Oilfield Electric Power Distribution

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***Abstract*—The uniqueness of power system designs for oilfield distribution is seldom acknowledged or addressed. Utilities provide construction typical of either commercial or rural applications. Oilfields commonly have large concentrated loads separated by thousands of feet. To minimize line losses, medium-voltage power is distributed and stepped down at the point of use. In addition to common load flow analysis and protection coordination, transformers, surge arresters, and grounding connections are important considerations for reliable production operations. Recloser settings typical for residential distribution cause major damage to submersible pumps. In remote areas where long neutral wires are necessary, solidly grounded power contributes to equipment failure but is nevertheless necessary for safety in surface equipment. The corner-grounded delta connection eliminates the neutral wire and is often used by rural utilities, despite its dangers. High-voltage three-wire construction can cause ferroresonance. Grounding influences the effectiveness of lightning and switching surge protection.**

***Index Terms*—Dirty power, electric submersible pumps (ESPs), ground fault current, grounding, power quality, reactive power compensation, surge arresters, surge protection devices (SPDs), transient voltage surge suppressors (TVSSs), ungrounded power, voltage impulses, voltage sag, voltage swell, wellhead grounding.**

I. Introduction

ELECTRIC power distribution for onshore oil and gas production operations tends to be rural. Construction often follows rural utility service (RUS, formerly REA) designs. In contrast with either standard rural loads or large industrial loads, production loads tend to be large, concentrated, and widely separated. The particular layout of a production field depends to a large extent on well spacing. Wells are rarely closer together than 300 ft, whereas it is common in today's production environment for pads to be separated by 5000 or 10 000 ft. In order to handle these large distances, medium-voltage power systems are used. Typical voltages are 7.2/12.47 kV and 14.4/25 kV, three-phase. It is common for production loads to be several megawatts in a single field, with individual loads commonly in the megawatt range [2].

By comparison, residential and light commercial is typically served at 120/240 V single-phase. In rural locations, these loads can be separated by hundreds of feet; however, the load size is only a few kilowatts at most. Industrial loads are typically served at 480 V three-phase. Loads in industrial facilities can be megawatts in size but are rarely separated by more than dozens of feet. Due to the vast difference in the size distances of loads, utilities have little experience with design and construction of distribution for oilfields.

Normal oilfield loads consist of pumping units (beam pumps or pump jacks), saltwater injection pumps, and electric submersible pumps (ESPs). Power ratings for pumping units are commonly 5–40 Hp, flow rates are typically less than 1000 barrels per day (BPD), and pumping depths are less than 5000 ft.

Saltwater injection and transfer pumps are most frequently rated for 200–700 Hp and operated at 480 V three-phase.

ESPs in water-driven formations can run up to 2000 Hp with flow rates of 1000–60 000 BPD and depths in excess of 15 000 ft. At many locations, there are multiple ESPs powered from a single pad location, with pad locations separated by several thousand feet.

Injection pumps and ESPs most commonly will have dedicated banks of step-down transformers for each piece of equipment powered. In contrast, multiple pumping units are sometimes run on a single bank of three-phase 480-V transformers. For these applications, reduction of line loss and voltage drop requires the use of large conductors when compared with higher voltage equipment.

Front-end design for an oilfield electric distribution system primarily depends on an estimate of how much will be produced from that field at some future date. Rarely are appropriate efforts and resources put into properly designing an electric system from the beginning. Typical power system designs focus on single or limited locations. Often, field development changes due to new technologies, different pump design, or production in new and unanticipated zones. Power quality suffers, and redesign and reconstruction are required at some point in the life of the field.

Similarly, seldom is much design effort expended on point-of-use, i.e., well site, equipment. Specification of grounding, transformer connections, lightning arresters, and surge arresters is often left to the electrical contractor, rather than an engineering professional. This often results in underspecified and underperforming equipment and connections.

In the following sections, load flow analyses and protection coordination are reviewed as they apply to the oilfield. Power quality is a major issue because many fields are simply connected to existing distribution that was never designed for large loads. In such cases, voltage sags to unacceptable levels, resulting in higher current draw for induction motors. Several methods to upgrade power quality are reviewed. Adjustable speed drives (ASDs) eliminate direct-on-line current surges and compensate for weak power systems but do introduce bothersome harmonics.

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Later sections are dedicated to a review of three distribution constructions and grounding connections as they affect equipment operations at the well site. This is particularly true for surge arresters that can actually cause equipment damage if improperly connected. The different between equipment and system grounds is important to understanding how voltage impulses are impressed onto the supply power. Grounding, ground faults, wellhead grounds, step potential, surge protection, and ferroresonance are also reviewed.

II. Distribution Design

A. Load Flow Analysis Inputs

The basis of any new system design should be a load flow analysis (LFA). This analysis allows the user to design the system for maximized efficiency and minimized costs. The use of an LFA is not limited to initial system design, however. LFA is essentially a software simulation of the system under different assumptions or conditions. As with any simulation, the most important aspects are the inputs and assumptions to the system.

LFA depends, at a minimum, on the following input parameters:

1) geographic location of loads;
2) characteristics of load;
3) configuration, location, and routing of distribution lines;
4) location and size of other connected loads.

The first input to any LFA is the location and size of the loads that the distribution system will serve. This includes not only existing loads but also all reasonably anticipated future loads. For most production development fields, a reasonable expectation of location of future loads can be developed from drilling plans. For many LFA software packages, the locations of the loads can be geolocated (GIS), allowing for more accuracy and ease of simulation.

The second necessary inputs to a proper LFA are the characteristics of the load. For simple analyses, all that is necessary is the Hp (kW) and power factor (pf) of the connected loads. This will allow an analysis of proper conductor size and basic voltage support analyses. For more involved analysis, such as motor starting, fault, or harmonic analyses, additional information is required as follows:

1) speed–torque curves of drivers (motors) and mechanical loads, along with inertia;
2) characteristic model of motors;
3) variation of pf and Hp with loading;
4) harmonic characteristics of connected drives/equipment;
5) characteristics of starting equipment.

The characteristics of the load should include the size and configuration of any transformers used to connect the load. In addition to size and impedance, of critical importance is the grounding connection of the transformers.

The configuration (see Fig. 1) location and routing of distribution lines is important for determining the impedance of the conductors serving the field loads. At a minimum, this information needs to include the overall length of the conductors, whether overhead or underground, and the size of those conductors. These data are required not only from the utility meter but should include the entire length of conductors from the analyzed loads to the utility substation.

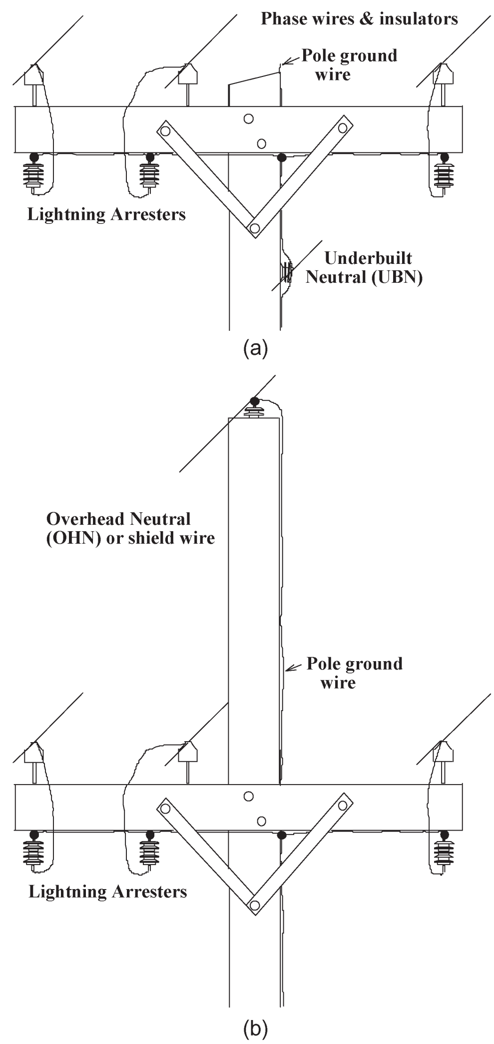

Fig. 1. Common oilfield distribution construction. (a) Four-wire construction with underbuilt neutral (UBN). (b) Four-wire construction with an overhead neutral (OHN).

The configuration of the conductors significantly affects the impedance of the power system. For detailed and accurate analyses, the construction configuration of overhead power lines and underground duct banks should be included.

Finally, the size and location of other interconnected loads should be obtained as an input to the system. This includes any other production, commercial, or residential loads connected from the end of the circuit all the way back to the substation. If the oilfield loads to be analyzed comprise a very large percentage of the total load on the system, other connected loads can be included as single or multiple lumped loads.

B. Benefits of LFA

The use of a proper LFA offers several potential improvements [1], [2] to the distribution system:

1) decreased losses on the system;
2) increased voltage support;
3) increased efficiency of substation usage;
4) increased system reliability.

Ultimately, each of these benefits contributes to reduced overall costs to the end user.

1) Decreased Losses on the System: One of the most significant benefits of an LFA is the reduction in losses in the system. Improperly sized conductors cause the most easily recognized of these losses. Conductors that are too small for the load that they serve create unnecessary I^2R losses. A properly analyzed system will allow the user to balance increased capital costs (conductor size), with reduced long-term operating costs (energy). For each kilowatt of reduced losses on the system, there is a corresponding kilowatt decrease in demand charges to the user, as well as a ~726-kWh decrease in monthly energy charges.

In addition to the I^2R losses remedied by proper conductor sizing, the addition of power factor correction capacitors allows for a reduction in losses on the system. Consider the two following scenarios:

Scenario 1:

Real Load	12000 kW
Power Factor	85% (uncorrected)
Voltage	7200/12470
Current	653A

Scenario 2:

Real Load	12000 kW
Power Factor	98% (corrected)
Voltage	7200/12470
Current	567A.

The addition of properly located and sized power factor correction capacitors allows for an ~32% reduction in I^2R losses on the system. This translates to a significant monthly savings on demand and energy costs. In order to gain the most benefit, the power correction capacitors must be placed in locations near enough to the load to reduce losses, but at points where the system power factor never crosses unity. The balancing of these points to allow for optimal placement of capacitors is nearly impossible without a properly developed LFA.

2) Increased Voltage Support: A properly developed LFA aids the design of a distribution system that provides proper voltage to the loads. Proper voltage is necessary not only for proper operation and starting of equipment but also for reduction in overall load costs. Undersized conductors and poorly placed correction capacitors lead to low voltage at equipment and voltage dips or sag during starting. The most critical impact of low voltage is the inability of the system to support standard starting of induction motors. Proper voltage support is provided by increased system voltage, proper size of conductors, and optimal placement of correction capacitors. All of these are supported by a well-designed LFA.

An additional consideration is the continued operation of large induction motors during a voltage sag. In the short term, induction motors are a constant power device. As a result, these must supply the same power during a sag. Required torques and speed are virtually unchanged. Thus, if applied voltage decreases, supplied current must increase to maintain almost the same power. The increased current not only causes increased system losses and demand but also can lead to inadvertent tripping of adjacent equipment.

One way to combat this phenomenon is to enforce a staggered starting of all equipment. This not only ameliorates the voltage sag problem, by reducing total system draw during motor start, but also reduces peak current draw. The latter reduces demand charges from the utility.

3) Increased Efficiency of Substation Usage: One often overlooked benefit of proper system design and planning is the increased efficiency of substation equipment usage. An improperly designed system with excessive losses, improper voltage support and low power factor leads to unnecessary load being applied to substation equipment. If load on the substation equipment is reduced to just the necessary, more equipment can be added to the existing substation without the need for expensive and time-consuming equipment upgrades. This increases uptime and reduces total cost to the user.

4) Increased System Reliability: The final benefit of a proper distribution system analysis is increased reliability of the protected equipment. Production operations are, in large part, a continuous process. Downtime due to electrical system unreliability not only decreases production but can also have a significant impact on the overall efficiency of the recovery operation. In many secondary and tertiary production systems, the efficiency of recovery (e.g., BOE/BH_2O) is relatively flat or trends upward as runtime on the individual wells continues. Any interruption of production lowers this recovery efficiency significantly for some period of time after the interruption. This is particularly true for dewatering and shale recovery operations.

An LFA can improve reliability in a number of ways:

1) proper coordination of protection equipment;
2) analysis of redundant feed scenarios;
3) proper sizing and location of backup generation equipment;
4) identification of "critical" line sections that may justify additional maintenance or vegetation management operations.

Of these benefits, one of the most significant is the proper coordination of protection equipment. In "typical" utility feed operations, fuse and recloser sizes are designed for maximum uptime of the individual piece of equipment or line segment, with less regard for segmentation or sectionalizing the system. An LFA will allow for coordination of protection equipment (fuses, reclosers, sectionalizers, etc.) so that, in a fault condition, a minimum amount of equipment is taken offline while still maintaining integrity of the rest of the system.

A special case of coordination exists with the presence of reclosers and large rotating equipment, such as ESPs. Many standard recloser operations are designed to restore power to the system as rapidly as possible after an intermittent fault, such as vegetation contact or a lightning event. Rapid recloser operation is typically what causes light flickering during a thunderstorm. By momentarily removing power, the fault is cleared.

This type of rapid operation can cause significant damage to ESP units in an oilfield. In the case of rotating equipment, a six- or eight-cycle recloser operation will often reapply voltage before magnetic fields in the motor have collapsed. This produces an excessive motor torque that can lead to broken motor shafts, particularly in higher Hp units. Analysis of startup and shutdown conditions of equipment connected to a distribution system, along with the ride-through capabilities of that equipment, allows for reasonable recloser settings. Recloser operation speed should be limited to the amount of time necessary to allow complete shutdown of any equipment that cannot ride-through the interruption. An additional concern is that an ESP without a check valve will backspin, and attempts to direct-on-line start during backspin will cause excessive torque on the shaft, often resulting in shaft breakage.

III. Well-Site Design

Oilfield distribution construction generally falls into one of three categories, shown in Fig. 1, as follows:

1) three wires only, no UBN;
2) four wires with a UBN;
3) four wires with an OHN or shield wire.

The choice of construction primarily hinges on cost. Obviously, three wires are less expensive than four wires, and three-wire construction is not uncommon. However, with only three wires, all grounding must be done at the well site. The exception to this is primary windings connected either corner-grounded delta or corner-grounded open delta. An open-delta connection requires just two instead of three transformers, reducing construction costs even further.

Four-wire construction with an OHN or shield wire is the most effective technique, but necessitates use of longer, more expensive poles to maintain live wires at acceptable heights above ground. Without proper load connections, electrical equipment at the drop pole is in jeopardy. If the ground wire down the pole connects to the ground terminal of a surge protection device (SPD), lightning damage to equipment may actually increase. This phenomenon and separate ground wires are discussed below.

Four-wire construction with a UBN is the most common. As with the OHN, all pole ground wires connect to this neutral, providing multiple paths to ground. In arid regions, lightning arresters are not just installed at a power drop pole but also along the feeder. At higher primary voltages, the neutral of wye-connected windings is often connected to a UBN or OHN either directly or through a contactor to avoid ferroresonance when transformers are initially energized. The contactor is subsequently opened to reduce power loss in the UBN or OHN.

Distribution voltages are generally selected by how much power must be sent over what distance. For a relatively compact field near a substation 7200/12470 V is common. For fields with greater distances or larger loads, distribution voltages are often increased to 14.4/24.9 kV. For more extreme distance and loads, 20/34.5 kV is used. In many cases, however, voltage is dictated not by necessity but by what is "normal" for the supplying utility.

Four different transformer configurations, i.e., wye-wye, wye-delta, delta-wye, and delta-delta, are commonly used to step voltages down to equipment levels (see Fig. 2). Windings can be grounded or ungrounded. Each connection has benefits and drawbacks. The use of corner-grounded open-delta windings eliminates one conductor and one transformer and is the least expensive construction. Nevertheless, the increase in risk to safety makes this a poor choice. Additionally, the rating of the transformer bank is 58% of a standard three-transformer design. The lower kVA rating must be put into an LFA to ensure proper system design.

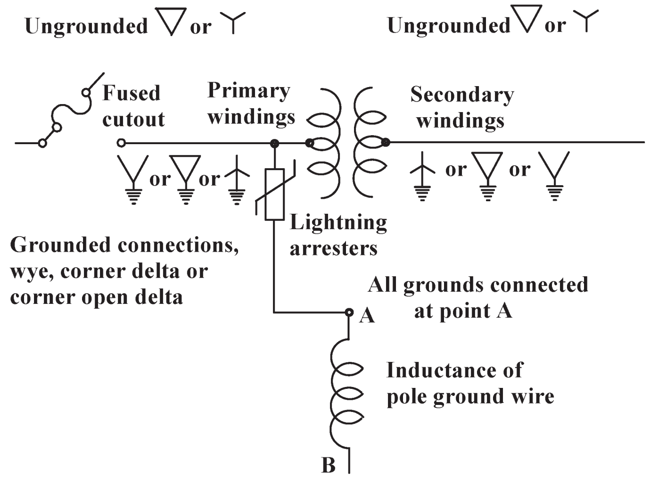

Fig. 2. Common oilfield transformer connections.

For ESP operations, transformer secondaries are normally tap changing. This plus either wye or delta connection allows for the wide range of voltages necessary for ESP operations.

Residential and commercial installations often derive single-phase power between the neutral and phase wires of wye-connected secondary windings. Transformers connected ungrounded wye primary, grounded wye secondary supply very peaked single-phase voltages. This connection does not provide for the third-harmonic magnetizing currents necessary for sine wave power. Delta windings provide third-harmonic currents, but without a delta, the wye primary neutral point must be connected back to the substation. This is not often a concern for oilfield connections, since these locations normally use dedicated 480/120-V transformers or PTs to obtain single-phase power.

Problems with oilfield-distribution and well-site design include grounding and ground faults, step potential, switching surge and lightning protection, bilateral metal oxide varistor (MOV) operation, and ferroresonance. These topics are covered in the following sections.

A. Grounding and Ground Faults

Connections to ground are necessary to provide effective personnel and equipment protection. However, many small rural utilities and electrical contractors make no distinction between equipment and systems grounds.

Equipment grounds involve grounding and bonding all accessible metal that an untrained person could touch. How such grounds are arranged is essential for proper operation of protective equipment when lightning, switching surges, faults, and overcurrents occur. Bonding is simply the electrical connection of all exposed metal surfaces so that there are no potential differences between those surfaces.

System grounds in the oilfield involve only those ground connections made to transformer windings. Most all of the

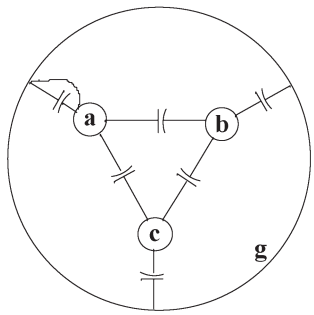

Fig. 3. Faulted phase inside shielded cable.

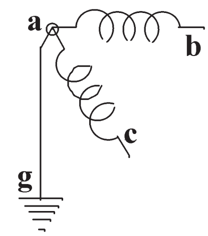

Fig. 4. Corner-grounded open-delta windings.

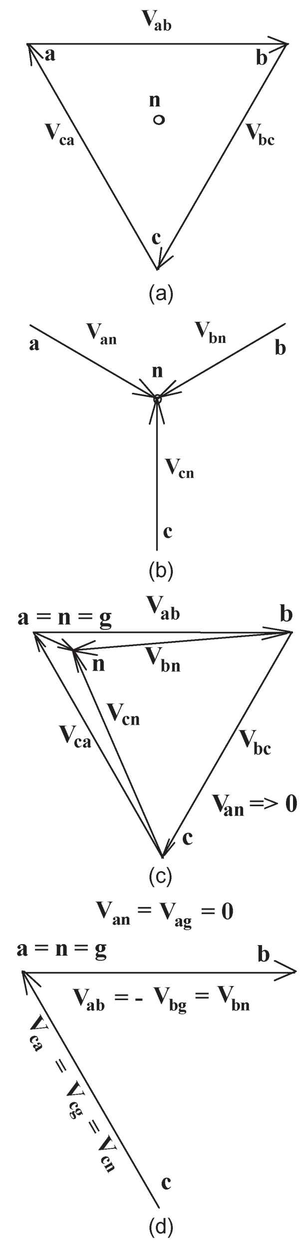

Fig. 5. Vector relationships. (a) Line voltages. (b) Phase voltages. (c) A phase faulted or intentionally grounded. (d) Phase-to-ground voltages.

possible ground connections are depicted in Fig. 2. Clearly, transformers should not be accessible to any untrained person.

One of the more questionable practices is the down-pole grounding of a corner-grounded delta system having only three wires. This involves using a current-carrying wire as ground, thereby increasing the possibility of ground-fault currents and shock hazards. The dangers of the latter were explained some years ago [3], and a parallel ground wire was recommended. This has not been generally accepted by utilities. Despite the serious well-known risks, corner-ground delta power is still being installed.

Two reasons seem plausible for the use of corner-grounded delta power. First, with one phase of a motor already grounded to the motor frame, a fault in either of the other two phases will cause an overload trip. Only three wires are needed to distribute power, making it a question of economics, regardless of safety. This is only appropriate in a controlled plant environment, where the system is continuously monitored and faults quickly identified.

The second reason for utility to install system grounds is the elimination of arcing faults [4]–[6]. An arcing fault can add unacceptably high dc voltages to ungrounded power. When power is supplied in parallel to numerous motors or other equipment, all will experience the same dc component. Several factories experienced this phenomenon 60 years ago [4]. The best solution in terms of both safety and effectiveness is high-resistance grounding. Today, such grounding includes means for locating the faulted equipment. For ESP operations, the resistor is considered too expensive, and voltage clamping with an SPD is often used.

In the oilfield, the only devices commonly connected in parallel are pumping units. Depending on horsepower ratings, sometimes, as many as a dozen units will be powered from a single transformer bank. With grounded power, the first faulted equipment will experience an overcurrent trip, but other units on the same feeder will not be appreciably affected.

A more detailed examination of ungrounded windings with a single phase-to-ground fault provides insight into operation with a corner-grounded delta. Nothing in this paper should be construed as recommending or condoning corner-grounded delta connections. Nevertheless, it is so prevalent, and analysis is appropriate.

ESP cable with armor grounded and a-phase faulted is illustrated in Fig. 3 below. Corner-grounded open-delta windings are shown in Fig. 4, and electrically, they are equivalent to the faulted-phase cable.

In both cases, $V_{\rm an} = V_{\rm ag} = 0$. Capacitances are shown phase-to-phase and phase-to-ground. A vector or phasor diagram showing how these voltages are related is presented in Fig. 5.

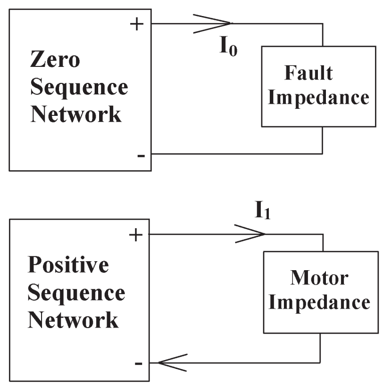

Fig. 6. Sequence circuit for a single ground fault and corner-grounded power.

Conversion of these voltages into symmetrical components with operator $a = e^{j(2\pi/3)} = 1/\_120°$ produces an interesting insight. Obviously, the line voltages applied to the ungrounded motor are still balanced, and

$$V_{\mathrm{ab}} = V/\_0°$$
$$V_{\mathrm{bc}} = V/\_-120° \text{ and}$$
$$V_{\mathrm{ca}} = V/\_+120°$$

where V is the root-mean-square line voltage.

The positive sequence

$$V_1 = (1/3)(V_{\mathrm{ab}} + a \times V_{\mathrm{bc}} + a^2 \times V_{\mathrm{ca}}) = V \tag{1}$$

the negative sequence

$$V_2 = (1/3)(V_{\mathrm{ab}} + a^2 \times V_{\mathrm{bc}} + a \times V_{\mathrm{ca}}) = 0 \tag{2}$$

and the zero sequence

$$V_0 = (1/3)(V_{\mathrm{ab}} + V_{\mathrm{bc}} + V_{\mathrm{ca}}) = 0. \tag{3}$$

Equations (1)–(3) describe balanced three-phase voltages.

Applying the same transformation to the faulted phase voltages,

$$V_{\mathrm{ag}} = 0$$
$$V_{\mathrm{bg}} = -V_{\mathrm{ab}} = -Ve^{\mathrm{j}(\pi)} = V/\_180° \text{ and}$$
$$V_{\mathrm{cg}} = V_{\mathrm{ca}} = Ve^{j(2\pi/3)} = V/\_120°$$
$$V_1 = V/\sqrt{3} \tag{4}$$
$$V_2 = 0 \tag{5}$$
$$V_0 = -V/\sqrt{3} \tag{6}$$
$$V_{\mathrm{ag}} = V_0 + V_1 = 0. \tag{7}$$

Continuing this analysis, sequence voltages and system impedances would be connected as shown in Fig. 6. A similar analysis was done some years ago [7]. There, positive and negative sequence voltages accurately predicted ESP motor performance for installations with no phase-to-ground faults or grounded power. In the latter cases, zero-sequence currents prevented an accurate correlation of calculated to measured currents. For an ESP system, the conclusion was that actual currents into the submerged motor were not equal to currents measured at the surface.

Further, the zero-sequence impedance of an induction motor is infinite because three, equal, in-phase currents into a node must sum up to zero. Thus, the motor impedance in Fig. 6 is only connected across the positive-sequence network.

Converting back from sequence to actual currents,

$$I_2 = 0 \tag{8}$$
$$I_a = I_0 + I_1 \tag{9}$$
$$I_{\mathrm{b}} = I_0 + I_1/\_240° \tag{10}$$
$$I_{\mathrm{c}} = I_0 + I_1/\_120°. \tag{11}$$

Obviously, fault impedance will dictate the magnitude and phase angle of fault current I_0. Grounds such as the well casing, pole butt wraps, and numerous ground rods are all part of the ground impedance. The central question is whether zero-sequence ground fault voltage will produce dangerous ground fault currents. The answer is yes. Ground fault currents can be sensed and designed into motor controllers. However, this practice is rarely followed in oilfield systems.

Eight different wiring configurations are presented in the Appendix. Three each are for ESPs (see Figs. 25–27) and three for pumping units (see Figs. 20–22). The three configurations considered are corner-grounded delta power, grounded neutral wye power, and ungrounded power each with a single fault. For the first two, overcurrent protection trips on a single fault. For the ungrounded case, two faults must occur to operate this protection.

Corner-grounded power must not have any overcurrent protection, fuses, circuit breakers, etc., in the grounded phase. Otherwise, an open in that phase would jeopardize overcurrent protection. Further, the grounded phase must be consistently connected. In many instances, full line voltage between the wellhead and power system can be produced.

In each configuration, the question of wellhead grounding is important. Often, no such connection is made at pumping units; however, although the polish rod through the stuffing box might not make an electrical connection, the pump itself in the saltwater downhole does. For ESP operations, wellhead grounding does improve lightning protection.

With pumping units, the more important consideration is whether the power system ground is connected to the unit itself. If this is not done, the entire unit could be elevated to some voltage when power is supplied from remote grounded windings. Without that ground, overcurrent protection cannot operate.

For widely separated pumping units fed from a single transformer bank, a ground wire should be carried to each unit. Ungrounded windings could prevent a fault from tripping the overload, and voltages to all units would be elevated, as mentioned before. Balanced wye-connected windings with a neutral ground provide ample tripping current. Some fields go even a step further using 460-V windings connected grounded wye and motors rated for 796 V. This has the added advantage of reducing line loss by a factor of 3 for equal loads.

Larger and more concentrated loads such as ESPs and disposal pump motors normally are located at a single site, have

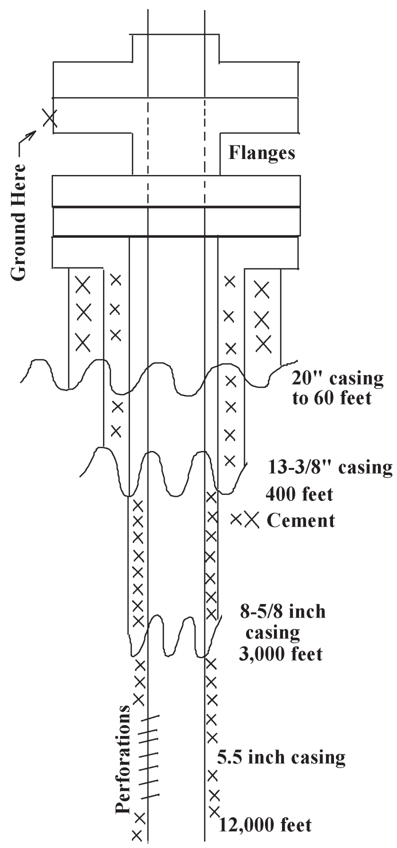

Fig. 7. Example oil well construction.

no other machinery in parallel, and receive ungrounded power. Should an arcing fault become a direct phase-to-ground fault, equipment will continue to run until a second fault occurs. With grounding designed to contain fault current, safety is assured for an ESP totally inside a well casing powered through armored cable.

Because personnel involved with oil production are graded on the quantity produced, maximizing equipment run-life is a primary goal, and ungrounded power extends run-life. ESP operations are expensive, and it is expensive to pull a unit with a single phase-to-ground fault when continued production is possible. It must be emphasized, however, that all surface equipment be properly grounded and bonded.

B. Wellhead Ground and Step Potential

The avoidance of ground water contamination has been a major factor in the design of oil wells. Significant efforts have been made to isolate hydrocarbon production from ground water as illustrated in Fig. 7.

In this example, three cemented casings were installed around the production casing to depths of 60, 400, and 3000 ft, respectively. The production casing extended much further down, to 12 000 feet.

Calculations of wellhead ground resistance were made for 8–5/8-in casings 100 and 1000 ft deep with 1.5 in of concrete surrounding each casing over a range of soil and cement resistivities [8]. For the 1000-ft surface casing alone, the ground resistance was just one ohm even when the soil resistivity was

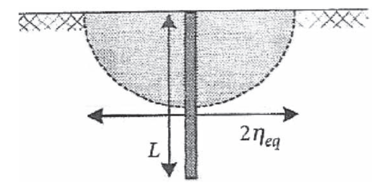

Fig. 8. Equivalent hemisphere for a ground rod [9].

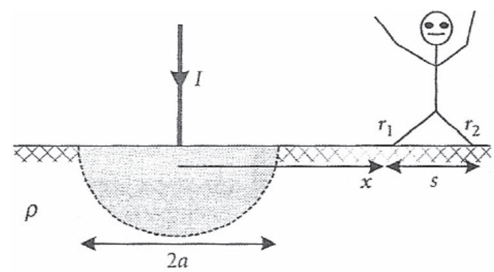

Fig. 9. Calculation of step potential near a single ground rod [9].

200 ohm-m. The much deeper well shown in Fig. 7 would obviously have a much lower resistance, and in the author's experience, wellhead ground resistance has not been measured over one ohm. There is some concern regarding the accuracy of common ground resistance measurements when dealing with an oil well.

For calculation of step-potential, Kaiser[9] employs conductive concentric hemispheres. Taking the outer hemisphere to an extremely large radius, ground resistance is

$$R_{\text{hsphr}} = \rho/(2\pi a) \tag{12}$$

where

ρ resistivity in Ω-m;
a inner hemisphere radius in m.

The general equation for a single ground rod is

$$R_{rod} = [\rho/2\pi L]\,\{\ln(4L/a_r) - 1\} \tag{13}$$

where a_r = radius of the rod and L = rod length [6]. The hemisphere of influence for a ground rod has a radius of influence, i.e., η_{eff}, determined by equating the formulas in (12) and (13). Thus,

$$\eta_{\text{eff}} = L/\{\ln(4L/a_r) - 1\}. \tag{14}$$

This is illustrated in Fig. 8. In subsequent figures, η_{eff} is simply referred to as a.

The situation depicted in Fig. 9 represents the possible voltage an individual would experience walking across a current-carrying earth. Current is injected at $x = 0$. Using an equivalent hemisphere, the step potential for that individual would be

$$V_{\text{step}} = (\rho I/2\pi) \times [(1/r_1) - (1/r_2)] \tag{15}$$

where I is current into the earth.

r_1 distance to the foot nearest the injection point,
r_2 distance to the other foot.

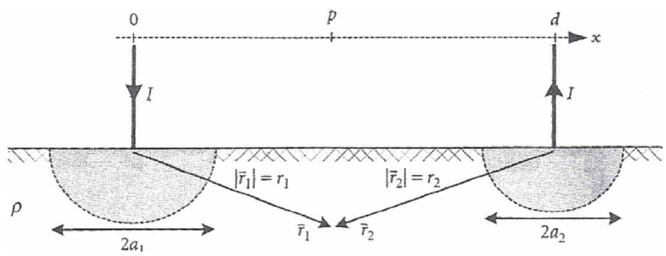

Fig. 10. Separate grounds with current injected into one and collected in another [9].

Quite obviously, the size of the step, i.e., $r_2 - r_1$, in a radial direction away from the ground rod has a major effect as does the magnitude of current I injected into the earth. Injected current depends on:

1) the size of voltage gradients near fallen power lines or close to nearby lightning strikes, i.e., at the injection point;
2) resistivity of the earth;
3) shape, location, and size of nearby metallic objects such as ground rods and wellheads.

This latter point can be generalized into two separate grounding structures as shown in Fig. 10.

Assuming that the Fig. 10 configuration accurately represents well-site grounding, the leftmost electrode with an equivalent hemisphere radius of a_1 might be the pole butt wrap along with any nearby ground rods, and the rightmost hemisphere might be the oil well. Their separation is symbolized by d. Kaiser calculates step potential at a point $p = x$ on the earth's surface with step size $s = r_2 - r_1$ as

$$V_{\text{step}} = (\rho I/2\pi)\left[\{s/(x+s)\}\left\{2/(\mathrm{x}-d)(x+\mathrm{s}-d)\right\}\right]. \quad (16)$$

Near the power-pole grounds at $x = 0$ and for small steps, (16) can be approximated by

$$V_{\text{step}} = (\rho I/2\pi)[s/\{x(x+s)\}] \text{ if } d >> x,\ d >> s,\ x > a_1. \quad (17)$$

At the well, $x = d$, and for small steps near the wellhead

$$V_{\text{step}} = (\rho I/2\pi)\left[s/(\mathrm{x}-\mathrm{d})^2\right] \text{ if } d \approx x, d >> s, (d - a_2) > x. \quad (18)$$

One major question arises about the use of such a calculation. Using the dimensions in Fig. 5 for the 5.5-in casing, 12 000 ft deep, a_r equals half of 5.5 in and $L = 12\,000$ ft. Converting all units to metric, the hemisphere of influence has a radius of $a_2 = 325$ m $= 1066$ ft. Obviously, $(d - 325) < x$. Further, the hemisphere of influence for a 3/4-in-diameter 10-ft-long ground rod at the power pole would be $a_1 = 1.74$ m $= 5.7$ ft. Thus, the rod is well within the radius of influence of the wellhead, as illustrated in Fig. 11.

This being the case, a closed-form calculation for step potential seems rather impossible. Maybe a finite-element or conformal mapping solution is possible, but considering the inhomogeneous anisotropic properties of earth materials around a wellhead, one has to question the accuracy of a step-potential calculation. Indeed, except for a faulted transformer, downed power line or a close-proximity lightning bolt, step potential is not a major concern.

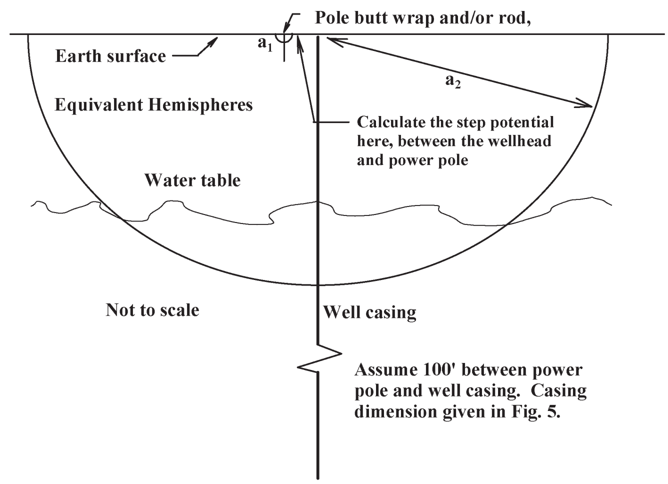

Fig. 11. Equivalent hemispheres for a well casing and pole grounds.

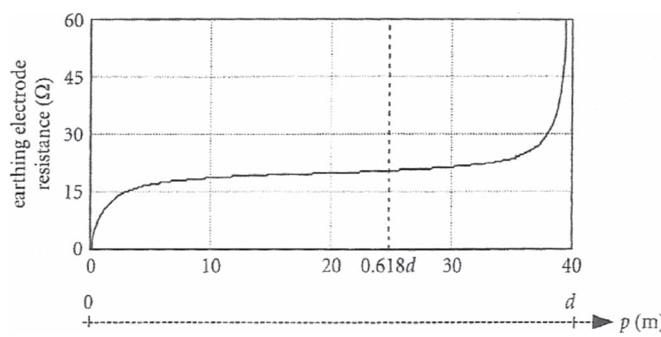

Fig. 12. Ground rod resistance as a function of distance to potential electrode [9].

Still, the possibility of a step potential cannot be trivialized. Another view of ground resistance versus distance away from the grounding structure is presented in Fig. 12.

This figure represents one very common method for measuring ground resistance. Current is injected a distance d away from the rod being measured. Voltage is measured at the 0.618 distance to obtain the resistance.

It is rather obvious that the equivalent hemispheres do not overlap for such a measurement. The equivalent radius a_2 in Fig. 11 would be much greater than d in Fig. 12. Thus, it is questionable just how accurate such a measurement of wellhead resistance could truthfully be. However, should the soil around the wellhead be of high resistivity, isotropic, and homogeneous, an individual standing near the wellhead would be in little danger.

This statement completely ignores the fact that the resistivity of wet alkaline soil on the surface is very low. Therefore, it is particularly prudent for a field personnel to remain in the truck during a lightning storm or in case of a downed power line.

The larger problems normally involve casing contact with ground water and casing corrosion caused by steady-state currents circulating in the earth. The authors were recently involved in litigation where a rural residence had to be abandoned because of electrical shock from the well water. The residence was approximately 1500 ft from a pumping unit motor with a

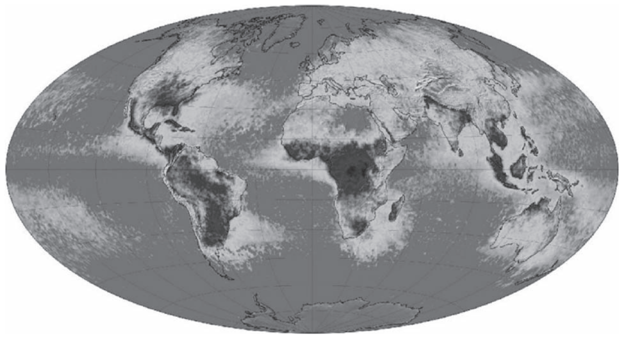

Fig. 13. Worldwide lightning density.

phase-to-ground fault. Power was supplied to the motor with ESP cable lying on the ground, a cable that is not approved for this application per NEC. No ground wire was provided.

The cable armor was completely rusted and provided no connection to ground. Transformer windings were grounded, and the residence received single-phase power with a power company ground. Thus, there was a 277-V potential between the well casing and the residence ground (see Fig. 24). This caused several incidents of shocks at the residence. Additionally, there were multiple cases of corroded metallic piping as a result of the imposed currents.

Although NEC 250.112 M recommends ground conductor connection to a metal well casing, the oil industry has frequently experienced casing corrosion problems when such connections are made to the power system ground. Replacing corroded casing is an expensive problem.

It is shown in the next section that a wellhead connection is essential for ESP lightning protection. A TVSS or SPD is incapable of delivering any sustained current without being destroyed. Therefore, there should be no corrosion problem associated with connecting an SPD ground to the wellhead.

C. Switching Surge and Lightning Protection

A high percentage of on-shore oilfields are located in relatively flat terrain surrounded by vegetation that could be classified as scrub. Additionally, some of the world's oil-producing regions are located in areas of relatively dense lighting activity (see Fig. 13). The combination of these conditions causes lightning damage to be a major issue. Should lightning cause an arc that is subsequently sustained by the grid, reclosers operate, causing switching surges. Either way, the result is high-voltage impulses causing equipment damage.

Modern MOV-based lightning arresters and SPDs can operate in less than one microsecond. The fundamental frequencies of lightning are in the megahertz range. As a result of these phenomena, the inductance of ground wires and resistance earth connections become important considerations. Impulses do pass through transformers due to mutual inductance and interwinding capacitance. However, impulses that bypass transformers through interconnected primary and secondary grounding have, from experience, been the larger problems.

One item frequently overlooked is where the actual ground connection is made to the secondary windings. It is nearly always at point A, as shown in Figs. 14–16. When impulse voltages are considered, either a lightning strike to a primary line or the OHN or a switching surge, the voltage at point A will be nearly the same magnitude as the impulse. This is a result of the impedance at point A, inductance of the pole ground wire in series with the parallel combination of butt wrap or rod resistance at the pole and the series impedance of ground-wire inductance to the wellhead and wellhead ground resistance.

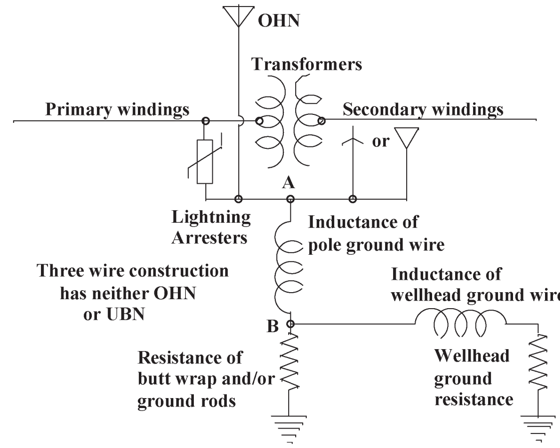

Fig. 14. Grounded secondary windings.

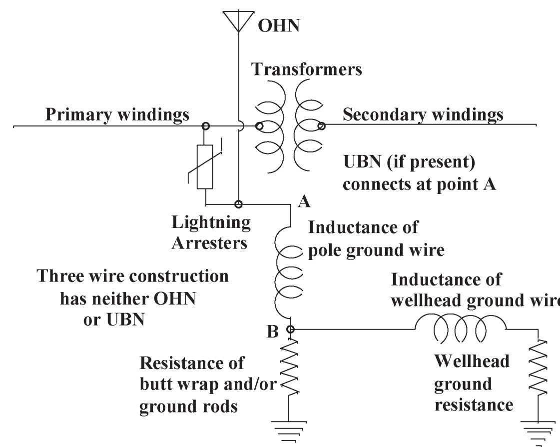

Fig. 15. Ungrounded secondary transformer windings.

Further, well casing is steel, which has higher resistivity than copper but also has inductance. Thus, transient ground impedance will be even higher.

Since the impulse voltage at point A is directly imposed onto the power wires feeding the ESP (see Fig. 14), grounded secondary windings increase the probability of ESP damage. This is another reason why the industry has embraced ungrounded secondary windings, as illustrated in Fig. 15.

Other devices are still frequently connected from point A to the secondary windings. At one time, secondary lightning arresters were thought to be a good idea (see Fig. 16). On closer examination, these devices still conduct that portion of the impulse voltage that exceeds the threshold voltages of the two lightning arresters in series. Again, an impulse voltage is impressed onto the windings, feeding the ESP and possibly damaging it.

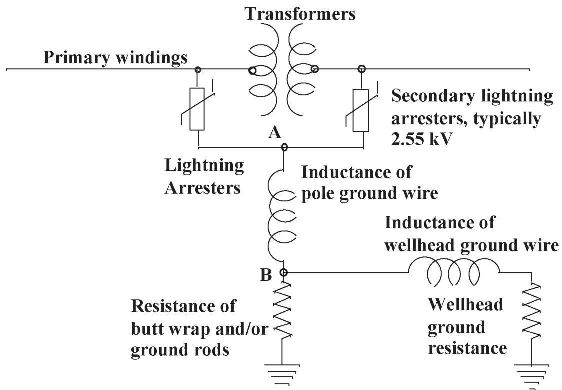

Fig. 16. Secondary lightning arresters.

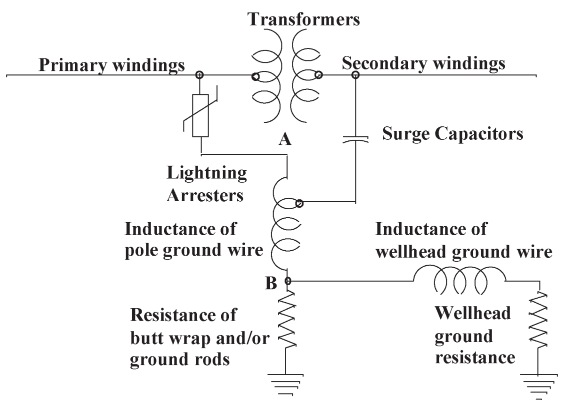

Fig. 17. Secondary surge capacitors.

Surge capacitors are often used to limit impulse voltages, and at one time, these were thought to be a good idea for ESP lightning protection, as shown in Fig. 17. Typically, a lower cross arm was installed for the mounting of these capacitors. Because capacitor voltage does not instantaneously change, most of the impulse voltage at point A is again directly transferred into the power cable feeding the ESP.

D. Bilateral MOV Operation

The MOV is a bilateral device, i.e., the volt–ampere characteristics are identical in both the first and third quadrants, i.e., positive–positive and negative–negative. Threshold voltages measured at 1-mA dc will be imperceptibly different positive or negative. Failure to acknowledge negative conduction has produced unintended equipment failures [10].

An SPD includes multiple MOVs. Devices connected just wye or delta are referred to as three mode. A combination having both delta and wye MOVs would be six mode. Four MOVs having one common connection point form a four-mode SPD, which can utilize lower voltage MOVs.

The majority of electrical equipment insulation failures occur phase-to-ground. For this reason, an SPD must have a ground terminal. Thus, the three-mode delta SPD cannot protect against impulses occurring phase-to-ground, and its usefulness is rather questionable.

It was recently emphasized that multiple SPDs on a single ground wire can and do interact [10]. As a minimum, all oilfield distribution has pole-mounted lightning arresters; thus, connection of an SPD to that ground wire presents the possibility of interaction. When the impedance of the grounding circuit is considered, it is readily seen that large impulse voltages can exist on the ground impedance. Adding this to the simple fact that once the threshold voltages of the SPDs are reached, any excess voltage must be applied to the grounding impedance, the problem of protection of well-site electrical equipment from lightning and switching surge damage becomes clearer.

Again, lightning can and does produce a surge voltage on the pole ground wire at point A. For four-wire construction with an OHN, the OHN is intended to take a direct strike. For four-wire with a UBN or three-wire construction, lightning is coupled onto the pole ground wire once the threshold voltage of the arresters is exceeded.

1) Switchboard-Operated ESP: A wiring diagram for switchboard-operated ESP equipment is illustrated in Fig. 18. Every well site should have at least two ground connections, i.e., the pole butt wrap and the wellhead, but it is surprising how often no connection is made to the wellhead. Sometimes, it is simply neglect, but at other times, it is a serious concern about well-casing corrosion.

With a three-wire system, all grounding must be done at the well site. Since the best ground connection is the wellhead, such a connection should be seriously considered.

It is quite difficult to obtain consistently low resistance ground connections with butt wraps. Soil moisture has a major effect. By contrast, wellhead ground resistance is consistently less than one ohm. Ground resistance was discussed above.

Connection of SPDs between the pole butt wrap and wellhead can also have unintended consequences. One cannot depend upon the butt wrap for a low ground resistance. The lightning surge will produce voltages all along the wire to the wellhead. Connecting a bilateral device such as an SPD between point B and the power into the switchboard will inject a portion of the lightning directly onto wires feeding equipment.

As shown in Fig. 18, the recommended place for the SPD is on a junction box electrically isolated from the main or power system ground wire. This prevents the SPD from backward conduction of impulse voltages on the power system ground onto the conductors powering the ESP. A separate ground wire runs from the ground connection on the SPD to the wellhead.

The NEC has little to say about these ground connections, simply that ground wires must be bonded. NEC250-6 states that grounds can be disconnected to avoid objectionable currents. NEC 250-4BC discusses a low-impedance path for a ground fault; however, in Fig. 18, each possibly faulted device is on a separate ground wire connected to the lowest ground resistance, i.e., the wellhead. For 60-Hz fault currents, reactance of the wire is negligible.

2) ASD-Operated ESP: Because oil well productivity can widely vary, ASD operation of ESPs has been universally adapted to cope with this variation. While downhole ESP protection is still the major concern, ASD damage due to impulse

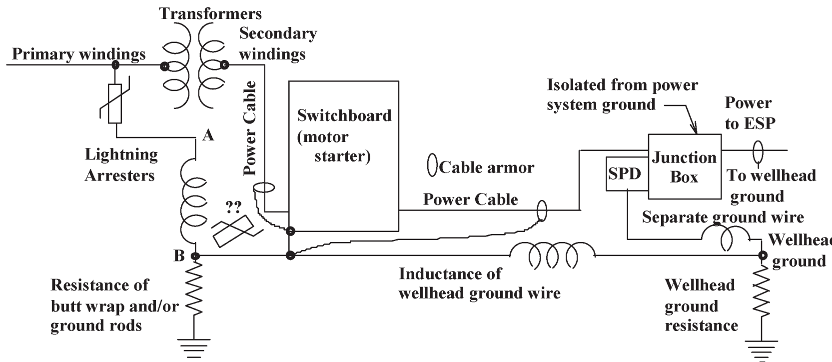

Fig. 18. Switchboard ESP operations.

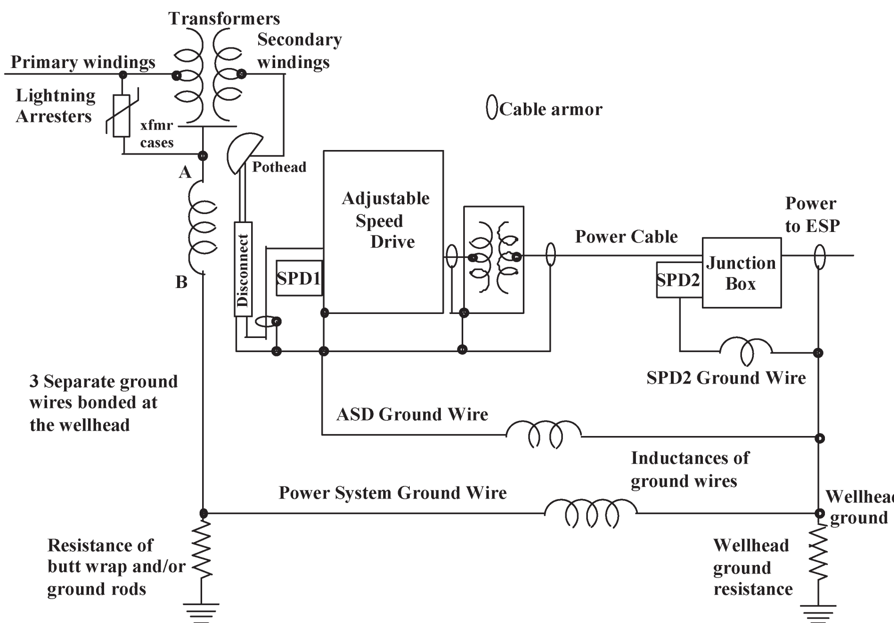

Fig. 19. ASD operation.

voltages can be quite expensive. Fortunately, unlike the ESP, the ASD is accessible.

The wiring diagram presented in Fig. 19 keeps lightning arresters and SPDs on separate ground wires bonded at the wellhead. In so doing, one surge protector cannot interact with another. Although transformer windings feeding the ASD and ESP are ungrounded, the surge equipment prevents arcing faults. Cable armor is grounded as indicated. If a metal junction box is used, it must only be grounded to the wellhead and isolated from other grounds. Cable armor leading back to the ASD should not contact the junction box.

For redundancy, i.e., to compensate for a cut or broken ground wire, additional ground rods might be installed at the power pole, ASD, and junction box. However, this must not interfere with the separation of ground wires.

Lightning-induced failures are known to be more frequent for equipment operating at the end of a distribution feeder. From transmission line theory, any combination of parallel wires has surge impedance. Depending upon how the line is terminated, a voltage impulse will be positively reflected, negatively reflected, or totally absorbed. These correspond to reflection coefficients greater than zero, less than zero, and zero, respectively. Oilfield equipment has impedance greater than the surge impedance of the feeder. Thus, at the end of a line, the reflection coefficient is positive and nearly $+1$, which produces a near doubling of the impulse voltage magnitude. Increased failure rates for end-of-line equipment have been observed for many years.

One common solution to this problem carries power distribution one span past the transformer pole and mounts arresters on the new last pole. These arresters connect to earth via the pole ground wire and possibly the wellhead. Once the threshold voltage of these arresters is exceeded, the terminal impedance is less than the surge impedance of the feeder, the reflection coefficient is negative, and a negative voltage impulse is reflected. This reflected impulse subtracts from the incoming impulse, thereby reducing the magnitude of the total impulse at the equipment pole. Thus, the new end pole, arrester, and ground compensate for the possible doubling effect of the traveling wave [6], [11].

Sometimes, power and ground wires at a well site are run inside steel conduit. To be sure, this prevents mechanical damage. However, steel is a ferrous material, and running a ground wire inside a steel pipe increases the inductance of that wire. From a lightning protection viewpoint, increased ground wire inductance reduces the effectiveness of surge protection.

E. Ferroresonance

When well sites are widely distributed over vast regions, as frequently occurs in the Middle East, higher voltages are a necessity. One typical voltage is 34.5 kV, and it is questionable as to whether this is a transmission or a distribution line. Nonetheless, switching transformer primary windings can excite a condition known as ferroresonance. The basics of this were explained in an earlier paper [8], and Greenwood [12] provides an excellent analysis.

The common solution for ferroresonance is wye connection of transformer primary windings with the neutral connected back to the substation. Thus, when switching is done, transformer-magnetizing inductances and cable capacitances are not in series. Occasionally, ferroresonance is a problem as low as 14.4/24.9 kV, and some contractors install a cutout switch to momentarily ground the neutral during starting.

IV. Conclusion

In practice, for on-shore production, most things are just built. Analysis and design comes later when problems and failures occur. In today's information age, we can do better. LFA programs are generally available for electric power distribution design. These also include protection coordination features.

At a well site, ground-fault currents, lightning protection, and overcurrent protection are serious problems. For pumping units, grounded power is essential for overcurrent protection, and the most cost effective way to accomplish this is with three-wire corner-grounded delta windings, since overcurrent protection is only needed in two phases. However, currents circulating in the earth and hazardous step potentials also deserve consideration. Containment of ground fault currents is a major problem, and more expensive four-wire grounded neutral wye windings are safer.

Ground fault currents can be easily measured with a CT around all phase wires. Use of such a measurement should be seriously considered in the design of motor controllers.

For ESP and injection pump operations, ungrounded power is the norm, because it minimizes lost production. Such operations only involve one site, and safe containment of ground-fault currents is less of a problem. Due to the critical nature of the operations and the cost of repairs, effective lightning and switching-surge protection is important. To be effective, experience has shown that SPDs need to be on separate ground wires only bonded at the wellhead.

Appendix
Transformer Connections for Well Sites

The major difference between a pumping unit and an ESP is rather obvious; the ESP has a submerged motor and cable. However, grounding structures, surface equipment, and transformers are quite similar. In Figs. 20–27,

R_{wlhd} ground resistance of the well;
R_{bw} ground resistance of the pole butt wrap and rods;
R_{g} resistance between the butt wrap and well.

Transformer primary windings can be connected in a multitude of ways, as described in Fig. 2. The concern about primaries is how the lightning arresters are wired. Alternatively, only three winding connections to the respective motors are of interest, i.e., grounded neutral wye, corner-grounded delta, and ungrounded.

For power frequencies, electric cable is typically modeled using discrete components, series resistance and inductance, shunt conductance, and capacitance. With the short cables used for pumping units, only the series resistance is of any importance. Being much longer, ESP cable has higher impedance and admittance. At 60-Hz series reactance is about 15% of series resistance, thus only the resistor is shown. New cable has very low shunt conductance, i.e., high shunt resistance, and only capacitance C is illustrated. Still, it must be acknowledged that this resistance can vary from very high megohms to zero for a fault.

Since it is common for multiple pumping units to be served by a single transformer bank, a disconnect box is usually provided at the drop pole. The control panel is normally mounted on the beam unit itself.

Almost without exception, each ESP has its own transformer bank because of the much higher power required. Here, fused disconnects and lightning arresters are needed on the high-voltage primary side. Industry nomenclature commonly refers to an ESP control panel as a switchboard, but it is nothing more than a direct-on-line motor starter.

A. Pumping Units

For very small units, single-phase power is not uncommon, but such units are never over 10 Hp. Only higher power units are considered here, and these invariably use 480-V three-phase power. Occasionally, 230-V three-phase power is also found. Without exception, the major concern is economics.

Certainly, the least expensive installation will have only three wires and just two transformers, the latter being connected open-delta. When ungrounded windings are used, the unit must be grounded back to the power system for safety reasons. A grounded wye, four-wire system is the most expensive, but it is also the safest and most reliable.

A grounded wye installation is shown in Fig. 20. The first motor fault will either trip the circuit breaker or blow the fuse in a control panel. Motor currents are monitored for overload

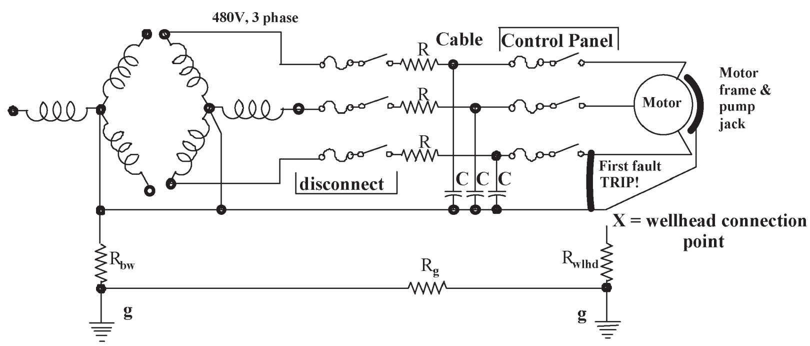

Fig. 20. Pumping unit with grounded wye power.

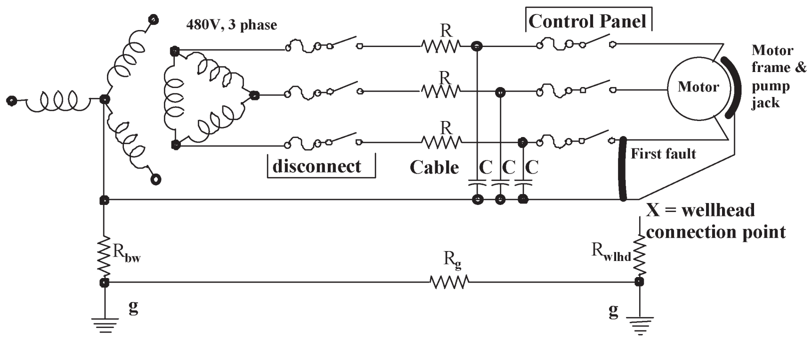

Fig. 21. Pumping unit with ungrounded power.

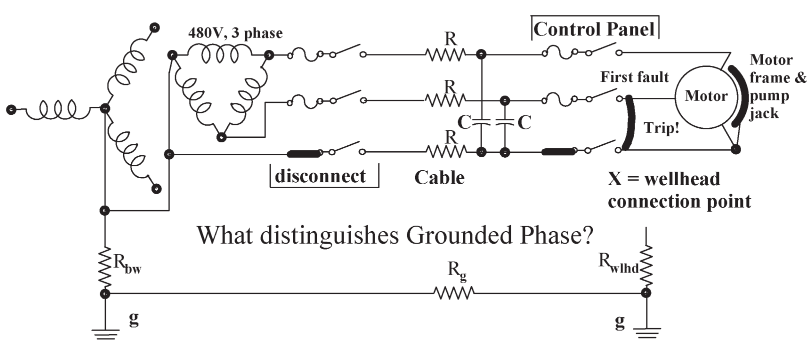

Fig. 22. Pumping unit with corner-grounded delta power.

and unbalance. A severe case of unbalance, loss of a phase, must be detected to prevent single phasing and damage to the motor.

Should wellhead be directly connected to the system ground? Lightning protection and an NEC requirement would say so. However, even if such a connection is not directly made, it can be argued that the rod string and pump are operating in saltwater, thereby inadvertently providing a ground. Any real connection between the polish rod and stuffing box would be suspect.

Ungrounded power is depicted in Fig. 21. Here, the first motor fault does not stop production, which is a major goal for production personnel. A second fault will. For purposes of safety, the units must be grounded to the power system as shown, and cable armor should be grounded.

A three-wire corner-grounded delta is illustrated in Fig. 22. In some cases, both primary and secondary windings are open-delta. To ensure motor protection, no fuses for circuit breakers should be in the grounded leg in either the disconnect or control panel.

Identification and continuity of the grounded phase is of paramount importance. Since the three phases are similar in appearance, that is not a trivial concern. In fact, a situation where the phases were switched (see Fig. 23) nearly electrocuted an electrician.

The authors were involved with litigation where a family had to abandon their home due to electrical shock from their well water. Transformer windings were connected grounded wye at the power pole, and this same ground went into the residence. However, there was no ground connection to the

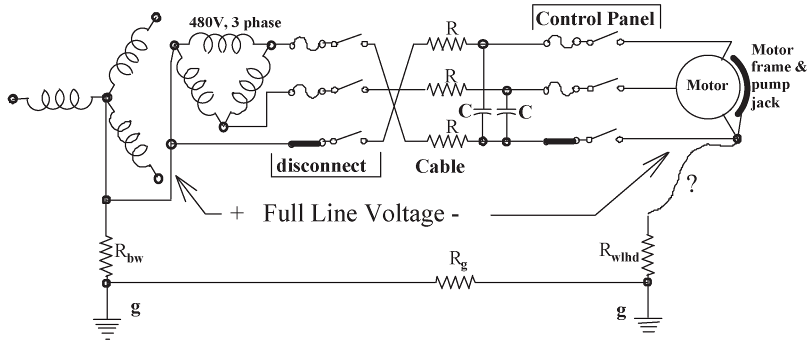

Fig. 23. Cross-connected phases with corner-grounded delta.

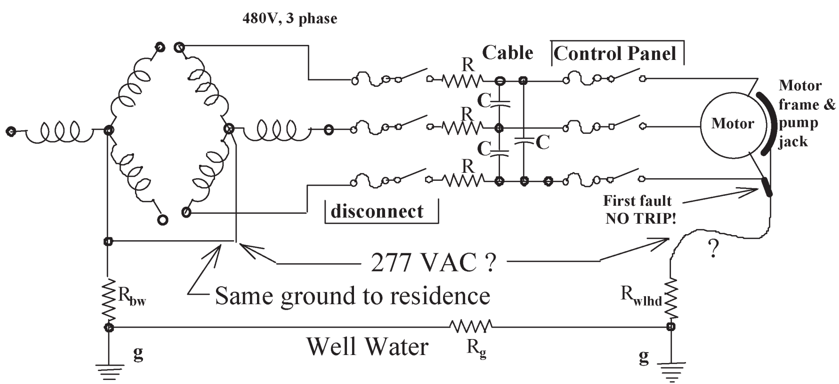

Fig. 24. No ground connection between pumping unit and power system ground.

pumping unit approximately 1500 ft from the house. Thus, full phase voltage existed across the water table between the well and the residence (see Fig. 24).

B. ESPs

Operating a motor on a long power cable, sometimes longer than 2 mi, presents a different set of problems. Obviously, ASDs, with switching times less than one microsecond, create multiple-reflected waves. The cable must therefore be treated as a transmission line with a characteristic impedance and reflection coefficients. PWM drives have solved this problem by placing a low-pass filter between the drive and step-up transformers. Older technology six-step drives produces significant ringing on each step, where step-voltage magnitude nearly doubles. Thus, the voltage rating of a TVSS must be increased to prevent TVSS damage.

At power frequencies, the lump-parameter model for the cable is used as described before, with R as the series resistance and C as the shunt capacitance.

Switchboards were mentioned above, but they differ from a control panel in that medium voltages are used, and circuit breakers for such voltages are quite expensive. Consequently, every switchboard has a disconnect switch on the input, but that switch is not rated for load-current interruption.

Although the NEC states that the power-circuit grounding electrode should connect to a metal wellhead, making this connection to the power system ground produce casing corrosion problems. It was stated earlier that a wellhead connection is essential for ESP lightning protection, and a TVSS is incapable of delivering any sustained current without being destroyed. Hence, is connection of the power system ground to the wellhead necessary?

Because ground electrode resistance can be quite high in many oilfields, a direct connection to the wellhead is important for effective lightning arrester operation. Casing corrosion problems are commonly solved with cathodic protection (CP). It would seem that a CP direct current between an anode bed and the well casing that exceeds the peak value of power system ground ac would still prevent corrosion. We are unaware of any such comparison being made in the past, and because of stray currents from pipelines, the CP industry has summarily demanded that all other connections be eliminated. As explained above, ungrounded power is preferred because equipment run-life is extended (see Fig. 25). A single line-to-ground fault will not cause an overcurrent trip. A second fault is required. Since ESP cables are metal armored and that armor should be grounded, the system is not unsafe. The only problem might be a possible voltage difference between the cable armor and the wellhead.

Grounded power to an ESP increases the probability of lightning damage since the grounding point is in close proximity to the lightning arrester common, and a lightning bolt can be easily injected onto the ESP power wires. Nonetheless,

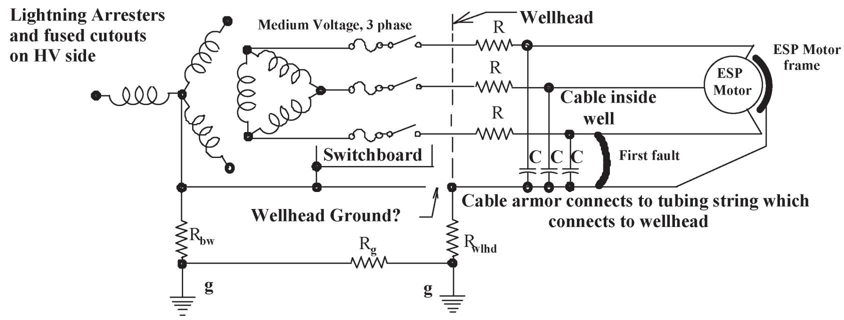

Fig. 25. Ungrounded ESP power.

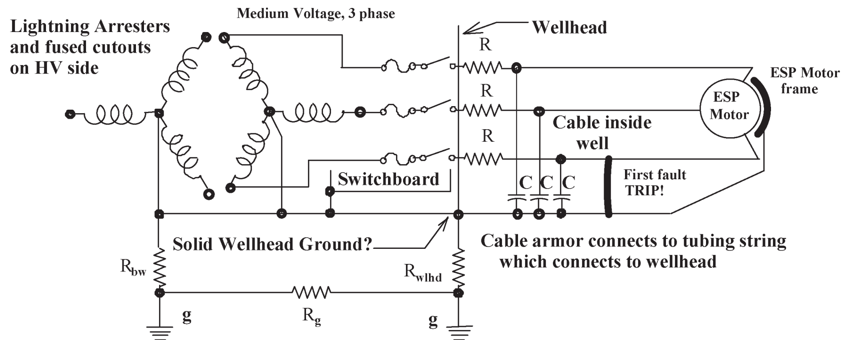

Fig. 26. Grounded wye ESP power.

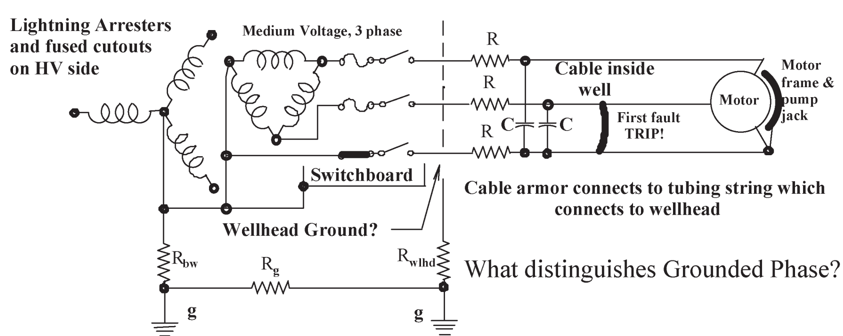

Fig. 27. ESP with corner-grounded delta power.

grounded power is used, and the first fault shuts the ESP system down (see Figs. 26 and 27). With corner-grounded delta power, the grounded phase must be conscientiously identified and connected, and no protection should be in the grounded phase.

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