PETROLEUM INDUSTRY

The growth of the petroleum and chemical industries coincided with the availability of electricity to do the work of processing crude oil into finished products. Electricity is used in all aspects of this industry: from extracting crude petroleum from the ground (called the "production" sector of the industry), to transporting petroleum products (the "transportation" sector), to processing the petroleum into finished products for consumer or industrial use (the "manufacturing" sector).

Oil wells are part of the production sector of the industry. Electrically driven drills and hoists are used to drill holes up to thousands of meters through rock formations and to raise or lower the drill pipes and well casings into and out of the earth. To prevent an uncontrolled well, called a "blowout," lubricants with the consistency of mud are used during the drilling process. The drilling mud is circulated through the well using electric-motor-driven "mud pumps," and the rock debris is sifted and removed from the mud before it is returned to the well. Once a well produces oil and gas, often the oil must be treated before it enters a pipeline or a tanker truck or ship. This treatment may include the removal or separation of water, salt, or gas, or the extraction of poisonous gas such as hydrogen sulfide. Salt is usually removed by an electrostatic process with high voltage imposed between two grids submersed in the crude oil flow. Often, extracted natural gas must be reinjected into the oil formation to maintain the flow of oil from a well. The natural gas can also be used as a fuel for gas-turbine-driven electric power generation at the production site. Some types of oil-bearing rock formations are responsive to the injection of pressurized water to optimize the amount of oil that can be recovered from the oil reservoir. In many cases, electric motors are used to drive the pumps and compressors required for the treatment or injection processes. Offshore oil production platforms often use ventilation fans or blowers driven by electric motors to prevent the accumulation of flammable vapor and air mixtures in confined or enclosed areas. In cold climates, electrical heating elements, called heat-tracing cable, are wrapped around pipes or valves that are in danger of freezing (see INDUSTRIAL HEATING for a thorough treatment). The systems used to control most of the modern production facilities are all electronic-based and use electrically actuated valves or other means of process control such as variable-speed drives.

When the produced oil or gas is ready to be transported, if not transported by tanker or truck, it enters a pipeline system. While some pipeline systems use pumps or compressors driven by engines or gas turbines fueled directly from the pipeline product itself, most liquid pipeline pumps are driven by either fixed- or variable-speed electric motors. These may be up to several thousand kilowatts in output rating. Since many of the motors are in remote locations, the electrical power infrastructure feeding these motors may be relatively small in capability. Special starting methods are required to accelerate the motors to avoid depressing the electric utility supply voltage in the area. Transportation uses electronic monitoring and control systems extensively to regulate flow rates and monitor for pipeline breaks or leaks. Many of the pipeline systems are buried in the ground or traverse water and must be cathodically protected. This involves the use of an alternating current-to-direct current (ac-to-dc) rectifier and forcing current to flow from a sacrificial anode, buried in the ground along the pipeline, through the earth or water to the steel pipeline (the cathode). This prevents the pipeline from corroding. Power sources other than ac utility power, such as photovoltaic, thermoelectric, or galvanic (the natural voltage difference between two different metals in an electrolyte), are commonly used as power sources for cathodic protection of steel pipelines.

Manufacturing is the sector of the industry where the raw material is converted from crude oil or natural gas to a finished product. Examples are motor gasoline, jet fuel, diesel, fuel oil, asphalt, chemicals for feedstock to a chemical plant (an intermediate product), plastics, synthetic fibers, fertilizers, and many other products that are based on petroleum. To make the products, the plants have reactors, where chemical or physical conversions take place. These facilities depend on a reliable source of power to supply electric-motor-driven pumps, compressors, extruders, fans, and blowers. The processes are almost exclusively controlled by digital control systems to obtain maximum plant product output and equipment utilization.

All sectors of the petroleum and chemical industry have common needs to install electrical equipment safely in a potentially explosive environment. The first step is to determine the "electrical area classification" of certain physical locations within the facility. This is covered in more detail later, but the electrical area classification given to a certain location defines the risk of electrical ignition in that location. Once the area classification is defined, electrical codes define the electrical installation required.

Personnel safety is extremely important in electrical power systems that use motors up to 13.8 kV in rating and that may have equipment, rated up to 230 kV, or above. Appropriate isolation, grounding, and testing for high voltage are necessary to avoid shock hazards. The energy levels available at equipment are high enough that precautions are necessary against the flash burn hazard while working near equipment where an electrical arc could occur. These hazards and applicable personal protective equipment are discussed later.

Motor application guidelines unique to petrochemical industry installations are also discussed, with particular attention given to electrical surge protection for rotating electrical machinery. Electrical surges can originate from lightning, but

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

more commonly are the result of switching on the power system. Power electronic converters, which supply a power source to motors applied as variable-speed drives, are common at petrochemical installations.

Finally, application of cogeneration facilities within petrochemical facilities is discussed with particular emphasis on generator voltage and power control. A sample power distribution configuration that provides good isolation from electrical utility disturbances external to the processing and cogeneration plants is illustrated.

CLASSIFIED AREAS

A classified area is a physical space within a facility where a flammable or explosive mixture of material can exist. The material can be a liquid, a gas, or a dust, but most of the classified areas within the petroleum and chemical industry involve flammable liquids and gases [these are defined as "Class I" materials in the American National Standards Institute (ANSI) and National Fire Protection Association (NFPA) standards on the subject]. An important part of the design phase of a plant is to determine the electrical area classification of the plant. Industry standards (1,2) are invaluable to defining the area classification. Once the area classification is defined, Chapter 5 of the National Electrical Code (NEC) (3) details the electrical equipment installation requirements.

Plant areas are classified to avoid ignition of materials released into the air. The potential ignition source is typically an electrical arc or spark, or the hot surface of a piece of electrical apparatus. Electrical area classification designations are a function of the probability of material release and the degree of ventilation at the location. The probability of the sparking or hot surface being present at the same time of the release determines, to a degree, what type of electrical installation is permitted.

Until 1996, all of the classified areas in the United States were defined under the "Division" system, which has two subcategories, Division 1 and Division 2. Division 1 areas are those where ignitible concentrations are expected to exist under normal operating conditions, and Division 2 areas are those where ignitible concentrations are expected infrequently, under abnormal conditions. The risk of an ignition is higher in a Division 1 area than in a Division 2 area, so the electrical equipment safety requirements are more severe for Division 1. Table 1 is a summary of typical equipment and wiring requirements for Division 1 and 2 installations.

For the first time in 1996, the NEC adopted the area classification system used in most countries outside North America. This system defines three designations: Zone 0, where ignitible concentrations of flammable gases or vapors are present continuously or for long periods of time; Zone 1, where ignitible concentrations are expected to exist under normal operating or maintenance conditions; and Zone 2, where ignitible concentrations are expected infrequently, under abnormal conditions. Zones 0 and 1 are essentially encompassed in the definition of Division 1, and Zone 2 is equivalent to Division 2. The NEC adopted the "Zone" system in the interest of worldwide standards harmonization. It also enables application of international electrical equipment explosive protection techniques in the United States. Individual equipment approval requirements (testing laboratory listing or labeling) may differ for the United States. Table 1 lists some of the equipment categories available when an area is classified using the Zone designations.

An electrical area classification drawing prepared with the use of Ref. 1 or Ref. 2 will usually be conservative. Experience and engineering judgment are important parts of the process. Recent developments that could affect the extent of a defined classified area include the technique of evaluation based on material volatility. Computer simulations of the type of material released, its quantity, temperature, and pressure, and assumptions of local wind conditions can significantly influence and sometimes reduce the extent of the classified area. This technique is covered in Appendix D of Refs. 1 and 2. Investigations continue today on safe application of induction motors in classified areas. An electrical machine winding that is susceptible to corona is a continuous ignition source. If an external flammable vapor–air mixture can come into contact with such a machine winding, an ignition will occur. While there have been few recorded incidents, investigations continue on determining the lowest rated operating voltage that is a risk. The physical cleanliness of the winding, which is usually determined by the machine's enclosure, also influences the degree of emitted winding corona. A running motor with hot rotor surface has a lower risk of igniting a flammable vapor–air mixture than a stationary hot surface. Investigations continue to quantify the risk of motor applications in Division 2 and Zone 2 areas.

PERSONNEL SAFETY

Safety around electrical power systems of high voltage and energy is not unique to the petroleum and chemical industry. All other industries that use electrical power have the same concerns. While utilization voltage levels of 2400 V, 4160 V, and 13,800 V are common in the petroleum and chemical industry, many injuries and electrocutions occur on systems of 600 V and below due to the relatively high population of electrical equipment at the low-voltage level. Most of the practices discussed in this section are applicable to a broad spectrum of industrial and commercial facilities.

Applicable Regulations and Standards

The Occupational Safety and Health Administration (OSHA) has established numerous regulations on safe isolation of energy sources. These "lockout and tagout" procedures are required of all industrial facilities in the United States. The regulations are based on common sense, but were instituted because too many people were hurt. Following are the basic steps of electrical safety:

1. Make sure that all possible sources of energy input (in this case, voltage, but this also applies to mechanical stored energy as well as other nonelectrical sources of energy) are physically isolated and locked out.
2. Treat all conductors as energized until tested otherwise.
3. Ground all electrical sources that could possibly become energized with adequately rated grounding clamps and conductors (capable of withstanding the available power system short-circuit energy).

Table 1. Electrical Equipment Requirements for Use in Classified Areas[a]

Equipment Type	Division 1	Division 2	Zone 0	Zone 1	Zone 2
Wiring	Rigid metal conduit, intermediate metal conduit, or metal-clad cable[b]	Any Division 1 method, enclosed and gasketed busways or wireways, tray cable	Intrinsically safe only	Same as Division 1	Same as Division 2
Contactors, switches, or circuit breakers	Mount within explosionproof enclosures	Mount within explosionproof enclosures, hermentically sealed or explosionproof chamber for contacts	Not permitted, unless in an intrinsically safe circuit	[c]	[d]
Fuses	Mount within explosionproof or purged enclosures	Nonindicating, filled, current limiting type in general-purpose enclosure	Not permitted	[c]	[d]
Transformers	Special vaults	No special requirements	Not permitted	[c]	[d]
Lighting fixtures	Approved fixtures	Low-surface-temperature fixtures	Not permitted	[c]	[d]
Heaters	Approved heaters	Low-surface-temperature heaters	Not permitted	[c]	[d]
Motors and generators	Explosionproof, purged, or totally enclosed forced ventilated types	Conventional, with nonsparking contacts	Not permitted	Flameproof, increased safety, or purged	Conventional, with nonsparking contacts
Surge protection	Mount within explosionproof or purged enclosures	Sealed, metal-oxide varistor surge arresters and conventional surge capacitors in general-purpose enclosures	Not permitted	Mount within flameproof or purged enclosures	Mount within flameproof or purged enclosures

[a] This is a summary; see the latest NEC for current requirements.

[b] The cable must be listed for use in a Division 1 or Division 2 area, as applicable.

[c] Applicable protection techniques for Zone 1 may include flameproof, increased safety, encapsulation, oil immersion, purged and pressurized, or powder-filled. See the NEC for more detail.

[d] Applicable protection techniques for Zone 2 may include purged and pressurized and nonsparking or restricted breathing apparatus. See the NEC for more detail.

Only then can the electrical equipment be worked on safely. These can be further detailed as a set of principles for safe electrical work (4):

1. *Maintain Distance.* An effective way to maintain safety is to keep a safe distance from exposed energized conductors or circuit parts.
2. *Test Before Touch.* Consider every electrical conductor or circuit part energized until proven otherwise.
3. *De-Energize If Possible.* De-energize all equipment before you work “on” or “near” exposed electrical conductors or circuit parts.
4. *Recognize Potential Hazard.* Installing barriers, barricades, and de-energizing (switching) are potentially hazardous tasks.
5. *Plan All Jobs.* Plan all jobs carefully, regardless of size.
6. *Anticipate Unexpected Events.* Before beginning work, ask “What if . . .?” and decide what you will do if something goes wrong.
7. *Use the Right Tool for the Job.* Identify the tools required and do not perform the task until you have the correct tool.
8. *Use Procedures as Tools.* Establish and adhere to procedures to accomplish a job safely.
9. *Isolate the Equipment.* Lock, tag, try, and test.
10. *Identify the Hazard.* Identify and address each hazard.
11. *Minimize the Hazard.* Use insulating barriers, safety grounds, and safe work practices.
12. *Protect the Person.* Avoid exposure to electrical hazards wherever possible. Use appropriate personal protective equipment (PPE) for each potential hazard.
13. *Assess People’s Abilities.* Evaluate the person’s qualifications, capabilities, and physical and mental state at the time a potentially hazardous task is to be done.
14. *Audit These Principles.* Audit the principles frequently to verify they reflect current practices.

OSHA recognized the merits of a “consensus standard,” rather than regulations adopted by legislation. This is why the NFPA Technical Committee on Electrical Safety Requirements for Employee Workplaces was established in 1976. This group is responsible for ANSI/NFPA 70E (5). This standard is processed through the NFPA public proposal and comment process periodically. One of the concepts introduced in the 1995 edition of ANSI/NFPA 70E is the "flash protection boundary."

Flash Protection Boundary and Safe Work Distance

The flash protection boundary is that distance within which an incurable skin burn may occur from an electrical arc. The hazard from the arc depends on the arc power (the system voltage and the available short-circuit current) and the total clearing speed of the disconnecting or isolation device (a circuit breaker and its protective device setting, or a fuse). The flash protection boundary distance can be determined by the following (5):

$$D_c = 0.305 \times (2.65 \times \mathrm{MVA_{bf}} \times t)^{1/2} \tag{1}$$

where

D_c is distance of person from an arc source for a just curable burn (in meters)
$\mathrm{MVA_{bf}}$ is bolted fault MVA at the point involved
t is time of arc exposure (in seconds)

Flash Hazard Analysis

Establish a flash protection boundary from Eq. (1), or the more conservative table in Ref. 5, and require that all personnel crossing the boundary wear appropriate PPE. This procedure will provide protection from vaporized metal, arc radiation, or hot gases from an arc flash within equipment. The flash protection boundary is determined by the available short-circuit MVA and the clearing time of the protective device (fuse or circuit breaker) upstream of the point of fault.

Use NFPA 70E-1995, Section 2-3.3, to determine the flash protection boundary for a particular application; however, the following list is a conservative guideline:

1. Systems under 750 V: 0.9 m (3 ft)
2. Systems over 750 V, not over 2 kV: 1.2 m (4 ft)
3. Systems over 2 kV, not over 15 kV: 5 m (16 ft)
4. Systems over 15 kV, not over 36 kV: 6 m (19 ft)
5. Systems over 36 kV: determine by Eq. (1)

Table 2 relates typical energy levels for applications and the recommended PPE for the application based on typical task working distances. A person close (in working proximity) to a high-energy source (i.e., Level 1) within the flash protection boundary requires layered protection. The following exposure definitions apply to Table 2:

1. *Direct Exposure.* A person is directly exposed to the potential arc (bare or poorly contained conductors).
2. *Door Closed.* A metal door or cover, without holes or gaps, is securely fastened and protects the person from direct exposure to the arc. Some action changing the state from dead to live, or vice versa (e.g., switching or racking), is taking place.
3. *In Area.* Personnel in the vicinity of equipment when no switching or work is taking place.

PPE is recommended for the following activities, which have the greatest risks of creating an electrical arc flash:

- When operating open-air switches
- When doing any switching with doors open on switchgear or motor starters
- When racking circuit breakers or motor starter contactors in or out
- When working on motor control centers with open doors (unless the power components at 480 or 600 V are well-guarded) or when removing or installing starters
- When installing or removing safety grounds
- When taking voltage measurements
- When working on exposed energized parts or conductors

Use Table 2 to determine the degree of PPE that is appropriate for the energy level of the equipment on which work will be done. The NFPA Technical Committee now is considering more definitions of PPE for the next edition of ANSI/NFPA 70E. Until PPE is better defined in the consensus standard, Table 2 should provide guidance.

Safety in Design

Several things can be done during the design of an electrical system to enhance safety:

- Specify insulated bus for all electrical switchgear and control gear. Insulated bus prevents or minimizes arc propagation within the gear after the fault initiates, and it can reduce the arc flash hazard.
- Design for the power system to include fast protection to clear faults as quickly as possible to reduce the arc exposure time. Differential protection, with a total fault clearing time of approximately 0.1 s, will greatly reduce arc exposure and the probability of escalation to a more severe fault involving two or more phases. Differential protection should be considered for medium-voltage (>1000 V) switchgear.
- For low-voltage (<1000 V) motor control equipment, consider the use of current-limiting fuses as the short-circuit protective device, either by itself or in combination with a motor circuit protector (a magnetic-trip-only circuit breaker). The extremely quick fault clearing time, less than a few milliseconds, can drastically reduce the arc flash hazard for faults downstream of the fuses.
- For continuous-process facilities that have maintenance personnel readily available to locate and repair a ground fault, consider specifying a "high-resistance" grounded system (see GROUNDING). This grounding technique is applicable to most low-voltage and some medium-voltage systems rated 4.16 kV and below. While application of high-resistance grounding does not limit the current magnitude of a line-to-line or a three-phase fault, it does significantly reduce the current magnitude of the most common fault—the line-to-ground fault.
- Consider specifying "arc-resistant switchgear." This type of construction is designed to safely relieve the pressures

Table 2. Flash Hazard Analysis and Personal Protective Equipment (PPE) Requirements

Energy Level/Application	Calculated Flash Protection Boundary	Direct Exposure	Door Closed and Latched	In Area, No Equipment Interaction
Level 4—typical 208 V, three-phase panel with <7 kA short circuit; typical 240/120 V, single-phase panel with <11 kA short circuit; typical 120 V control circuits. All upstream main CBs for panels are “instantaneous” trip type	0–6 inches	Safety glasses, hard hat,[a] light leather gloves, long-sleeve cotton or wool shirt	Safety glasses, light leather gloves	No flash PPE
Level 3—typical 208 V, three-phase panel with <30 kA short circuit with a main CB with “instantaneous” trip; work on 480 V motor control center control circuits with a “barrier” preventing contact with circuits	6–12 inches	Safety glasses, hard hat, face shield,[b] 4.5 oz. flame-resistant coveralls, light leather gloves	Safety glasses, hard hat,[a] light leather gloves, long-sleeve cotton or wool shirt	No flash PPE
Level 2—480 V motor control centers (MCCs) with <15 kA available at the MCC bus, upstream clearing time of 0.18 sec	12–30 inches	Safety glasses, hard hat, flame-resistant hood,[b] 6 oz. flame-resistant coveralls, long leather heat-resistant gloves	Safety glasses, hard hat, flame-resistant hood,[b] 4.5 oz. flame-resistant coveralls, light leather gloves	No flash PPE
Level 1—All MCCs and panels above 15 kA short circuit available at the MCC bus; all 480 V and higher voltage switchgear and switches	30 inches or greater	Safety glasses, hard hat, flame-resistant hood,[b] two layers consisting of 6 oz. flame-resistant coverall or 100% cotton inner layer (long sleeves), long leather heat-resistant gloves	Safety glasses, hard hat, flame-resistant hood,[b] 6 oz. flame-resistant coveralls, long leather heat-resistant gloves	No flash PPE

[a] Optional.

[b] Face shield and hood to have polycarbonate shield with ultraviolet protection.

internal to the switchgear during an arc of defined magnitude and duration. There is no consensus in the industry that this is cost effective or required for personnel safety (6), since there have been few incidents of ANSI-constructed switchgear exploding due to internal fault pressures.

MOTOR DRIVES AND ELECTRICAL SURGE PROTECTION

Primary Motor Uses and Types

As discussed in the introductory paragraphs of this article the electric motor is used as the prime mover for pumps, compressors, blowers, fans, extruders, conveyors, and many other applications within the industry. The required output ranges from a fraction of a kilowatt to several megawatts. In some cases, precise speed control is important, but in most cases it is not. The squirrel cage induction motor (SCIM) is the most commonly used in the industry. Its construction is simple, it can be built over wide size and speed ranges, and it does not have arcing components in normal operation. The latter characteristic makes the SCIM suitable for application in Division 2 or Zone 2 classified areas. Synchronous motors of the brushless excitation type are commonly used for slow-speed (<600 rpm) and high-power output applications. Brushless excitation is used almost exclusively due to the inherent problems with arcing brushes and slip rings in a classified area. The synchronous motor is generally more energy efficient in larger output ratings, and it has the advantage of providing voltage support to the local utilization bus during power system voltage dips. The self-excitation feature that aids the system during voltage dips can also be used to provide reactive power (power factor correction) for the power system. However, capacitors are generally more economic for this function.

Typical Enclosure Protection

Many petroleum and chemical facilities are in severe or dirty environmental conditions, so there is wide use of totally enclosed motors. This is almost exclusively true for output ratings below 200 kW, where the totally enclosed fan-cooled (TEFC) motor is the choice. For larger motors of voltage ratings 2300 V and above, the weather-protected type of motor is also in wide use. This construction uses outside air to cool the motor’s interior parts and is not suitable for extremely dirty or dusty environments. Where dirty conditions exist for the larger motor output ratings, the totally enclosed air-to-air-cooled enclosure or the totally enclosed water-to-air-cooled enclosure are well-suited. All of the enclosures described above are suitable for Division 2 or Zone 2 locations. For the small percentage of locations classified Division 1, totally enclosed motors of the explosionproof, forced ventilated (pipe ventilated), or purged types are the appropriate choice. For Zone 1 applications, the same motor types apply as for Division 1 (except "explosionproof" is called "flameproof" in international standards) and another type of construction, the "increased safety" type, is also applicable. Motors are not permitted in Zone 0 locations.

Motor Specifications

The IEEE and the American Petroleum Institute (API) have created several motor and generator specifications or standards that reflect the industry's severe environmental conditions and reliable service requirements for motors or generators (7–9). Low winding and bearing temperature requirements, along with strict bearing protection from dirt, are the primary contributions of IEEE Std 841 (7) for medium-sized, TEFC, induction motors. These motors are built for severe environmental service. The API standards (8,9) have evolved to be comprehensive purchase specifications with many purchaser choices. Blank data sheet forms, with guides to assist their completion, are included with the standards. The API standards include comprehensive testing requirements, particularly for mechanical vibration performance. These are particularly important for some of the large, high-speed variable-speed drives used in the petroleum and chemical industry (10). Some of the largest high-speed drives have been installed on a direct drive (no gearbox) compressor application. Reference 10 describes a 3500 hp, 11,000 rpm motor and variable-speed drive package.

Electric Machinery Surge Protection

Philosophy throughout the world differs on the need for the inherent capability of electrical machinery winding to withstand power system voltage surges. Electrical surges can be introduced into the system by a circuit breaker's arc interruption during a short circuit, motor switching, or capacitor switching, or by its current-limiting fuse interruption. Lightning could be a source, depending on the physical exposure of the power line to direct lightning strikes or strike inductive effects. In general, surges with short rise times ($<0.5\ \mu$s) are due to switching surges, and those with rise times of 1.2 μs are due to lightning surges. Surge capability is expressed in per unit (pu), where one pu is the crest of the line-to-ground voltage, or

$$1\,\mathrm{pu} = (2/3)^{1/2} \times V_L \qquad (2)$$

where V_L = rated line-to-line voltage.

The fast-rise-time surges are the most damaging to motor insulation due to the tendency for the entire surge voltage to impress itself across the first coil and, consequently, on the first turns within that coil. The insulation between turns can easily be destroyed by a fast-rise-time surge. As the surge rise time becomes greater than 5 μs, the surge tends to distribute itself over the entire winding and imposes less stress on the winding.

International standards establish surge withstand levels based on the machine operating voltage (11). For the fast-rise-time surges of 0.1 μs to 0.5 μs, a 2.3 kV machine winding's design must withstand 4.9 pu, a 4 kV machine 4.2 pu, a 6.6 kV machine 3.8 pu, and a 13.2 kV machine 3.5 pu. These values are 65% of the lightning (1.2 μs rise time) withstand levels for 2.3 kV of 7.6 pu, for 4 kV of 6.4 pu, for 6.6 kV of 5.8 pu, and for 13.2 kV of 5.4 pu. The National Electrical Manufacturers Association (NEMA) establishes the United States standards for motor winding surge capability without regard for the motor operating voltage at 2.0 pu for fast-rise-time surges and 4.5 pu for lightning surges. A NEMA option is 3.5 pu capability for fast-rise-time surges and 5.0 pu for lightning surges (this option corresponds to IEEE Std 522-1992 requirements). Building surge capability within a winding affects the amount of insulation required between the turns of a multiturn coil. The more surge capability required, the less room there is for copper in a winding slot. This generally means a larger machine with 0.2% to 0.3% lower efficiency for a 3.5/5.0 pu capability than for the base 2.0/4.5 pu capability machine.

The petroleum and chemical industry uses many machines with the 2.0/4.5 pu standard insulation system and uses a significant number of 3.5/5.0 pu systems where machines have been purchased to the API standards (8,9). Very few machines have been purchased in the United States to the more stringent international standards. For machines in critical plant service, it is common practice to apply a surge protection package similar to that shown in Fig. 1. The package is comprised of (a) a surge capacitor to extend the rise time of any surge to 10 μs or greater and (b) a station-class surge arrester to limit the magnitude of the surge voltage. The placement of the surge protection package directly at the motor terminals is important, because this may be a point of surge impedance mismatch between the cable feeder system and the motor. A surge amplification of almost double the incident surge could occur at this point.

The typical surge capacitor is designed with minimum internal inductance and is 1.0 μF per phase for application at 600 V or less, 0.5 μF for up to 4.16 kV, and 0.25 μF for 6.6 kV and above. The surge capacitor is typically a single-phase device, but can be purchased as a three-phase unit at the lower voltage ratings. Surge arresters specified are the metal-oxide varistor type and station class for a close protective margin. Specify a 2.7 kV arrester for 2.3 or 2.4 kV application, a 4.5 kV arrester for 4.0 or 4.16 kV application, a 7.5 kV arrester for 6.6 or 6.9 kV application, or a 15.0 kV arrester for machines rated 13.2 or 13.8 kV. Where the motor is kept running during a ground fault (on a high-resistance grounded power system), specify a 3.0 kV arrester for 2.3 kV or 2.4 kV application and a 6.0 kV arrester for 4.0 kV or 4.1 kV application. This is required to keep the voltage applied to the arrester during a continuously applied ground fault within the arrester's maximum continuous operating voltage rating. In Fig. 1, note the importance of keeping the connection lead lengths as short as possible. Bond the grounding lugs of the components to the terminal box metal enclosure at the component mounting location. If this is not done, the fast-rise-time current through the connection lead inductance could negate the effect of the surge capacitor or arrester. The best, lowest inductance path between the terminal box enclosure and the machine enclosure is the solidly bolted "throat," but this must be electrically continuous without gaskets. A supplemental ground wire should be bonded to the stator winding core and routed through the throat, with the wire connected to the terminal enclosure ground. Insulating blocks are recommended

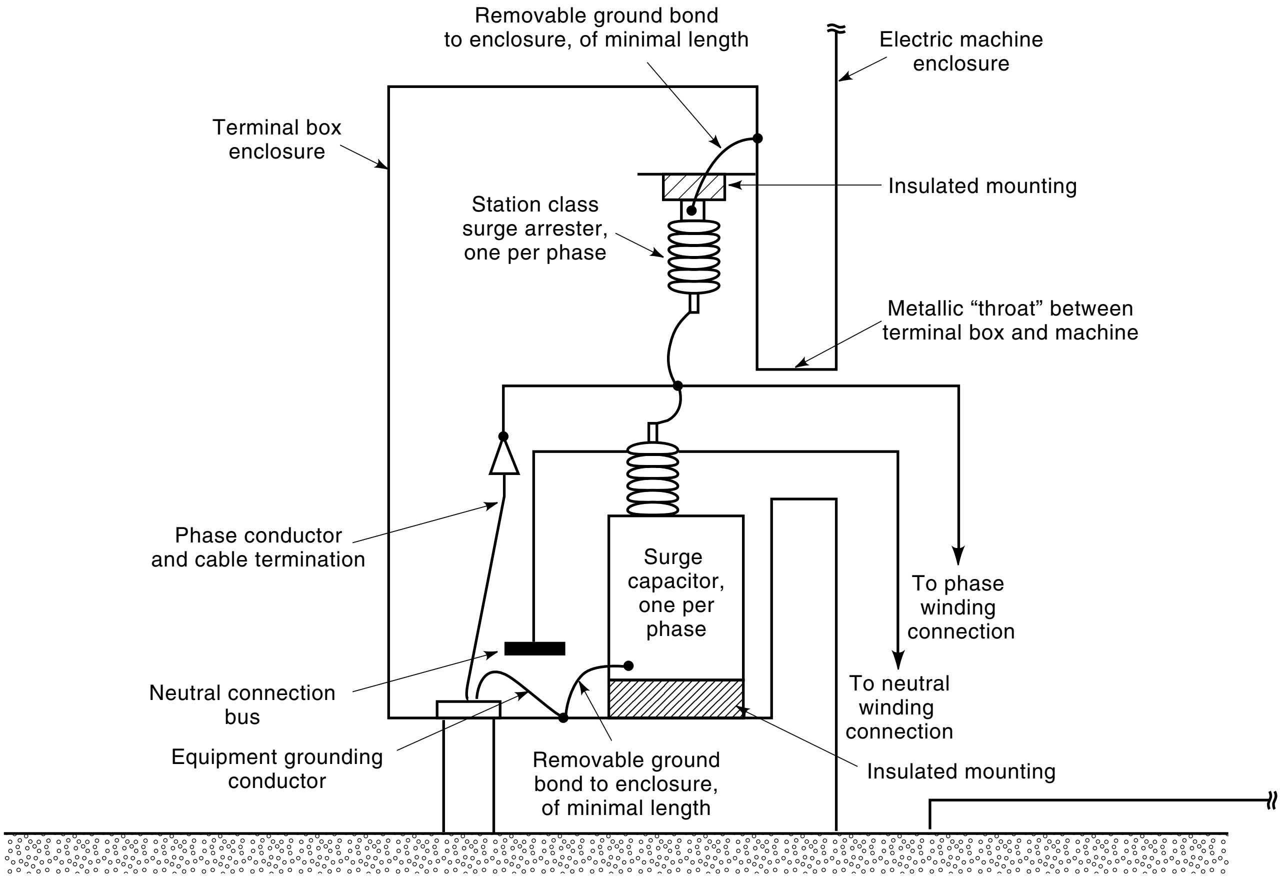

Figure 1. Recommended configuration for mounting surge arresters and capacitors within an electrical machine terminal enclosure. Shown here is an interior view of the box with only one phase included for clarity; the other two phases' surge arresters and capacitors are in line, directly behind those shown. All connection leads associated with the surge protective components should be as short as possible, and ground bonds should be made directly to the metal enclosure. Supplemental grounding conductors can be added to the surge protective components to provide a low-impedance, power-frequency return path for fault current.

beneath the surge components to permit their isolation during routine maintenance insulation-resistance or overpotential testing. This isolation may also be desirable if on-line partial discharge monitoring will be used for the machine (12).

COGENERATION AND LOAD SHEDDING SYSTEMS

Cogeneration is a major topic of this encyclopedia (see COGENERATION), and some applications to the petroleum and chemical industry are discussed in this section. The manufacturing sector of the industry is a large user of heat for its processes. Oil production may require injecting steam into petroleum reservoir formations to extract more crude oil. The steam requirements can be generated either by fuel-fired boilers or through cogeneration. The most common cogeneration configuration is to use a gas turbine to drive an electrical generator, take the hot exhaust from the turbine and introduce additional heat through a fuel burner duct section (since oxygen content of the gas turbine exhaust supports combustion), and finally pass the hot exhaust gases through heat recovery steam generators. Process heat needs are then met with the high-pressure steam. Lower steam pressure requirements may be met by the use of extraction steam turbines or noncondensing steam turbines to drive additional electrical generation. In many situations, the electricity generated during the process meets or exceeds the internal electrical demand of the facility. Most petroleum and chemical cogeneration is connected to the local electrical transmission system either for backup power supply or to export excess electrical generation. This may present problems during electrical transmission system problems external to the plant.

Load Shedding Systems

Load shedding systems are more properly termed "load preservation systems (LPSs)," since preservation of plant loads and product output is the intent. An LPS is needed when the load imposed on generation exceeds the supply capacity available. When load exceeds generation, the power system frequency declines at a rate determined by the overload and the kinetic energy available within the rotating machinery still connected to the power system. This situation may occur during a regional power emergency during transmission system disintegration. Frequency decline rates of 2 Hz per second are not uncommon during such an emergency, and the plant power system may quickly collapse if prompt action is not taken.

Events occur too quickly for human operators to intervene. The first element of an LPS is a digital underfrequency relay. This is connected to the power system bus through a voltage transformer and monitors the system frequency. If the system frequency drops below a set frequency, typically chosen between 59.0 Hz and 59.8 Hz on a 60 Hz power system, after a short delay (typically 0.05 s) the relay initiates a trip of the circuit breaker (which takes an additional 0.10 s to open) between the plant and the electrical transmission system. The total time between sensing the underfrequency to separation would be approximately 0.15 s, during which time the system would have declined an additional 0.3 Hz below digital underfrequency relay setting (at a frequency decline rate of 2 Hz per second). If the plant internal load exceeds the remaining internal generation, the frequency will continue to decline. Further action is necessary.

Internal Plant Load Preservation

Modern plant control systems may integrate the LPS function and monitor sequence of events (SOE). However, the normal update times of a computer control system are typically not fast enough for the SOE function, since power system protective relay initiation, equipment shutdown trips, and circuit breaker operations may occur during a fraction of a second. An SOE monitor is recommended on cogeneration systems to help quickly determine the root cause of a problem during failures. If the SOE function is used, the control system selected must have a resolution of approximately 1 ms to be of diagnostic use. To maintain this degree of event time-stamped resolution over a widely dispersed plant site, a common system time clock is necessary. There are global positioning satellite time clocks commercially available to provide this function.

A plant control system may also be used to continuously monitor loads throughout the plant for additional LPS load management during a system emergency. Loads can be divided by priority into several tiers that are disconnected at various digital underfrequency relay set points. The frequency and time delay settings for the LPS should be determined by a dynamic simulation of the power system. This can be accomplished through use of a power system stability computer program.

For systems with small generation capacity in relationship to the plant load, special provisions may be required. It may be necessary to immediately trip the plant-to-utility tie or to trip large blocks of low-priority plant load during a system emergency. Underfrequency-based LPSs alone may not enable power system recovery. Consider the set points and operating times of generator and distribution system protective relays whenever an LPS is applied. The protective relay settings must be compatible with the LPS.

Control Considerations During Isolation

While making the transition from parallel operation with the electrical utility to independent plant operation, there are a few generation control aspects that require attention. Turbine speed governing systems typically have two modes of operation: isochronous (constant speed) control and droop (speed reduces with load increase) control. Some governor types have an isochronous, load sharing feature that allows multiple generators on isochronous control to operate in parallel. Most cogeneration plant's governors operate in the droop mode, unless the governor is equipped with an isochronous, load sharing feature. When separation occurs and the control is in the droop mode, the frequency of the isolated system will establish itself according to the load, and multiple generators will not share load well. For this reason, an LPS is typically configured to automatically switch the governor on one generator (typically the largest unit) to isochronous control, while the others remain on droop control. Minor speed adjustments may need to be made after a separation to load the generators properly.

Similarly, most generator voltage regulators have two operating modes: voltage control and reactive-power/power-factor (VAR/PF) control. While it is easiest to operate a generator in the VAR/PF control mode, this may inhibit the generator excitation system from reacting during a severe system voltage depression. If the power system can be configured to use other means to control reactive power interchange between the cogeneration plant and the utility (such as a load-tap-changing transformer), generators should be kept in the voltage control mode for best response.

Sample Configuration for Cogeneration

Figure 2 illustrates a good way to integrate a cogeneration plant generator into a process plant power system. Plant process loads are fed from the same bus as the internal generator. As utilities enter deregulation, more severe faults and disturbances can be expected at the utility level (230 kV on Fig. 2). With the system parameters shown, the voltage at the 13.8 kV switchgear level can be maintained above 70% rated even during a bolted, three-phase fault at 230 kV. This configuration also makes good use of a duplex reactor (13) to control short-circuit current levels at the 13.8 kV level while also enhancing system voltage support.

A duplex reactor is formed when two identical single-phase reactors are physically oriented so that when they are connected in series, and current is passed through both reactors in series, their magnetic fields interact in opposition. The effect is that the series reactance of the two reactors in close physical proximity to each other is greater than the self-inductance of the two reactors added together. If X_1 is the reactance of the first reactor and X_2 is the reactance of the second reactor, when current is passed in series through both, the equivalent reactance is $X_1 + X_2 + f_C X_1 + f_C X_2$, where f_C is the coupling factor. The coupling factor represents how closely linked the two reactors are magnetically. Air-core, duplex reactors (15 kV voltage class) have coupling factors of approximately 0.3, while oil-immersed, iron-core reactors may attain coupling factors of up to 0.5. The equivalent circuit for the duplex reactor is given in Refs. 13 and 14 for analysis. The advantage of the configuration is that a portion of the reactance is canceled for normal current flow from the generator to the two 13.8 kV buses, but the reactor's coupling factor adds reactance if there is a short circuit on one 13.8 kV bus, and there is short-circuit contribution from the other 13.8 kV bus. A 115 kV or 230 kV fault is similar to the situation of normal generator current flow, when there is equal and opposite current flow through the duplex reactor. There is a reduced effect on system voltage drop at the 13.8 kV level from

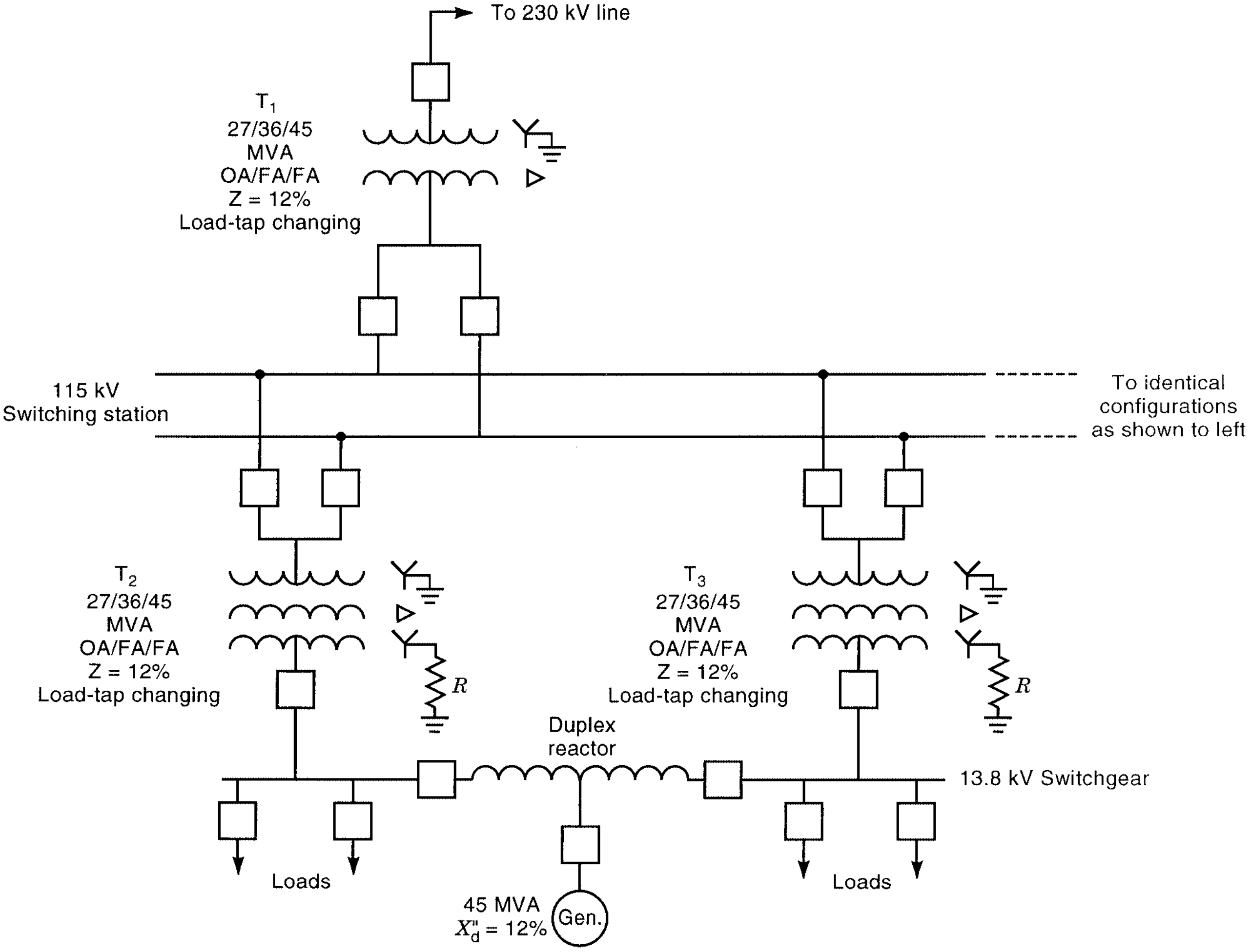

Figure 2. Sample configuration for cogeneration connected at the load utilization level. The 115 kV switching station shown is a "double breaker" scheme, but could be configured as a "breaker-and-a-half" or another way and not affect the immunity of the 13.8 kV system from severe 230 kV utility system faults. If the 115 kV system has fault exposure (e.g., aerial transmission lines and open-air substations instead of enclosed switchgear and insulated cables), reactance grounding of the 115 kV system level is recommended.

the duplex reactor's characteristic compared to two, normal current-limiting reactors in the same configuration. With the configuration of Fig. 2 and a duplex reactor with a center-to-end reactance of 0.25 Ω and a coupling factor of 0.4, generators rated up to 70 MVA rating could be accommodated within available ratings of 15 kV switchgear (1000 MVA Class short-circuit rating and 3000 A continuous current rating). This assumes transformers T_2 and T_3 of the rating and impedance shown and also assumes a 70 MVA generator with a subtransient reactance of 12%.

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PHASED ARRAY RADAR. See Antenna arrays.

PHASED ARRAYS. See Scanning antennas.

PHASE EQUALIZERS. See All-pass filters.