OIL FIELD GROUNDING

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ABSTRACT

Lightning damage costs the oil industry millions of dollars each year in lost production, replacement equipment and service. Simple compliance with the National Electric Code is not sufficient because oil field operations involve concentrated electrical loads widely separated from each other. To efficiently serve these loads three-phase power is typically distributed at 12,470 volts. Installing lightning arresters only at poles having or feeding equipment is simply inadequate. Ground resistance, ground lead inductance, lightning arrester connections, power system grounds, shield wires, slack spans, ground bonding and transformer connections should all be considered in a comprehensive lightning protection plan. The intent of this paper is to strive for some consensus in equipment connections and grounding techniques which will produce the best reliability in rod and sub pump operations.

INTRODUCTION

Today the production and related storage of oil in the contiguous United States is increasingly being done by small, independent oil companies with low overhead and production costs. However, the low price of crude and the steadily increasing price of everything else are squeezing these independents. Crude oil simply has not kept up with inflation.

To stay solvent in this type of business environment, close attention must be paid to the "bottom line." Lost production and the costs of replacement equipment, facilities repair and service must be kept to a minimum. These facts are in themselves quite obvious, but since many of these costs seem closely related to lightning storms, would lightning protection of equipment and facilities not be a sound investment with a reasonably short payback?

Welker [1] estimated that the annual cost of lightning damage in the Permian Basin alone could be as high as $85 million. In spite of this it was his observation that lightning protection was the exception rather than the rule.

One major reason for this state of affairs is that past experiences with lightning protection equipment have been anything but positive. Was the protection equipment actually faulty? Hardly! Lightning arresters, surge capacitors and transient voltage surge suppressors are widely used with demonstrable success throughout industrial buildings and residences across the country. The only plausible explanation is that oil field operations present a unique challenge to the successful connection of protection equipment. That challenge is grounding.

Grounding involves two distinct problems, finding a low resistance ground and keeping ground wires short. If the ground resistance is not low, it is difficult to put the massive lightning charge into the ground. As a consequence surface equipment often experiences high and destructive voltages. Protection devices have maximum effectiveness if they are connected directly between the line being protected and ground. Any length of wire necessary to effect this connection detracts from the effectiveness.

It is the intent of this paper to explain the electrical problems involved so that some consensus about oil field grounding can be achieved. Oil field equipment requiring lightning protection includes tank batteries, rod pumps, sub pumps, starters, automation electronics, telemetry and the power distribution system itself.

GROUNDS AND GROUND WIRES

A ground is simply an electrical connection into the earth. The definition is easy; however, earth is a very complex substance. One could say it consists of clays, humus, organic materials, rocks, minerals and, of course, water. As such it is able to conduct electricity to some extent, and that degree of conductivity is measured in ohms. Since soil moisture determines the mobility of ions and moisture content varies significantly throughout the year, it is quite reasonable that ground resistance changes also. Generally in the Northern Hemisphere soil moisture is greatest and ground resistance lowest in June. At the other extreme moisture is the least and resistance the highest in December.

Ground resistance measurements are usually made with a three-point meter. The theory behind operation of this meter was worked out some 80 years ago, and it is quite esoteric. Fortunately the meter itself is easy to use. The meter is first connected to the ground connection to be measured. A metal stake is then driven into the ground 100 feet away and a wire is attached between this current injection stake and the meter. A second voltage sensing metal stake is driven into the ground about 64 feet away and connected to the meter with a second wire. The two stakes are in the same line away from the meter. With these connections made a button is pushed on the meter to complete the resistance measurement.

The above procedure is time consuming and somewhat tedious. From experience the authors have never measured a wellhead ground greater than one ohm. As such a wellhead could be used as a reference to measure the ground resistance of nearby rods, grids, chemical grounds, etc. A new "ground resistance" meter, which resembles a clamp-on ammeter, can measure the resistance in a conductive loop. If that loop comprises the wellhead, a wire connected between the wellhead and the rod, the rod and a path though the earth back to the wellhead; the meter will then read the ground resistance of the rod.

Lead wire used to connect electric apparatus to ground has both resistance and inductance. A good way to visualize resistance and inductance is in term of fluid flow in a pipe. Current is analogous to flow, and voltage is analogous to pressure. In this scheme an increase in the steady flow rate would produce an increase in the pressure drop along the pipe. Electrically this is referred to as ohms law, where current times resistance equals the voltage drop along the wire.

Inductance is seen to be analogous to the mass of the fluid in the pipe. Newton's second law, force equals mass times acceleration, can be used to explain inductance. Acceleration is equal to the rate of change in velocity or flow. Consequently the change in pressure along the pipe is equal to the fluid mass times the rate of change in flow, and this is analogous to the behavior of an inductor where the voltage drop along a wire equals the inductance times the rate of change in current.

The National Electric Code (NEC) requires a solid copper wire no smaller than #6 AWG for grounding purposes. In many instances an insulated, stranded #2 AWG is preferred because it is less susceptible to breakage. For 1000- and 100-ft lengths of these two wires a 10,000-A current would produce the following voltages:

#6	0.3951 ohms/1000-ft	3941 volts	0.03951 ohms/100-ft	394.1 volts
#2	0.1563 ohms/1000-ft	1563 volts	0.01563 ohms/100-ft	156.3 volts

Thus a common 100-ft length of either wire would not have an appreciable voltage compared to typical oil field standards.

For normal lightning strikes it is easily shown that lead wire inductance is the predominant factor. Virtually independent of the wire gauge, lead inductance is approximately 0.5 mH per foot. Thus 100-ft lengths of either gauge wire would have an inductance of 50-mH. If the 10,000-A peak current was reached in 8 microseconds, the rated of change in current would be 10,000/8 = 1,250-Aims. Thus the voltage along the wire would be:

$$50\text{-mH} \times 1{,}250\text{-A/ms} = 50\times10^{-6} \times 1250/(1\times10^{-6}) = 62{,}500 \text{ volts.}$$

Obviously lead inductance is the major concern and the reason why any ground wire should be made as short as practically possible.

Where lead inductance absolutely must be kept to a minimum, a good solution may be the coaxial ground wire. The manufacturer claims that inductance can be reduced to 0.01-mH/ft, compared to the .5 mentioned above or a 50 times improvement. The only drawbacks are price, about $10/ft, and means for connecting to ground. Ground bonding, discussed in the next section, is the preferred connection method.

THREE-PHASE ELECTRIC POWER

Electric power to oil field pumps is always at a power level that mandates three-phase. In fact to keep losses in the power system to reasonable levels, power is distributed throughout the oil field at 12,470 volts and stepped down to pumping levels with transformers located at each well site. The questions are then what transformer connections should be used, and if a system ground is used, where should it be connected.

Three transformer windings, corresponding to the three phases, can be connected either in delta or wye configurations as illustrated in Fig. 1. Therefore the primary (12,470-V) and secondary windings can be connected respectively as wye-wye, wye-delta, delta-delta or delta-wye. An extended delta connection is treated the same as a regular delta connection, the only major difference being that higher voltage levels are possible with the extended delta.

The wide range of voltages required by sub pumps necessitates special design considerations for the secondary windings. These windings must have multiple taps so that the appropriate voltage can be selected for a given sub pump. Further, they can be connected delta for the lower voltage range and wye for higher voltages. Only off-load taps are used because voltages are never changed when a sub pump is running.

For rod pumps the secondary windings are usually connected delta at 230- or 460-V. Variable speed drives also us the delta connection at 460-V.

Of the four connections depicted in Fig. 1, it is the ungrounded wye-wye configuration that causes the most problems. For a transformer to put out sine wave shaped voltages it is essential that the magnetic flux in the steel laminations is also a sine wave. The primary current necessary to do this has a rather irregular wave shape, as shown in Fig. 2a, and a third harmonic (180-Hz) component of current is required to produce this wave shape. However, each phase in a transformer is separated from the other two by +/- 120 degrees, but this angle just happens to be the entire period for a third harmonic. Consequently, the third harmonics are all in phase as demonstrated in Fig. 2b.

Third harmonic current of this type can easily circulate in either a primary or secondary delta connected winding, Fig. 3a, and this accounts for the successful use of the three connections having at least one delta. However, without a neutral point connection the three third harmonic currents can not exist in an ungrounded wye-wye transformer bank just like water can not flow from three separate hoses connected together at some junction if they are all at the same pressure, Fig 3b. Without this current the line-to-neutral voltage of the transformer is quite peaked in nature and can cause significant equipment damage. A representative line-to-neutral voltage waveform is shown in Fig. 3c.

The particulars of earth grounds and ground wires were discussed in the previous section. Ground wire connections are generally divided into two categories, equipment grounding and system grounding. "**Equipment grounding** is essential to safety of personnel. Its function is *to* insure that all exposed noncurrent-carrying metallic parts of all structures and equipment in or near the electrical distribution system are at the same potential, and that this is the zero reference potential of the earth [2]." Since the attention paid to oil field grounds can be somewhat sporadic, the first action any electrician should take when stepping onto a well site is to check all ground wire connections. Finding an energized equipment enclosure could be a fatal surprise.

"**System grounding** connects the electrical supply, from the utility, from transformer secondary windings, or from a generator, to ground [2]." In the oil field the number of generators and substations is far less than the number of water-source or producing wells, so the major concern is transformer secondary winding connection. Ungrounded, solidly-grounded and resistance-grounded transformer windings are illustrated in Fig. 4. Resistance grounds are commonly divided into low- and high-resistance cases.

A comparison of these four grounding methods is presented in Table I [3]. Ungrounded and solidly grounded systems, depending on the characteristic, exhibit the worst behavior. Over all the high-resistance ground is preferred because it performs best for most of the characteristics considered.

"A <u>solidly-grounded</u> system produces high fault currents, usually with arcing, and the faulted circuit must be cleared on first fault within a fraction of a second to minimize damage. An <u>ungrounded</u> system will pass limited current into the first ground fault-.............Therefore, on first ground fault an ungrounded system can continue in service, making it desirable where power outages cannot be tolerated. However, if the <u>ground fault is intermittent</u>, sputtering or <u>arcing</u>, a high voltage — as much as **6** to 8 times phase voltage — can be built up across the system (cable) capacitance, from the phase conductors to ground. **....** This high transient phase-to-ground voltage can puncture insulation at weak points, such as motor windings, ...[2]"

Proponents of the ungrounded system have always cited the continuous service feature arguing that oil production is a continuous process. Arcing faults are indeed a problem with ungrounded rod-pump motors, but not to the extent found in industrial plants. Plants normally have many motors operating in parallel from the same transformer windings, and an arcing fault on one motor elevates the voltage on all the motors.

Arcing faults are more difficult to prove in ungrounded oil-filled sub pump motors. The oil could have an inhibiting effect. However, having seen the melted copper wire, black oil and carbon in failed sub motors, it is hard not to believe that arcing faults exist.

SUB PUMP ELECTRIC FEATURES

To fit inside an oil well a sub pump must have a small diameter, and to develop the necessary head to lift crude from great depths it must have many pump stages and motor rotors. Consequently a fully assembled sub resembles several, skinny telephone poles stacked end-to-end. With such an extreme length to diameter ratio the rotary inertia is very small, and sub pumps typically start (0 to 3500 rpm) in less than 0.5 seconds.

Other features have a more direct bearing on electrical performance. To get the required electric power down to the pump on a reasonable sized cable, medium voltages (600-4160) are essential. Operating a motor on the end of a mile or more of cable is significantly different than operating it on the surface within a very short distance of the distribution feeder.

Submergence requires that the motor be filled with some liquid substance. Lubrication, heat transfer and electrical insulation combined mandate that the substance should be refined oil. Since oil expands with an increase in temperature, this expansion must be accommodated in the design or the motor seals will be blown. When the motor is shut down, the oil cools and contracts. Several means have been developed to allow for this expansion and contraction; however, keeping well fluid out during the contraction phase is always a problem, to some degree. Ingested well fluid is usually salt water, which being heavier than oil sinks to the bottom of the motor. As salt water is electrically conductive, small holes in the insulation can easily lead to winding-to-winding or winding-to-housing shorts through the salt water.

Most well casings extend several thousand feet into the ground, and if anything in the oil field could be counted on as an electrical ground, it is the wellhead and casing. The motor housing is in direct electrical contact with the casing through the tubing string and wellhead, and it is indirectly in contact through the surrounding well fluid. Thus any increase in the voltage between the motor windings and housing puts additional electrical stress on the winding insulation. Shorts in this insulation are frequently precipitated by electrical impulses caused by lightning or switching surges. If the windings are ungrounded, the electrical stress can be many thousands of volts due to arcing faults or static charge.

From these argument it would seem that an ungrounded system is precisely the wrong one to use. Solid, low-resistance or high-resistance grounds would all eliminate any static charge build-up on “floating” or ungrounded motor windings.

Why then are nearly all sub pumps operated ungrounded, and why does “conventional wisdom” maintain that this is the best system ground? Entrepreneurial types equate conventional wisdom to “pooled ignorance.” However, before condemning the practice it might be prudent to ask how this practice got started in the first place, if the reasoning behind the practice has not been totally lost to posterity. Those with no knowledge of history are destined to repeat history’s mistakes.

A seemingly plausible scenario might have been as follows. In the early days of sub pump development, 70 to 80 years ago, the motor may have been powered from a grounded system. At that time oil wells contained little water and had substantial amounts of gas. When a short to the housing occurred in one phase of a motor winding close to the neutral point, the short could not be detected at the surface, and no action was taken to clear the fault. However, the short continued to arc over to the housing, metal was liquefied and a hole was eventually burned through the housing. Once that happened the well was ignited, and the ensuing conflagration was unforgettable.

After such a debacle someone had to be held responsible. Obviously the pump caused the problem. It might therefore have been reasoned that by taking the housing out of the electrical circuit no serious arcing to the housing would ever occur. This could be done by eliminating the system ground and operating ungrounded. Two phases would then have to short to the housing before the motor failed, and all arcing would be contained within the housing.

Whether this ever actually happened is certainly debatable. However, anyone having enough experience with electrical equipment has seen the results of serious electrical faults. Indeed, holes are burned through steel walls. The rest need only be left to a conviction that Murphy’s Law is true. Summarized that is, “If things can go wrong, they will.”

One major problem with sub pump system grounding is measurement of current unbalance. It is generally assumed that the motor currents measured at the surface are the same as the currents actually entering the motor at the bottom of the well. Some years ago it was demonstrated that this is not true when the system is grounded [4].

California, at that time, required that all sub pump motors be grounded, and most were fed from step-up, 480-VAC autotransformers with the neutral point grounded. Any time there is a system ground other paths exist for current to get back to the generating source. These are called ground or zero-sequence currents, and because their exact nature is almost impossible to predict, they are very difficult to simulate.

An example where they could possibly be predicted is with corner-grounded delta transformer windings. For the phase that is grounded there is no voltage across the cable capacitance between that phase and ground, and therefore no current. However, for the other two phases the voltage is 1.732 times larger, and the current is proportionally larger. Since the currents measured are the combination of these capacitor currents and the motor currents, it is impossible to know what the actual motor currents are. This being the case, current unbalance and subsequent motor heating can not be known.

For the past 30 years bottomhole pressure has been measured by putting a DC current on all three phases simultaneously. The return path is through the ground. The circuit is completed through a resistor type pressure sensor installed between the motor neutral and ground. Pressure is then proportional to the DC resistance measured. If the system is grounded this type of measurement will be shorted out and no reading will be possible. Many petroleum engineers are unwilling to give up bottomhole pressure information strictly for, to them, some niceties about the power system.

As stated above general industry prefers the high-resistance ground for the reasons given in Table l. This type of ground would also provide benefits for sub pumps. However, grounding through a non-linear resistor like a metal oxide varistor (MOV) provides additional benefits. The MOV has a very high resistance at low voltage, but this resistance decreases dramatically at high voltage. The curves shown in Fig. 5 illustrate the principle. **A** high resistance is drawn on the curve for comparison, and recalling that resistance in ohms is simply volts divided by amps, it is represented as a straight line.

The MOV in Fig. 5 has two distinct advantages over a simple resistor. First, at low voltages, equivalent to sub motor voltage, the resistance is higher, there is less power in the MOV and less energy wasted. Since energy (kWhr's) costs money, the MOV's are less expensive to operate.

A second advantage is that the maximum voltage is severely restricted, and this extends insulation life. Electrical insulation fails through repeated episodes of partial discharge and tree growth. When the tree stretches from one electrode to another the intervening insulation has failed. Partial discharge is an arcing at some small void or imperfection in the insulation caused by a high voltage. The MOV virtually prevents high voltages that cause partial discharges.

ROD PUMP ELECTRIC FEATURES

Induction motors driving rod pumps are almost always a standard NEMA (National Electrical Manufacturers Association) frame size. Frame sizes were standardized around the lengths and diameters that would give the best efficiency for a given horsepower and temperature rise. Normal starting times are from three to ten seconds. Typical voltages are 230- or 460-V, three phase. Rod pump motors are frequently a NEMA design D, which greatly reduces the difference in current between the up stroke and the down stroke.

Rod pump grounding is usually not a problem. The walking beam rests on a concrete foundation that has a rather large contact area with the soil. Since the concrete is alkaline with some internal moisture, it is quite conductive. Thus the beam is inherently ground; however, to insure a good ground a short, #2 AWG wire should be connected between the well casing and the beam. That wire should be bonded to both the beam frame and the casing.

Failures of rod pump motors are fairly rare. The 230- or 460-V power could be supplied from wye connected transformer windings with either a solidly grounded or resistance grounded neutral. When supplied in this manner transient voltage damage from lightning or switching surges is greatly reduce.

Frequently the 230- or 460-V power is supplied from a delta winding. This is done to avoid the wye-wye transformer connection problem discussed earlier. Often the 12.5-kV primary windings are operated ungrounded because no ground is available. Consequently some type of transient voltage surge suppressor should be connected between the motor leads and ground to protect against impulse voltages. This is not difficult to do, because the motor is readily accessible and the frame is grounded. Ground leads can be very short.

POWER SYSTEMS

Pole and line constructions for oil field distribution systems are incredibly varied, despite the fact that there are only a few distinct voltage ratings between 4160-V and 34.5-kV. Possibly this is due to different soils and terrain, but more likely it can attributed to the creative solutions of a multitude of utility company engineers over many years.

With passage of the Rural Electrification Act (REA) some seventy years ago electric distribution lines were extended into the countryside. At that time the main load was lighting; however, in the intervening years more lighting and motor loads were added. Consequently the original systems had to be upgraded several times to supply the increased load. Upgrading typically meant reconductoring (larger diameter wire) or taking the voltage to a higher level. Sometimes the higher voltages required new pole constructions.

Since three-phase electric power could be supplied with only three wires, it is not uncommon to see three-wire systems throughout the oil patch. If the system was reasonably balanced, the neutral point was approximately at zero volts anyway, so why worry about a fourth wire? Beyond that, a fourth wire costs practically as much as each of the other three, and installation time and labor has to similarly increase. How is a poor low bidder going to survive if he does not cut comers somewhere?

In all this the electrical importance of the fourth was grievously over looked. **As** voltages were increased wye primary windings became more prevalent. The fourth wire was needed to provide the third harmonic current in the primary side of a wye-wye transformer bank. In such usage it is termed a "neutral" connection.

The fourth wire is also widely used as a ground. No transmission lines (high voltage long distance) are ever constructed without an overhead ground/neutral wire to shield the phase wires against lightning. However, adding an overhead shield wire to an existing three-wire distribution system is not an easy task, and for the sake of safety the line should be de-energize while the work is in progress. The lost production while this shielding neutral/ground wire is being installed may make the true cost intolerable.

One solution to this is stringing the fourth wire beneath the three phase wires on the cross arm. In this "under built" construction the wire is supported by the pole and is electrically connected to pole ground wires running down each pole. Pole ground wires are connected to any one of a number of grounds, a butt wrap on the bottom of the pole, a butt plate on the bottom of the pole, one or more lightning rods, a ground grid or a chemical ground. Since the fourth wire connects all pole ground wires in parallel, the effective ground resistance is greatly reduced. Even when a fourth wire is not installed; pole ground wires are necessary to protect the pole against being split by lightning.

Although the NEC only requires lightning arresters at poles having connections to electrical apparatus, the oil field situation probably should have additional arresters installed simply because of the distances involved between concentrated loads. In relatively flat and arid terrain a good procedure to follow is connection of three lightning arresters at every fifth pole. If this is deemed to be excessive the center, highest line should at least have a lightning arrester every fifth pole in conjunction with three arresters every tenth pole. Of course each arrester would be connected into the fourth, neutral/ground wire run with the distribution.

All this should not be overly expensive. Lightning arresters can routinely be purchased for less than $80 a piece. Labor and materials to string and connect a fourth wire should also be quite reasonable.

Over the years the NEC has had increasing problems in defining what exactly is ground. At one time it was simple. Cold water pipes were copper pipes soldered together and run underground from the house to the water main beneath the street. The advent of plastic water pipe and plastic inserts in gas lines to alleviate corrosion made finding a decent ground much more difficult. More recently reinforcing steel bars are bonded together in the concrete footers of buildings, and connection to this has been approved as a suitable ground.

Grounding techniques used with pole ground wires were mentioned above. However, in some locations even the parallel connection of pole ground wires does not produce a low ground resistance. The only ground with consistently low ground resistance is the wellhead. In an industry that should always be trying to reduce ground resistance, it is amazing that the wellhead is frequently not connected into the power system ground.

Why is the most common wellhead connection just a bronze clamp that frequently works loose and sometimes does not even hold the ground wire tightly? Ground bonding or exothermic welding (Cadweld, Thermoweld, etc.), where copper ground wires are welded to steel rods and plates, is used in almost every other industry. It would seem very desirable to have a permanent, reliable ground connection to the well casing below the wellhead so that the connection would not be disturbed, or worse yet forgotten about, during a workover or changeout. Ground bonds are very low resistance, rugged and reliable connections that are unaffected by lightning of any magnitude.

It might be argued that welding to the casing is dangerous because of the possible ignition of internal natural gas.

Certainly this is a concern. However, casings are high strength, low carbon steel (typically L55, K55, etc.) and they are always more than a quarter inch thick. The bonding weld will not penetrate through such a casing.

For sub pump protection provision should be made to bond at lease two, #2 AWG wires to the casing. The rationale for this is explained later.

A #2 AWG, stranded, insulated copper ground wire bonded to the casing should be buried back to the equipment to be grounded. Burial does not need to be deep, because the main source of ground wire breakage is grazing cattle. It could be argued that burial makes it harder to check; however, any electrician could easily perform such a check in a few seconds. Further, burial greatly reduces copper loss due to theft. The chief benefits of ground wire bonding and burial are the permanence and reliability of the installation.

GATHERING AND DISPOSAL FACILITIES, ELECTRONICS

Produced fluids from rod and sub pumps are brought to the surface for storage, separation, disposal of by-product, and transportation. These facilities are critical and must be protected from transients and preventable failures. They warrant special attention because the field must be shutdown if there is no place to put the produced product. At such time equipment cost is a minor consideration. As a partial solution the authors have used Intermediate class arresters with dedicated ground beds one or two spans before the facility. These have helped to eliminate transients from upstream sources, but they address only part of the problem. Lightning arresters are still required at the end of the line as demonstrated in Fig. 7e.

Metal vessels and tanks should be solidly connected to the facility grounding system to prevent static discharge hazards and to provide a secure path for current in the unlikely event the structure is hit directly by lightning. Durham *[5]* noted that vessels and tanks using steel 3/16" thick or thicker are not likely to be punctured by lightning. He also noted that facilities with a footprint greater than 500-ft^2 should have a surrounding ring-type grounding bus plus a grid with cross-connection conductors no more than 50-ft apart, Fig. **6.**

Ground rods should be installed at the intersection of each of the ground lead points shown in Fig. **6.** In some areas ground rods should also be supplemented with enhancement material of some type. There are several types **of** enhancing backfill that are available such as synthetics, organics, cements, etc. This extra precaution for getting a good ground is necessary for locations where the well casing is not accessible for grounding. If grounding rings or branches get within 6-ft of metallic fencing, then the ground should be extended on and the fencing materials bonded to the grounding system to prevent sideflash. On locations where water disposal or injection of some type coexists within the storage facilities, the wellhead can also be include in the ground system.

Grounding of fiberglass tanks used for produced water storage is an especially challenging problem. Fiberglass itself is an excellent insulator and has a bad tendency to build up a charge on its surface as dust and particles move across the material. The authors have seen this affect the reading of transmitters and other electronics attached to the fiberglass tanks. All metallic objects on these tanks should be tied back to the grounding system, and some people have even suggested that the tank be wrapped in ground wires similar to Christmas tree lighting. A ground lead dropped into the tank and extending to the bottom is another possibility for relieving some of this charge.

Notwithstanding all this, the direct strike issue must be given major, detailed consideration. Especially for fiberglass tanks, overhead shield wires and air terminals should be used to divert lightning energy and safeguard the tanks.

Automation, communication, and sensitive electronics are typically the heart and soul of the modem-day storage and disposal facility. This equipment is highly sensitive to transients and grounding problems. A standard single-point star grounding arrangement will typically avoid any ground loop problems. Low ground resistance is critically important to trouble-free electronics. Analog signals, sent back to automation equipment, should use shielded, twisted-lead cables. Except for extremely long runs shields should only be grounded at one end of the cable. This eliminates stray currents in the shield and that can induce noise onto the signal. Although these concepts have been known for a long time, they still create problems on those occasions where they are neglected. All these concepts apply equally to communications equipment.

SLACK SPANS

Before starting on this topic it is imperative that the term "Slack Span" is defined. Some refer to this as a "build by," and some say it has to do with the tension forces in the wires. Others maintain that a slack span is nothing more than an extension of the power wires beyond the last connection or power drop pole that provides mechanical support for the pole. However, in the local oil production industry it has come to mean something different from all of these.

"A slack span is a section of distribution line built past the last connection pole that provides additional lightning protection." It is well known that a voltage surge nearly doubles at an unprotected, open-circuit end pole. If the end pole and last connection pole are one and the same, electrical apparatus connected there will be very prone to electrical damage because of the doubling effect. A properly constructed slack span compensates for this effect.

The surge performance of transmission and distribution lines is quite different from performance with 60-Hz, sinusoidal voltages. In fact electrical surge performance has many similarities to hurricane storm surges. Possibly the best known hurricane was the one which did massive damage to Galveston in 1900. Examining exactly what happened then and shortly afterward has some interesting parallels in electricity.

As the Galvestonians waited out the storm on that fateful day, they were totally unaware of the storm surge bearing down on them. The energy associated with that 20-foot wall of water would in a short time damage most of their houses, kill many of them outright and injure a great many more. In a similar manner a fast, high-voltage electrical surge such as lightning travels down a distribution line damaging weak electrical equipment in its path.

After 1900 a high, concrete seawall was constructed around Galveston. Now when the 20-foot high storm surge strikes the seawall the front of that water doubles in depth to 40-feet. A second 20-foot high surge has been created that goes back out to sea riding over the top of the incoming surge. This is directly analogous to the behavior of an electrical surge traveling down a distribution line and encountering an open circuit dead end. The voltage doubles as a second, backward traveling wave is created, Fig. 7a. Electrically the seawall is equivalent to insulation that can withstand the higher voltage without arcing over and failing.

If a very deep and wide crevasse existed right at the shore line, an incoming storm surge would immediately drop to the bottom of that crevasse and the water depth right at the edge would still be zero. This is equivalent to a short circuit at the end of a line. A short circuit has zero voltage. **A** backward traveling wave is produced again but with the opposite polarity of the incoming wave. The two add together and exactly cancel each other, giving a net zero result, Fig. 7b. No power system can actually operate into a short circuit, and this is the reason why spark gap arresters always had a series resistor.

Here the analogy has a minor flaw, since electrically a negative, backward-traveling wave is created. Once the complete positive wave has passed, all that remains is the backward-traveling, negative wave, Fig. 7b. From experience it is hard to imagine a 20-foot trough or hole in the water that is going out to sea.

Metal oxide varistor based lightning arresters combine the open-circuit and short-circuit behaviors described above. Below the threshold voltage the lightning arrester has very high resistance and looks like an open circuit. Voltages below this level will pass on down the line unaffected. However, above the threshold the lightning arrester looks like a short circuit. This produces a backward-traveling, negative wave. For an end of line situation two cases need to be considered, surge voltage less than the MOV threshold and greater than the threshold, Fig. 7c&d.

Using the above descriptions some conclusions can be drawn about the proper construction of slack spans. If the end pole is left as an open circuit, the surge voltage is still going to double there due to the backward traveling wave. Now the length of the surge observed at the connection pole is going to be extended by the time it takes the surge to travel to the end pole and back. Thus, instead improving equipment protection, an open circuit end pole can actually put greater electrical stress on the equipment.

For this reason three lightning arresters and a good ground should always be installed at the end pole. **As** previously mentioned, MOV lightning arresters appear as either a short circuit or an open circuit depending on whether the applied voltage is above or below the threshold voltage, respectively. Slack span operation for an assumed span length is demonstrated in Fig. **8.** Span length must be related to how far the surge travels, and surges travel at the speed of light, 300-m/ms. Indeed the time duration of high voltage levels at the connection pole is reduced.

Unfortunately the authors were unable to find any slack span information in the technical literature. Calls to three professors specializing in power systems, including the authors of references [5&6], were completely unfruitful. The most urgent question is, how long should a slack span be? As seen in Fig. **8,** this depends mainly on how fast the surge is, or alternately how little time is required to go from zero to maximum voltage on the surge. Faster means less time.

Finally, extra lightning arresters and wires and an extra pole and ground are not inexpensive items. One therefore has to make some judgement as to whether a slack span is really an effective use of limited financial resources or if there might not be a less expensive way to get the same or better performance.

An alternative is to install lightning arresters on the pole just ahead of the drop pole, as mentioned under facilities. This will take a chunk out of the surge voltage at that pole as portrayed in Fig. 7e; however, a surge of threshold voltage size still propagates on down to the end pole. Lightning arresters must be installed here at the end/drop pole to avoid voltage doubling.

CATHODIC PROTECTION

Cathodic protection systems apply a DC voltage between a pipe or vessel that is being protected and a sacrificial anode. This effectively halts metallic corrosion due to galvanic action. The rectifier supplying the DC, like any other piece of equipment connected to the power line, should have surge protection and a good solid ground.

Under normal circumstances cathodic protection should not affect the grounding systems that have been previously examined. However, two situations are worthy of note here.

Anytime multiple earth connections are made stray currents may arise. Therefore to provide uniform corrosion protection, especially for large objects, it is important to identify the source of stray currents and to isolate them, if possible. Should this not totally correct the problem, the solution is to systematically bond the system together with #4 AWG wire. *[5]*

Another situation that requires detailed consideration is two separate cathodic protection systems on the same location. An example of this is isolation of a pipeline having its own cathodic protection from a protected vessel. Here it is important to realize that ground bonding the equipment could effectively tie the two cathodic protection systems together. The accepted fix for this situation is bonding through a controlled-resistance jumper, Fig. **6.** That resistance must be low so that fault currents can trip protective devices, but even a low resistance restricts stray current.

TOWARD A GROUNDING CONSENSUS

Rod pumps are generally well grounded through the concrete pads they sit on, but an additional ground connection to the adjacent well casing is recommended. Lightning damage is rare, but when it does occur, the equipment to be repaired is readily accessible. A TVSS should be employed to protect the motor, and suitable low-voltage surge suppressors should be installed in the electronics.

For facilities the ground commonly consists of ground rods connected to a loop of bare copper wire circling the tanks. The wire should also be buried. Encasement in about six inches of concrete lowers the ground resistance of the loop but adds to the cost. Metal tanks are connected at multiple points into this ground. Fiberglass tanks, being insulated, should certainly have a shield wire installed above them to take any direct strikes. Shield wires should be connected into the ground loop at multiple points also. When cathodic protection is applied additional attention must be paid to stray currents.

Sub pump electric power usage is substantial, ranging from 100- to 800-kW. Much of the equipment damage is caused by surges propagating down the power wires after lightning strikes at some other point. Power system construction is immensely variable; however, at any well site the sub pump and related equipment is easily catalogued.

Transformers, lightning arresters and the power system ground are all mounted to the power drop pole at the site. Sub pump equipment consists of the switchboard, junction (vent) box, cable, wellhead, tubing string, pump and motor. Electrical behavior of sub pump motors, lightning arresters and TVSS' was explored earlier. Although three-phase transformer connections were presented in some detail, the transient behavior of power and control (switchboard) transformers still needs to be explored.

A detailed analysis of the surge, impulse or transient (used synonymously here) behavior of transformers gets very involved and is best left to graduate texts in electrical engineering [6]. However, it is possible to summarize most of this behavior in terms of two transformer parameters, inductance and the capacitance between windings.

For high frequency events such as surges, inductance becomes a large (high ohm) reactance. In fact it could almost be treated as an open circuit. Line end open circuit behavior was explained under slack spans. Since the capacitance effect must also be considered, it seems reasonable that only two-thirds of the incoming surge (voltage) is reflected and becomes a backward traveling wave. This result was measured by a leading ESP transformer manufacturer [7]. Unfortunately it has some rather ominous repercussions for transformer protection.

Even though a lightning arrester will limit the incoming surge to something around the threshold voltage, that limited surge is going to increase by two-thirds when it hits the transformer, similar to the operations depicted in Fig. 7e. This effect is made even worse by the inductance of the interconnecting ground and phase wires. Therefore the preferred lightning arrester mounting is directly to the grounded case of the transformer as depicted in Fig. 9.

Interwinding capacitance allows about one-third of the incoming surge to be transferred through to the secondary winding. The same transformer manufacturer measured this effect and proposed a Faraday shield, Fig. 10, which would all but eliminate the capacitance between windings. Tragically after all the expense of building and installing these shielded transformers, they did not perform as expected. And the problem was — improper grounding of the shield.

Switchboard failures predominantly involve the large, high VA potential transformer (PT). Surges in and through it are somewhat similar to the power transformers just described. Surge suppression is essential to PT protection, but frequently the high-voltage, primary winding is not even vacuum impregnated to improve the high-voltage withstand.

A second major failure problem in switchboards is the solid state motor controller. Most of that damage can be attributed to surges getting through the PT onto the 115-VAC power feeding the controller. This type of failure can be virtually eliminated with low voltage MOV's and low-pass filters on the 115-VAC line out of the PT.

Earlier it was emphasized that the only consistently low resistance ground at any well site is the well casing and wellhead. Obviously the equipment ground for all the sub pump components should be connected to the wellhead, for safety sake if for nothing else. Should the power system ground also be connected to the wellhead? Some argue that the power system ground should stand-alone because the transformer provides an additional barrier to the transmission of surges. Since the power lines are the main entrance for surges into a sub pump and the transformers can pass one-third of the surge straight through, a better idea might be to intercept as much of that energy as possible before it even get to the transformer. By connecting power system ground to the wellhead, ground resistance is as low as possible, and the drop pole lightning arresters have the best chance of getting surge energy into the ground.

It also seems reasonable that **separate ground wires should be provided, from the wellhead to the utility ground and from the wellhead to the sub pump devices ground.** Fig. 11 illustrates how these connections should be made. Why should the huge voltage drop, due to lightning current through the arresters and the lead inductance, be added to the ground reference for the ESP equipment? This is exactly what happens when only a single ground wire connects the utility ground to the sub pump equipment and to the wellhead.

Installing a TVSS in the junction box as shown in Fig. 11, provides the best protection for the downhole sub pump because the ground wire is as short as possible. Extending this ground on back to the switchboard provides protection for the PT and controller.

Earlier a case was made for burying ground wires. Actually separate ground wires should be buried in separate trenches to minimize problems with side-flashes and coupling between the wires. The coaxial ground wire presented earlier greatly reduces the possibility of side-flashes.

What is the solution to oil field grounding? There is no one, silver bullet, and universal solution. Quite a number of options must be considered. However, some solutions are inexpensive and easy to incorporate. A reasonable solution priority could be as follows:

- Connect the power system ground to the wellhead with a ground wire separate from the one going from the wellhead to the sub pump components
- Install a ground/neutral wire throughout the field, grounded at every pole and with lightning arresters installed at appropriate locations.
- Install a non-linear resistance system ground, such as a MOV based TVSS. The preferred location is in the junction box where the wellhead ground wire is the shortest

- Ground bond the ground wires to the well casing and bury them back to the electrical equipment
- Connect three additional arresters between the transformer high-voltage leads and their cases, Fig. **9.**
- Consider shielded transformers
- Consider coaxial ground lead wire
- Carefully evaluate whether construction of a slack span can be justified.

CONCLUSIONS AND SUBSTANTIATIONS

Certainly there is agreement that the lowest resistance grounds and the shortest ground wires are the best. Where the distance between the equipment and ground is significant, a coaxial ground wire might be justified.

A system ground connects the transformer windings to ground. Four grounding methods were compared, and the high resistance ground had the most favorable characteristics. An improvement even on this is the non-linear resistance ground, such as a MOV, where resistance is high at low voltages and low at high voltage.

The transformer connection to be unequivocally avoided is the ungrounded wye-wye. A wye-wye connection can only be used if the primary winding neutral point is grounded, preferably back to generation.

Power systems that include a fourth, neutral/ground wire provide far better lightning protection for the attached electrical apparatus. Carrying the fourth wire throughout the oil field makes it much easier to dissipate lightning strikes before equipment damage occurs, and consequently the entire power system is much less susceptible to lightning damage.

From the behavior of transformers to surges on the power system, ground should be connected to the wellhead. By running a separate ground wire back from the wellhead to the power system ground, the sub pump components experience far less voltage stress when lightning strikes. Improved transformer protection is possible if three additional lightning arresters are mounted directly to the transformer case.

Proving that oil-field grounding is a worthwhile investment has always been a major challenge. With oil prices low and uncertain, the general tendency is to just let things rock along. Still, other industries have much lower lightning induced failure rates. Theory confirms that proper grounding improves equipment protection, and those who have made the expenditure to improve oil-field grounding are confident they are experiencing much lower failure rates.

Today we continue to learn more about the precise nature of lightning. We now believe that it does not strike just a single object in an area but multiple points simultaneously. Lightning is still a random event, but the national weather service tracks every lightning strike according to time and location. Likewise the electric utilities have records of every switching event on their systems. Often surges due to lightning and switching can be directly correlated with equipment failures.

However, one common experience is that the equipment failure frequently occurs one week after the lightning storm. Still, it was that surge that weakened the insulation to the point where any minor disturbance or even continued normal operation would result in a failure.

On a personal level we rarely experience lightning damage in our homes, although we usually put surge suppressors on our home computers so as not to tempt fate. Electric utility lines are now almost all buried, and we seldom have any metal objects sticking **up** from our houses. The oil field is not so. Power wires and pump jacks are usually the tallest things on the horizon. As such they are prime targets for lightning, and grounding is the first and most important requirement for the protection of all oil field equipment.

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Table I
Comparative Benchmarks for Various Grounding Methods

Characteristic	Ungrounded	Method of Grounding: Solid Grounded	Low Resistance	High Resistance
Immunity to transient over voltages	Worst	Good	Good	Best
Increase in voltage stress under line-to-ground fault conditions	Poor	Best	Good	Poor
Equipment protected against arc fault damage	Worst	Poor	Better	Best
Safety to personnel	Worst	Better	Good	Best
Service reliability	Worst	Good	Better	Best
Maintenance cost	Worst	Good	Better	Best
Continued production after first ground fault	Better	Poor	Poor	Best
Ease of locating first ground fault	Worst	Good	Better	Best
Permits designer to coord-inate protective devices	Not possible	Good	Better	Best
Ground fault protection can be added easily	Worst	Good	Better	Best
Two voltage levels on the same system	Not possible	Best	Not possible	Not possible
Reduction in frequency of faults	Worst	Better	Good	Best
First high ground-fault current flows over grounding circuit	Best	Worst	Good	Better
Potential flashover to ground	Poor	Worst	Good	Best

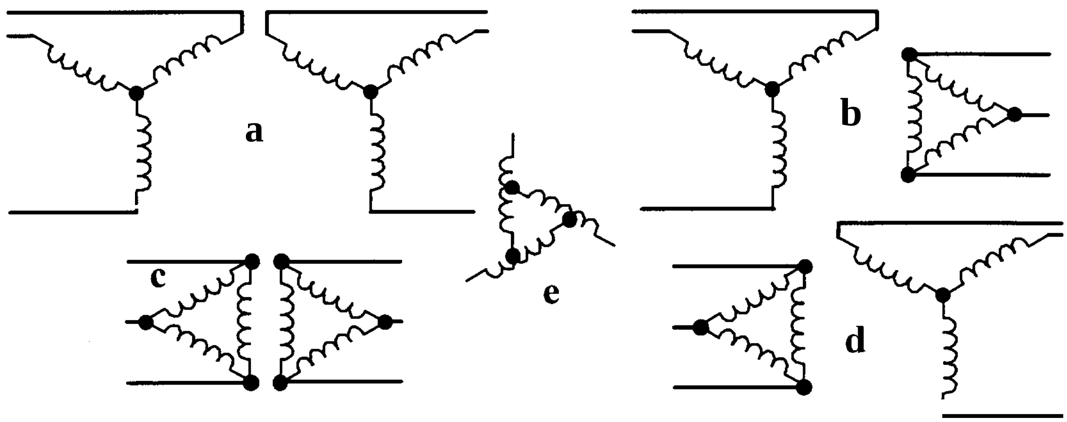
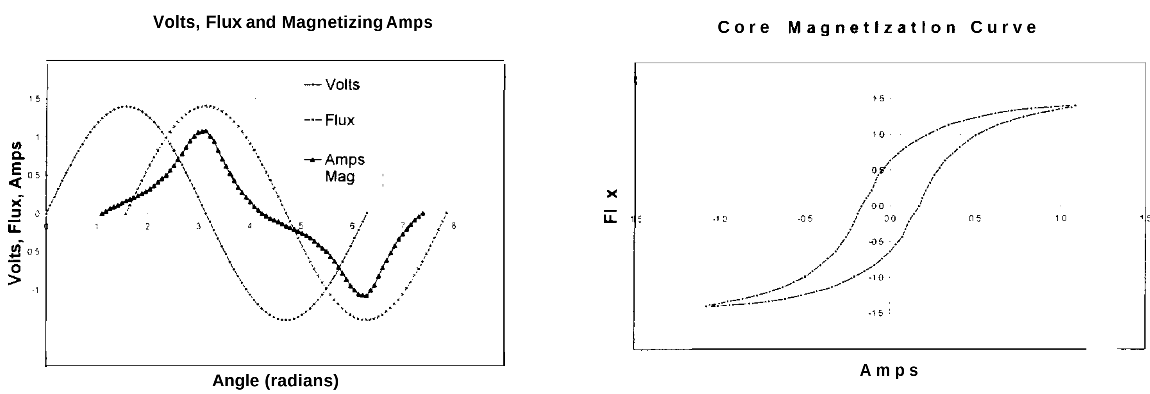
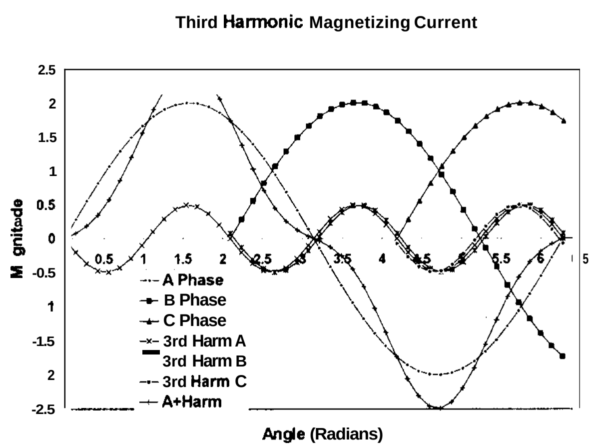


Figure 1 - Three Phase Transformer Connections a. wye-wye **b.** wye-delta
c. delta-delta d. delta-wye e. extended delta



a



b

Figure 2 - a. Sinusoidal voltage and flux requires peaked
magnetizing amps having a third harmonic.
b. Third harmonics are all in phase.

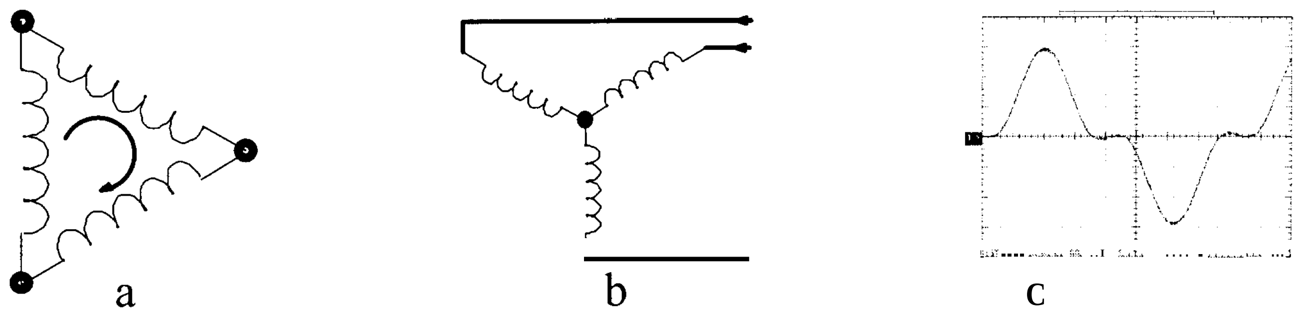


Figure 3 - a. Third Harmonic Current Circulating in a Delta, b. No Third Harmonic in an Ungrounded Wye c. Line-to-Ground Voltage in an Ungrounded Wye-Wye

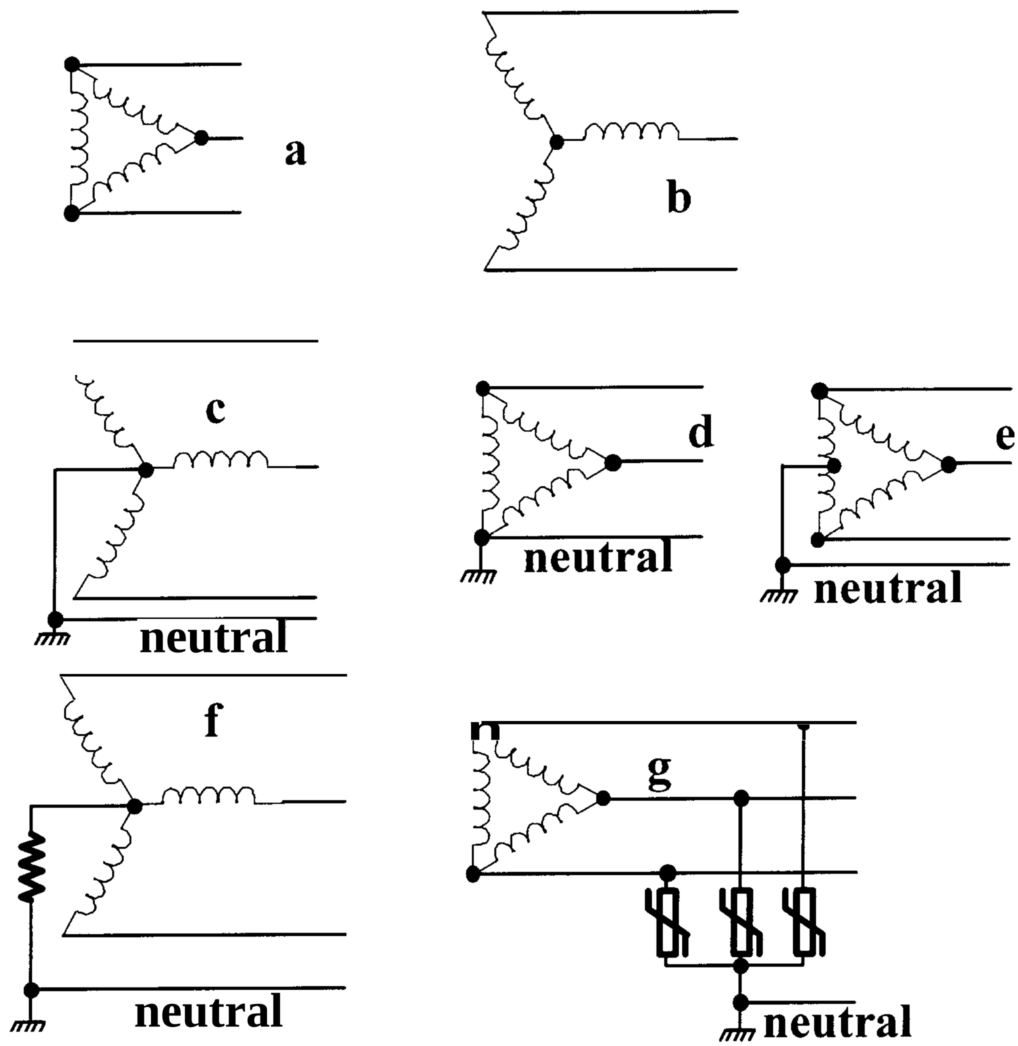


Figure 4 - a&b Ungrounded Windings, c,d&e Solidly Grounded Windings, f Resistance Grounding, g Nonlinear Resistance Grounding

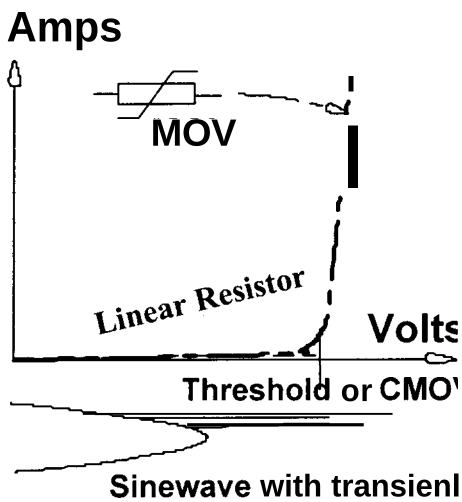


Figure 5 - Linear High Resistance and Non-Linear Resistance System Grounds

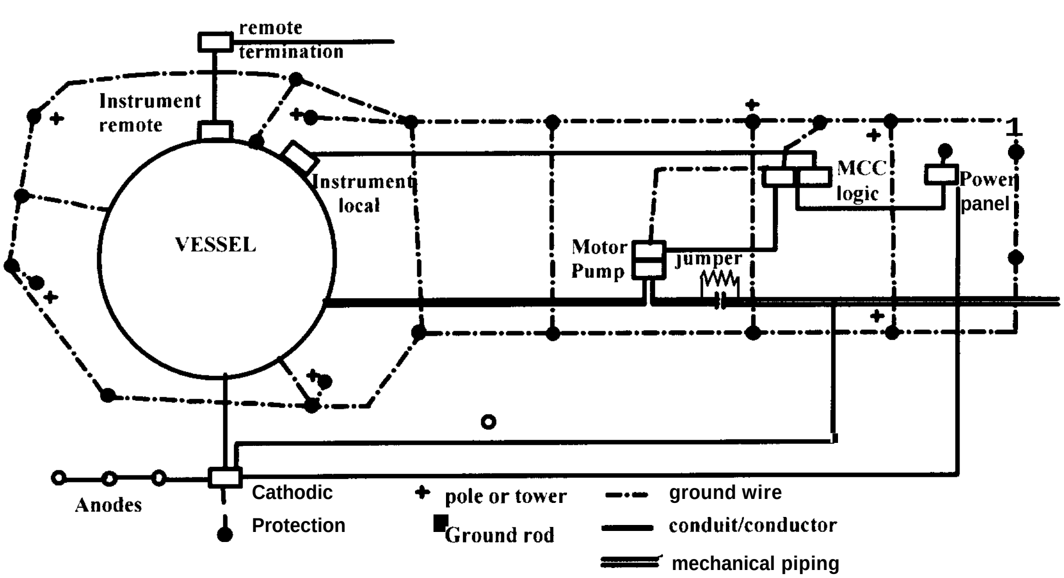


Figure 6 - Facilities Ground System (After Durham)

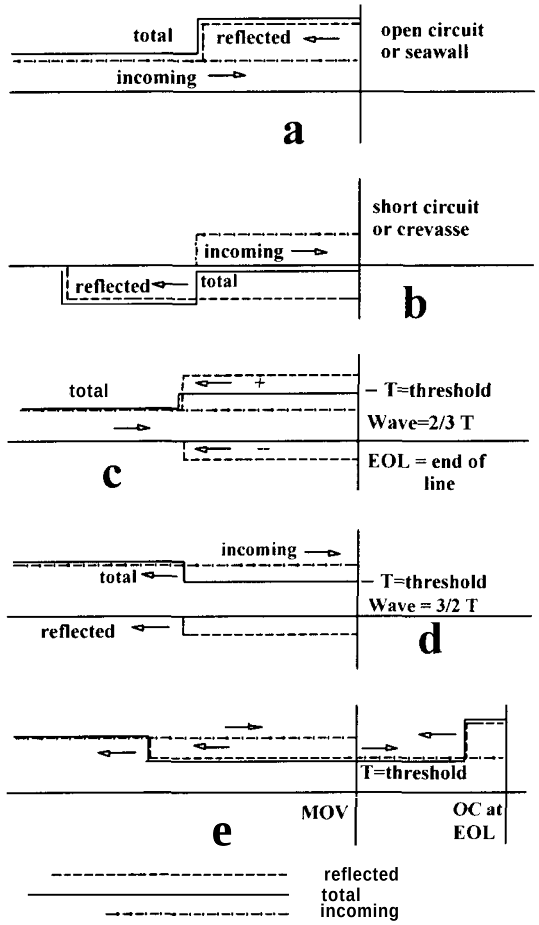


Figure 7 - Surge Reflection From: a. Open Circuit (Seawall)
b. Short Circuit (Crevasse) c. EOL MOV Wave=2/3 T
d. EOL MOV Wave=3/2 T e. MOV before EOL OC

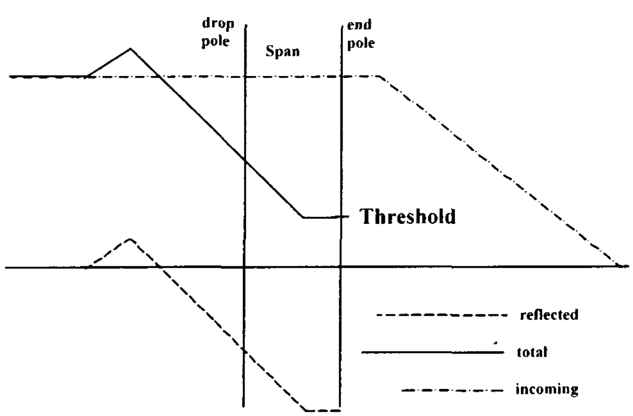


Figure 8 - Operation of the Slack Span

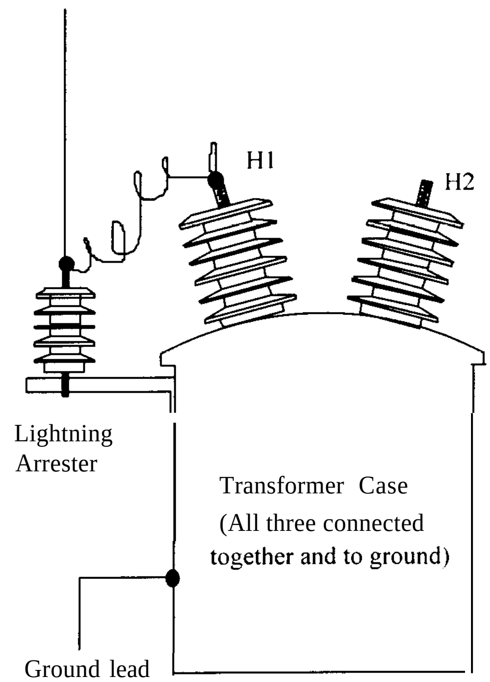


Figure 9 - Recommended Transformer Protection
Lightning Arresters to Case

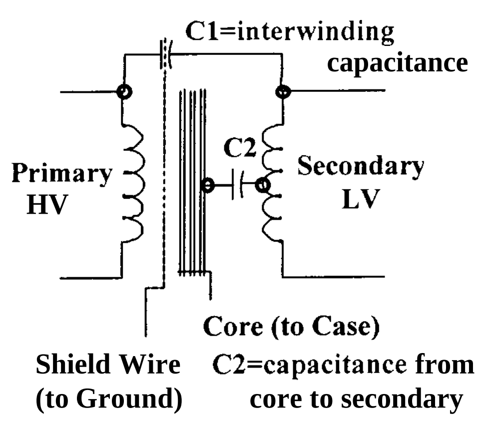


Figure 10 - Shielded Transformer

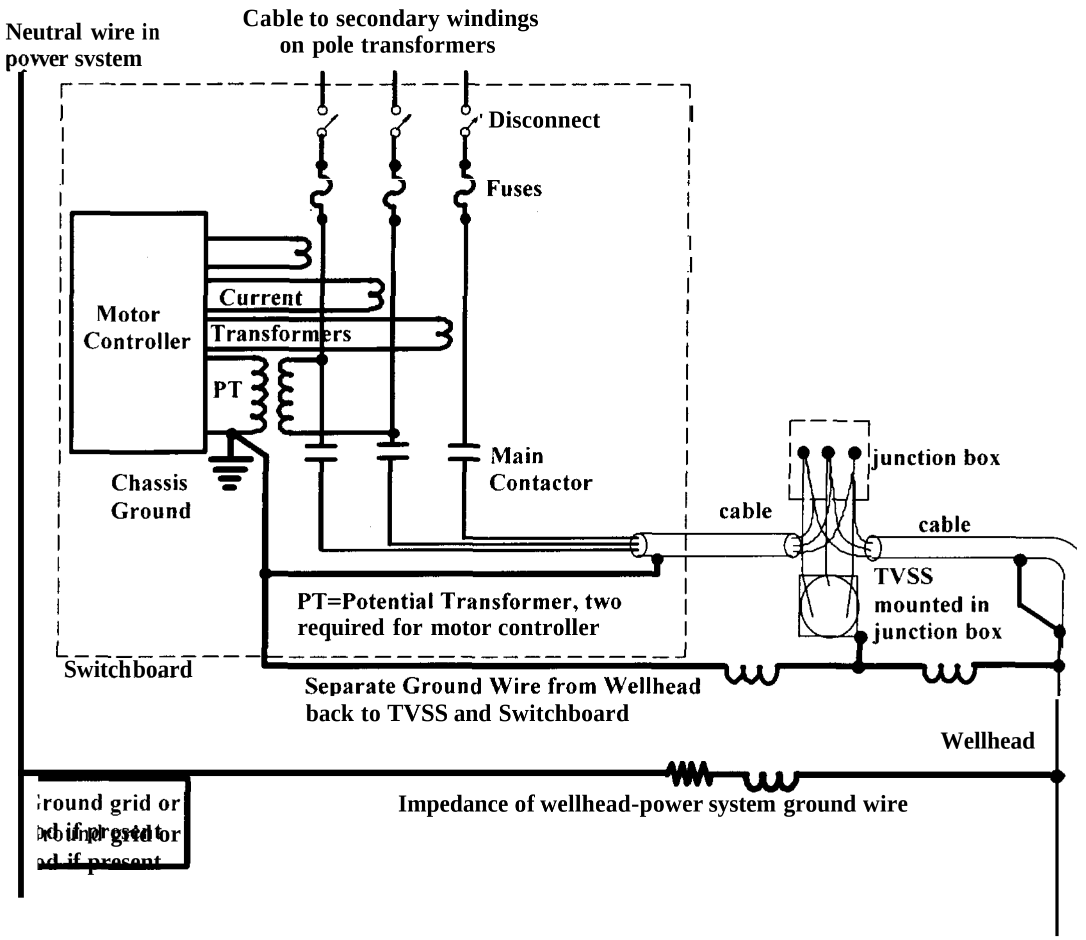


Figure 11 - Separate Wellhead Connections to Power
System and Sub Pump Components