THE DESIGN AND OPERATION OF OILFIELD ELECTRICAL DISTRIBUTION SYSTEMS

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INTRODUCTION

The design of a distribution system that will provide adequate and reliable service at a reasonable cost is becoming increasingly important. The system should be engineered from the source to the last motor, to provide an optimum system that will not only serve the load adequately with minimum line losses but eliminate as many sources of trouble as possible.

This paper will consider the factors that go into such a system. The proper sizing of conductors to eliminate excessive line losses can conserve energy and money. Adequate pole requirements, anchors, and crossarms can be used to keep the system in operation in destructive weather. The selection and coordination of automatic protective equipment can reduce down-time and the loss of production. Power factor and load factor are also a large part of the economical operation of the system. The selection of the proper protective equipment, such as lightning arresters and fused disconnects, is a necessary part of this system. Formulas useful in the design of electrical distribution systems are shown in Table 1.

TABLE 1—MISCELLANEOUS DATA

$$KVA = \sqrt{(KW)^2 + (KVAR)^2}$$

$$AMPS = \frac{KW}{Voltage(line\text{-}to\text{-}line)(1.732)(Power\ Factor,\ Decimal\ Form)}$$

Line-to-Line Voltage (Wye System) = 1.732 x Line-to-Ground Voltage

KW/hp		
	Full Load	.746 KW/hp Nameplate
	Constant Load	.671 KW/hp Nameplate (Typical)
	Cyclic Load	.373 KW/hp Nameplate (Typical)

$$\%\ Voltage\ Drop = \frac{(KVA)\left[(Resistance)(Cos\ A) + (Reactance)(Sin\ A)\right]}{10(KV)^2}$$

$$Voltage\ Drop\ (approximate) = \frac{Current \times Distance\ in\ Ft \times 1.732 \times Resistance/1000'}{1000}$$

$$Line\ Losses\ (KW) = \frac{Current^2 \times Total\ Resistance\ of\ Line}{1000}$$

$$Total\ Resistance\ of\ Line = \frac{Distance\ in\ Ft \times 3 \times Resistance/1000'}{1000}$$

$$Depth - Pole\ Setting\ 40'\ and\ Above = \frac{Pole\ Length}{10} + 2\ Ft.$$

35 Ft = 6 Feet

TRANSVERSE LOADING

Maximum Moments = Wind Load on Pole + Wind Load on Conductors + Square Foot Area on Other Equipment on Pole

$$Wind\ Load\ on\ Pole = (FH)^2\left[\frac{d_1 + d_2}{72}\right]$$

F = Pounds Per Square Foot of Wind
H = Height of Pole Above Ground, in Feet
d_1 = Diameter of Pole at Ground Line, In Inches
d_2 = Diameter of Pole at Top, In Inches

$$Wind\ Load\ on\ Conductors = \left(\frac{D}{12}\right) FHSN$$

D = Diameter of conductor plus twice the thickness of required ice loading, in inches.

N = Number of conductors at one elevation

F = Pounds per square foot of wind

H = Height of conductor above ground, in feet

S = one-half (1/2) of the span on both sides of the pole, in feet

$$Moment\ of\ Resistance\ of\ Pole = .000264\ FC^3$$

F = Fiber Stress (Southern Yellow Pine - 7400 Pounds Sq. Inch)

C = Circumference at ground line, in inches

$$Maximum\ Tension\ in\ Guy\ Wire = T\frac{\sqrt{D^2 + H^2}}{D}$$

T = Total breaking strength of conductors

D = Distance from pole to anchor

H = Height of conductors above ground

Typical Electrical Values

	Impulse Withstand	Low Frequency Flashover
Wet Wood	60 KV/Ft	
Average Air	200 KV/Ft	
15 KV Pine Insulator	110 KV	40 KV
6 In Disc Insulator	100 KV	30 KV
10 In Disc Insulator	125 KV	50 KV

LOAD DETERMINATION

The electrical load varies considerably over the life of nearly any project. The two points that need to be considered include the existing load and the maximum load. The present load is a matter of calculating the kw/hp on the existing equipment. The future load is more difficult to determine, but production curves for the unit can be used to estimate the power requirements for any particular time, if the water-cut is taken into consideration. The trend in the West Texas area has been toward increased injection and infield drilling, which can change the picture drastically. So, this possibility must be kept in mind.

To begin with, let's review the definitions and relationships of the criteria that will be used.

1. kw (kilowatt) is the rate of consumption. This is the measurement of the rate of actual productive energy being used. kw integrated with time will be kwh.
2. kwh (kilowatt-hour is the actual power consumed.
3. kva (kilovolt ampere) is the apparent power on the system. This is vectoral addition of the true power (kw) and the reactive power (kvar).
4. kvar, sometimes denoted Rkva (kilovolt ampere reactive), is the power required to set up the magnetic fields in electric motors, transformers, etc. There is a small amount required for the lines themselves, but it is negligible. Transformers require very little compared to motors.

The relationship of the kw, kvar, kva, is the precise relationship of the right triangle. The kw being the base, kvar is the opposite side, and the kva is the hypotenuse. This relationship is true for all ingredients of the electrical circuits.

Another relationship to keep in mind is that 746 watts equal one horsepower.

Input hp is the power required by the motor to do a specific job. This takes into account the hydraulic hp, unit and motor efficiencies. The nameplate hp should be somewhat over this figure.

When figuring the kw on constant loads, if the actual input hp is not known, this writer uses 90% of the nameplate hp. This is a combination of an 80% load and 90% efficiency. This type of load will normally have a power factor of approximately 90%.

The cyclic load on a production unit has a wide variation over a period of time due to several factors—paraffin, temperature, volume, water-cut, etc. All of these vary individually from well to well, which makes calculating electrical load a little less precise.

The accepted ratio of 2 hp nameplate for 1 hp hydraulic is a pretty good rule-of-thumb; however, in some instances this has been carried too far, resulting in motors being oversized for a unit. The power required to do the work is practically the same regardless of the size of motor on the unit. The high-slip motor is commonly used with beam-pumping equipment. One of its advantages is that it allows the polished rod speed to be reduced through the change of direction of the rods. The motor must be loaded to obtain this slip.

Experience has shown that in most cases the load per nameplate hp on beam pumping will vary from 0.2kw/hp to 0.5kw/hp. A good average is 0.373kw/hp.

CIRCUITRY

The design of the circuits is controlled by many factors: well spacing, high voltage areas, injection stations, power supply, right-of-way, physical obstructions, economics, etc.

The ideal location from which to take power is in the electrical center of the unit. This is not always apparent, but normally it is relatively close to the physical center of the unit. High volume areas and water injection stations can shift this some.

The number of circuits vary with each unit, depending on the size of the load, the operating areas within the unit, location of power supply, and economics.

The least amount of line common to the whole unit will lower the chances of having the whole unit down due to trouble. In most units the circuits either approach each other or cross at some point. The author's recommendation is that switches or bar disconnects be installed at these points to enable a portion of a circuit to be isolated during trouble or to be used to shift load on the circuits to permit portions of the line to be de-energized for additions and repair.

The line should be checked as to proper phasing before the installation of the disconnects. This will ensure proper rotation and permit sections of the circuits to be transferred without interrupting service.

CONDUCTOR SELECTION

Tensile strength, ampacity, voltage drop, and line losses are some of the things to consider in the selection of a conductor. Voltage drop and line loss are normally the limiting factors.

Tensile Strength

The National Electrical Safety Code (NESC) prescribes the minimum construction standards of electrical systems.[1] A utility must meet or exceed these requirements.

NESC has the country divided into three ice-loading zones—heavy, light, and medium. The South Plains area is in the medium ice-loading zone. Apparently the ice age is coming back; the heavier ice storms are moving south. This area has experienced ice and wind far in excess of the amount specified as "heavy" loading in Yoakum and Gaines Counties. Consequently, it is recommended that one consider building to the heavy loading requirements, particularly the main feeder circuits. This requirement is that at 0°F, 1/2 in. of radial ice, and a 4-pound wind (48 mph) the load on the conductor will not exceed 60% of its tensile strength.

The critical point for icing is at 30°F with precipitation. If the temperature drops much below this, the ice will not build up.

Ampacity

A rule-of-thumb for ampacity is 50%. When the load reaches 50% of the rated capacity of a conductor, one should consider increasing the conductor size, particularly in the design stage.

Voltage Drop

The limiting factor for most conductors is the voltage drop. Voltage drop can be equated to pressure loss in a hydraulic system. There must be enough voltage left at the end of the system to do the job required. The critical test of the system is its ability to start the last motor in the system under full load.

Most transformers in oilfield conductor systems have taps that can be used to raise the voltage on the secondary side if the primary voltage is low. This, in itself, can give some problems if the difference between the primary voltage at full load and no load becomes excessive. This difference, known as voltage regulation, works like a pendulum—the further from the source, the wider the difference. This can give high voltages on the secondary side of the transformers at low system loads, which can result in difficulty in starting the motors—especially the newer motors.

This voltage swing is a problem often encountered in urban distribution. Since the load on a system can vary widely during the day, it can produce an unacceptable voltage swing. Southwestern Public Service Company uses voltage regulators that will automatically raise or lower the primary voltage to a pre-set level. This is the reason we buy very few distribution transformers with taps.

SWPSC substations in the oilfield have voltage regulators that will reduce the voltage if the load reduction is large enough. The load on any one circuit will probably not be enough to let the voltage regulator operate enough to be of any great benefit. Normally, the load in the oilfield is constant enough to preclude the use of this type of equipment in each circuit, especially since these items are expensive and require constant maintenance.

Line Losses

Line losses go hand-in-hand with voltage drop. Normally, when one is solved, the other will be acceptable. The reduction in line losses will quite often economically justify the larger conductor. The kw in line losses costs the same as the kw used to turn the motors.

Primary or secondary circuits to serve individual wells is mainly a matter of economics. To serve each well with its own transformer usually costs more than using one transformer bank and secondary for two or more wells. This depends on the well spacing and the size of motors on the well. The closer the wells and the smaller the motors, the more attractive secondary service appears.

Since voltage drop varies directly with distance and current, and line losses vary directly with distance and the square of the current, it would appear that motor size is the ruling point. As a rule-of-thumb, the breaking point between primary and secondary is about 40 hp.

The line losses are a function of the square of the current times the resistance, and on a given conductor the line losses vary as the square of the ratio between the primary and secondary voltages. For instance, the losses will be 675 times greater on

480 V than they will be at 12,470 V, for any size motor, on a given conductor.

There are some advantages to using individual transformers for each motor. These include: better voltage regulation at each well; only one well down if you lose a transformer; and more uniformity in transformer sizes.

Connections

Connections are the source of a large percent of trouble in an electrical system, especially with aluminum conductors; but use of compression connectors can reduce this considerably. This is especially true where copper and aluminum are being tied together. "Hot line" clamps are an easy way to make hot connections since they are installed and removed with a"hot stick" without killing the circuit. If they are used, care should be taken to ensure proper installation. We recommend installing a stirrup on the line with the clamp attached to it—never attached to the line itself. This practice should be limited to low current connections.

Compression sleeves should be used to splice the conductors. Conductor compound should be used in the installation of sleeves, as well as all connectors, to eliminate any air spaces in the connection.

A valuable aid in designing the system is a good computer program. With this available, you can vary conductor sizes and load and achieve an optimum system.[2]

LINE CONSTRUCTION

The poles selected for a specific line must be able to provide minimum clearance to any object in its path and to withstand adverse weather conditions. Although it might be possible to overdesign a line that some storms could not tear down, through good design, lines can be built to withstand a reasonable amount of bad weather and provide dependable service.

The poles that seem to be most in demand are Southern Yellow Pine, pressure-treated with creosote. These poles have an ultimate fiber stress of 7400 psi.

Vertical and Transverse Loading

There are two types of loading to be considered on poles—vertical and transverse. Vertical loading is seldom a limiting factor in distribution circuits unless it is a large transformer bank or deadending large conductors. Transverse loading will be the limiting factor of the span length on large conductors. The minimum ground clearance will generally limit the span length on the smaller conductors.

Transverse loading is primarily a result of icing and crosswinds. The maximum moments placed on a pole due to this kind of loading will be at the ground line. The amount of moment a pole is able to resist is determined by its circumference at the ground line and the ultimate fiber stress for that particular kind of wood. ASA has specified the minimum circumference for all classes and types of poles. These can be obtained from the NESC handbook, or your supplier should be able to furnish them.

The maximum moment placed on a pole should not exceed 25% of its resisting moment.

Well spacing and control points will dictate span lengths within the limits in most cases.

The standard 3-1/2 in. x 4-1/2 in. x 8 ft crossarm will handle the load of the conductors on tangent poles. but great care should be taken not to exceed the breaking strength of the crossarms on deadends and corners. The 5-3/4 in. x 7-3/4 in. x 8 ft double crossarms can withstand about 10,000 lb/conductor, assuming one conductor on the pole and one conductor on the arm (on either side of the pole). For conductor requirements beyond this, use bridle guys and standard crossarms.

Guying

Southwestern guys for the full breaking strength of all conductors on a pole.This is not required by code, but it is known through experience that the loading in the area can exceed 60%, and that through time, the anchors will deteriorate some. It is felt that this gives an acceptable margin of safety, and allows the conductor to be the weakest part of the line. It is better to splice a conductor during bad weather than it is to replace poles, especially deadend poles.

The soil in the West Texas area is subject to high galvanic action which will deteriorate anchors and rods. For this reason we use copperweld anchor rods for our oilfield circuits.

All guys should be insulated for safety. This also eliminates the flow of electrolytic current in the anchor. Electrolysis can cause severe damage to an anchor.

Slack spans are sometimes a necessary evil, but should be avoided when possible. The unguyed pole has a tendency to "give" towards the slack span, throwing extra slack in the conductors. This will cause a high incidence of trouble during periods of high wind.

The basic insulation level (BIL) of a distribution system is another important feature. The proper BIL will allow the installed protective equipment to bleed off voltage surges, such as lightning strokes, without damage to the circuit.

Lightning Protection

There are basically two types of lightning surges—direct strikes and induced voltages from nearby strikes. The direct strike has been recorded with voltage as high as 5000 kv. The induced voltages from nearby strikes range from line voltage to about 300 kv.

Providing a low resistance path to ground is one of the first items to be considered in lightning protection. The soil in this area normally will provide a high resistance ground. The moisture content of the soil varies the resistance considerably. The flow of current in a ground system will bake out the moisture around the grounding device and, in some cases, actually make an insulator out of it. A system neutral with multi-grounds on it can help. There are some problems with system neutrals that are beyond the scope of this paper. This is a problem the experts are still arguing. There seems to be no middle ground, they are either avidly for or against it. The main objection is that you can get surges off of the suppliers system through the neutral. One way around this would be not to tie the system neutral into the suppliers system. Safety is another reason—the neutral should be treated as a current-carrying conductor. If the neutral is cut, line-to-ground voltage can develop on a wye system and line-to-line voltage can develop on a delta system.

A lightning arrester is a device with specifically designed resistance for a line of a particular voltage. It is designed so that no current will flow through the arrester at line voltage. When a surge comes through the line, e.g., a lightning surge, and increases the voltage to a point above the rated voltage of the arrester, the valves (usually thyrite blocks) in the arrester will arc-over and allow current to flow to ground, bleeding off the excess voltage to a point where it can no longer sustain the arc in the arrester.

The surges from nearby strikes can normally be handled by lightning arresters. The surges from direct strikes will normally exceed the BIL of the line before the arresters can bleed it off. When this occurs the line will arc to ground, or to another phase, at the point of least resistance (lowest BIL). Once this occurs, the air is ionized sufficiently to become faulted. The power system will continue feeding current into this fault until the power supply is interrupted long enough for the air to return to normal. (The time span on lightning strikes is measured in micro-seconds).

A 15-kv system will usually support the flow of follow-through current on a line that has a BIL of 300 kv or less. If the line has a higher BIL, the ionization will probably be too weak for the system to support the flow of follow-through current. The following is a list of commonly accepted flashover values:

Air (average)	200 kv/ft
Wood (wet)	60 kv/ft
Insulators, 15 kv	110 kv

To figure the flashover value or BIL, all paths must be considered separately. For example, consider two phases on a crossarm two feet apart. There would be two paths for the flashover, one straight across through the air which would equal 2 x 200 or 400 kv. The other path would be down one insulator to the arm, then across the arm and up the other insulator which equals 2 x 110 plus 2 x 60 or 340 kv. This will be repeated for all phases to each other, as well as to ground.

The shielded line has reduced problems with lightning. The crossarm is dropped down the pole to place the phase conductors within a 45 degree cone from the neutral wire installed on the top of the pole. A ground wire is run from the overhead neutral to a butt wrap and ground plate attached to the base of the pole.

The high impulse, nonshielded line works on the same principle except it uses a phase wire in the top position. The minimum path to ground is controlled by the use of surface-mounted electrodes.

The use of additional arresters on existing lines can improve the operation during lightning storms. This is less expensive than rebuilding the system. SWPSC is presently experimenting on such a design and preliminary results have been excellent. The test circuits have arresters installed on all three phases of the line with a maximum spacing between arrester stations of one-quarter mile.

LINE PROTECTION AND COORDINATION

To help ensure minimum down-time, the distribution system should have devices to isolate the portion of the line in trouble, and to leave the rest in service. This can be done with fuses and/or oil circuit reclosers (OCR) and sectionalizers. Fuses are the least expensive "way to go" and they are easily available. However, there are some drawbacks to fuses. First, they are a oneshot device. Since most faults are transient in nature, a man must be sent to replace a fuse even when there is no damage to the lines. A fuse is also a single-phase device; when one blows it will leave at least a part of the unit operating in a single phase condition.

Oil Circuit Reclosers

An OCR is a device that by its construction will detect current in excess of the trip current it is designed to carry, open the circuit and reclose in a specified time. If, when it recloses, the fault is gone, the OCR will remain closed and will reset to its original position. Should the fault remain on the line, it will reopen. After a specified time it will reclose. If the line is clear it will stay on and reset itself. This continues through four operations; it will lockout on the fourth operation and remain that way until the line is repaired and the OCR is manually reclosed.

Sectionalizers

The sectionalizer is a device designed to work in conjunction with an OCR. The sectionalizer will sense current in excess of a preset amount, but it will not open the circuit; rather, the OCR upstream will open. The sectionalizer will count as the current falls off. When the OCR closes, the sectionalizer will again sense the excess current, if the fault is still there. The OCR will open and the sectionalizer will count again as the current falls off. The OCR will reclose once more; if the fault is still there the sectionalizer will sense the excess current. The OCR will open again, the sectionalizer will open and lockout while the OCR is open. The OCR will reclose and reset itself within a five-minute time span and be ready for four more operations. If the line clears any time before lockout on the sectionalizer, both devices will reset to their full count. The sectionalizer can be set to lockout on from one to three counts.

Any number of sectionalizers can operate in parallel with one OCR. If sectionalizers are installed in series, each must have one less count to lockout than the previous sectionalizer. Fuses can be coordinated to work behind either an OCR or a sectionalizer.

(For further information, refer to Reference 3.)

LOAD FACTOR

The ratio of the actual kwh used in a given period to the maximum that could have been used at the peak demand is known as the "load factor".

A large part of the cost of electric service is in providing the capacity in generating, transmission, substations and distribution. This capacity must be available at the customer's meter when he desires. The cost of providing the capacity is about the same whether the customer uses the peak demand for one hour or all month.

There are several benefits in having a good load factor. The first is that it will save money. The kwh is measurement of the work done. Assume that the kwh will remain constant. The bill will be reduced approximately $2.20 for each kw that the demand is reduced at current rates. Also, line losses are a function of the square of the current, so by reducing the demand it will reduce the line losses. Better voltage regulation can be realized with a good load factor. Most of our oilfield customers on demand rates have a load factor between 85% and 95%.

(For more information on load factor, refer to Reference 4.)

POWER FACTOR

The reactive current (kvar) on a distribution system can load the facilities as well as the current that is doing the work. This current is out of phase with voltage by 90 degrees and the kw and kwh meters do not measure it.

The reactive current will increase the line losses (which the meter does measure), and increase the voltage drop. For a 70% power factor, only 70% of the electrical facilities are available for useful work.

The best way to correct a power factor is by installing capacitors, which can be installed either on the primary or secondary. Secondary capacitors cost considerably more than primary capacitors, but they can do more for you, especially on long secondary runs. They will aid starting, reduce voltage drop, and will also help reduce peak voltage surges.

The capacitor creates a reactive current, which is exactly opposite from the reactive current required to excite a motor. The two reactive currents will cancel each other, so, in effect the capacitors are providing the excitation for the system.

Since the kw and kwh meters do not measure the reactive current, most power companies have a power factor adjustment included in their rate. Normally, there will be two points on this adjustment. Below one point the bill will be increased, and above the other point the bill will be decreased.

The capacitors will do the most good out on the system where the reactive current is created. One word of advice—a good ground is *essential* for a capacitor installation.

(For more information on power factor, refer to Reference 5.)

TRANSFORMERS

The proper selection of transformers for a system is essential to good operation. The voltage on a system will vary considerably from the source to the end of the line. Transformers should be selected with taps that will enable the desired voltage to be produced at any point on the system.

The delta connection is the most popular in the oilfield. The 480 V delta is the most common secondary. Some companies use a 480 V wye system with a line-to-line voltage of 832V. This is more commonly known as a 762 V system, (the difference is a matter of terminology). The older motors were 440 V, and 1.732 times that is 762. The transformers are rated 480 V, and 1.732 times that is 832.

The higher voltage will allow additional load to be carried on the same conductor with less losses. Most equipment available is rated with a line-to-line voltage. For example—600 V panels. This equipment is used on the wye system and some manufacturers have tested and approved their equipment for 832 volts. However, most manufacturers will say such equipment may be used in these installations, but they will not guarantee that the equipment will perform under all conditions as they will for conditions of 600 V or less. The voltage from phase-to-ground on an 832 volt wye system will be 480 V, provided the system is grounded. This requires a fourth wire and the presence of harmonics is more prevalent. The majority of oil companies will not ground a wye system. It is possible on an ungrounded wye system to get line-to-line voltage on line-to-neutral equipment.

CUTOUTS OR DISCONNECTS

Fault current is the amount of current that will flow if a circuit is shorted, either phase-to-ground, phase-to-phase, or all three phases. The closer the short occurs to the source, the higher the fault current. For shorts occurring further from the source, the impedance of the additional circuit will reduce the available fault current. The growth of electrical load in the oilfield is requiring installation of more and more substations, with some loads requiring the full capacity of a substation transformer. Some of the equipment normally used will not be able to handle the increased fault current.

A cutout, or disconnect, is designed to hold a fuse of specified size that will allow the operation of loads under normal conditions. The fuse is installed in the barrel of the cutout and when a fault occurs, the fuse separates and an arc is drawn between the receding ends. The heat of the arc produces a gas from the chemically treated inner lining of the barrel, blowing out the arc. The barrel drops out, killing the line. The higher the fault current, the higher the stresses in the barrel, requiring that it be designed to withstand these stresses. If the barrel ruptures without extinguishing the arch, current will continue to flow in the ionized air until some other device opens or until the fault burns clear. Normally, some other device opens and kills the arc, but not before some expensive equipment is destroyed or damaged.

A cutout has a voltage rating, a maximum fuse rating, and a maximum interrupting rating. All three need to be considered when selecting cutouts. The same design considerations also apply to automatic circuit breakers, oil circuit reclosers, fuses and other devices that will be opened under fault or high load conditions.

ARRESTERS

The proper selection of lightning arresters will eliminate a large portion of power outages.

The arrester for a wye system that has a system neutral is one that is designed for the line-to-ground voltage. The system neutral will keep the center point tied down and restrict the voltage from each phase-to-ground to approximately the same level. The lower the kv rating on an arrester, the sooner it will flashover and limit the surge voltage. However, the arrester must be able to open the path to ground when the voltage reaches a preset level and return the line to normal. The phase-to-ground voltage on a wye system, without a system neutral, can reach phase-to-phase voltage. This happens quite often under adverse weather conditions, and the failure rate of line-to-ground rated arresters on such circuits is extremely high. The use of line-to-line rated arresters will solve this problem, even though it permits a higher peak on the surge before bleeding over. *The importance of a good ground cannot be overemphasized!*

The preceding discussion has been concerned with line type arresters. There is another type of arrester that is more efficient - the station type arrester. Although it costs more, it is used in locations where more expensive equipment must be protected. This is the type of arrester used in our substations and power plants.

SUMMARY

We have touched briefly on the more important points of a good distribution system. Such a system will also be an economical system over a period of time. A routine maintenance program will extend the life of any system. A visual inspection of the facilities will permit damaged equipment to be replaced before it causes trouble; i.e., broken poles, crossarms, insulators, lightning arresters, ground wires.

Most power companies welcome the opportunity to provide assistance with the design of your system.

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