# THE EFFECTS OF POWER SUPPLY INTEGRITY ON ELECTRIC SUBMERGIBLE PUMPING SYSTEMS

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## ABSTRACT

Little has been written regarding the effects of electric power integrity on submergible pumping systems. The remoteness of a site and/or the economics of the distribution system can result in power which affects equipment life and efficiency. Other installed electric devices or systems can also impact the quality of supply. The purpose of this paper is not to condemn the circumstances which lead to deficient power supply situations, but rather to address their effects and discuss practical means of correcting or minimizing their effects.

## INTRODUCTION

The importance of maintaining crude oil supplies and the economics of providing reliable artificial lift methods will continue to place emphasis on the integrity of electric submergible pumping systems. This paper will address the effect of electric power supply integrity and its impact on the economics of recovery when electric subs are employed. Power integrity can affect the units reliability and run life and, hence, have economic impact in terms of replacement equipment costs, pull and run costs, and finally the costs associated with lost production. Supply integrity can also affect the direct costs of production since it impacts unit efficiency or the unit power consumption per unit of fluid produced.

Deficient power supply may be characterized by voltage phase unbalance, improper voltage level, inadequate transmission capability for starting, abnormal susceptibility to lightning or switching transients, frequent outages, and equipment intentionally added to achieve some other desirable effect.

This paper will define the effect of deficient supply conditions on the sub's life and efficiency while offering methods of correcting or minimizing the source problem.

## ELECTRIC SUBMERGIBLE PUMPING SYSTEM

### The Application

When high-volume fluid production is required the electric submergible motor driving a centrifugal pump has proven its superiority to other methods. A typical system is comprised of the following components: electric motor, multi-stage centrifugal pump, protector, motor flat cable, power cable, switchboard, and power transformer(s). Fig. 1 shows a typical system.

In the most typical application a pump is chosen consistent with the well casing diametric restriction and expected production rate. The number of stages required is determined by dividing the total dynamic head required by the head developed per stage. The motor is then sized by dividing the pump hydraulic Hp as corrected for specific gravity by the pump efficiency. The motor voltage will be selected from the available values and consistent with available transformers. Generally the motor voltage should be maximized (consistent with insulation limits) to provide minimum current and hence minimum cable size and cost. The surface transformer taps and switchgear are then rated at a level which is the sum of the motor voltage and cable drop.

## Hydraulic and Mechanical Components

This section will describe the components of the system which are functionally hydraulic or mechanical. A subsequent section will describe the components which are predominantly electrical with emphasis on the areas which are inherently more susceptible to supply system induced stress.

The multistage centrifugal pump is offered in a wide variety of diameters with capacity ranges from 200 BPD to over 60,000 BPD and in lift capacities up to 15,000 ft. Through the use of corrosion resistant materials, pump wear and corrosion are minimized and long-term predictable performance in all normally encountered fluids is assured. Due to the hydraulic limitations associated with the diameter limitation, the lift per stage is relatively low. However, as many as 500 or more stages have been run to meet high head requirements.

Immediately below the pump is the intake where the produced fluid enters the pumping system. It is designed to maximize the gas separation in the annulus and to insure the optimum gas-lock free charging of the lowest pump stages through the use of a specially designed charge propeller in the base of the unit.

The final mechanical element is the protector. This component is installed between the motor and the pump. It provides a fluid barrier which prevents the migration of the produced fluid into the motor while simultaneously allowing pressure communication across the protector. This fluid seal thus assures equalized pressures between the inside of the motor and the wellbore which is a critical factor in the electrical cable pothead integrity. The protector chambers allow for motor oil thermal expansion as the motor oil temperature first rises during installation and then additionally rises to the operating temperature after start-up. The protector also houses the main thrust bearing which absorbs any upthrust or downthrust transmitted through the pump shaft.

## Electrical Components

The electrical submergible motor is a three-phase two-pole squirrel cage induction type. Owing to the diametric restrictions the unit is extremely long and slender, and is oil filled. The oil, having low compressibility, makes it compatible with the high external ambient pressures existing due to submergence. Further, it provides bearing lubrication and effective heat transfer for dissipation of the losses radially outward through the motor housing. The stator is wound as a single unit. The squirrel cage rotor, however, is comprised of several discrete rotors with bearings between them to accommodate the long slender construction. The stator magnetic path is interrupted between rotors (at the bearing locations) to more effectively use the available magnetic flux to do work and to minimize the inductive heating in the bearing area. This is accomplished by inserting nonmagnetic laminations in the stator at the bearing areas.

The life of the motor is a function of several interrelated system parameters assuming a balanced three-phase voltage of motor nameplate value exists at the terminals of the motor. These are:

1. The ambient temperature of the produced fluid.
2. The composition of the produced fluid in terms of its capacity to carry the heat away.
3. The velocity of the produced fluid past the motor.

These parameters establish the ambient, the rise, and in turn the total temperature experienced by the stator windings. The rate of deterioration for insulating materials commonly used in subs is an exponential function of winding temperature. It is generally accepted that the useful life of the winding is reduced 50 percent for every 10°C increase in winding temperature.

The life of the motor is also related to the ability of the design to maintain the internal oil in a clean and uncontaminated state. Internal oil contamination may occur via any or a combination of the following events:

1. Corrosion attack penetrates the outer housing.
2. Corrosive and/or abrasive fluids destroy the pump bearings leading to excessive vibration and loss of shaft seal in the protector.
3. The unit is operating in a region of casing which results in its operation in a bent mode leading to excessive bearing wear, vibration and eventual protector seal loss.

Contamination of the motor oil significantly reduces its effectiveness as part of the insulation system. Further, the contaminants generally accelerate the rate of thermal degradation for the other materials by several fold.

Because of the geometric restrictions of the design the stator winding tends to be more susceptible to transient dielectric stress than a comparably rated surface motor. Most surface motors in the 25 to 1000 Hp range are many times larger from a diametric standpoint. Thus more insulation and much larger radius end turns can be employed at the ends of the motor. Stated another way, the end turn geometry of a typical submergible motor relates closely to that which might be expected on a surface motor in the fractional Hp range. However, fractional Hp units are not rated at voltages up to 3300V as subs may be. All manufacturers utilize sophisticated dielectric systems to control the voltage stress in the end turn area but it remains an area of great susceptibility.

The final motor area is the pothead where the transmission cable is terminated. On a dielectric basis it is similar to the motor end turns due to geometric restrictions. The pothead is often more critical due to the very severe geometry combined with the fact that this component must also provide a seal to prevent invasion of the well fluid. Great strides have been achieved in advancing the integrity of this critical area in recent years but it remains a potential point of susceptibility.

The next electrical component is the flat cable extension which originates over the pump and is there spliced to the main power cable. This armored extension then passes between the pump and the casing ID and terminates at the pothead entering the motor. Again, the critical element is space and often this cable must pass through minimal annular clearance and survive the installation process.

The tubing is usually of smaller diameter than the pump and the main power cable is less critical geometrically. Hence greater design margins can and usually are exercised in this component.

The final electrical area is the surface equipment consisting of the surface cable, vented junction box, switchboard, and transformer bank. These more familiar elements offer the greatest flexibility to provide protection to the downhole system and hence will be discussed further in later sections of the paper.

This section of the paper has described the components of a typical submergible pumping system. Further, the areas of susceptibility to unusual supply conditions have been identified and the mechanisms for degradation in these areas have been briefly discussed. In the next section supply problems and their consequences at the points or areas of susceptibility will be explained.

## POWER SUPPLY SYSTEM DEFICIENCIES

### Causes for Deficient Supply

It has often been stated that "Mother Nature enjoys observing our search for oil--and consequently locates reservoirs in some very unusual places". Therein lies the principal cause for deficient electric power service, that is the remoteness of the site combined often with very hostile terrain. The utility, if one is available, may have to construct the transmission/distribution capacity for an oil field or attempt to upgrade an existing system intended for rural single phase service. These prospects often create financial burden on the utility who often faces a myriad of government regulations and restrictions similar to our industry. Thus, it should be understood that while this paper is critical of the effects of deficient electric power supply there is immense appreciation for the job they have been able to do. Thus the ultimate goal of this paper is to understand what each of us can do to provide the most cost effective solution to these problems and hence provide mutual benefits.

### The Effect of Voltage Level

The generally accepted voltage tolerance in our industry is ± 10% at the motor terminals. A motor applied within this tolerance but not at the nominal value should not experience significant life degradation. However, there is only one optimum voltage for a given motor operating under a given set of conditions and any variance from that optimum will result in some form of performance degradation. To illustrate this, consider a submergible motor rated at 200Hp and 2200V. That motor's performance is summarized on Table 1.

| VOLTAGE | CURRENT | POWER FACTOR | EFFICIENCY | MOTOR LOSSES |
|---|---|---|---|---|
| +10% | 62.2 | 66.7% | 85.0% | +3.4% |
| + 5% | 57.3 | 75.6% | 85.2% | +2.1% |
| NOMINAL | 55.4 | 81.8% | 85.5% | NOMINAL |
| - 5% | 55.6 | 86.2% | 85.3% | +1.4% |
| -10% | 57.6 | 88.5% | 84.8% | +4.8% |

TABLE 1—200HP MOTOR PERFORMANCE VS. VOLTAGE LEVEL

Table 1 clearly indicates that motor life should not be significantly affected since the increased losses peak out at about 5.0 percent. On a motor with a 100°F temperature rise this would result in an additional rise of 5°F which for all but the very hottest bottom hole temperatures should not significantly affect real life. The operating costs (power costs) are increased by the reduced motor efficiency and the extra current in the cable. If this unit were set at 5000 ft. and the nominal cable drop on a per phase basis was 15 volts/1000 ft. the net annual power bill at 5 cents/KWH would increase almost $1100 for the worst case shown in Table 1.

Another "trick" which may be exercised relative to motor voltage rating is to de-rate the motor Hp by reducing motor voltage. A crude approximation is that motor Hp is proportional to the square of motor voltage. Note this only applies for reductions; an increase in voltage above the allowable 10 percent will saturate the motor magnetic paths and lead to poor performance and premature thermally induced failure. One must first acknowledge the uncertainty of his Hp requirements. Then he could specify an overrated motor on the basis of expected worst case. By voltage reduction that oversized motor could then be matched to the actual load and would perform efficiently and reliabily. Obviously, at the next change out he could go in with a properly rated unit based on the actual demand in service. The cost of the additional motor Hp would have to be justified based on an expected increase in run life resulting from the absence of motor degradation due to a potential overload on underrated equipment.

The following points regarding voltage level may now be summarized:

1. Operation at any voltage other than rated will negatively impact performance.
2. It is better to operate slightly low rather than slightly high.
3. An oversized motor can be tuned to the load requirements with maintenance of performance simply by reducing the voltage level at the terminals.

The author feels strongly that the purchase of a transformer with adequate taps to cover the expected spectrum is a wise investment for any user.

## The Effect of Voltage Balance

Technically, voltage balance represents one of the more difficult problems to address. All commercial generation sites and major load centers are able to closely control balance by controlling the distribution of load. The phase balance problem generally arises in remote areas which are distant from either a generation or load center. Phase voltage unbalance is particularly harmful to electric rotating machines (such as induction motors) because it typically manifests itself in a resultant current unbalance of 3 to 10 times the voltage unbalance.

A motor derives its rotation via a rotating magnetic field orginating in the stator due to currents in the stator windings. It can be shown mathematically and experimentally that an unbalanced voltage and the resultant currents can be resolved into two distinct stator rotating magnetic fields within the motor. The first rotates in the desired direction and drives the rotor. With no unbalance this is the only field within the motor and is full strength. With unbalance this desirable field is reduced in strength. The second field resulting from unbalance rotates in the OPPOSITE direction and actually tries to drive the motor in the wrong direction. Fortunately, it is much lower in magnitude but the negative torque it creates reduces the positive torque available and further degrades the motor's output capability.

These concepts are illustrated on Fig. 2, the motor speed torque relationship. The curve labeled $T_B$ is the normal motor torque characteristic with a balanced supply of correct value. As previously described, unbalance will reduce the positive torque available to drive the motor. For that unbalanced situation the positive torque T+ would exist. The component of negative torque resulting from the field rotating in the wrong direction is T-. Finally, the net torque with an unbalanced supply is shown and labeled $T_{UB}$. The pump load speed torque characteristic is also shown as $T_p$. Table 2 has been prepared to illustrate the effect of unbalance. Fig. 2 supplements this by showing one important factor not presented in the table. That is the fact that speed will be reduced owing to the lower net motor torque available. On Fig. 2 this speed reduction is the difference between $N_B$ and $N_{UB}$. Therefore, with unbalance one will produce less fluid.

On Table 2 the first two columns show percent voltage unbalance at the motor terminals and the RESULTING percent current unbalance. "RESULTING" is emphasized because the current unbalance will vary from motor to motor and from system to system for a given voltage unbalance. The data in Table 2 is, however, representative. These quantities may be defined as follows:

$$\%\text{ VOLT. UNBAL.} = 100\% \times \frac{\text{MAX. DEVIATION FROM THE AVG. PHASE VOLTS}}{\text{AVG. PHASE VOLTS}}$$

$$\%\text{ CURRENT UNBAL.} = 100\% \times \frac{\text{MAX. DEVIATION FROM AVG. PHASE CURRENT}}{\text{AVG. PHASE CURRENT}}$$

The next column represents the average loss level in the motor and may be thought of as being proportional to the average motor temperature rise. The next and most important column represents the LOCAL LOSS LEVEL IN THE PHASE HAVING THE GREATEST CURRENT and may be visualized as being proportional to the HOT SPOT temperature rise in the motor. It is this parameter which will have the greatest impact on motor life. The final three columns represent the level of phase current in the respective phases.

| % VOLTS UNBAL. | % AMPS UNBAL. | % MOTOR AVG. HEAT | % MAX. COIL HEAT | % PHASE AMPS | | |
|---|---|---|---|---|---|---|
| | | | | MAX | INT | MIN |
| 0% | 0% | 100% | 100% | 100% | 100% | 100% |
| 1% | 4% | 100.26% | 108.4% | 104% | 102.2% | 93.9% |
| 2% | 7.9% | 101.06% | 117.2% | 108.3% | 104.9% | 87.8% |
| 3% | 11.8% | 102.34% | 126.9% | 112.6% | 107.9% | 81.8% |
| 4% | 15.6% | 104.15% | 137.2% | 117.2% | 111.1% | 75.7% |
| 5% | 19.4% | 106.50% | 148.3% | 121.8% | 114.6% | 69.6% |
| 10% | 39.2% | 126.33% | 213.9% | 146.3% | 135.2% | 39.5% |
| 20% | 43.8% | 215.65% | 402.1% | 200.5% | 187.9% | 29.8% |

TABLE 2—THE EFFECT OF VOLTAGE UNBALANCE

In conclusion, one may interpret the data on Table 2 and Fig. 2 to arrive at the following fundamental guidelines:

1. One should interrogate current unbalance rather than voltage unbalance since the amount of current unbalance is system dependent given a level of voltage unbalance. In other words, current unbalance is the bottom line.
2. Current unbalance should be limited to 5% if optimum life and performance are to be realized in practice.
3. Unbalance affects not only the motor but the cable which carries the same current, the pump whose output will be reduced, and the protective surface controls which may be in a tripping situation due to the divergent values of phase current.
4. Finally, when the total system is considered the operating power cost per unit of fluid produced may rise dramatically as shown on the case study illustrated by Fig. 3.

Phase balance is an important determinant of equipment life and efficiency. For severe cases its effect is dramatic and every action should be made to maintain balance as close to perfect as possible.

The Effect of Insufficient Transmission Capability

Submergible pump applications are generally affected by insufficient transmission capability during the starting operation. When the motor starts with full voltage AT THE MOTOR TERMINALS, it will draw about six times rated current which will decay in a multi-exponentially fashion to rated in about 0.25 sec. during which time the motor accelerates to full speed. In a real system as shown on Fig. 4a, the voltage at the motor will be reduced by the additional drop across the cable, transformer, and system impedances at the starting inrush current levels. A system with insufficient transmission capability is one where $X_s$ is too high and the drop across it reduces the starting voltage at the motor sufficient to increase the motor starting time beyond 1 sec.

Another problem in real oil wells relates to the pump break away torque required when corrosion, deposition or scaling, and plugging enter into the problem. For this case a reasonable and experience-verified guideline states that the voltage at the motor terminals should never drop below 50% of rated. This is quite consistent with the 1 sec maximum start time mentioned previously. The final area of difficulty arises when several motors are operating simultaneously on the system and another is started. Fig. 4b illustrates this where motors $M_1$ and $M_2$ are operating and motor $M_3$ is to be started. When the contactor controlling $M_3$ is energized and its inrush commences the voltage $V_B$ at the pump supply bus may dip sufficient to cause an undesirable trip on the other motors common to the bus. The aforementioned dip is momentary and if the protection control time constants are set tolerantly no problem would be anticipated if the $V_B$ bus voltage did not dip below 90% of its prestart value. This is a conservative figure, but remember that when the starting motor begins to achieve rated speed the other motors, which have slowed slightly during the depression, will have to be reaccelerated to rated steady-state operation. The system must be sufficiently stiff to accomplish this. In any event the system must be carefully modeled, both electrically and mechanically, and studied in detail to evaluate the total performance.

The consequences of insufficient transmission capacity and hence long start times are summarized below:

1. The starting torque may be insufficient to break away the pump.
2. The pumping system may pass through torsional critical speeds as it accelerates. In order to prevent buildup and possible shaft overstress these criticals should be traversed as quickly as possible.
3. Companion or closely coupled units (electrically) may interpret the start of an additional unit as an abnormal condition and trip.
4. The thermal input to the motor varies from 10 to 20 times the normal dissipation. On the basis of heat storage the motor coil temperatures can rise at a rate of 10-15°F/sec which can lead to serious overheating if the unit is frozen or if repetitive attempts to start follow in close time succession.

The motor start represents a traumatic event in its history. These starts cannot be successfully accomplished unless the power transmission/distribution system is capable of maintaining sufficient voltage at the motor terminals.

## The Effect of Voltage Transients

Transients arise from several sources. The most difficult source to control is lightning. The probability of lightning being a problem is a function of the amount of thunderstorm activity in a given area. This activity is most often displayed on an Isokeraunic map showing the historical number of thunderstorms-days in a year. Another factor is the type of soil prevalent in the area. If a given strike occurs over a dry sandy terrain where ground (electrically speaking) is a high resistance entity the lightning transient will tend to travel much further over the transmission system "looking for ground". Conversely, If wet conductive soil is prevalent it will go to ground quickly and tend not to travel as far on the transmission grid.

Another source of transients results from switching operations on the power system. These may simply be the connection or disconnection of a circuit or load or they may result from reclosures following the tripping of a given line to clear some fault condition on the line. The most detrimental consequence of such activity usually results from a momentary loss of power on a line for which the duration is sufficient to cause contactor drop-out but not sufficient to reset the control circuits and hence when restoration occurs the contactor recloses while the rotating system is coasting down and due to the motor self-excitation from the cable capacitance the unit can experience a damaging electro-mechanical torque surge in either direction. It is analogous to synchronizing a generator out-of-phase.

The final transient source results from an arcing fault in the surface equipment or in another failing downhole system. It is not uncommon for a failure in one unit connected off the same power transformer to induce failure in some or all of the sister units.

One common effect of a severe transient is to ground a given phase of the downhole system. This might occur at the pothead, in the cable, or in the motor winding. Since most subs operate off a delta secondary at the surface (or an ungrounded wye) and since the motor winding is not grounded downhole this single fault to ground will not remove the unit from service. This type of incident is illustrated on Fig. 5. Before the fault there are no connections to ground. The establishment of potential in the cable and windings is dependent on the distributed capacitive linking to ground. Assuming balance among the three phases, the condition shown on Fig. 5a with zero motor neutral voltage to ground is realistic. Then a condition of high stress prevails on phase "C" (lightning for example) and the motor flashes to ground near its #3 terminal. This is depicted on Fig. 5b. Since the insulation has been punctured, terminal #3 will remain grounded. It can then be shown that the neutral N now has full phase voltage to ground impressed upon it. Further, it can be shown that the point 1 or 2 voltage to ground is now 173 percent of the phase value. If a weakness appears in phases A or B it will be stressed 173 percent of normal and thus the probability for a second failure is much greater. Most operators continue to pump with a grounded phase. They should, however, recognize the existence of extra stress on the other phases and be prepared to change the unit out.

Voltage transients frequently damage the control and protective circuits at the surface rendering an otherwise operable unit out of service. These accessible circuits are the simplest to protect but often this option is not exercised.

Transients are in the "most unpredictable" category and most difficult to diagnose. After the problem has been identified and confirmed, there are many cost effective ways to address each if one desires to do so. No "catch all" fix can correct all transient problems. Again, proper understanding of the problem represents a significant step towards affecting a solution.

## The Effect of Power Factor Correcting Capacitors

Capacitors can be safely applied to submergible pumping systems to correct power factor. This section will present some general guidelines and suggested approaches to insure that the operator has considered all potential effects of capacitors application.

There are at least two potential reliability problems which might arise from capacitor application:

1. Overvoltage due to motor self-excitation
2. Transient torques

Overvoltage due to self-excitation may occur on the removal of a unit from the line where the capacitors are switched with the motor. This case, where the capacitors are on the motor side of the motor contactor, is illustrated in Fig. 6a. Induction motors receive VAR excitation from the line to magnetize the iron circuits within the motor. This excitation must be furnished by either capacitors or generation equipment. If the motor contactor is opened and the available VAR excitation from the capacitors exceeds the VAR requirements for the motor at no-load the MOTOR WILL ASSUME WHATEVER VOLTAGE IS REQUIRED TO CONSUME THE CAPACITIVE VARS. Thus, an excessive amount of capacitor compensation (any amount exceeding the motor no-load exciting current) will result in A VOLTAGE GREATER THAN RATED. The magnitude of this voltage will then be established by the air gap magnetization and the saturation of the motor iron. This may be illustrated in Fig. 6b, which is a typical no-load characteristic of a motor. This represents a plot of the current to excite the magnetic circuits in the motor as a function of the applied voltage. Note, the different voltages which will result from the removal of the unit from the line at the levels of capacitor compensation shown. The capacitors must be sized so that the motor no-load current is never exceeded.

Transient torques will always result when a motor is started or if the motor is temporarily disconnected from the line and subsequently reclosed before it coasts down to zero speed. If capacitors are employed these torques may be of much higher magnitude. In any event a restart of a motor, with or without capacitors, is not recommended until it has come to a complete stand-still. If capacitors are to be applied, the following steps should be considered:

1. Establish the maximum safe compensation level which will not result in motor overexcitation. Cable capacitance must be included in this calculation. The required motor and cable data must be acquired from the manufacturer.
2. Establish the proper surface transformer tap. The addition of compensating capacitors will reduce the current feeding the motor-capacitor set. Hence, the voltage drop from the power system infinite bus to the motor will be reduced and the resultant motor voltage will be increased. The magnitude of this increase could require that a lower ratio tap be employed for the motor to be operating at or near its rated value. If no tap change were employed, the reduced system and cable voltage drops will result in a higher than rated voltage at the motor which could be detrimental to its performance and life.
3. Readjust the motor protective circuits. It is assumed most compensating capacitors will be switched with the motor and thus the protective circuits will sense the combination motor and capacitor current which will be reduced due to the overall KVAR reduction. This may require changing the set points on the overload and underload circuits to restore the protection to its pre-compensated status.

## SYSTEM CORRECTION

Power supply system deficiencies can be categorized in three broad areas. These are voltage level and balance problems, insufficient starting capacity (insufficient transmission capability) and voltage transient problems. A fourth area exists where the operator takes actions to achieve some other result and thus affects system integrity. This includes the addition of power factor correction capacitors switched with the motor or a synthesized waveform device such as an inverter. In this section only the first three areas will be addressed.

## Voltage Level and Balance Correction

The obvious answer to this problem is to demand that the utility regulate his supply system to be at the proper level and balance. This may be determined unfeasible from an economic standpoint. The author does believe that most, if not all, utilities wish to provide the level of service required to operate these critical production facilities. Thus, the first step which can be taken, after one has documented the true system integrity, is to meet with the utility and discuss the problem. Often, there are corrective actions which can be taken to improve the power quality at minimum expense. These can be as simple as redistributing the load to improve balance or as complex as completely re-evaluating the distribution system and making changes to the system to improve quality. I re-emphasize the importance of opening discussions with the utility. One classic illustration which in the author's opinion requires definitive utility action is the use of open delta transformers. This may be an adequate technique to save capital when the loads are single phase. When three phase motors of hundreds of Hp are involved, this method of transformation will have detrimental effects on the equipment and correction should be requested.

If it is finally determined that correction for level regulation and/or balance control cannot be accomplished on the power supply system some form of auxiliary control might be considered by the operator. One such method (and there are others) is shown on Fig. 7. This system regulates the level and balance by regulating the voltage drop across a series reactive element. The system shown utilizes saturable reactors individually controlled by a dc bias signal. The transformer feeding the system must be tapped at a higher than needed voltage such that the resultant swings on that tap will never drop below the required surface voltage to the pumping system.

## Insufficient Starting Capacity

The only possible power system solutions to this problem would entail a closer tie to the generation grid via an additional line or through a less distant substation, etc. Generally, these kinds of changes are impractical. One can partially "buy" himself out of such a problem (or make it less severe) by purchasing an oversized or low impedance transformer, and/or an oversized cable and motor.

## VOLTAGE TRANSIENT PROBLEMS

Transients in the context of this paper are random in frequency of occurrence and equally arbitrary in magnitude and shape. This, of itself, represents the major problem. When transient activity is suspected to be the source of equipment distress or failure the first logical step is to monitor the system and try to establish the types of phenomena requiring correction. The author's personal experience has been with a Dranetz 606-3 Power System Analyzer which records slow changes in individual phase magnitude, the magnitude and duration of sags and surges, and the magnitude and occurrence rate of rapid rise voltage transients. Any system dependent problem will usually be identified in 10 to 20 days of monitoring. Any weather related protection inadequacies will generally be identified with one occurrence of the weather condition responsible. Obviously, all protection from transients must be installed at the surface. Overkill in transformer protection (i.e., arrestors and surge capacitors) probably offers the greatest protection to the equipment. In other words, intercept the transient before it ever reaches the pump supply power system. There are commercially available systems to suppress lightning but these are expensive and should be applied only when a confirmed need is established. The most typical protective scheme for a submergible installation is shown on Fig. 8. This scheme combined with the dissipative effect of the submergible pump cable to surges will generally do the job.

## CONCLUSIONS

This paper has presented an overview of the kinds of problems which arise from the marriage of the equipment to its power supply system. Many of these problems seem "too big to attack". The author disagrees with this attitude and feels that in many instances an accurate determination of the problem cause can lead to a cost effective remedial program to correct the deficiency.

Submergible electric pumps have proven their worth when high volumes of sub-surface fluids must be lifted. It is hoped that this paper will shed enough light on the operation and protection of these critical systems to result in an improvement of our overall capability to supply our nation's energy needs.

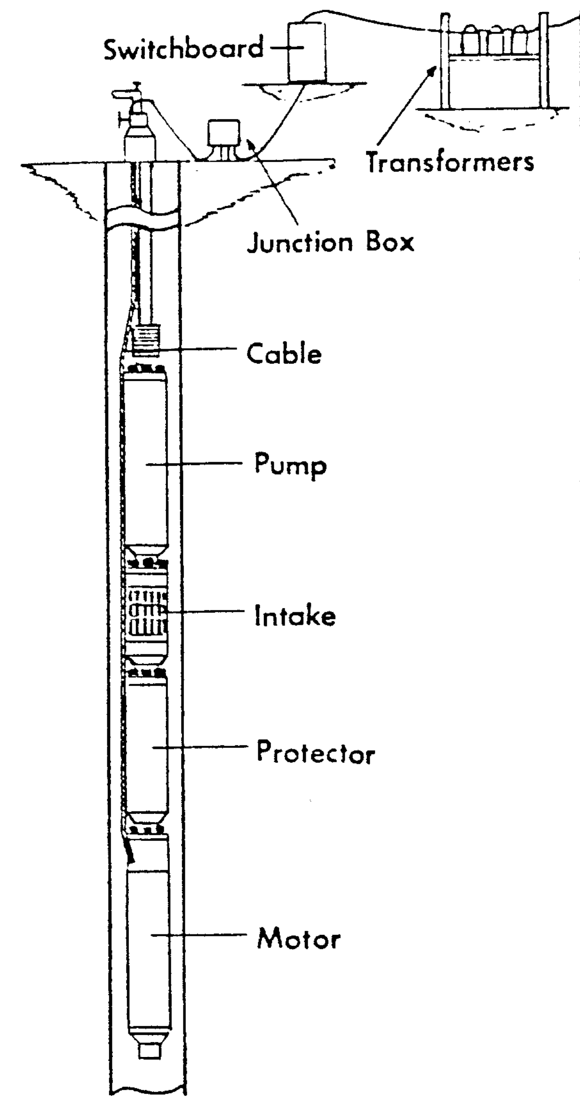



FIGURE 1—SUBMERGIBLE SYSTEM

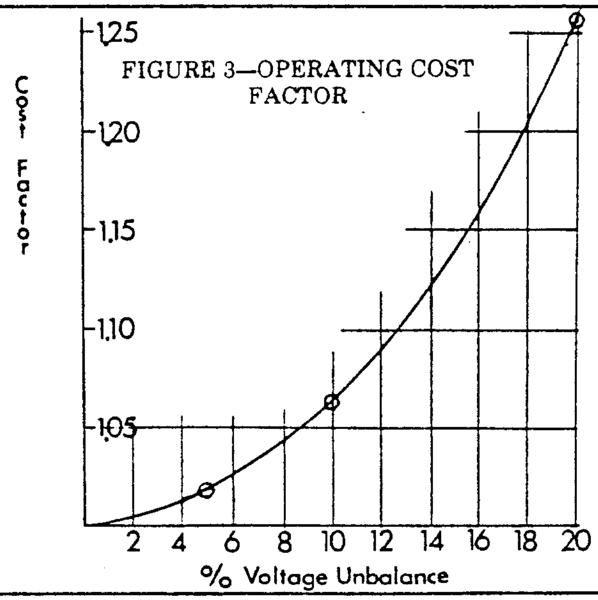



FIGURE 3—OPERATING COST FACTOR

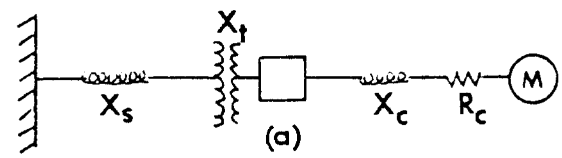
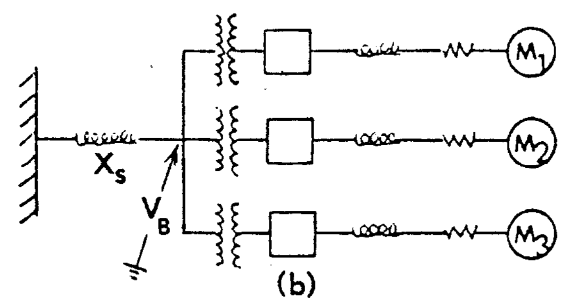



FIGURE 4—STARTING VOLTAGE



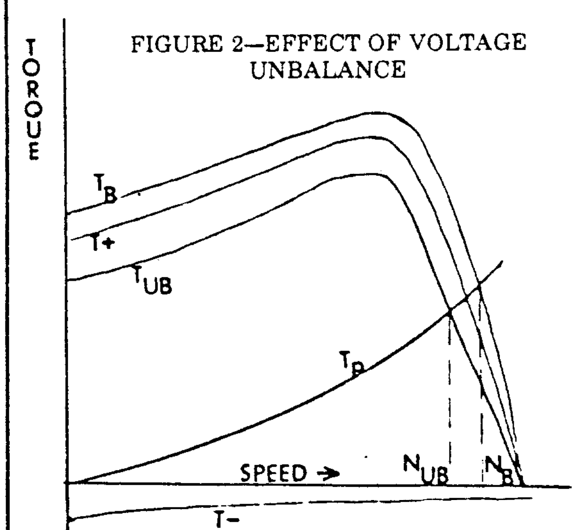




FIGURE 2—EFFECT OF VOLTAGE UNBALANCE

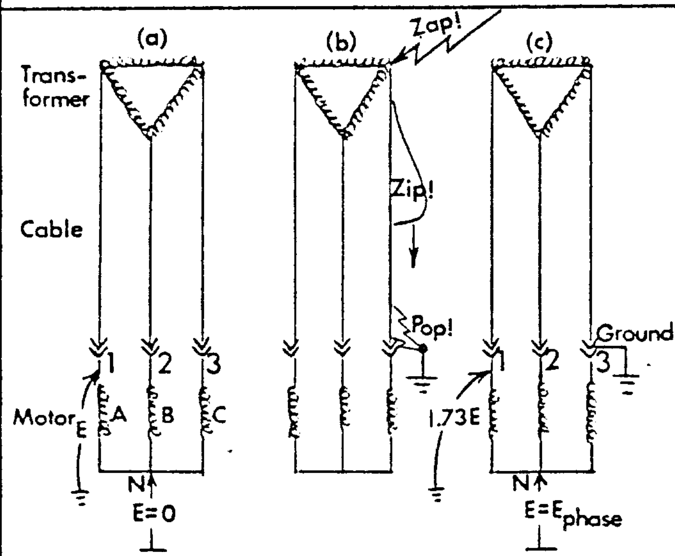
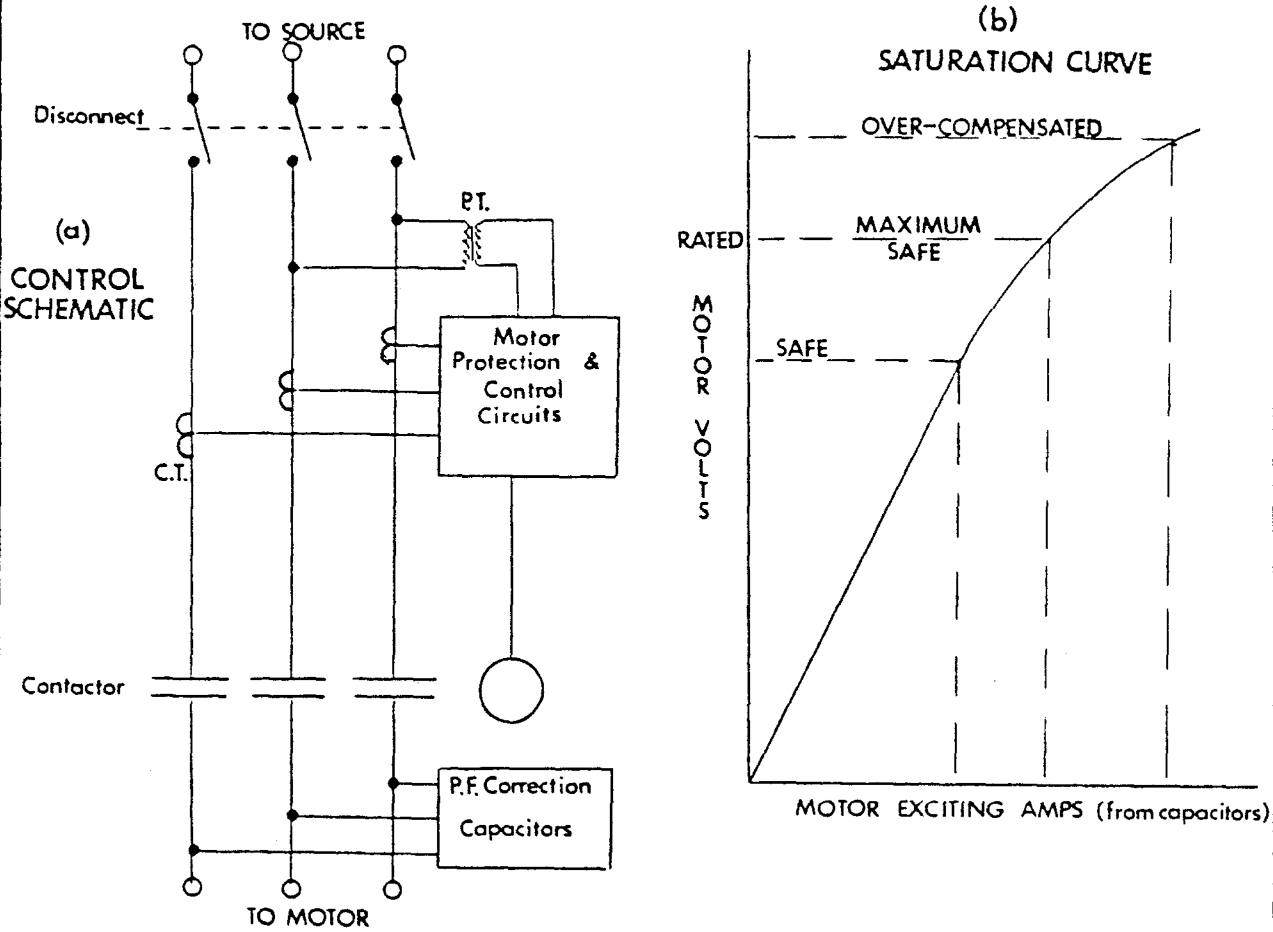



FIGURE 5—A SINGLE GROUNDED LEG

FIGURE 6—P.F. CORRECTION



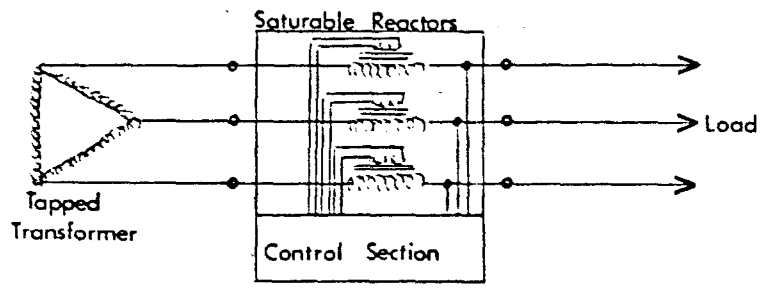




FIGURE 7—VOLTAGE LEVEL AND BALANCE CONTROL

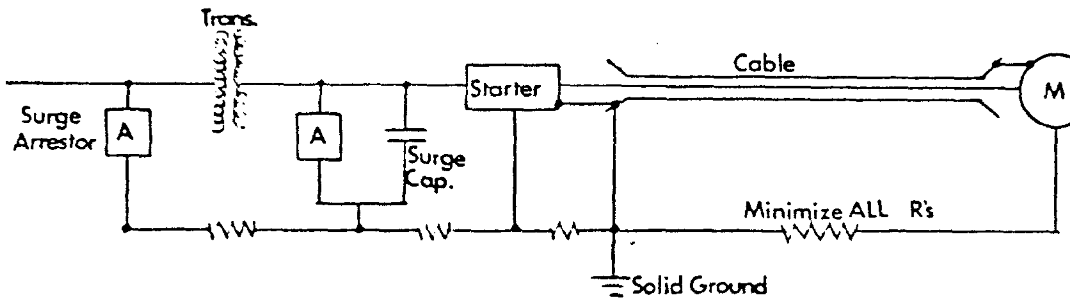



FIGURE 8—TRANSIENT PROTECTION