COVERING ALL THE BASES

Industrial Power System Design in a Utility Environment

BY ROBERT A. DURHAM & MARCUS O. DURHAM

TYPICALLY, LARGE LOADS ASSOCIATED with petroleum distribution systems are located in a relatively confined plant area. Scattered distribution systems do not often have very large capacity. The combination of large industrial requirements coupled with the geographic requirements of a utility system calls for a challenging design.

One of the primary duties of electrical engineers in the petroleum industry is the design and construction of power distribution systems. In most other cases, larger systems are located within a defined plant environment [1]. Systems spread over a large area tend to be smaller in load.

The scheme discussed here is unique: a large electrical network is spread over a very large geographic area. This creates an exceptional set of circumstances.

At the beginning of the design process, several goals were identified.

- Downtime must be minimized. Due to the inherent physical characteristics of the process being powered, even short downtime has serious financial consequences.

- In conjunction with reducing downtime, it was desired that a protection system be designed so that a fault in one area does not affect loads in another area [2].
- Under normal conditions, a voltage drop of less than 5% at the end of the system is desirable. This is crucial to assure that full voltage is available on the load side of the transformers [3], [4].
- Under contingency conditions, it was preferred that the load could be served successfully from either one of two utility sources.
- Necessarily, the system would be designed so that the heating of conductors would not cause any additional sag that would damage the integrity of the load service [5].

The only way to effectively address these issues is to conduct a series of computer model analyses prior to the beginning of construction.

STANDARD UTILITY CONSTRUCTION TECHNIQUES ARE COMBINED WITH INDUSTRIAL DESIGN TO MEET THE REQUIREMENTS OF THE SYSTEM.

Loads

There are primarily two kinds of loads served from this system. The first type are 150–400 hp, three-phase, 2,400-Vac centrifugal pump motors. The motors are two-pole induction machines, having low inertia and a very steep torque-speed curve. Efficiencies are in the 80% range with a 78% power factor (PF).

The second type consists of 2,400-Vac, 1,000 hp, four-pole, three-phase, squirrel-cage induction motors serving reciprocating compressors. Synchronous machines were not an option because of the equipment constraints imposed by other users.

Starting is a consideration for both type motor loads. The first-type pump motors are generally started across the line, though some are served from variable-frequency drives. Across-the-line starting is only possible because of the inherent robustness of the system.

The compressors, however, require a more advanced approach. Voltage drop caused by standard starting current for these large motors would cause other motors to trip inadvertently. To combat this, the compressor motors use a soft-start system. Maximum starting current is approximately 60% full-load amperes (FLA) [6].

Individual transformer banks are used for each motor in the system. The primary reasons are voltage drop and loss. The relatively large size of the motors, coupled with the geographic diversity of the loads, would make voltage drop and loss on medium- or low-voltage service unacceptably high.

The total connected load is approximately 20 MW. The motor loads served from this system spread over a 900-square-mile area in central Oklahoma. A single main trunk line provides service to the loads. This line is in excess of 25 miles in length.

Subtrunk lines of 1–12 mi in length radiate from this main line. Each of these lines serves between 1–5 MW of load. This necessitates constructing overhead lines on power poles similar to a utility installation.

Line Construction

The similarity between this system and a utility system is in the physical construction [7]. Both designs utilize wood poles and crossarms, aluminum conductor steel reinforced (ACSR) cable, and overhead construction. Conductors are placed in a triangle configuration, with the center phase pinned in the top of the pole. The neutral is mounted on the pole below the crossarm. Although it is desirable to have a static wire above the phases for lightning protection, the physical size of conductors, risk of neutral falling into phases, and personnel safety issues preclude such a design for this system.

The difference between this system and a utility system is the operating philosophy. Utility philosophy is to keep the system energized, or re-energized, until some piece of equipment burns down. This allows for locating faults on a very geographically scattered system. Industrial philosophy is to maximize operating time of the equipment while minimizing system interruptions. An industrial design places poles much closer together, uses substantially more protective equipment, and uses a different protection coordination scheme.

The difference in design philosophy is purely a matter of economics. For a utility, downtime is simply loss of revenue from the sale of electricity. For the industrial user, downtime results in loss of revenue from production and sale of product. Any disturbance in continuous production can cause damage to the production process that may be unrecoverable.

Construction Constraints

The company constructing and operating this system is a natural resource exploration and production firm, not an electric utility. As a result, an emphasis on construction techniques that would minimize required maintenance over the expected seven to 12 year life of the project is necessary.

Contractors are used for line construction in place of company construction crews. Construction is done on a day-work basis rather than on a package bid. This reduces lead-time, planning, and contract administration. It also allows for faster response to the rapidly changing load requirements.

Another concern is storm and ice damage. Central Oklahoma has the most extreme meteorological conditions in the United States. Temperatures range between 47 °C (110 °F) and −23 °C (−10 °F). Thunderstorms are common and often severe, with 55 isoceraunic days per year. The area where this system is constructed is in the "heavy" ice-loading district, and basic wind speed for this area is 36 m/s (80 mi/h), according to section 250-B of the National Electric Safety Code [5]. Finally, the system is located in the heart of "Tornado Alley," and annual tornados in the area are expected. There is even the occasional earthquake.

Since no applicable industrial design standard, recommended practices, or specifications exist for these conditions, it was necessary to reference utility practices [6]. However, these kind of meteorological conditions, coupled with the operating philosophy described above, necessitate building well beyond standard rural utilities services (RUS) and utility distribution line construction techniques [7].

The goal in this design is to minimize the need for line repair or maintenance. The ruling span length is the base length between poles for a specific conductor size. For utilities and coops, this is in the 90-m (295-ft) range for conductors 1/0 ACSR and smaller, and 76 m (250 ft) for 4/0 and 477 kcmil ACSR. Class 6 and smaller poles are common.

WITH THE AID OF MODERN TOOLS, A SYSTEM CAN BE CONSTRUCTED THAT SERVES THE NEEDS OF AN INDUSTRIAL USER IN A UTILITY ENVIRONMENT.

Table 1 shows the more stringent construction specifications for ruling span length, pole size, and anchor size.

Tree trimming is one of the most expensive and time-consuming aerial line maintenance activities. Efforts are made to eliminate the need for any tree trimming. Utility corridors are cleared to a minimum of 100 ft. In places where soil erosion is a major concern, larger trees are cut flush with the grade, and treated with an herbicide. This leaves the root ball for erosion control until new vegetation can be established. After three to four years, the corridor is treated with an herbicide to reduce tree growth.

An illustration of the difference in philosophy between utilities and industrials occurred last winter. There was severe icing in the region. Some areas were without utility power for over a month because of extensive storm damage. The system discussed here had a single incidence of blown fuses because of tree branches across the power line, with no other physical damage.

Supply

There are a limited number of transmission voltage (69 or 138 kV) lines in the area of operations. The high cost of constructing both new transmission lines and transmission substations prevents a transmission level system. As a result, electric service is provided by the utility at distribution voltage levels (25 kV). Utility service is provided from two 138/25-kV, 22-MVA substations. One sub is located at the southeast end of the served area. The other is located somewhat centrally, in conjunction with a gas processing facility.

TABLE 1. LINE CONSTRUCTION PRACTICES.

Conductor Size	Ruling Span Length	Pole Size	Anchor Size
477 kcmil ACSR	64 m (210 ft)	Class 3	Class 1
4/0 ACSR	69 m (225 ft)	Class 5	Class 3
1/0 ACSR	69 m (225 ft)	Class 5	Class 5
#2 ACSR	76 m (250 ft)	Class 5	Class 5

Each 25-kV substation is dedicated to the operation of this network. Benefit is accrued from raising supply voltage above normal levels. Supply voltages of up to 120% of nominal are available by use of offline tap changers and assist with voltage conditions.

Ordinarily, 120% overvoltage would cause damage to NEMA equipment [3]. Overhead electric construction, however, is rated with a basic-impulse level (BIL) of approximately 800% of its normal rating. In this case, 120% is applied on the primary (overhead) so that the secondary equipment can maintain rated voltage.

The load is geographically contained within multiple electric utility service areas. Pricing of electric service varies substantially between the several companies. Under state law, the utilities have designated areas of service. However, there are techniques that can be implemented to operate without these restrictions. The price difference is enough to justify the construction of additional lines to allow the use of a single utility.

Electrical Constraints

There are varieties of singular constraints that apply to the electric system under discussion. Commonly, overhead conductor size is determined primarily by thermal limitations. The amount of current that the conductor can carry is influenced by the height of the conductor above any obstacles, the sag in the conductor between structures, and the ambient temperature [5].

In the condition where a large load is served from very long conductor runs, voltage drop becomes the controlling constraint. Exacerbating the situation is the low PF of the motors. This causes excessive current to flow on the conductors and through the transformers, resulting in additional voltage drop.

The large currents, long conductor runs, and associated voltage drop necessitates a larger conductor than would normally be necessary for this size load.

The above-mentioned constraints required the use of 477-kcmil ACSR conductors for the main trunk line. The majority of the subtrunk feeders use 4/0 ACSR conductors. Radial branches use either 1/0 or #2 AWG ACSR conductors. This increases cost not only through the conductor itself, but also by necessitating heavier physical construction.

Controls and Load Shedding

About 95% of the total volume of material produceddur-ing production is waste. This necessitates an extensive control system to ensure that disposal of waste material is accomplished in an environmentally responsible way.

Control is accomplished using an elegantly simple load-shedding system adapted from a fail-safe technique used in the early days of electric systems. In its most basic form, a single overhead conductor is energized with 120 Vac. During a process upset, the 120-Vac source is removed, opening relays at multiple production locations. This causes the motors to shutdown automatically on a system upset. The line may be several miles in length between the source contact and the farthest load relay.

Conventional SCADA systems have not been installed to this point due to the large expense inherent in such a widely spread system. Some monitoring is available using cellular and Internet technologies. However, one would not want to rely on this technology for environmentally sensitive operations.

Capacitors

Without any correction, the PF of the system as planned would be less than 80%. This low PF would contribute to the voltage drop problem discussed earlier. Under standard conditions, PF correction capacitors would be placed on the 25-kV system at regular intervals to combat this problem. Switching safety and motor protection requires that no single bank of capacitors exceed 450-kvar. Additionally, capacitors located close to the load center would lend the most benefit. The exact location of these capacitors is determined by system modeling.

Associated with the geographically wide distribution of these motors is an extensive load-shedding system. Should a large amount of load be shutoff without switching the associated capacitor banks, an unacceptable leading PF and high voltage condition would exist.

Combating this conundrum requires automatic switching of the capacitor banks with the associated load-shed signal. Conventionally, placing oil switches at each capacitor bank and tripping them automatically would be the solution used. Automatic closing of switches is not used to prevent unintentional leading PF and high voltages.

An alternative used in this situation is to place medium-voltage PF correction capacitors at (or near) the motor terminals. The most convenient location for the capacitors is at the load side of the motor contactor. This has several benefits:

- Capacitors are automatically switched on and off with the load they are correcting. This, consequentially, maintains the PF of the system at an acceptable level.
- PF correction nearer to the load or, in this case, at the load, contributes the most to improving voltage conditions.
- The PF corrected motor load requires less apparent power (kVA) than an uncorrected load. This reduces the size requirements of supply transformers and protection fuses.
- The cost of the additional capacitor banks is less than the cost of the additional automatic switches that would be required at each distribution voltage capacitor bank.

A negative effect of placing the capacitors downstream of the motor contactor is the necessity to reset the motor overloads. This is a minor, but necessary, consideration.

Line regulators are sometimes used by utilities for voltage-correction devices. Since this is strictly a three-phase load, these would potentially cause more problems than they would solve. The losses associated with regulators, as well as concerns about misoperation, make their use undesirable.

Protection

Overcurrent protection of such an extensive system is an undertaking in and of itself. Two distinct types of protection are required. The first is protection of the motors and transformers at each individual load point. The second is overall protection of the main feeder lines.

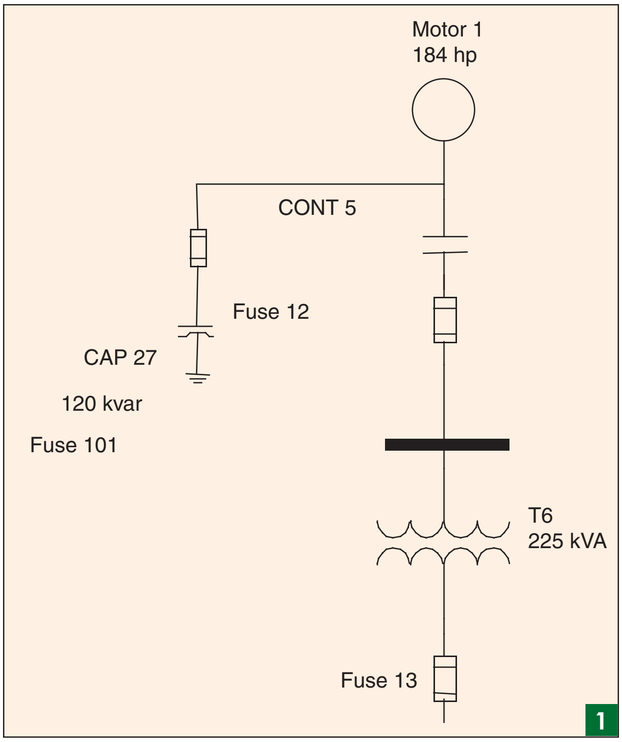
Conventionally, line cutouts associated with fuse links are used to reduce the potential of damage to the system. This is the technique used for each individual load service (Figure 1). Fuses are sized as tightly as possible to ensure that an overcurrent condition trips only the loads required for protection. High-speed (X-speed) fuse links are used [6].

However, for the main-trunk line and subtrunk line protection, fuses are not acceptable. The reasons include

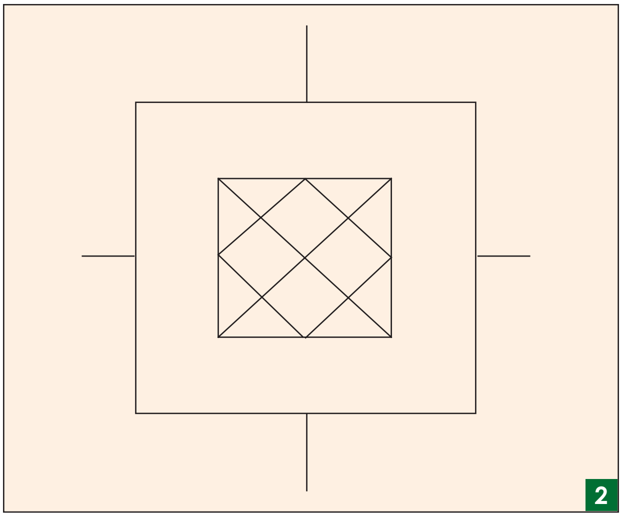
- The risk of motor damage due to single phasing (one fuse blown) is too high.
- The high rating of fuses required makes coordination with the utility system difficult, if not impossible.
- Electric storms can cause an unacceptable number of outages due to arrestor operation.
- Outages require the services of an electrician to restore, resulting in costly downtime. Often, this requires hours before service can be restored.

As a result, more advanced and costly protection schemes are necessary.

At a minimum, automatic oil reclosers are placed at the utility supply point and at the take-off of the subtrunk



A single-motor model.



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A subtrunk feeder model.

feeders. A subtrunk feeder is defined as any section of line that serves more than 2 MW of planned load. An example is shown in Figure 2.

In addition, oil reclosers are placed on the main trunk line at intervals of 10 MW of planned load. This ensures that all protection devices can be coordinated.

Oil reclosers are used instead of vacuum or SF6 devices. Under current technology, the cost and size of newer technologies for low-current devices makes them inappropriate. Additionally, switching transients caused by the operation of vacuum type devices would cause damage to motors. Transients would also cause trips of upstream motor control devices.

For each of the main line reclosers, microprocessor-based trip devices (relays) are used. Technology in the area of microprocessor relays has advanced to the point where cost and flexibility make them desirable for any advanced application. Settings for this type of relay are easily changed to adapt to changing load conditions and protection requirements.

For each of the subtrunk circuit reclosers, standard electronic plug-setting relays are acceptable, although microprocessor type devices are used whenever they are available.

Lightning

Lightning protection is a major consideration in the system area. According to *The IEEE Green Book*, there are in excess of 55 isoceraunic days in this region [9]. General lightning protection guidelines have been extensively discussed in previous documents [10]–[12]. Some specific requirements will be discussed here.

Due to the high number of electric storms in the area, the odds of either a direct or induced strike to the widespread system is very high. To fight this, distribution surge arrestors are placed at the transformer connection point for each load. In addition, sets of surge arrestors are placed at each distribution level capacitor bank, and at 1,300–1,500-ft intervals along the line. This is a substantially greater number of arrestors than the standard utility practice.

At each arrestor bank, care must be taken to ensure that energy from lightning strikes can be dissipated safely. At a minimum, 8-ft ground rods are driven at each location. In particularly rocky soil or clay, a triad of rods is used to give adequate earth connection.

Connection from the rod to the surge arrestors is made using #6 AWG solid copper wire or larger. Any bends are made using sweeping turns with a minimum radius of 8-in to minimize the amount of inductive reactance. Use of coiled stingers from the line to the arrestor is strictly prohibited.

In addition to grounding the arrestors, the neutral wire is grounded at every pole. For the most part, this is accomplished using butt-wrap or butt-plates on the poles.

Finally, each piece of equipment on the system, transformers, capacitors, motors, and control panels, are grounded through an 8-ft driven ground rod.

As is true in all lightning protection applications, a proper grounding system is imperative [5].

Another concern associated with lighting is damage to the control and load-shedding system. Since the 120-Vac conductor is located on the overhead poles, it is very susceptible to surges induced from nearby lightning strikes. These surges destroy the load relays, resulting in motor shutdown, even without a process upset.

A simple, inexpensive, yet effective protection system is applied to the coil of the load relays. This surge protection scheme has been used before to protect remote instrumentation [10].

The design of the protection scheme is constructed using two metal-oxide varistors (MOVs), a pencil, and two lengths of 14 AWG wire. The MOVs are placed between the hot and ground of the 120-Vac control circuit ahead of the relay coil. An inductor created by wrapping the 14 AWG wire 20 times around a pencil is placed between the two MOVs.

The effectiveness of the system is obtained by the combination of the inductors and the MOVs. The inductor blocks the high-frequency lightning signal from reaching the relay coil. The energy is then dissipated through the MOVs to ground.

During a recent retrofit of an existing system, approximately 50% of the motors had the protection scheme in place when an electric storm passed through the area. Without exception, those motors protected stayed operational. Those that were not protected had equipment failure, associated downtime, and lost production.

Computer Modeling

The size of the system, number of individual load points, variables in system protection, and length of the conductors generates a host of conditions. All must be considered when looking at system design and operation. The number of different conditions that may be present make it impossible to effectively design and maintain a system of this complexity using conventional means [13]. It is necessary to create a comprehensive system model to determine design factors.

The advance of PC-based computer modeling programs has made it easy for an engineer with basic knowledge to create an effective model. The cost of the modeling software is around US$10,000. This is less than two weeks of engineering time. For a system of this complexity, this is an insignificant cost.

There are numerous products on the market for computer modeling. After evaluating utility and function, the list was reduced down to two. One is more appropriate for in-plant power distribution design. Only one appeared to couple functionality for a large, geographically distributed system with the ease of use of GUI-based software [14].

To develop familiarity with the software, a small subsystem was initially modeled. This included a single motor, transformer, switching devices and capacitors (Figure 1). A single utility service point was also modeled.

To reduce the complexity of the larger diagrams, the motor subsystem shown in Figure 1 is replaced with the symbol shown in Figure 3.

Once some level of fluency was acquired, a model of one of the subtrunk feeders was developed (Figure 2). A system of several subtrunk feeders connected to the main trunk line was then compiled to yield the overall system configuration.

The final levels of detail added were protection devices. Models of fuses, switches, starters, electronic- and microprocessor-based relays, and motor-protection devices were added. The software allowed coordination of settings for these devices based on both available fault current and full load amps. Figure 2 is shown simply to illustrate the complexity of one small part of the system. Therefore, its scale is purposely reduced to eliminate the details.

System Results

The original model was assembled as a design tool during the initial phase of the project before any construction was started. This allowed many alternative configurations to be considered for size of conductor, length of individual branches, system protection, and physical system configurations.

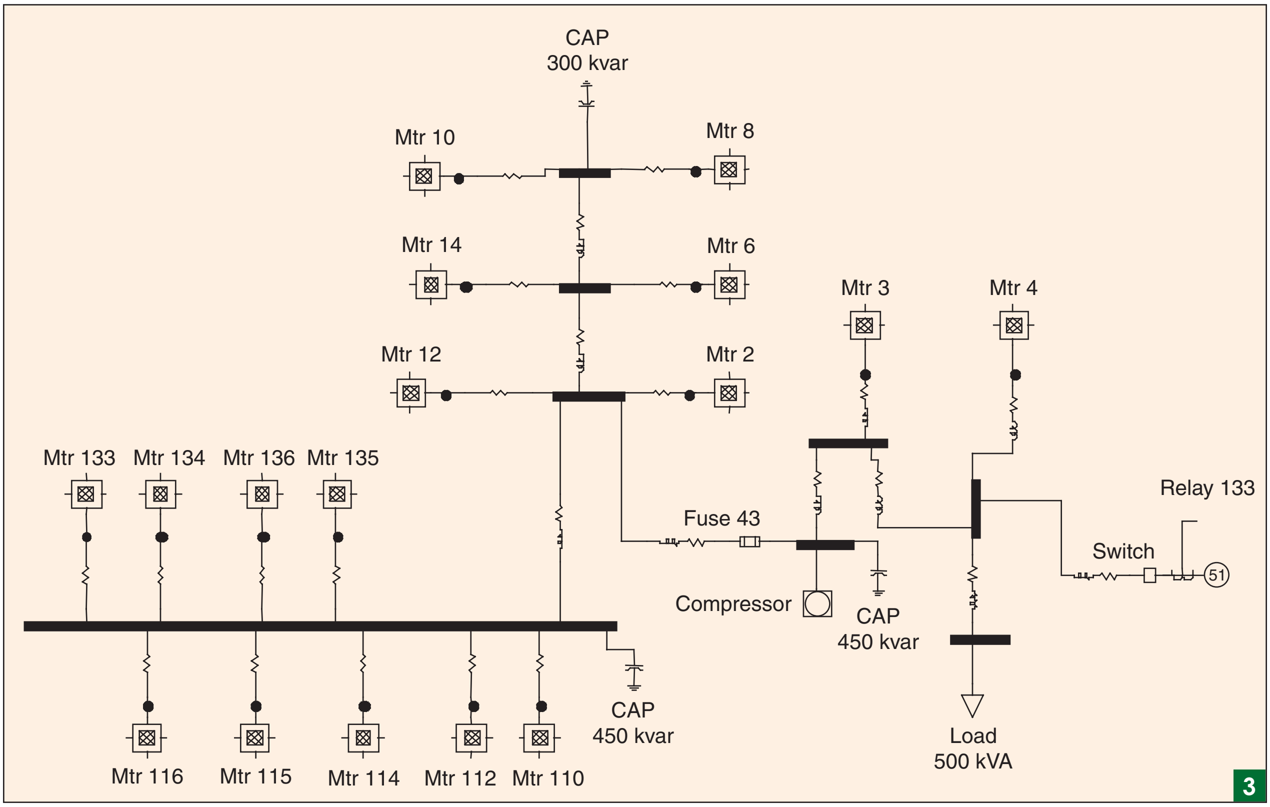
Once the model was built, the software yielded the following types of results for all points on the system:

- current loading
- voltage
- PF
- fault current
- motor starting
- voltage drop
- kVA losses
- protective-device coordination.

The results of computer model analysis show that the majority of the initial requirements are met. Under normal conditions, voltage drop at the far end of the system is 8%—somewhat higher than desired but within acceptable parameters.

The network can be served from either of two supply points with acceptable voltage conditions in all but the most heavily loaded circumstances. With supply voltages raised to approximately 115% of nominal, loads can be served continuously from either end of the system.

Software coordination of fuses and relays before construction allows the use of advanced protection devices with minimum onsite configuration time. Additionally, installation of more devices into the network is feasible.



A motor subsystem symbol.

This allows for protection of the motors, without system-wide outages. The use of properly coordinated protection devices eliminates spurious outages and minimizes downtime.

Irrefutably, with the tools available today, a reasonably competent engineer can plan and design a large distributed network from the front end. Challenges that would remain unforeseen to all but the most experienced practitioner are readily identified and resolved before actual construction and operation.

The system model has additional benefits once the original construction is complete. Location and size of motor loads on the system are in a state of continual change. Using an updated accurate model allows the designer to modify the system as appropriate to deal with these changes.

A recent system upgrade demonstrates the value. The system model was used to recommend additional capacitors for PF correction, fuse size, and conductor size upgrades. The recommended upgrades resulted in an 8% reduction in electric bill charges. This yielded a six-month payout on the investment.

Conclusions

It is uncommon that an industrial system is spread over a large geographic area. The combination of large loads, relatively large motors, and very long distances creates a series of unique problems. Even though the electrical construction resembles utility design, the operational parameters are uniquely industrial.

Construction specifications and techniques are used that increase the reliability of the system above standard utility practices. This adds to the cost of the project, and necessitates modified approaches to overhead line construction.

Transformer selection and design is greatly influenced by the size of the load, as well as overhead pole construction. PF correction is accomplished using both standard distribution level capacitors, and using medium-voltage capacitors at the voltage terminals. Lightning protection uses both standard surge arrestors on the line, as well as advanced grounding systems.

In each of these cases, standard utility construction techniques are combined with industrial design to meet the requirements of the system.

Without the use of computer-based system modeling, proper design and operation of such a complex system would be impossible. Computer models give an accurate picture of the loading on the system in a particular configuration. They also aid the engineer in selection and coordination of protective devices, as well as power-factor correction.

Conclusively, with the aid of modern tools, a system can be constructed that serves the needs of an industrial user in a utility environment.

Acknowledgments

We would like to thank Ted Olsen, Daniel Doan, William Wood, and Eugene Fagan for their exceptional suggestions, comments, and observations.

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Robert A. Durham is with EDG Power Group, Inc. in Tulsa, Oklahoma. Marcus O. Durham (mod@superb.org) is with THEWAY Corp. in Tulsa, Oklahoma. Robert is a Member of the IEEE and Marcus is a Fellow of the IEEE.

This article first appeared in its original form at the 2001 IEEE Petroleum and Chemical Industrial Committee Technical Conference.