

# IEEE Guide for Maintenance, Operation, and Safety of Industrial and Commercial Power Systems

Sponsor

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of the  
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**Abstract:** Guidelines for the numerous personnel who are responsible for safely operating and maintaining industrial and commercial electric power facilities are provided. This guide provides plant engineers with a reference source for the fundamentals of safe and reliable maintenance and operation of industrial and commercial electric power distribution systems.

**Keywords:** electrical hazards, electrical maintenance, electrical safety program, fire protection, grounding, infrared, inspection, maintenance, operation protective devices, record keeping, safety single-line diagram, testing

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# Introduction

(This introduction is not a part of IEEE Std 902-1998, IEEE Guide for Maintenance, Operation, and Safety of Industrial and Commercial Power Systems.)

The purpose of this document is to provide guidelines for the numerous personnel who are responsible for operating industrial and commercial electric power facilities.

The Working Group on a Guide for Operation, Maintenance, and Safety of Industrial and Commercial Power Systems was formed in 1981. It was sponsored by the Industrial and Commercial Power Systems Engineering Committee of the IEEE Industry Applications Society through the Safety, Operations, and Maintenance Subcommittee. The requirements of the then-new Occupational and Safety Health Act (OSHA, a U.S. law) and the limited information that was generally offered at that time were prime driving forces. The first task of the Working Group, a formidable task, was to agree on a scope that would produce a publication of reasonable size. The final product provides basic philosophies and approaches to problems without going into great detail on any one aspect of the subject.

The Working Group recognizes the international applicability of this guide. The Working Group also recognizes that this first edition of the guide refers to some practices that are U.S. oriented. As a practical matter, the consensus was to publish this edition now and to start the first revision promptly, with international content. The Working Group and the Safety, Operations, and Maintenance Subcommittee have committed to incorporating international information in the first revision.

Over the years, a great many people have contributed to the development of this guide. The names of these contributors, to the extent known, are listed below. Undoubtedly, some names have been missed. We extend our apologies to those people for such inadvertent oversight.

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# IEEE Guide for Maintenance, Operation, and Safety of Industrial and Commercial Power Systems

## Chapter 1 Overview

### 1.1 Introduction

Even with the best design and equipment, the expected safety and reliability performance of a power system is largely dependent on the quality and capability of its operation and maintenance. Optimizing maintenance and operation often can be the most cost-effective approach in improving system performance.

The phrase “industrial and commercial power systems” covers a broad spectrum. At one end of this spectrum is the large, industrial complex that can justify a staff of highly-skilled and knowledgeable maintenance and operation personnel. At the other end of this spectrum is the small, simple system in which the owner may have little or no electrical expertise.

The objective of this guide is to provide plant engineers with a reference source for the fundamentals of safe and reliable maintenance and operation of industrial and commercial electric power distribution systems. These fundamentals are independent of system size or complexity. The most effective utilization of the information contained in this guide would be its inclusion in a long-term maintenance and operation strategy that is tailored to the individual needs of each power system.

The fundamental elements include

- a) Maintenance, operation, and safety considerations in system design;
- b) Development of a maintenance and operations strategy to ensure long-term reliability;
- c) Development of record-keeping and documentation files;
- d) Development and implementation of testing and inspection methods;
- e) Development of procedures for auditing maintenance and operation performance;
- f) Development of procedures to ensure personnel safety.

## 1.2 How to use this guide

Chapter 1 provides an overview of this guide.

Chapters 2 through 4 offer guidance for the establishment of administrative procedures, control procedures, and organizational capabilities to ensure a reliable system operation.

Chapters 5 and 6 review various maintenance strategies that are designed to achieve the desired level of performance reliability.

Chapters 7 through 12 provide safety information, a review of available safety equipment, and recommendations on the management of unusual or hazardous activity.

## Chapter 2

# Operating diagrams

### 2.1 Introduction

Operating diagrams are the road maps to the operation and maintenance of an industrial or commercial power system. The diagrams can be considered as the primary tool for work on a power system. Without the guidance that is provided by the information contained on these system diagrams, the operation and maintenance of an industrial or commercial complex would be extremely difficult and potentially unsafe.

Vendor's drawings and instruction manuals, plant drawings, maintenance histories, spare parts lists, standard operating procedures, and other documents should be systematically filed and readily available to the personnel who are involved in system operation. A plant's core distribution system may have a life of 30 or more years. Complete, up-to-date equipment documentation is essential not only for supporting routine daily activity, but also for the successful implementation of system expansion or modification. System documentation should include simplified one-line drawings that show only power sources, transformers, voltage levels, major loads, disconnecting devices, switches, and breakers. These drawings are essential for the planning and illustration of operation activity. A master file should be kept in which all revisions are noted and the drawings are subsequently updated because there may be several copies or files of essential drawings that depict the plant. The use of computer-aided drafting systems may expedite the process.

The drawings and the equipment identifications should agree. Frequently, equipment identification is incomplete and poorly located. Staff reliance on such documents may result in errors, if a system is not in place to ensure accuracy. Disconnecting means, switch operators, circuit breaker control switches, circuit breakers, push buttons, motors, and other devices should have complete stand-alone identification nameplates attached in immediate full view (i.e., "FDR 12, Sub. 3" vs. "FDR 12" for a switch control handle). Identification should be unique and affixed to all associated apparatus. The location of the identification nameplate can be as critical as the accuracy of the nameplate.

Critical process operations have been accidentally shut down because circuit breakers in panelboards were not properly identified. The identification of circuits during commissioning should always be verified. A mandatory policy requiring the regular review and updating of panelboard schedules should be instituted.

No standard diagram or type of diagram that is available can suffice for all industrial plants or commercial complexes. No standard electric distribution system is adaptable to all industrial plants because two plants rarely have the same requirements. This chapter outlines the types of diagrams and information that are available to map any distribution system. Consistency is an important factor, however, in keeping diagrams readable and understandable.

## 2.2 Single-line diagram (one-line diagram)

A reliable single-line diagram of an industrial or commercial electrical power distribution system is an invaluable tool. It is also called a one-line diagram. The single-line diagram indicates, by single lines and standard symbols, the course and component parts of an electric circuit or system of circuits. The symbols that are commonly used in one-line diagrams are defined in IEEE Std 315-1975.<sup>1</sup>

The single-line diagram is a road map of the distribution system that traces the flow of power into and through the system. The single-line drawing identifies the points at which power is, or can be, supplied into the system and at which power should be disconnected in order to clear, or isolate, any portion of the system.

### 2.2.1 Characteristics of an accurate diagram

The following characteristics should help to ensure accuracy as well as ease of interpretation:

- a) *Keep it simple.* A fundamental single-line diagram should be made up of short, straight lines and components, similar to the manner in which a block diagram is drawn. It should be relatively easy to get the overall picture of the whole electrical system. All, or as much as possible, of the system should be kept to one sheet. If the system is very large, and more than one sheet is necessary, then the break should be made at voltage levels or at distribution centers.
- b) *Maintain relative geographic relations.* In many cases, it is possible to superimpose a form of the one-line diagram onto the facility plot plan. This is very helpful toward a quick understanding of the location of the system's major components for operating purposes. It may, however, be more difficult to comprehend the overall system operation from this drawing. Such a drawing could be used for relatively simple systems. For more complex systems, however, it should be used in addition to the fundamental single-line diagram.
- c) *Maintain the approximate relative positions of components when producing the single-line diagram.* The drawing should be as simple as possible and should be laid out in the same relationship as an operator would view the equipment. The diagram does not need to show geographical relationships at the expense of simplicity.

NOTE—A site plan with equipment locations may be required to accompany the single-line diagram.

- d) *Avoid duplication.* Each symbol, figure, and letter has a definite meaning. The reader should be able to interpret each without any confusion. In this regard, equipment names should be selected before publishing the document; then, these names should be used consistently.

<sup>1</sup>Information on references can be found in 2.4.

- e) *Show all known factors.* All details shown on the diagram are important. Some of those important details are as follows:
  - Manufacturers' type designations and ratings of apparatus;
  - Ratios of current and potential transformers and taps to be used on multi-ratio transformers;
  - Connections of power transformer windings;
  - Circuit breaker ratings in volts, amperes, and short-circuit interrupting rating;
  - Switch and fuse ratings in volts, amperes, and short-circuit interrupting rating;
  - Function of relays. Device functions used should be from IEEE Std C37.2-1991;
  - Ratings of motors, generators, and power transformers;
  - Number, size, and type of conductors;
  - Voltage, phases, frequency, and phase rotation of all incoming circuits. The type of supply system (wye or delta, grounded or ungrounded) and the available short-circuit currents should be indicated.
- f) *Future plans.* When future plans are known, they should be shown on the diagram or explained by notes.
- g) *Other considerations.* Refer to IEEE Std 141-1993 for further discussion of single-line diagrams.

## 2.2.2 Uses of the single-line diagram

The single-line diagram may be used in a number of important ways in operating and maintaining an industrial or commercial power distribution system. Frequently, the single-line diagram, with all of the listed information, becomes too crowded for information to be used effectively in some of the operating activities. In those instances, it is wise to produce a set of single-line diagrams, with each different diagram in the set containing the pertinent information that is required for a particular activity or set of activities. Some of the needs for special single-line diagrams are

- a) *Switching functions.* When the primary use of the diagram is to provide information to system operators for switching in order to isolate portions for maintenance or for load control, then only the data required to make the decisions necessary for system switching are included on the diagram. Sometimes, when the distribution system is complex, a separate version of the single-line diagram in block form is more usable than a complete single-line diagram. This may be identified as a "system operating diagram."
- b) *Load flow control.* This diagram is used exclusively for load flow control. It only includes the data that show system component capacities and other data that pertain to load flow.
- c) *Relaying and relay logic diagrams.* These single-line diagrams are used to describe the system protective relay systems. These diagrams are used particularly as logic and tripping diagrams that may contain a unique language used only to depict the sequence of relay or system protective component operation under various fault conditions.
- d) *Impedance diagram.* This is a single-line diagram that shows the system input impedance and the impedance of all system components in which the impedance of each circuit branch is maintained for system short-circuit analysis. This diagram should include all reactance data on large rotating apparatus or the equivalent data for groups of machines.

### 2.2.3 Special single-line diagrams

For a large facility that has regularly changing conditions on its electrical distribution system, a mimic bus-type, single-line diagram is very useful. This type of single-line diagram could be a fairly simple pegboard arrangement with movable circuit symbols and tapes in several colors to identify voltage levels; or it could be a light-indicating board that indicates remote switch position via telemeter information and includes load flow data. Modern systems may have this data displayed on a computer monitor.

#### 2.2.3.1 Switching simulator

A switching simulator can be very useful for verifying the effects of any set of switching operations. Low-voltage toggle switches are substituted for circuit breakers and disconnect switches. Signal lamps indicate whether a circuit path has been omitted in the switching sequence, thereby offering the system operator a check on the switching plan prior to performing switching on the distribution system.

Interactive computer programs have been developed to provide the same system modeling as in the electrified-system one-line diagram. These programs can be rapidly manipulated to test any planned switching of an industrial plant's power system. They can be used to check a proposed set of switching instructions and, in some cases, to print a set of instructions to be used in the field.

### 2.2.4 Schedules

Panel schedules are not one-line diagrams by definition, but they often fulfill the same purpose. Low-voltage lighting and power panel schedules should be maintained as well as all other electrical distribution system diagrams, since they may be used in lieu of the one-line diagram.

## 2.3 Plan (equipment location plan)

A site plan usually is a necessary accompaniment to the single-line diagram for a complete description and mapping of the industrial and commercial electric distribution system. The locations of the major components of the system are usually easy to visualize; however, circuit routing is difficult to comprehend without a site plan.

Site plans are important for a number of reasons, all of which could affect the operation of the industrial plant or commercial complex at some time. If a major catastrophe such as fire, flood, or storm damage should occur, a site plan would be an important tool if the distribution system were to be reconstructed. The expansion and/or rearrangement of an electrical distribution system could be extremely difficult without accurate records of the location of existing system components. The site plan can be important for identifying the proximity of electrical system components to other maintenance work that may be taking place.

## 2.4 References

This chapter shall be used in conjunction with the following publications. If the following publications are superseded by an approved revision, the revision shall apply.

IEEE Std 141-1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (*IEEE Red Book*).<sup>2</sup>

IEEE Std 241-1990 (Reaff 1997), IEEE Recommended Practice for Electric Power Systems in Commercial Buildings (*IEEE Gray Book*).

IEEE Std 242-1986 (Reaff 1991), IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (*IEEE Buff Book*).

IEEE Std 315-1975 (Reaff 1993), IEEE Graphic Symbols for Electrical and Electronics Diagrams (Including Reference Designation Letters).

IEEE Std C37.2-1996, IEEE Standard Electrical Power System Device Function Numbers and Contact Designations.

IEEE Std Y32.9-1972 (Reaff 1989), American National Standard Graphics Symbols for Electrical Wiring and Layout Diagrams Used in Architecture and Building Construction.

## 2.5 Bibliography

Additional information may be found in the following sources:

[B1] *Guide to Industrial Electric Power Distribution*. Compiled by the editors of *Electrified Industry*, Chicago, IL: B. J. Martin Co.

[B2] "The Electric Power System," *Plant Engineering*, Oct. 15, 1981.

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<sup>2</sup>IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://www.standards.ieee.org/>).

## Chapter 3

# System management

### 3.1 Introduction

A well designed and constructed power system will not provide a safe and reliable operation unless it is properly managed. Any electrical power distribution system, from the smallest system to the largest and most complex system, needs to be managed. As systems become larger in size and complexity, the problems of system management increase, thereby requiring more time and attention from the system-operating personnel.

Good design, proper installation, quality assurance, and sound operating and maintenance programs provide the basic foundation for the safe and reliable operation of industrial electric power systems. A plant engineer who is faced with the task of improving the plant's electric power system performance, however, will likely find that programs to reduce human error are more cost-effective than system modifications or additional preventive maintenance. In fact, given good design and a sound maintenance program, the inherent system reliability can only be achieved by the reduction of operating error.

The operation of an electric power system should also address the problem of human errors. The following examples should be considered:

- Following a severe thunderstorm, a plant shift supervisor made a walk-through inspection of the plant's primary distribution switchgear. Upon seeing a red light for each circuit breaker, he immediately tripped each circuit breaker in order to obtain a green-light indication. Because he incorrectly thought that the red light meant "open," he shut down the entire plant.
- One of a plant's two steam boilers was down for annual inspection and maintenance. An electrician who was assigned to make a modification to the boiler control circuit erroneously began working on the operating boiler control circuit and shut down the operating boiler.
- An investigation of a 15 kV outdoor bus duct fault revealed that production personnel routinely turned off outside lighting at the beginning of the day shift by switching off circuit breakers in a 120 V distribution panel. The bus duct heater circuit was incorrectly identified, and was being switched off with the lighting circuits.

It is a natural tendency to blame equipment for failures, rather than human error. The bus duct fault in the last example could have been classified as an equipment failure; however, the prime cause was improper operation (human error) of the bus duct heaters.

Most plant electrical outages that clearly are not due to equipment failure, lightning, or utility disturbances can be prevented by making an objective investigation of the potential for outages and by following these guidelines:

- a) Document the system and identify the equipment.
- b) Plan switching operations in detail.
- c) Secure equipment from unintentional operation.
- d) Clearly define operating responsibility and adhere to it rigidly. System operation can and should be managed.

Effective managers of a power system will consider load distribution, system integrity, power factor, system protection coordination, and operating economics. Each of these areas is discussed in this chapter, thus showing how all of these considerations relate to each other. No area of industrial and commercial power system management is independent of the other.

## 3.2 Load distribution

How and where loads are connected to a distribution system normally are determined early in the system design. If the logic that is used in determining the load arrangement has been documented by the system designers, then the system operators may obtain and understand that logic. If it has not been documented, the logic should be developed later. Information for the development of that logic can be obtained from interviews with the system designers, if they are available, or by studying the loads and classifying them by type. Loads should be classified by their criticality to the operation of the facility that is served by the electrical distribution system. For example, loads such as boiler fans or boiler feedwater pumps would normally be listed as more critical to an industrial operation than the load of a single production area because loss of the boiler area could trigger a chain reaction that would affect the entire industrial plant.

The importance of various loads should be kept foremost in the system operator's mind when planning or performing any switching of the system. Switching should be done in such a manner that the integrity of service to critical loads is maintained or, at least, the possible increased exposure to service interruption is minimized. The system operator should have studied the consequences of a service interruption, and what actions to take should an interruption occur. Because the exact nature or cause of a service interruption cannot be determined before the fact, a definite course of action cannot be predetermined. General guidelines can be established, however, such as protecting the integrity of alternate sources. It is important not to use all alternatives and therefore get the power system extended into a long series of circuits such that a single failure can cause a total system collapse. Some computer programs can assist greatly in determining the consequences of each switching action.

The system operator should always monitor the electrical system load distribution in terms of nominal electrical load measurement parameters such as watts, vars, and amperes to ensure that some circuits are not overloaded while other circuits are underutilized. Where parallel or alternate circuits are available to carry the load, the system load should be balanced between the circuits, if the system connections make it possible. Critical service loads should be served from alternate circuits so that a single outage on one of the alternate circuits will not remove service from all critical loads. This concept may create a situation in which the load magnitudes are not balanced. The judgment should be made as to whether the operator wants load balance or a reduced probability of the upset of critical facility operations.

### 3.3 System integrity

Operation of electrical distribution systems should keep the system whole (totally in service) for as much of the time as possible. When a system has redundant circuits, as in the case of primary or secondary selective systems, the amount of time of operation as a radial system should be held to a minimum when an alternate circuit is removed from service for maintenance or other reasons. This is not intended to restrict maintenance or repair time, but to ensure that system integrity is maintained while a circuit is out of service. (See IEEE Std 141-1993.)<sup>1</sup>

A complex industrial plant may contain many redundant features that are related to the electrical power distribution systems. Redundancy allows for maintenance or repair on a portion of the system with minimum disruption to plant production. Some traps exist, however, that can easily undermine the reliability of redundant systems. Subclauses 3.3.1 through 3.3.4 discuss some of these traps and ways in which they can be avoided.

#### 3.3.1 Considering outside forces

All external influences should be considered when protecting the integrity of the electrical distribution system. The system should be protected, to the greatest extent that is practical, from damage or interference from outside sources. The operator needs to protect the system from negative environmental influences. The abbreviated list below outlines some of the factors for consideration.

- a) Maintain good housekeeping at all times. Good housekeeping in the substations and around all apparatus is necessary if uninterrupted service is to be maintained.
- b) Strictly avoid using electrical rooms and spaces for manufacturing or storage, except for minor parts that are essential to the maintenance of the installed equipment.
- c) Provide good general maintenance consistently. This applies to area maintenance as well as to electrical maintenance.
- d) Carefully consider the possible need for operation of cranes in the area where outdoor bare conductors are used as a part of the distribution system. The unexpected movement of crane booms near energized power lines can affect system integrity as well as the safety of personnel in the area.

#### 3.3.2 Equipment location

Ideally, distribution equipment should be isolated in a locked area, either indoors or outdoors, and should be accessible only to qualified personnel. Some electromechanical protective relays are vulnerable to vibration and accidental jarring, which could cause undesired relay operations. Janitors' brooms have an uncanny ability to find a control switch or bump the most sensitive relay. If substations or distribution switching equipment are located near pedestrian or vehicular traffic ways, traffic paths should be clearly marked and identified to keep personnel and vehicles away from the electrical equipment.

<sup>1</sup>Information on references can be found in 3.7.

### 3.3.3 Congested construction/maintenance activity

During maintenance shutdowns or during construction tie-in activity, the area around distribution equipment can become congested with materials and personnel. The protection of nearby operating equipment from accidental operation should be addressed. In redundant systems, such as primary selective or secondary selective distribution arrangements, a portion of the system may be energized while the equipment adjacent to it is serviced. In this situation, the two pieces of equipment should be individually barricaded, with personnel access strictly controlled during the periods of maintenance or construction. No exposure should exist that would allow personnel to accidentally bump against a control switch or protective relay.

### 3.3.4 Operating integrity

Operating integrity of the power system will also be affected adversely by inadequate system maintenance programs. Failure to perform maintenance work on a system adversely affects its integrity. The system operator should evaluate the merits of a redundant system, with portions that are occasionally out of service for maintenance, vs. waiting for a total shutdown on a simple radial system. The best maintenance plan for the particular power system in question should be determined.

## 3.4 Power factor

Low power factor will reduce system capacity. This reduction occurs because the equipment, particularly transformers and wiring, is forced to carry larger currents than would be necessary otherwise. This results in the increased heating of the equipment and conductors, as well as an increased voltage drop on the distribution circuits. Because of reduced voltage, utilization equipment operates less efficiently and motors overheat. The effects of low power factor are manifest throughout the distribution system back to, and including, the source (e.g., a utility company tie or self-generation). Some utility tariffs include power-factor penalty clauses that add surcharges on the utility bill if a facility does not keep its power factor above a predetermined value. The following should be noted:

- a) System operators need to be aware of low power factor anywhere on the power system so that they can evaluate and correct the situation.
- b) Correction can take the form of adding power-factor correction capacitors either to motor circuits or as shunt banks for system sections or entire systems.
- c) The operator should take advantage of any synchronous machines that may be on the system by using them to supply reactive flow into the system. Typically, synchronous generators are operated with a leading power factor to supply vars to the system. Synchronous motors usually are not loaded to their nameplate capability so these motors can be operated in an overexcited condition to supply vars to the power system.
- d) The use of high-power-factor lighting ballasts will avoid introduction of power-factor problems, and may improve the plant power factor significantly if lighting is a substantial part of the system load.

### 3.5 System protection coordination

When an electrical distribution system is designed and constructed, a fault-current coordination study should be conducted, and circuit protective devices should be sized and set according to the results of the study. In time, however, the electrical system configurations are often changed due to the changing needs of the end users. If the coordination and capability of the electrical equipment are not reviewed at the time of the changes, faults could result in unnecessary tripping of a main breaker or, even worse, an explosion of equipment that was thought to be in good condition. When system conditions change, the results that were obtained in the original fault-current coordination study may no longer apply to the current system. Unnecessary tripping, known as lack of selectivity, could be caused by poor coordination. An equipment explosion could result from the interrupting capability of the circuit breaker being exceeded. Both indicate a clear need for an updated fault-current coordination study.

#### 3.5.1 Utility systems delivering higher fault currents

The demand for electricity, particularly in the industrial and commercial environment, has been steadily increasing. Consequently, utility systems have grown much larger and have become capable of delivering much higher fault-currents at service points than in the past. Therefore, protective devices that were properly applied at the time they were installed may have become inadequate after system changes, and the protective system may no longer be coordinated. When available fault current increases to the point at which it exceeds protective device interrupting and withstand ratings, violent failure is possible, regardless of how well the devices are maintained.

#### 3.5.2 Protection in an electrical distribution system

System and equipment protective devices are a form of insurance. This insurance pays nothing as long as there is no fault or other emergency. When a fault occurs, however, properly applied protective devices reduce the extent and duration of the interruption, thereby reducing the exposure to personal injury and property damage. If, however, the protective system does not match system needs, just as an insurance policy should keep up with inflation, it is no help at all. It is the responsibility of the system operator to ensure proper system protection and coordination.

#### 3.5.3 Protective equipment set to sense and remove short circuits

In medium-voltage systems, the protective equipment for feeder conductors is often set to sense and remove short circuits, but not necessarily to provide overload protection of circuits. Device settings sometimes are purposely chosen low enough to sense and provide a degree of overload protection. Operators should be aware of this so that a protective device that is set lower than necessary for coordination does not cause a false tripping action during system switching procedures. System protection coordination is an important consideration in switching systems with loop feeds and alternate sources. To avoid false tripping action, operators should be aware of the settings and any probable temporary overloads or circulating currents during switching.

## 3.6 Operating economics

It is important to operate an electrical distribution system economically because of the high costs of losses and the cost of system expansion. Today, there are numerous methods for monitoring and controlling the power flow through the distribution system. These methods range from simple ammeter, voltmeter, wattmeter, and varmeter systems to complex supervisory control and data acquisition systems. A system can be designed to fit the needs and budget of any size facility.

### 3.6.1 Energy conservation

Energy conservation is the key to the economic operation of a power system, regardless of the methods that are used to monitor and control the energy flow through the system. Energy conservation begins with thorough and complete design practices. The system should be operated in such a manner as to keep losses to a minimum and to minimize any utility power factor or demand charges.

### 3.6.2 Power-factor correction

Power-factor correction, by the addition of capacitors at the facility service point, reduces power-factor charges from the serving utility. This, however, does not release any capacity of the load-side distribution system. Power-factor correction, closer to the loads, reduces currents in the main feeder conductors. This reduces the system losses, reduces power-factor billing charges, releases circuit capacity, and improves voltage regulation. The release of circuit capacity may be used to avoid costly system expansion projects by allowing additional circuit loading.

### 3.6.3 Utility demand charge

Most utilities have a demand charge that is based on kilovolt-amperes and kilowatts, or kilovolt-ampere-hours and kilowatt-hours, which automatically includes power factor, and they charge a financial penalty for loads that operate below a specified minimum power factor. The demand level is dependent upon the type of industrial plant or commercial facility. The system operator should develop the logic of that operation so that effective demand control can be practiced. Demand charges normally are maintained at peak levels for finite time periods after a new peak is established. The cost of a single peaking event could have a recurring cost for as long as 12 months. Lack of demand control can escalate one apparently small indiscretion into a very expensive event. The unnecessary operation of spare equipment that adds load to the system, even for a short time, should be avoided so as not to increase demand peaks. The operator should be aware of the serving utility rate/demand structure in order to operate at peak effectiveness and to avoid any unnecessary demand charges.

### 3.7 References

This chapter shall be used in conjunction with the following publications. If the following publications are superseded by an approved revision, the revision shall apply.

IEEE Std 141-1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (*IEEE Red Book*).<sup>2</sup>

IEEE Std 241-1990 (Reaff 1997), IEEE Recommended Practice for Electric Power Systems in Commercial Buildings (*IEEE Gray Book*).

IEEE Std 242-1986 (Reaff 1991), IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (*IEEE Buff Book*).

### 3.8 Bibliography

Additional information may be found in the following sources:

[B1] Beeman, D., ed., *Industrial Power Systems Handbook*. New York: McGraw-Hill, 1955.

[B2] Smerton, R. W., ed., *Switchgear and Control Handbook*. New York: McGraw-Hill, 1977.

[B3] “The Electric Power System,” *Plant Engineering*, Oct. 15, 1981.

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<sup>2</sup>IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://www.standards.ieee.org/>).

## Chapter 4

# System control responsibilities and clearing procedures

### 4.1 Introduction

Everyone who interacts with the power supply and distribution system of an industrial or commercial establishment has some responsibility for the control of that system. The owner has primary and ultimate responsibility for all operating occurrences on the power distribution system. Those who perform maintenance on the system, any contractors or others who may work on the system, and the utility, however, also have control responsibilities.

The complexity of control, and the level of technical and management attention required, increases with the complexity of the system. A simple, single-source radial supply system with one distribution panelboard or switchboard usually does not need detailed clearing procedures (i.e., de-energizing a portion of the system and/or shifting load) for making the system ready for work. A system with loop feeds and alternate sources requires carefully studied and detailed procedures to ensure personnel safety.

### 4.2 Responsibility of the owner

The owner has the ultimate responsibility for system control. This includes the responsibility of being assured that all other parties perform at a level that is consistent with their responsibilities. In effect, the owner becomes responsible, to some degree, for the actions of all parties that perform work on or with the power distribution system in the facility.

The owner, or the owner's representative(s), should be aware and knowledgeable of all work that is performed on the system. This does not mean that the owner shall possess the technical details of any and all work to be performed; however, a general understanding is required. The owner needs to provide for the de-energization of the system, isolation, lockout and/or tagout, and testing that are required before personnel are allowed to work on any portion of the system.

If the system is large and complex, the owner or the owner's representative(s) normally should utilize their clearing procedures to get the system ready. This usually includes all switching that is required to de-energize the system or portion of the system in the work area that applies grounding devices and the necessary tagging or locking-out of all the isolating devices. On a simple radial feeder system, personnel may be permitted to open the isolating device lock and/or tag the isolating device themselves and apply grounding devices when necessary. The owner still is responsible to see that it is done properly.

Another responsibility of the owner is to control access as required by law. The owner is responsible for the protection of the general population of the location from possible harm by making certain portions or components of the power distribution system accessible only to

qualified persons. That responsibility can be carried out, in part, by the proper posting of warning signs.

### 4.3 Maintenance role

Maintenance personnel shall take the necessary steps to ensure that the system or portion of the system on which they plan to work is in an electrically safe working condition. They should then add any additional protective devices, such as locks and tags. Before maintenance personnel start any work on the power distribution system, they are responsible for assuring themselves that the system is safe for work. Maintenance personnel should maintain the system isolation devices and lockout mechanisms in good working order. For a more complete discussion concerning safe practices and lock and tag requirements, see 10.4.2.

### 4.4 Utility responsibilities

It is the responsibility of the serving utility company to switch for isolation of the utility power supply prior to the service point to any facility. The utility shall supply to the facility owner or the owner's representative(s) a point at which to padlock the service disconnect or provide some other means of service isolation control.

It is also the primary responsibility of the serving utility company to protect the service from possible disturbances or damage from outside influences. The serving utility shall also protect its service equipment from access by unauthorized personnel.

### 4.5 Other workers

Outside contractors (i.e., nonowner personnel) shall assure themselves that they have an understanding of the system on which they are going to work and how it is isolated from all energy sources. They should understand how isolation and protection are achieved, and should comply with the owner's clearance procedures to ensure their continued safety. Contractor employees should add their own lockout/tagout device(s) to the appropriate isolation point(s). Relevant drawings and other information should be made available and should be reviewed with persons working on the system. (See Chapter 2 for a more complete discussion of drawings.)

### 4.6 Clearing procedures

The complexity of the system normally determines the level of detail planning that is required for system clearing procedures. A simple, single-source, radial supply system may only require opening a single switch or circuit breaker for circuit isolation. The clearing procedures for even so simple a case, however, should include checking to ensure that no other sources exist and that the correct isolating device is being operated. It is important that all persons who may be exposed to a hazard, as a result of a switching action, be notified prior to the action.

Complex power distribution systems that require several switching steps to isolate a portion of the system require more elaborate clearing procedures. It is necessary to use written switching instructions for systems that may have several sources into an area. When written instructions are used, a third party, who is familiar with the power system, should review them for errors and omissions. The consequences of learning about switching errors while in the act of switching are usually costly, especially when the wrong portion of the system is accidentally de-energized. It is important that written procedures be shared with all persons who are involved in the switching process.

A single-line diagram should accompany the written switching instructions so that the switch operator can keep track of the progress through the system. A real-time, single-line mimic bus on a very complex system allows for the independent monitoring of the switching process through the system as component status is changed. Some mimic-bus systems allow the operator to simulate switching of the system off-line, which allows for the detection of possible errors before the actual switching is performed.

The clearing procedures should be completely written, checked, and understood by all persons involved before they are applied to any portion of the power distribution system. The instructions and/or procedures should include a verification that the power has been removed (by live-line testing or other means) followed by the placement of grounds and the locking/tagging of isolating devices.

## 4.7 References

This chapter shall be used in conjunction with the following publications. If the following publications are superseded by an approved revision, the revision shall apply.

Accredited Standards Committee C2-1997, National Electrical Safety Code® (NESC®).<sup>1</sup>

IEEE Std 141-1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (*IEEE Red Book*).<sup>2</sup>

IEEE Std 241-1990 (Reaff 1997), IEEE Recommended Practice for Electric Power Systems in Commercial Buildings (*IEEE Gray Book*).

NFPA 70E-1995, Standard for Electrical Safety Requirements for Employee Workplaces.<sup>3</sup>

<sup>1</sup>The NESC is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://www.standards.ieee.org/>).

<sup>2</sup>IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://www.standards.ieee.org/>).

<sup>3</sup>NFPA publications are available from Publications Sales, National Fire Protection Association, 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, USA (<http://www.nfpa.org/>).

## Chapter 5

# Maintenance strategies

### 5.1 Introduction

The research and analysis of the optimum maintenance program for electrical equipment have been ongoing tasks of the maintenance manager for as long as electrical equipment has been used to support facility or plant operation. In spite of the findings from decades of analysis, maintenance programs still vary from breakdown maintenance programs to very sophisticated preventive maintenance programs. Preventive maintenance programs may include predictive maintenance as well as a more sophisticated reliability-centered program. The many variables that exist, from the types of electrical equipment to the types of applications in which they are used, make the universal definition of an exact maintenance program very difficult. It is believed almost universally, however, that some form of maintenance is necessary.

NFPA 70B-1994 [B3]<sup>1</sup> states the following:

“Electrical equipment deterioration is normal, but equipment failure is not inevitable. As soon as new equipment is installed, a process of normal deterioration begins. Unchecked, the deterioration process can cause malfunction or an electrical failure.”

It is necessary to control equipment deterioration in order to maintain the use for which the equipment and systems were originally designed and installed. Although most parties would agree that preventive maintenance is necessary in order to ensure the reliability of electrical power systems, there remains a wide disparity as to the content of a preventive maintenance program.

### 5.2 Definitions and acronyms

#### 5.2.1 Definitions

For the purposes of this guide, the following terms and definitions apply. IEEE Std 100-1996<sup>2</sup> should be referenced for terms not defined in this subclause.

**5.2.1.1 breakdown maintenance:** Those repair actions that are conducted after a failure in order to restore equipment or systems to an operational condition.

**5.2.1.2 electrical equipment:** A general term that is applied to materials, fittings, devices, fixtures, and apparatus that are a part of, or are used in connection with, an electrical installation. This includes the electrical power generating system; substations; distribution systems

<sup>1</sup>The numbers in brackets correspond to those of the bibliography in 5.7.

<sup>2</sup>Information on references can be found in 5.6.

including cable and wiring; utilization equipment; and associated control, protective, and monitoring devices.

**5.2.1.3 maintenance:** The act of preserving or keeping in existence those conditions that are necessary in order for equipment to operate as it was originally intended.

**5.2.1.4 predictive maintenance:** The practice of conducting diagnostic tests and inspections during normal equipment operations in order to detect incipient weaknesses or impending failures.

**5.2.1.5 preventive maintenance:** The practice of conducting routine inspections, tests, and servicing so that impending troubles can be detected and reduced or eliminated.

**5.2.1.6 reliability-centered maintenance (RCM):** A systematic methodology that establishes initial preventive maintenance requirements or optimizes existing preventive maintenance requirements for equipment based upon the consequences of equipment failure. The failure consequences are determined by the application of the equipment in an operating system.

## 5.2.2 Acronyms

|      |                                              |
|------|----------------------------------------------|
| EPM  | electrical preventive maintenance            |
| NETA | InterNational Electrical Testing Association |
| RCM  | reliability-centered maintenance             |
| UPS  | uninterruptible power supply                 |

## 5.3 Preventive maintenance

### 5.3.1 Philosophy

Most people recognize the need for the maintenance of electrical equipment. The debate really focuses on how much maintenance is enough. The key to the discussion over the proper amount of maintenance centers on the economic balance between the cost of performing maintenance and the importance of reliable power. For example, a computer center with a downtime cost of \$100 000 or more an hour would justify a much more extensive maintenance program than would a small facility whose downtime cost might be minuscule in comparison.

Moreover, it has been shown that there is a balance to the amount of economic benefit that is achieved from performing maintenance. A lack of maintenance eventually results in failures and a high cost to a plant. Likewise, an extreme amount of maintenance is wasteful and also results in a high cost to a plant. The optimum maintenance program lies somewhere in between. This balance point can vary for different types of facilities.

There are two benefits to having an effective preventive maintenance program. The first is that costs are reduced through the minimizing of equipment downtime. The second benefit is

obtained through improved safety and system performance. Other intangible benefits include things such as improved employee morale, better workmanship, increased productivity, reduced absenteeism, reduced interruption of production, and improved insurance considerations. In planning an electrical preventive maintenance (EPM) program, consideration must be given to the costs of safety, the costs associated with direct losses due to equipment damage, and the indirect costs associated with downtime or lost or inefficient production.

### 5.3.2 Design considerations

The best preventive maintenance programs start during the design of the facility. A key design consideration in order to support preventive maintenance is to accommodate planned power outages so that maintenance activities can proceed. For example, if delivery of power is not a 24 hour necessity, then extended outages after normal work hours can be allowed for maintenance activities. Otherwise, consider design features that can speed up the maintenance process or reduce the duration of the outage to loads. These might include redundant circuits, alternate power sources, or protective devices such as drawout circuit breakers (rather than fixed-mount circuit breakers).

Additional consideration should be given to the accessibility of the electrical equipment for maintenance. Circuit breaker location can be critical to the maintenance process. An example would be circuit breakers that are installed in a basement that has only stairway access through which equipment can be brought down to the circuit breaker location. In addition, access to the back of switchboards or switchgear, as opposed to their being mounted against the wall, may be necessary in order to perform thorough maintenance.

The environment in which the equipment is installed can play an important part in maintenance. Where equipment is mounted (inside or outside) and whether it is properly enclosed and protected from dust, moisture, and chemical contamination are all factors that influence the frequency with which maintenance tasks should be performed.

The design phase is also the period in which the establishment of baseline data for the equipment should be considered. This can be done by including in the design specifications the acceptance or start-up testing of the equipment when it is first installed. The InterNational Electrical Testing Association (NETA) provides detailed specifications for electrical power equipment in NETA ATS-1995 [B1].

Design drawings are very important to an effective maintenance program. As-built drawings should be kept up-to-date. An accurate single-line diagram is crucial to the effective and safe operation of the equipment. This helps the operator to understand the consequences of switching a circuit that can interrupt power in an undesirable or unplanned mode. More significantly, it can help avoid the accidental energization of equipment.

As part of the procurement of the electrical equipment, consideration should be given to the tools and instruments that are required to perform effective maintenance, such as hoists or manual-lift trucks that are used to remove and install circuit breakers. These tools and instruments will help to ensure safety and productivity. Finally, the installation, operation, and maintenance manuals should be obtained and filed.

### 5.3.3 Creating an EPM program

To be successful, a preventive maintenance program shall have the backing of management. There should be the belief that operating profit is increased through the judicious spending of maintenance dollars. Financial issues should be considered when evaluating the need for continuous electrical power. These factors will help to dictate the level of importance that a facility places on a preventive maintenance program. The cost of downtime or lost production, and how that can be minimized through effective maintenance, also should be considered.

A complete survey of the plant should be performed. This survey should include a listing of all electrical equipment and systems. The equipment should be listed in a prioritized fashion in order to distinguish those systems or pieces of equipment that are most critical to the operation. The survey should also include a review of the status of drawings, manuals, maintenance logs, safety and operating procedures, and training and other appropriate records. It should be recognized that the survey itself can be a formidable task. It is likely that power outages may be required in order to complete the survey. The gathering of documentation is important. This includes not only the drawings of the facilities, but also all the documentation that is normally provided by the manufacturer of the equipment. The manufacturer's manuals should include recommended maintenance procedures, wiring diagrams, bills of materials, assembly and operating instructions, and troubleshooting recommendations.

Next, the necessary procedures for maintaining each item on the list should be developed. NFPA 70B-1994 [B3] and NETA MTS-1993 [B2] are valuable resources that provide much of this information. Procedures should also be developed that integrate the equipment into systems. People that are capable of performing the procedures should be selected and trained. At some level of technical performance, it may be desirable to contract parts of the maintenance program to qualified outside firms, particularly those functions that require special test equipment to perform.

Finally, a process shall be developed to administer the program. This process may be manual or software-based. There are many commercially available systems with varying levels of sophistication.

Consideration also shall be given to some of the less technical parts of the process. Pre-maintenance considerations might include the logistics of getting equipment in and out of the area to be maintained, general safety procedures, procedures to be followed in the event of an emergency, and record-keeping that has to be accomplished ahead of the maintenance activity, as well as follow-up maintenance, special lighting needs, and equipment-specific safety precautions. In addition, an ongoing task is that of keeping access to electrical equipment free from being blocked by stored materials, such as spare parts. Record keeping and maintenance follow-up activities also shall be considered.

### 5.3.4 Reliability-centered maintenance (RCM)

RCM is a systematic and comprehensive approach to the maintenance of systems and equipment in which reliability is critical. RCM was initially developed by the airline industry, but has since been adopted by several other industries. The process involves analyzing the criti-

cality and failure mode, and then determining for each component what is the appropriate and effective preventive maintenance activity. All possible failure modes and appropriate preventive maintenance are evaluated for each component, thus establishing a program that is proven to result in improved facility reliability. Other benefits include improved safety, decreased repair costs, shorter outages, reduction in overhaul frequency, and improved management of spare parts.

The following outlines the important philosophical topics surrounding RCM:

- a) RCM is simply organized, documented, common sense.
- b) The focus of RCM is to analyze and make changes to current preventive maintenance program activities in order to improve their applicability and cost-effectiveness.
- c) RCM evaluations determine the maintenance requirements of equipment based upon the function of the system and how the equipment supports the function. An RCM-based maintenance program provides a technical basis for preventive maintenance activity that is not strictly based upon regulatory requirements, vendor recommendations, or industry standards.
- d) RCM focuses preventive maintenance resources on equipment that is critical to maintaining important system functions. RCM emphasizes proactive, predictive maintenance techniques over traditional, time-directed maintenance techniques.

Implementing an RCM program involves taking an existing EPM program and modifying it to align with the “critical path” or “mission” of the facility. In a data center, that would include everything that is necessary to keep the computers running, which includes the uninterruptible power supply (UPS) as well as the air conditioning system. All the systems in the critical path would receive priority, while the remaining nonessential support systems would receive much less attention.

### 5.3.5 Specialized equipment

The maintenance of electrical power systems requires a wide range of materials, tools, and test equipment. Normal hand tools and maintenance supplies, such as cleaning materials, vacuums, and other shop-oriented tools, are necessary. At the other end of the spectrum are specialized test instruments, such as high-current test sets that are necessary for primary injection of low-voltage circuit breakers. Some protective devices now require computers in order to perform calibration.

Safety equipment is also necessary for maintenance. This may include safety grounds, flame-retardant clothing, and face shields; protective rubber goods such as blankets, gloves, and sleeves; and insulated hand tools such as screwdrivers and pliers. Also needed for safety are portable meters or instruments to determine the presence or absence of voltage. This determination is necessary at each voltage level within the facility.

### 5.3.6 Record keeping

Each maintenance interval should be documented by listing the equipment that is being serviced and the maintenance procedures that are being applied. Data sheets that record the results of all tests should be completed.

These data should be analyzed by maintenance management in order to help determine the condition of the equipment and to determine the necessary repairs. Repairs could be categorized by their critical nature, such as whether the repairs need to be done immediately before returning to service or whether they could be scheduled for a future date. The results of the maintenance records and the analysis of the data should lead management toward either increasing or decreasing the maintenance frequency, or toward determining that the frequency and procedures are adequate.

A short-circuit and coordination study should be maintained up-to-date. This document not only helps plant maintenance personnel evaluate the suitability of protective devices for safely interrupting fault currents that can occur in the plant, but also gives the information that is necessary to set adjustable circuit breakers and protective relays to provide for the optimum selectivity. Proper coordination will minimize plant power outages in the event of equipment failure.

## 5.4 Fundamentals of electrical equipment maintenance

### 5.4.1 Inspection and testing

The condition of electrical equipment is generally affected by the atmosphere and conditions under which the equipment is operated and maintained. Water, dust, temperature, humidity, corrosive fumes, vibration, and other environmental factors can adversely affect electrical equipment. Electrical equipment life can be extended dramatically by simple precautions that promote cleanliness, dryness, tightness, and the prevention of friction.

The thoroughness of maintenance procedures can be categorized into three different levels:

*Level 1*—General inspection and routine maintenance;

*Level 2*—Inspection, general tests, and preventive maintenance;

*Level 3*—Inspection, specific tests, and predictive maintenance.

Testing would include

- a) Insulation tests;
- b) Protective device tests;
- c) Analytical tests (e.g., time travel analysis, dissolved gas analysis, infrared, and contact resistance);
- d) Grounding tests;
- e) Functional tests.

Chapter 10 describes each of these tests in detail.

The following equipment should be in the maintenance program:

- Switchboards and switchgear assemblies
- Disconnecting switches
- Circuit breakers
- Capacitors
- Surge arresters
- Current transformers
- Voltage transformers
- Protective relays
- Network protectors
- Fuses
- Batteries and battery chargers
- Meters and other instruments
- Alarms and alarm systems
- Grounding
- Ground detection schemes
- Transformers
- Insulating liquids
- Cables
- Busways
- Busducts
- Motor control center and motor starters
- Motor protective devices
- Motor drives
- Transformer auxiliary systems
- Rotating equipment
- Lighting
- Wiring devices
- Uninterruptible power supplies
- Transfer switches
- Test and safety equipment

#### 5.4.2 Repairs

Repairs can be categorized by their sense of urgency. Some repairs must be accomplished before the equipment can be returned to service. Other repairs may require material items that are not stocked, and cannot be accomplished until those items have been received and properly installed. Some repairs can be postponed, thus allowing the electrical system to go back into service without undue risk. In this method, the repair could be scheduled for a future date when it is more convenient to the plant.

A part of EPM is determining which spare equipment or parts should be kept in stock, such as fuses, circuit breakers, and other components, in order to be able to repair critical items and return a shut-down facility to operation. This, like the maintenance procedure itself, is an economic benefit vs. cost of inventory balancing act.

### 5.4.3 Failure analysis

When equipment fails, it is important to understand the reason why. Failure analysis, when done properly, locates the root cause of the failure. This is important in order to take the necessary steps to prevent similar failures in the future. Failure analysis involves an effort to reconstruct, at least mentally, the conditions that existed prior to failure and the events that led to the nature of the failure. It is through this process that the root cause can be determined.

There are engineers that specialize in forensic and failure analysis. These people, through their experience, are generally able to recognize failure patterns and to draw accurate conclusions much more readily than the untrained person. This is a specialty that is generally contracted when firms do not have that capability in-house.

## 5.5 Inspection and test frequency

Equipment in a critical service would generally receive maintenance attention more frequently than other equipment. Manufacturer's service manuals should be consulted in determining an adequate frequency. They generally give frequencies that are based upon a standard, or average, or upon operating conditions. This is a good basis from which to start in determining the frequency for a given facility. A good guide for both maintenance frequency and routine inspections and tests is found in NFPA 70B-1994 [B3]. Proper maintenance record keeping, together with periodic reviews, should reveal where adjustments to the frequency may be necessary, based on the actual effectiveness of the maintenance program.

## 5.6 Reference

This chapter shall be used in conjunction with the following publication. If the following publication is superseded by an approved revision, the revision shall apply.

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.<sup>3</sup>

## 5.7 Bibliography

Additional information may be found in the following sources:

[B1] NETA ATS-1995, Acceptance Testing Specification.

[B2] NETA MTS-1993, Maintenance Testing Specification.

[B3] NFPA 70B-1998, Recommended Practice for Electrical Equipment Maintenance.<sup>4</sup>

<sup>3</sup>IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://www.standards.ieee.org/>).

<sup>4</sup>NFPA publications are published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269, USA (<http://www.nfpa.org/>). Copies are also available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

## Chapter 6

### Maintenance testing overview

#### 6.1 Introduction

Maintenance testing is an important procedure that is used to detect deficiencies in electrical equipment before the equipment fails in service, often catastrophically. The very nature of electricity creates this need for testing. In normal operation, electrical equipment transports and utilizes energy. When a problem arises, such as an overload or a short circuit, the system should detect the problem and isolate it in a safe manner. The only way to know if the protective system works before it is needed is through testing. By simulating the various failure modes with nondestructive test methods, deficiencies in the system can be located and corrected. Then when the system is called upon to operate in a fault condition, testing helps to ensure that it does its job properly and safely.

Electrical equipment is used in a variety of categories with respect to energy. Power flow starts with generation equipment. Next, electrical equipment such as transmission and distribution lines, power cables, and bus structures are used to transport energy. Other equipment, such as transformers, rectifiers, and converters, will change the form of the energy in some manner. A fourth category of equipment is used to detect and isolate problems. This includes the sensing devices, such as protective relays, along with the interrupting devices, such as circuit breakers, switches, or fuses. The final category of equipment utilizes the energy to perform work in such forms as motors, solenoids, or electric heaters.

Maintenance testing needs may vary with each of these categories. Keep in mind that the purpose of maintenance testing is to determine if the equipment will continue to properly perform its function. In many cases, the testing consists of simulating different operating conditions and evaluating how the equipment responds.

##### 6.1.1 Acronyms and abbreviations

|        |                                  |
|--------|----------------------------------|
| CT     | current transformer              |
| DLA    | dielectric loss angle            |
| hi-pot | high potential                   |
| PT     | potential transformer            |
| RCM    | reliability-centered maintenance |
| TTR    | transformer turns ratio          |
| VT     | voltage transformer              |

#### 6.2 Insulation tests

One characteristic that all types of electrical equipment have in common is the use of some form of insulation. At its most basic level, all electrical equipment have some part or parts that conduct electricity and other parts that do not. A bare overhead distribution line is held

up by insulators and also utilizes the air around it for insulation. Transformer windings have insulation around each turn of the conductors and, in some cases, use oil, in addition, to raise the insulation value between the conductor and the grounded components.

The primary factor that determines the level of insulation that is required is the operating voltage. Other factors, such as current and frequency, also play a part; however, they are secondary to voltage. Therefore, the first consideration in testing insulation is whether it can support the required voltage without breakdown. This is accomplished by measuring the leakage current that flows through the insulation medium when a voltage is applied.

There are almost as many types of insulation as there are different applications. There are several things, however, that they all have in common. Moisture and contamination decrease an insulator's ability to withstand voltage and increase the amount of leakage current that will flow. The insulation will also deteriorate with age. Overheating causes deterioration to be greatly accelerated. A common rule of thumb is that the life expectancy of the insulation is cut in half for every 10 °C above its rating that the equipment operates.

Another characteristic that some types of insulation have is that, as the voltage rises, the insulation will maintain its integrity until it reaches the point of failure. Then, near the point of failure, the insulating capability drops very rapidly, often accompanied by an arc or puncture in the insulation.

### 6.2.1 DC tests

The most common method of testing insulation integrity is to apply a dc voltage and measure the leakage current. The insulation resistance is then determined by dividing the voltage by the current. There are many commercially available test instruments that have specific voltage outputs and provide the readings directly in ohms. This is referred to as "insulation resistance testing," and frequently as "Megger testing" or "Meggering."

For low-voltage equipment, common test voltages are 100 V, 250 V, 500 V, and 1000 V. Test instruments are also available that have test voltages of 2500 V, 5000 V, and 10 000 V for use on medium-voltage equipment. For most testing beyond 10 000 V, the test equipment no longer has a fixed output voltage. This is considered "high-potential" testing, commonly called "hi-pot" testing; and the voltage is continuously adjustable so that it can be ramped up slowly. The leakage current is usually measured directly when hi-pot testing is being performed, since the voltage is no longer fixed and getting a direct readout in ohms would be more difficult.

Basic electrical theory helps explain how dc insulation resistance testing works and what information it provides. A capacitor can be defined as a device for storing electrical charge that consists of two conductors separated by an insulator. From this definition, it can be seen that many electrical components, such as cables, bus bars, motor windings, and transformer windings, have capacitance to ground, since the conductors of these items are separated from ground by an insulating medium. The amount of capacitance is determined by the sizes of the conductors, their proximity to each other, and the electrical properties of the insulation. When dc voltage is applied between the conductor and ground, the capacitor that is formed by the

bus, cable, etc., and ground charges up. Once this charging is completed, the remaining dc current (called “leakage current”) that is flowing is due to the dc resistance of the insulation. By dividing the voltage by the leakage current, the value of the insulation resistance is obtained. It is common practice to measure the insulation resistance over a specific interval (to allow the capacitance to charge) and then record the final reading.

#### 6.2.1.1 Insulation resistance tests

Insulation resistance tests are typically performed on motors, circuit breakers, transformers, low-voltage (unshielded) cables, switchboards, and panel boards to determine if degradation due to aging, environmental, or other factors has affected the integrity of the insulation. This test is normally conducted for 1 min, and the insulation resistance value is then recorded.

As mentioned earlier, the electrical properties of the insulation and the amount of surface area directly affect the capacitance between the conductor and ground, and therefore affect the charging time. With larger motors, generators, and transformers, a common test is to measure the “dielectric absorption ratio” or the “polarization index” of the piece of equipment being tested. The dielectric absorption ratio is the 1 min insulation resistance reading divided by the 30 s insulation resistance reading. The polarization index is the 10 min (continuous) insulation resistance reading divided by the 1 min reading.

Both of these provide additional information as to the quality of the insulation. Many types of insulation become dry and brittle as they age, thereby becoming less effective capacitors. Thus, a low polarization index (less than 2.0) may indicate poor insulation. Even though insulation may have a high insulation resistance reading, there could still be a problem, since the motor and transformer windings are subjected to strong mechanical stresses on starting. With the exception of electronic equipment (which can be damaged by testing), insulation resistance testing is normally done on most types of new equipment and is also part of a maintenance program. It is a good practice to perform insulation resistance testing on switchgear and panelboards after maintenance has been performed on them, just prior to re-energizing them. This prevents re-energizing the equipment with safety grounds still applied or with tools accidentally left inside.

#### 6.2.1.2 High-potential testing

High-potential testing, as its name implies, utilizes higher levels of voltage in performing the tests. It is generally utilized on medium-voltage (1000–69 000 V) and on high-voltage (above 69 000 V) equipment (see Figure 6-1). As stated earlier, the leakage current is usually measured. In some cases, such as in cable hi-potting, the value of leakage current is significant and can be used analytically. In other applications, such as switchgear hi-potting, it is a pass/fail type of test, in which sustaining the voltage level for the appropriate time (usually 1 min) is considered “passing.”

#### 6.2.1.3 Medium- and high-voltage cable testing

Most cables that are rated for use at voltage levels above 600 V are shielded cables. A shielded cable has a conductor in the center, a semiconducting layer over the strands that is



Source: electro • test inc.

**Figure 6-1 — Circuit breaker high-potential testing**

surrounded by insulation, a semiconducting layer, and then a metal foil or wire mesh that surrounds the whole assembly. There is usually another layer over the shield that makes up the outer jacket of the cable. It is a common practice to hi-pot test the cables on initial installation in order to verify that the cables were not damaged when they were pulled into place and that all the splices and/or terminations were installed properly. The voltage level that is selected usually is lower than factory test levels, frequently 80% of the dc equivalent of the factory test level.

There are normally two considerations that are given to hi-pot testing of cables as a routine maintenance practice. One is a function of the chosen maintenance philosophy [i.e., breakdown maintenance, preventive maintenance, predictive maintenance, or reliability-centered maintenance (RCM)]. The other depends upon the type of operation and how critical it is to have continuous power without interruption.

The debate on whether or not to perform maintenance hi-pot testing centers around the fact that a cable in marginal condition can be caused to fail by the hi-pot test itself. A cable that is in good condition should not be harmed. People who subscribe to maintenance testing feel that it is much better to have the cable fail under test. Cable maintenance testing frequently is performed at 50–65% of the factory test voltage. Problems can then be corrected while the circuit is intentionally shut down, thus avoiding an in-service failure that could interrupt production. It is important to remember that the necessary material, such as splice kits or

cable terminations, should be available to facilitate repairs should the cable fail during testing.

### 6.2.2 AC tests

The most common ac insulation test is ac hi-pot testing at 60 Hz. The capacitance of the insulation is a large factor in ac testing. With dc insulation testing, the capacitance of the insulation charges up over time and the residual leakage current is an indication of the resistance of the insulation. This is not true of ac insulation testing. Since the voltage is changing at 60 Hz, the leakage current may be predominantly the capacitive charging current of the insulation under test. For this reason, ac hi-pot testing is usually a pass/fail type test in which “passing” means that the insulation was capable of holding the required test voltage, usually for 1 min. A common rule of thumb in the U.S. for determining the value of ac test voltage for switchgear and panelboards is to apply twice the rated voltage plus 1000 V. This comes from UL 891-1994 [B55].<sup>1</sup> The practice in some other countries is to limit routine maintenance testing to 80% of this value in order to prevent the overstressing of the insulation through repetitive testing.

Typically, switchgear, panelboards, and bus ducts are tested using ac voltage. AC hi-pot testing has the advantage that it stresses the voids and air gaps more than dc, and thus provides a better test on switchgear and panelboard insulation. Because of the high capacitance of large motors, transformers, and long shielded cables, however, ac hi-potting may not be practical due to the limitations of the power capability of ac test equipment. The ac hi-pot has to have the capability of continuously providing the required charging and leakage current at the test potential. DC is normally used in place of ac for applications with a large capacitance.

### 6.2.3 Power-factor testing dielectric loss angle (DLA) testing

Power-factor testing is a special type of ac insulation testing. In power-factor testing, the phase relationship between the applied test voltage and the resulting leakage current is determined.

A special test set is used that supplies voltage and current at 60 Hz (see Figure 6-2). The volt-amperes and watts are measured with the test set and the power factor is determined.

The primary use of power-factor testing has been on medium- and high-voltage transformers, circuit breakers, and bushings, particularly when they are oil filled. Because of the high dielectric strength of oil, a dc insulation resistance test may not detect a problem unless the equipment is about to fail. Power-factor testing provides a means to evaluate the condition of the whole or parts of the insulation system and to track the deterioration of the insulating system as it ages. Many firms have contributed test data on transformers, bushings, and circuit breakers for several decades, thus creating historic trends on many of the common makes of equipment. This supplies additional data for evaluating a piece of equipment that has been in service and for which no prior test data exists. This test provides an extremely useful tool to help predict equipment failure so that it can be scheduled for replacement prior to failure.

<sup>1</sup>The numbers in brackets correspond to those of the bibliography in 6.8.

Utilities across the U.S. have been power-factor testing their large transformers and circuit breakers for many years and trending the information to help determine replacement or major repair needs.



Source: electro • test inc.

**Figure 6-2—Insulation power-factor testing**

### 6.3 Protective device testing

A “protective device” is generally referred to as any piece of equipment whose primary function is to detect an electrical abnormality or failure, such as an overload or fault, and to automatically initiate the removal of the problem. A fuse, for example, senses excessive current flow and “blows” to interrupt the flow of current. Some relays would be classified as “protective” while other relays would be classified as “control” or “alarm,” depending on what action the relay initiates. A relay would be considered a protective relay if it trips open a circuit breaker, switch, or motor contactor when an electrical fault occurs. A relay that operates a light or an annunciator, on the other hand, would not normally be considered a protective relay, but would be considered an alarm relay.

The most common types of protective devices are protective relays, fuses, and circuit breakers with integral trip units. Fuses and most low-voltage circuit breakers are self-contained, where the sensing and operating devices are all in a common housing. Medium- and high-

voltage circuit breakers, motor starters, and spring-loaded switches have separate protective devices, such as relays, that work together as a system to perform the overall protective function. Typically, protective relays sense voltage and/or current and operate a circuit breaker, motor starter, or spring-loaded switch when a predetermined level of voltage, current, power, frequency, etc., is reached.

### 6.3.1 Protective relay testing

Protective relaying is a very broad subject. Only a brief overview can be given here.

There are two major objectives in protective relaying. First, a protective relay serves to provide equipment protection (i.e., locate and isolate overloads, short circuits, undervoltages, and other types of electrical problems quickly in order to minimize damage). Second, the protective device that is closest to the problem should operate first to clear the problem, and no other device should operate unless the closest one fails. This concept, known as “selective tripping” or “selectivity,” maintains service to as much of the electrical system as possible by isolating only the problem area. In order to achieve these objectives, each relay must function as it was designed, and the relays must function in conjunction with the other protective devices in the system. Having all the protective devices function as one overall protective system is called “coordination.”

Each protective device has specific parameters within which it has been designed to operate. For example, a single element fuse has a value of current above which it opens. It takes a specific amount of time for a given current to melt the link away and open the fuse. Manufacturers of fuses publish “time-current” curves that show how long it takes a fuse to operate for varying current values. Generally, the higher the current, the shorter the time.

This same inverse current-vs.-time concept is used for overcurrent relays and for low-voltage circuit breakers. Relays and low-voltage circuit breakers (with internal trip units) have a range of “pickup” operating current that causes them to operate. In many cases, this value of current is adjustable. By properly selecting the type, characteristic, and/or setting of fuses, relays, or circuit breakers, the system can be coordinated so that the device that is closest to the problem opens before any device upstream of it. It is necessary to select compatible time-current characteristics of the devices for the entire system, in addition to selecting the proper settings for the devices.

Prior to performing protective relay testing, a coordination study should be completed to determine the proper settings for the relays to be calibrated. This is usually done by the design engineer when the system is first installed. If there have been revisions or additions to the system, a new study may be necessary.

Once the coordination study has been completed, the relays need to be calibrated to the proper settings. There are special test sets available for this purpose that inject currents and voltages, as necessary, and time the various operations of the relays. This type of testing is usually performed by a technician who specializes in this area. Depending upon the relay to be calibrated, quite complex test equipment may be required and in-depth training in protective relaying may be needed to properly set the relay.

### 6.3.2 Low-voltage circuit breakers

Low-voltage circuit breakers come in the following three major types:

- a) Power (air-frame) circuit breakers;
- b) Molded-case circuit breakers;
- c) Insulated-case circuit breakers.

Power circuit breakers start with a frame size of 600 A and go up to 4000 A. The sensing unit that operates the breaker on a short circuit or overload may be either an oil-dash pot with springs and copper coils (for older breakers) or may consist of current transformers (CT) and an electronic trip unit. With the advent of the electronic trip unit, the number of possible settings and trip functions has dramatically increased, making it easier to coordinate circuit breakers with other protective devices.

Molded-case circuit breakers and insulated-case circuit breakers are very similar in mechanical construction and insulation. The circuit breakers' contacts and operating mechanisms are totally enclosed in a molded plastic housing. The difference between the two is that a molded-case circuit breaker normally has a thermal-magnetic trip unit (i.e., a trip unit made up of two pieces: a thermal unit to sense overload that uses two dissimilar metals and a magnetic unit to trip on short circuit), while an insulated-case circuit breaker has CTs and an electronic trip unit built into the insulated case.

The most thorough test for all three types of circuit breakers is by "primary injection." A special test set that puts out high (fault level) current at low voltage (typically 6–20 V ac) is used to functionally test the circuit breaker. These test sets have built-in timing functions; therefore, the breaker can be tested at various currents in order to make sure that it operates within the time-current specifications that are provided by the manufacturer and that it is calibrated to perform in conformance with the coordination study.

For circuit breakers that have electronic trip units, it is often possible to do "secondary injection" testing. This is usually done with a special test set that is designed for the trip unit. It injects low-level test currents into the trip unit, directly testing only the trip unit. For this reason, primary injection testing is a better practice, as it tests the whole circuit breaker (CTs, shunt trip, etc.) in a manner that is similar to how the breaker would operate during a fault.

In addition to testing the tripping characteristics of the circuit breaker by injecting current, it is also normal practice to test the insulation resistance (usually at 1000 V dc) and the resistance of the breaker's contacts. The contact resistance can be measured directly with a low-resistance ohmmeter (usually in milliohms) or indirectly by performing a millivolt drop test. A millivolt drop test is performed by using a primary injection test set to inject rated continuous current through the breaker while measuring the millivolt drop across the breaker's poles. It is a comparative test between each phase of the breaker in which the millivolt reading typically should not differ by more than 50% between phases.

Power circuit breakers have mechanical adjustments and inspections that should also be periodically checked. The manufacturer's instructions list the adjustments for each model.