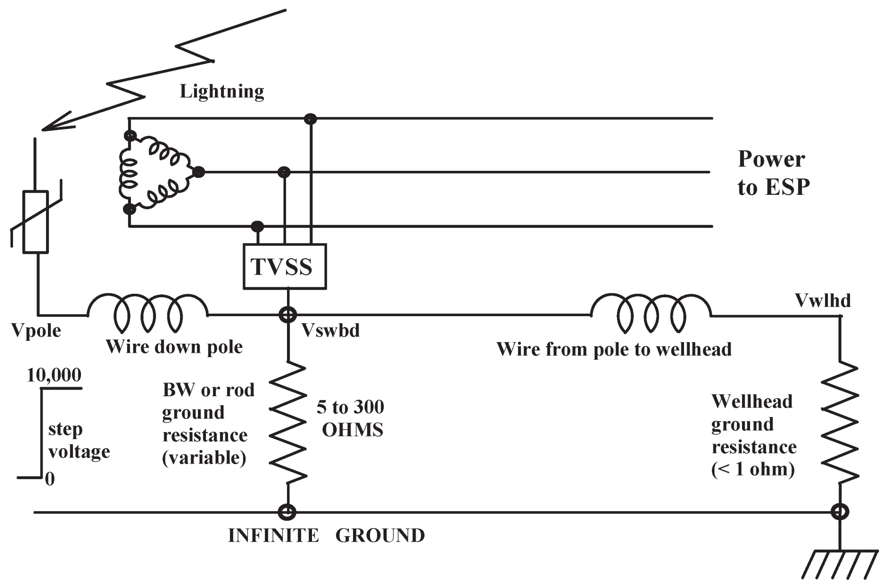

Fig. 6. Switchboard-mounted TVSS.

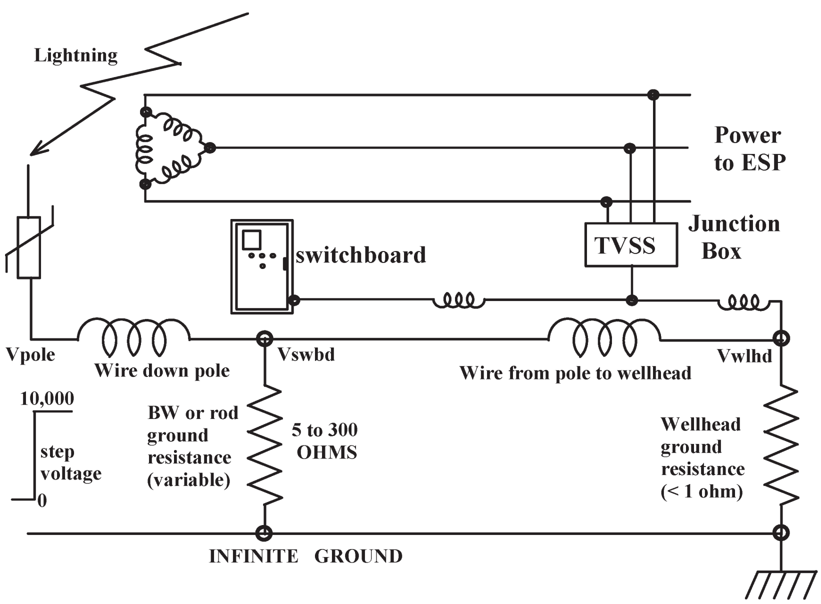

Fig. 7. Bonded separate ground wires.

Implementation of the grounding shown in Fig. 7 is somewhat complicated by the requirement to ground all power cable armors. The cable armor between the junction box and wellhead should be grounded at the wellhead. The cable armors between the pole and switchboard and the switchboard and junction box should be grounded at the switchboard. The armors should not be connected together at the junction box to eliminate the possibility of ground loops [8].

VII. Pole-Top Grounding

In Fig. 4, the voltage at the top of the pole is the lightning voltage minus the lightning arrester threshold voltage or $V_{\rm pole}$. This voltage is applied to the system ground wire when lightning strikes. Not only is this connection point the common terminal of all the arresters, but it also connects to the system neutral and the external cases of all the transformers. Since this voltage can be exceedingly high, where these connections are made is critical to equipment reliability during thunderstorms.

A multitude of solid system grounds are in use. Some of these are the following:

1) neutral grounded wye;
2) corner grounded delta;
3) center-tap grounded delta (red leg).

The difficulty with each of these connections is shown in Fig. 8. In this example, a high impulse voltage is transferred directly onto the cable leads feeding the ESP because of the connection made at the top of the pole. This often produces insulation puncture and failure.

Of equal concern is the large fault current that goes along with the first fault. This current usually causes so much damage

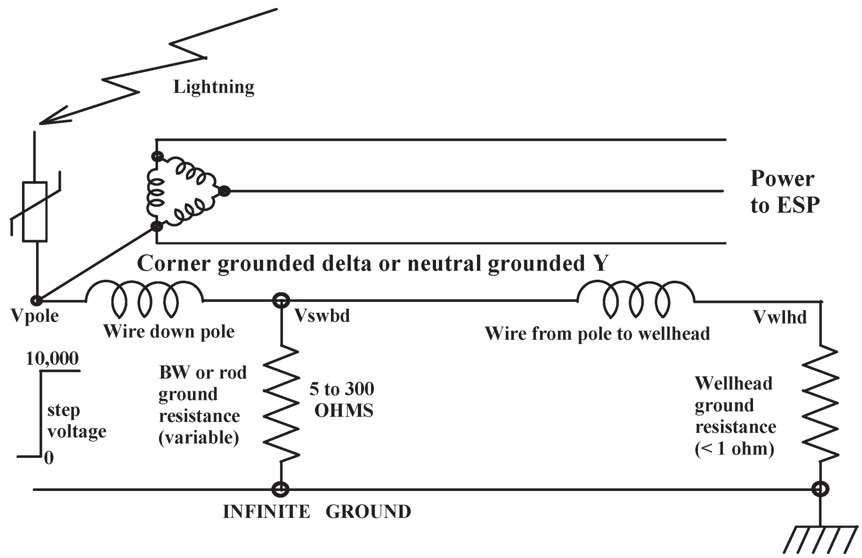

Fig. 8. Solidly grounded power.

TABLE II
TRANSFORMER CONNECTIONS

Voltage		Windings		
Line (kV)	Phase (kV)	Primary	Secondary	Problem
12.4	7.2	Δ	Y or Δ	Preferred – Wide Voltage Range
		Gndd Y	Y	A Δ sec load energizes open pri phase, overloads transformers
		Ungrounded Y	Δ	REMC favorite
		Ungrounded Y	Ungrounded Y	No third harmonic current, distorted phase voltages
24.9	14.4	Gnd Y	Y	Ferroresonance, sec Y to avoid energized open pri phase and overloading transformers
34.5	19.9	Gnd Y	Y	Ferroresonance, sec Y to avoid energized open pri phase and overloading transformers

that the ESP is rendered inoperable and must be pulled and replaced. Today, the revenue forfeited due to the lost production during downtime can easily exceed the costs of replacement equipment, rig time, and crew.

A neutral grounded wye at least produces balanced three-phase voltages that can be used for single-phase loads. Neither of the two delta winding connections can do this; indeed, the corner-grounded delta produces hazardous currents circulating in the earth that have reportedly electrocuted cows and could potentially injure personnel.

The corner-grounded delta is particularly popular with Rural Electric Membership Cooperatives because it eliminates the arcing fault problem and one fuse. Furthermore, a delta winding provides the third-harmonic magnetizing current necessary for undistorted sine-wave voltages and allows the primary to be connected ungrounded wye. This prevents any power losses in the power system neutral wire. Transformers with primary-windings wound for phase-to-ground voltages are less expensive than those designed for delta connection.

Transformer winding connections have a major effect on reliable TVSS operations. A summary of oil-field voltages and advisable connections is listed in Table II.

Ferroresonance is a major concern at line voltages of 24.9 kV and higher. The only sure cure for ferroresonance is grounded wye transformer primary-winding connection. These voltages are often considered subtransmission rather than distribution voltages. Power utilities always run a four-wire power system with an OHN for transmission. Unfortunately, this practice is rarely followed in the oil field.

Lack of third-harmonic magnetizing current produces very peaked voltages, phase-to-ground, at no load. A TVSS must be designed to clamp transient voltages that occur phase-to-ground. The result is that, in these connections, the TVSS voltage must be selected higher than needed to avoid damage from such repetitive peak voltages.

Metering is frequently cited as the reason why the power must be grounded. For medium-voltage power, current transformers and potential transformers are necessary for metering, and they can be connected without grounding the power. Even at 480 V, three-phase, there is no requirement to ground the power meter terminals. There is, however, a bonding requirement for the meter case.

Safety is sometimes claimed as a reason for solid grounding; however, the opposite is actually the situation. High fault currents and the possibility of arc flash are more prevalent with a solid ground.

Certainly, grounded power is essential if single-phase loads are to be supplied; however, a dedicated three-phase load, like an ESP, is more reliably supplied with a high-resistance ground or is ungrounded with a TVSS. Both of these techniques

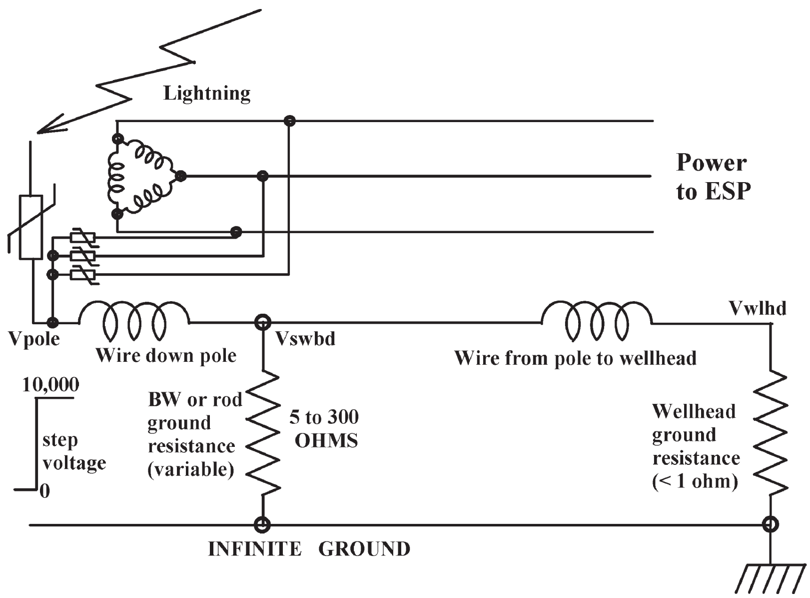

Fig. 9. Secondary lightning arresters.

eliminate any dc buildup on the cable leads that might occur due to an arcing fault. Oil production is a continuous process, and the ability to live through the first fault and continue producing has significant economic advantages.

Secondary lightning arresters, as shown in Fig. 9, are another source of transient-voltage damage to equipment. Here, the voltage injected onto the ESP cable leads is the lightning voltage reduced by the voltage drops across primary and secondary arresters. Again, the secondary lightning arresters are operating in the third quadrant (Fig. 2) or effectively conducting backward.

Secondary arresters used with a four-wire OHN distribution system present another interesting failure mechanism. In one application, three 600-V surge suppressors were connected between the common ground point at the top of the pole and the 480-V power feeding a variable-speed drive. Damage to the 480-V equipment and much of the other downstream equipment was caused by lightning striking the OHN and being conducted through the 600-V suppressors. One thunderstorm actually damaged three sets of equipment. They were all within one mile of each other on the same distribution.

A simple solution to this latter problem would be to connect the OHN directly to the grounding butt wrap without connecting any other equipment to it. A second ground wire could be run up the pole to connect the lightning arresters and transformer cases.

VIII. Conclusion

Oil-field electric submersible pumps provide an interesting opportunity to evaluate lightning protection designed for medium-voltage equipment. A wellhead is an ideal ground with very low contact resistance to infinite ground. Distribution feeders are frequently the highest structures on the horizon and are frequently struck by lightning. Grounding elements must be treated as discrete resistors and inductors, whereas the distribution line and ESP cable are transmission media.

Laboratory testing of ESP systems is questionably feasible. A history of failures, detailing what does and does not work, coupled with rather simple circuit calculations, provides some insight into the problem. Using this approach, the following conclusions can be reached.

A TVSS for ESP protection should be installed on the junction box and connected to the wellhead with a ground wire that is bonded, but separate, from the power system ground wire that also connects to the wellhead.

Power systems that are solidly grounded at the pole top are particularly prone to lightning damage because this ground is the common terminal of all lightning arresters.

Pole-mounted secondary lightning arresters produce failures similar to that in solidly grounded systems. Secondary arresters should never be connected to the OHN ground wire.

It is believed that these recommendations will have applications beyond oil-field ESP systems.

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