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guide for protective relaying of
utility-consumer interconnections

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An American National Standard
**IEEE Guide for
Protective Relaying of
Utility–Consumer Interconnections**

Sponsor
Consumers Relaying Coordination Subcommittee
of the Power System Relaying Committee
of the
IEEE Power Engineering Society

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Foreword

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This publication was prepared by the Consumers Relaying Coordination Subcommittee of the Power System Relaying Committee. The Subcommittee expresses its gratitude to past and present members, members of the Power System Relaying Committee, Liaison Committees, and Groups who have contributed their time and knowledge in preparing this guide. Members of the Subcommittee were:

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IEEE Guide for Protective Relaying of Utility–Consumer Interconnections

1. Introduction

The physical means by which electric energy is received from the electric utility is known as an electric interconnection. The primary elements include transmission or distribution circuits, transformers, and switching devices in the form of circuit breakers, fuses, and isolating disconnecting switches. The secondary elements include sensing devices to obtain information to operate the primary equipment intelligently, and relays to initiate removal of equipment from service automatically and quickly when an electric fault or disturbance occurs.

It is important to remember that the physical laws of nature which govern the operating behavior of an electric system do not recognize defined lines of electric facility ownership. Thus for a well-engineered interconnection it is mandatory that problems in electric-system protection be studied and analyzed critically without regard to ownership.

From the viewpoint of service reliability and service continuity, it is basic to understand that the best conceived, best implemented relaying system is no substitute for an adequately designed power system; and, indeed, inadequately applied protective relaying will contribute to inadequate and unsatisfactory performance of an otherwise well-designed electric system. In considering a new installation, or changes to an existing arrangement, it is very important that protective relaying and safety be given careful attention in the early stages of planning.

2. Scope and Purpose

This guide has been prepared to aid in the effective and uniform application of fuses, relays, and their associated switching equipment located at the point of interconnection between the utility and the consumer electrical systems.

Descriptions of the various devices, definitions of terms, and references to other techni-

cal publications have been included to make the guide useful not only to relay engineers, but also to other technical people who may not be intimately familiar with the art of relaying, but who nevertheless have a responsibility for the installation and operation of such interconnections. It includes examples for relaying of typical installations, both with and without consumer generation, and with service from utility radial or loop feeders, either directly from the utility substation bus or from a transmission line. It is expected that the guide will be used by consulting engineers, utility relay and sales engineers, and by consumer engineering and maintenance personnel.

The scope of this guide does not include the subject of lightning protection for electrical systems as provided by shielding or lightning arrester devices. Lightning is, of course, often the cause of short circuits on power systems, but only the clearing of these short circuits through the use of protective devices is within the scope of this guide. Reference material pertaining to lightning protection may be found in

(1) IEEE Std 28-1972, Surge Arresters for AC Power Circuits (ANSI C62.1-1971)

(2) ANSI C62.2-1969, Guide for Application of Valve-Type Arresters for AC Systems

This guide does not establish standards or recommendations with regard to personnel safety at the interconnection area with respect to ground-voltage-rise, transferred-potential, step-potential, and touch-potential considerations for faults on the utility system or on the consumer's system. Reference material pertaining to grounding and safety may be found in the following:

(1) IEEE Std 80-1961, Guide for Safety in AC Substation Grounding

(2) ANSI C2.2-1960, NBS H81-1961, Safety Rules for the Installation and Maintenance of Electric Supply and Communication Lines

(3) ANSI C1-1971, NFPA 70-1971, National Electrical Code

3. Consideration of Utility and Consumer Requirements

3.1 System Considerations. Before any decisions can be made concerning the interconnection requirements of equipment such as type, rating, and the manner in which it is to be connected, it is necessary that basic definitions be understood by both the utility and the consumer. Since utilities vary, sometimes substantially, in operating practices and standards regarding interconnection, comprehensive understanding is essential for proper engineering. The consumer should, where feasible and practical, conform to the guidelines established by the serving utility.

Of great importance is a clear understanding by the utility of the industrial plant process and its service requirements. A process that is insensitive to relatively minor voltage reductions of short duration, but cannot tolerate any interruption in service, should be served differently than one which requires extremely close voltage control and suffers as much from low voltage as from no voltage.

Such a reduction, referred to as "voltage dip," results from a temporary fault on the utility system which would not require an actual opening of the interconnection. This reduction will generally last from 5 to 60 cycles (60 Hz basis), depending upon the relays and switching equipment used, and may vary between the two extremes of normal and zero voltage. Initial understanding here is very important, since consumer process malfunctions resulting from a voltage dip are sometimes classified as outages by the consumer.

The design of the industrial control and protection system can minimize the effect of voltage dips by using motor controls with time-delay undervoltage releases, circuit breakers instead of contactors, rotating machinery with its inherent inertial effects (instead of static equipment), regulated or stabilized control buses, dc instead of ac control, and latching relays that require a reset operation to drop out. Particular care should be exercised in the selection of devices which interlock with other devices in the startup or emergency tripping procedures. Ac contactors and solenoids drop out in one to two cycles on

reduced voltage and will, therefore, drop out on any fault that reduces the voltage sufficiently. Synchronous motors with ac field and line contactors will require restarting for the same condition. On the other hand, synchronous motors with dc controls or stabilized ac control will not pull out for several cycles, and so the process can be maintained if remote faults are cleared fast enough. In some cases, such as air compressor drives, unloading of the compressor, removal of field, reapplication of field, and reloading the compressor can be accomplished automatically without disconnecting the machine from the line, and without noticeably interrupting the consumer's process should the system fault or voltage dip last for more than several cycles. Comprehensive engineering liaison between the utility and the consumer will result in a coordinated relaying system providing increased reliability and minimum duplication of equipment. It should be stressed that synchronous motors, in particular, require protective devices for a variety of faults, and the tripping of motor faults should be left to these protective devices and not to the starting and running control equipment.

Computers represent a special critical load which is susceptible to variations in system voltage and, sometimes, frequency that can occur during both faults and normal switching. This area is discussed more fully in Section 3.3.

An interruption or "outage" refers to a complete separation of the consumer system from the power system. Outages can last from one-fourth to one-half second if high-speed reclosing is used, 1 to 60 s or more if delayed automatic reclosing is used, and may continue for many minutes or hours if remote or manual switching is used, or if the fault is such that automatic reclosing is not successful. If the consumer's system has generation, synchro-check relays are necessary to block out-of-phase automatic reclosing of the utility tie. The loss of utility power will require that the consumer's load be reduced to the capacity of the in-plant generation as is the case when the utility-consumers tie is opened.

The design of the utility system can minimize service interruptions by providing circuit breakers instead of switches, automatic control instead of manual control, and loop

circuits instead of radial feeds. Each improvement incurs a cost that must be warranted by the process requirements. It is generally possible for the utility to estimate the number of short-time and long-time outages the customer can expect per year. The user evaluates the cost of avoiding either or both of these situations against the loss of product, damaged equipment, extra maintenance, etc. These data then form the basis for the design of an interconnection that will be consistent with the operating requirements.

Short-circuit currents are accompanied by magnetic forces and heat that can result in explosion or fire. It is essential, therefore, that switching devices of adequate interrupting capability be used and properly maintained to ensure clearing a fault as rapidly and reliably as possible. The magnitude of short-circuit currents is primarily a function of the utility system size, voltage, and configuration. Remedial measures can sometimes be taken by the consumer to reduce this current. The installation of reactors, special circuit arrangements which introduce impedance into the system, special operating instructions which would prevent paralleling transformers, or interlocks which would prevent tripping of underrated circuit breakers are all special measures and all introduce a risk of not operating as intended. Thus, failure of any of these methods would then subject the switching devices to service beyond their rating.

The speed with which a fault should be cleared depends primarily on the nature of the industrial equipment. The danger to personnel is obviously reduced when the fastest relays and circuit breakers are used. The extent of the equipment damage may or may not be significantly reduced by faster relays since the initial damage has already occurred and the major costs are thereby established. Secondary equipment damage, however, from overheating or from fire or explosion will, of course, be minimized by the faster relays and circuit breakers.

The primary concern in applying protection for faults is, of course, to minimize personnel hazard and equipment damage. However, the effect the protection equipment has on production continuity and restarting should not be overlooked. Many consumer processes suffer only loss of production time whereas other

consumer processes incur spoilage of product and damage to production equipment. In those events where fast interruption is not a major factor in limiting the extent of production equipment or product damage, the damage to electrical equipment may become secondary and tripping for certain fault conditions may be delayed. Also, many production lines operate in discrete sections while others must operate in a continuous flow. These factors must all be considered in the selection of which equipment to trip and which to reclose. Induction motors, in general, will ride through voltage dips or interruptions where high-speed reclosing is employed without any loss of production. Synchronous motors, on the other hand, can be made to ride through voltage dips with the proper controls, but often cannot be subjected to reclosure without damage. Many large industrial plants cannot tolerate instantaneous reclosure on a radial service from a utility for a variety of reasons other than the presence of synchronous motors. Conversely, many processes have sufficient storage or inertia to ride through outages up to several minutes.

For those consumer plants where an outage can result in loss of production facilities at considerable cost, it is often economical to provide some form of backup power. This can take the form of purchased power or in-plant generation with manual or automatic throw-over facilities or continuous dual supply. Each method has its advantages and disadvantages which can only be evaluated for the particular situation under study.

3.2 Load Considerations. Induction motor instability is a condition whereby the motor cannot drive its connected load at rated speed under steady-state operating conditions. This condition is caused by low voltage at the motor terminals and can result from the effort to start many motors simultaneously. Being aware that voltage dips tend to permit motor contactors to drop out, many users install latching devices on all of the motors in the plant. However, during a voltage dip, not only do contactors tend to drop out, but all motors slow down. The resulting motor acceleration current causes the voltage to remain depressed at the motor terminals due to voltage drop in the system to a point where the motors cannot reaccelerate.

Unlike the induction motor, the synchronous motor is readily subject to instability. Some of the factors that tend to make a synchronous motor unstable are the following:

- (1) Overload
- (2) Low inertia
- (3) Low field excitation
- (4) Motor large compared to utility supply capability
- (5) Low terminal voltage

Some of these factors, such as inertia and size, are rigidly determined by the process and product requirements. The other factors are relatively flexible and their effects on operation during faults should be considered in the early stages of design of the plant if unnecessary shutdowns or expensive revisions are to be avoided. Voltage drops should be calculated under extreme loading conditions and sufficient margin should be provided to ensure stable operation. Excitation and loading should not be marginal during normal operating conditions.

In addition to the operation of the equipment during normal and abnormal situations, protection and control equipment must meet various safety and insurance code requirements. These rarely contradict the factors considered thus far. The code requirements should, however, be kept in mind when considering these factors so that the equipment specified will be compatible and duplication will be avoided.

3.3 Computer Loads. Modern high-speed computer systems are very sensitive to disturbances in the electrical power supply source. Voltage and frequency transients, for example, cause errors in the computer such as memory alteration or complete memory loss, word structure alteration, or nonprogram jumps. Because the continuity of the utility power supply is often misunderstood, computers as an example of critical load are specifically mentioned.

Three broad classifications of computer systems are generally used. Each has its own implications of reliability and service requirements. These classifications are as follows:

- (1) Off-line business or scientific computers which do not operate on real time, that is, the output is obtained without regard to a time-

controlled sequence of events. Such computers can be shut down for a few seconds or minutes without seriously affecting the operation. The principal loss is the time required to rerun the problem. For many reasons besides power supply disturbances, the computer program should be designed to detect and correct for such incidents and should use storage tapes, discs, or drums to periodically save essential data and intermediate results. Memory circuits should be designed so that no loss occurs during a power supply disturbance. Consideration must be given, however, to a prolonged outage during which vital auxiliary equipment such as fans and air conditioners might stop, leading to failure of temperature-sensitive components.

- (2) On-line or process computers which are in continuous control of an actual industrial operation. In such cases, it is essential that normal operation continue during the transient or momentary voltage dips. A prolonged outage, however, will probably also shut down the other process equipment which the computer is controlling.

- (3) Communication-based computers which obtain input data from numerous distant points and must process this input continuously. This type of computer can stand loss of output facilities for a short time but cannot tolerate momentary lapses in input or garbled information.

Power requirements will, of course, vary for each application. The range of the other parameters, however, and particularly the range of tolerances, is fairly well defined. Most modern computer systems are designed for 120/208 V three-phase four-wire 60 Hz supply systems. They can stand, without error, voltage variations of ± 10 percent (occasionally $+10$ percent, -8 percent) and frequency variations of ± 3 percent (occasionally ± 0.5 percent). In some instances a specification may also include an allowable rate of change of voltage or frequency; typically 5 V/s or 1.5 Hz/s.

Although the steady-state requirements are relatively easy to provide, it is not possible to avoid the transient disturbances that occur on a supply system subject to faults and subsequent switching as discussed in Section 3.1. Not covered in that section, but of importance to such sensitive loads as computers, are the voltage transients that accompany

normal switching. The voltage “spikes” accompanying capacitor switching and the voltage “dips” accompanying motor starting are felt throughout the electrical supply system to a degree dependent upon the extent and configuration of the system. Similarly, the effect of welders, arc furnaces, elevator or air conditioner motors, filter precipitators, and other common office and industry equipment are all reflected to some degree in the supply to the computer.

3.4 Effect of Ownership and Responsibilities. Very early in the negotiations between a utility and a consumer, the line of ownership is very clearly defined. The effect of this ownership on the responsibilities involved as far as protection and control is concerned is not nearly so clear cut. The equipment will perform properly only if installed properly and calibrated and maintained regularly. The need for and the details of maintenance, operating, and testing procedures should be discussed and formally agreed upon. The specific responsibilities for each piece of equipment should be clearly outlined well in advance of the service date.

Following the installation of an interconnection and its associated protective devices, the system must be acceptance tested. This includes the functional testing of circuit breakers and disconnectors, proper operation and calibration of relays, meters, and instruments, and checking for correct output of current and potential transformers. Control systems must be checked along with their power sources, such as station batteries and station service transformers. In short, the entire system must be tested as a whole to ensure its ability to maintain service continuity under normal conditions and to protect equipment and isolate trouble under abnormal conditions. The system should be designed for economical periodic maintenance. A maintenance program must be carried out to ensure that the interconnection will function as designed throughout its life.

4. Abnormal System Conditions

4.1 Short Circuits. The purpose of a short-circuit study is to determine the magnitude of

the fault current that will be imposed upon elements of an electric power system when a short circuit occurs. The source of short-circuit current is rotating machines. An impedance diagram based on the system one-line diagram has been found to be the best method to present the appropriate electric equipment impedance data required to conduct such a study.

The basis for a short-circuit study is determined by the purpose of the study. It must be recognized further that any one study is based on a particular set of operating conditions. In most power systems, the operating conditions change constantly due to varying degrees of system dynamic loading or to operating procedures which result in opening or closing of circuit breakers. Therefore, the short-circuit current at any one point in a system may change considerably from day to day and from the results of any particular study.

With regard to the purpose of short-circuit studies, it is essential to recognize two distinct end uses:

(1) The selection of power-interrupting devices of adequate capability such as circuit breakers and fuses. In these cases, knowledge of the maximum available short-circuit current values is essential.

(2) The selection and rating or setting of short-circuit protective devices, such as fuses, relays, and direct-acting trips. In these cases, knowledge of not only the maximum, but also the minimum available short-circuit current value is essential. The latter values are required to evaluate protective device operation during system operating conditions which are likely to produce the minimum short-circuit currents (that is, generators and/or motors out of service).

In solidly grounded systems, short-circuit studies for relay purposes include the calculation of line-to-ground fault current magnitudes. In high- or low-resistance grounded systems such studies usually are not required because the ohmic value of the neutral resistor is high relative to the other circuit impedances encountered by the fault current; thus, the ohmic value of the resistor effectively determines the magnitude of the ground-fault current. Industrial high-voltage systems usually are resistance grounded.

4.1.1 Short-Circuit Studies to Determine the Duty on Interrupting Devices. The purpose

of these studies is to determine the first-cycle duty and the interrupting duty on fault-current interrupters such as high-voltage circuit breakers, current-limiting fuses, and low-voltage circuit breakers.

The specific calculation procedure for the particular equipment is determined by the appropriate equipment standard and application guide and should be followed.

4.1.2 Short-Circuit Studies to Determine Relay Operating Currents. The setting of relays and direct-acting trips on load branch circuits requires consideration of the characteristics of the equipment for which they must provide protection. On transmission, distribution, and tie circuits, relay settings require additional considerations of both equipment characteristics and system protective requirements.

A primary purpose of circuit protective devices is to separate a faulted circuit sufficiently fast to allow the remainder of the system including other loads to ride through the disturbance. An additional purpose of circuit protective devices is to furnish rapid interruption of faulted circuits in order to limit damage to circuits and equipment and to minimize hazards to personnel. Coordination between protective devices is required so that they will selectively remove only the smallest possible segment of the system. To attain proper coordination of protective devices, a knowledge of the distribution and magnitude of short-circuit currents is essential.

The maximum levels of symmetrical rms short-circuit current are generally used to establish the basic relay setting coordination requirements. In addition, the asymmetrical values should be used, or allowed for, for instantaneous relay settings. All settings should then be confirmed using minimum fault-current values to assure proper operation under these conditions also.

Minimum fault currents can approach the magnitude of maximum load currents. Thus it is also necessary to confirm that sensitive relay settings as indicated by minimum fault conditions will not cause undesirable tripouts under maximum load operations.

Minimum fault currents exist during periods of maximum system impedance. These conditions may include

- (1) Minimum generation
- (2) Equipment outages

- (a) on the supplying utility
- (b) within the industrial plant

(3) Minimum load periods during which induction and synchronous machines are disconnected from the lines

(4) High-impedance type of faults such as may occur on low-voltage systems or as turn-to-turn faults in motors or transformers.

In addition to minimum fault-current considerations, proper coordination of system protective devices also requires consideration of changes in the fault-current distribution throughout the network when there is any change in the network or connected loads. This aspect of coordination is particularly pertinent in determining backup setting requirements. For example, minimum fault current might be, say, 50 percent of its maximum value. If this comes about through disconnection of local generation which may normally supply 60 percent of the maximum fault current, then the fault current being provided from the utility connection may actually increase by 25 percent for this minimum fault condition relative to total current in a feeder fault. Protective device selectivity based only on maximum fault considerations may thus fail under minimum conditions. Instantaneous relays, so desirable in limiting fault damage, may aggravate these kinds of minimum fault-current situations. When the instantaneous relay must be set to operate only at nearly maximum fault conditions, coordination may be difficult to establish at other times when the instantaneous relay does not pick up. Similarly an instantaneous relay associated with a circuit breaker which also has a backup function, may pick up incorrectly during minimum fault conditions because of the increase in current through that specific branch of the network.

4.1.2.1 Calculation of 0--3 Cycle Maximum Short-Circuit Current. The purpose of these studies is to determine the maximum currents to which instantaneous, extremely short-time relays or direct-acting trips should respond.

The calculation procedure to determine these relay operating fault currents calls for the representation of all rotating equipments (generators and motors) by their equivalent subtransient reactance X_d'' . Passive system components (transformers, reactors, cables,

regulators, busways) are represented by either their reactances or impedances, depending upon the calculating technique employed. Analog computers can conveniently handle R plus jX components; this is equally true for digital computers if they are so programmed. In many systems, the effect of neglecting the resistive component and assuming that all the impedance is essentially reactance produces results not significantly different from those achieved by including the resistive component. Thus a simplified procedure using reactances exclusively is often justified.

Regardless of the technique employed, these studies result in a set of theoretical currents, expressed in symmetrical amperes, which represent the magnitude of the maximum 0–3 cycle short-circuit currents.

Instantaneous relays of the plunger and clapper designs respond to dc as well as ac current. It, therefore, is necessary to account for the dc transient current which is usually present when an ac fault is initiated. The term “asymmetrical current” is used to describe this initial current value.

The asymmetrical current values are derived by applying an appropriate multiplier to the calculated symmetrical ac amperes. This procedure accounts for the dc offset of the ac short-circuit current, which is a function of the X/R ratio of the system and the point on the voltage wave at which the short circuit is applied. Thus “total” short-circuit current can be considered as comprised of a decreasing dc component and a symmetrical ac component of fundamental frequency.

The total rms first-cycle current value of a completely offset wave (X/R ratio = ∞) is 1.73 times the rms symmetrical short-circuit current. Typical multipliers to calculate the maximum initial asymmetrical current are generally assumed to be 1.5 to 1.6, which allows for the fact that in practical systems a significant decrement in the dc component does occur.

4.1.2.2 Calculation of 3–60 Cycle Maximum Short-Circuit Current. The purpose of these studies is to determine the maximum currents to which time overcurrent relays operating in approximately 3 cycles (0.05 second) or more should respond.

It should be noted that the magnitude of the 0–3 cycle short-circuit current, calculated previously, is controlled by the subtransient reactances X_d'' of synchronous machines (gen-

erators and motors) as well as the contribution of induction motors, which is determined by the subtransient reactance of the induction motors (or locked rotor impedance).

The reactance of a synchronous machine varies from the low value of subtransient reactance to the high value of synchronous reactance X_d' in accordance with a short-circuit decrement curve. From the subtransient reactance value, reactance increases rapidly in the first few cycles to a value identified as transient reactance. The composite effect of the individual decrements of the synchronous machines is sufficiently complex to preclude a simple analytical study. Suffice it to say that for calculating the 3–60 cycle short-circuit fault current a resolution using subtransient generator reactances X_d'' and transient synchronous motor reactances X_d' will result in a conservative/realistic value. Still another aspect accounts for a further reduction in short-circuit current. A running induction motor will, when a fault is applied at its terminals, dissipate the electrical energy stored in its magnetic field into the fault in accordance with the short-circuit time constant of the motor and the external system impedance between the motor and the fault. Induction-motor short-circuit time constants by themselves are short (1–3 cycles). Typically external system impedance results in overall time constants of less than eight cycles. Consequently, induction motors are not considered in the calculation of short-circuit fault currents for time-overcurrent relays which operate in three cycles or more. It should be noted that these current values of short-circuit current are expressed in symmetrical amperes and that, after three cycles, any dc transient current has decayed to zero.

4.1.2.3 Calculation of 0–3 Cycle Minimum Short-Circuit Current. The purpose of these studies is to determine the minimum short-circuit fault currents to which instantaneous, extremely short-time relays or direct-acting trips should respond. The calculation procedure is the same as that in Section 4.1.2.1, except that minimum system operating conditions must be assumed (maximum impedance).

4.1.2.4 Calculation of 3–60 Cycle Minimum Short-Circuit Current. The purpose of these studies is to determine the minimum short-circuit fault currents to which time-

overcurrent relays operating in approximately one second or less should respond. The calculation procedure is the same as that in Section 4.1.2.2, except that minimum system operating conditions must be assumed (maximum impedance).

4.1.2.5 Calculation of Extended-Time Short-Circuit Current. The purpose of these studies is to determine the minimum currents to which long-time overcurrent trips, relays, or fuses should respond. On industrial power systems supplied by a utility, the extended-time short-circuit current is essentially the same as in Section 4.1.2.2.

When local generators contribute a large fraction of the short-circuit current, however, a severe decrement of short-circuit current may occur. An extended-time short-circuit study may be particularly useful in evaluating the operation of generator overcurrent relays with voltage restraint.

In magnitude, the extended-time short-circuit current is the steady-state current after all transients have disappeared and is a function of the generator excitation ceiling voltages and the generator synchronous reactances.

4.1.2.6 Line-to-Ground Fault Current Calculations. The purpose of these studies is to determine the distribution and magnitude of ground-fault currents to which ground relays should respond.

These calculations are simplest on resistance-grounded systems in that the resistance of the resistor(s) in each distinct zero-sequence zone essentially determines the maximum ground-fault current, the only required benchmark.

On solidly grounded systems these calculations require that the positive, negative, and zero-sequence circuits be considered. Calculations using the method of "symmetrical components" permit the ground-fault currents to be determined most easily.

In general, the philosophy and the system conditions considered to determine maximum and minimum ground-fault values and distribution follow the same logic and considerations as discussed heretofore for three-phase faults. It is to be noted that unlike the positive-sequence values of machines which change with respect to time, the negative- and zero-sequence impedances remain constant.

Negative-sequence impedances of passive system components (transformers, reactors, cables, busways, transmission and distribution circuits, and capacitors) are the same as their positive-sequence values. Zero-sequence values of passive components are constant with respect to time, and usually are different than their positive- and/or negative-sequence values. The core construction and connections used on three-phase transformer banks are of particular significance.¹

It is of prime interest to note that ground relays do not sense load currents provided that single-phase and three-phase loads are connected between phase conductors. On a four-wire grounded neutral system where loads may be connected phase to neutral, consideration must be given for load unbalance and single-phase situations where load currents can appear in the ground-current (zero-sequence) circuit.

4.1.2.7 Relay Settings Versus Load. Protective relays receive their information concerning primary system voltage and current and their phasor relation by means of potential transformers and current transformers, respectively.

Most current transformers have little or no continuous overload capability; they must be sized to carry the estimated design or peak load on the circuit.

The matter of load versus relay settings is usually involved only with phase relays. Where the consideration applies, protective phase relay settings must be set high enough so that they impose no limitations for normal or emergency system loading for the equipment or circuitry involved. In industrial systems, single-phase and/or three-phase loads are connected between phase wires. There are usually no single-phase loads connected phase to neutral. Load current does not need to be considered when setting ground relay taps. On solidly grounded systems, however, ground relay taps lower than 1.0 should usually be avoided due to the high current-transformer burden caused by very low tap settings. The

¹Several references on "Symmetrical Components" list typical values of positive-, negative-, and zero-sequence impedances for the usual equipments found in power systems together with analytical methods by which exact values may be determined. See Bibliography.

performance of current transformers on in-rush currents to motors and transformers can result in a current in the ground relay circuit and is of particular interest with respect to the use of an instantaneous ground relay. In fact, very low (less than 8–10 A) ground relay instantaneous settings may cause incorrect tripping of a feeder when a motor is started. In a delta system, simultaneous phase-to-ground faults involving different phases on separate feeders will result in a current in the CT neutral relay circuit of the feeders involved.

In general, protective relay settings are determined and coordinated to isolate the faulted segment of the system as fast as possible to permit the unfaulted part of the system to continue to operate satisfactorily. Such protective relay settings may not necessarily always provide satisfactory thermal overload protection for the circuit. In such cases, additional thermal overload devices will be required in specific cases. Since the Occupational Safety and Health Administration of the Department of Labor has adopted the National Electrical Code in its entirety, compliance with its rules are now mandatory for new electrical installations on consumer premises. However, the NEC is not mandatory for utility installations.

Instantaneous phase relay settings are determined by using specific fault-current data. For example, instantaneous phase relays on a feeder to a transformer are set not to operate for a fault on the low-voltage side of the transformer. Such resultant settings typically are many times higher than practical maximum loads.

In accordance with the National Electrical Code (ANSI C1-1971), the high-side overcurrent phase relays on a dedicated feeder to an askeral or oil insulated transformer may be set for not more than 250 percent (125 percent for dry-type) of the transformer self-cooled rating when there is no main low-side overcurrent device. If there is a main low-side overcurrent device, and it is set for not more than 250 percent (125 percent for dry-type) of the transformer bank self-cooled rating, the high-side overcurrent phase relays may be set for not more than 6 times the transformer self-cooled rating, provided the transformer impedance is not more than 6 percent; also, if the transformer impedance is greater than 6 percent but less than 10 percent the high-side

overcurrent phase relays may be set for not more than 4 times the transformer self-cooled rating. If there is more than one transformer on the supply circuit, the limitations stated above apply to the smallest transformer. Thus the number and mix of transformer sizes on one supply circuit is limited. The subject of transformer protection is covered in IEEE Std 273-1967, Guide for Protective Relay Applications to Power Transformers (ANSI C37.91-1972).

In general, time-overcurrent phase relays applied to multipurpose feeders or buses in simple-overcurrent or partial differential schemes are set for 1.5 – 2.0 times the estimated peak load.

On general-purpose motor circuits, instantaneous phase relays are set above the estimated largest motor-starting current by a factor typically of 1.5 – 2.0 times the locked rotor current value. The phase time-overcurrent relays usually are set for about 1.5 – 2.0 times the estimated peak load with a time-delay setting sufficient to ride through the load plus the starting time of the largest motor. The NEC requires overload protection for each phase of three-phase motors. On large motors which have their own dedicated circuits, more specific types of motor relay protection are required. These relaying requirements are covered in complete detail in IEEE Std 288-1969, Guide for Induction Motor Protection (ANSI C37.92-1972) and IEEE Std 329-1971, Guide for Synchronous Motor Protection (ANSI C37.94-1972).

4.2 Operating Abnormalities

4.2.1 System Swings. In the usual context, the term “system swing” refers to the behavior of system voltage and the exchange of watts and vars between synchronous machines and induction motors during and following a system disturbance. The steady-state aspect deals with the effects of relatively small system load changes, whereas the transient aspect deals with the effects of more abrupt changes in system loads, or system faults, or large changes in system impedance (switching) between machines or machine groups.

The critical switching time of any machine is the maximum time the machine can stand a disturbance and continue to operate satisfactorily when the disturbance is removed. In the usual situations for industrials, the critical

switching time of interest is that of a three-phase fault at the terminals of the machine. Industrial synchronous generators and motors are practically always connected to buses to which feeder circuits are also connected. Industrial feeder circuits (radial or loop) are generally short and are usually of cable. Their circuit impedance is low. Thus faults anywhere in the industrial system, for practical purposes, appear to be faults at the terminals of the machines.

The internal electric power angle of separation between synchronous machines is a measure of the stability. Typical critical switching time for three-phase faults at or near the terminals of loaded generators is in the order of 12 – 20 cycles (60 Hz basis).

Typical critical switching time for loaded synchronous motors is in the order of 4 – 12 cycles (60 Hz basis); the shaft load inertia is significant for synchronous motor stability.

Induction motors do not have dc fields as do synchronous motors. As such, the criterion for induction motor stability is not electric power angle; it is the motor terminal voltage. When a disturbance reduces the voltage at the terminals of the induction motor, the motor torque is reduced, the motor slows down, and its slip increases.

Typical critical switching times for induction motors are more difficult to discuss because the system impedance and the inrush current to other motor loads influence the system voltage following the fault removal. Also, the speed–torque curve characteristics of the connected motor shaft load are strongly influential, since some motors may be applied based on a no-load start. In general, if the resultant motor voltage following the disturbance is at least 80 percent with a reasonable estimate of inrush for all of the motors, it is likely that the induction motor(s) will recover. If this fact can be clearly established for the worst condition, that is, all motors in service, then the need for high-speed fault clearing time is not critical.

Rapid fault clearing minimizes any significant changes in the motor load speed–torque characteristics. Inrush demand, particularly for reactive current, is minimized. Thus system voltage depression following the fault is minimized.

In a two-machine system (one may be an infinite bus) the impedance from the infinite bus to the “electrical center” may be defined as the total impedance between sources divided by 2. When synchronous machines are 180 degrees apart, the voltage at the electrical center is zero. It is important to note that in many cases, where the industrial system has in-plant generation, the electrical center is near the terminal of the generator which is also the load bus. If the generator goes out of step because of a long fault clearing time, regardless of the type of fault, the entire system will be subjected to essentially a bolted three-phase zero-voltage fault effect for many cycles. Such an effect will be more severe than the original fault as far as running motors are concerned. Auxiliary contactors will drop out. Lights will experience “dips” and equipment such as computers and static power supplies will malfunction. These consequences can be eliminated or minimized by the application of high-speed protective relaying to an adequately designed power system.

It is usually necessary to conduct studies in system load flow and system stability to obtain the information required to evaluate problems involving these matters.

4.2.2 System Transient Frequency Oscillation. Faults, changes in load, or switching operations on an electric power system produce dynamic forces that result in phase angle oscillations between machines until equilibrium is restored. During such periods of oscillation, there is a momentary deviation in the system frequency throughout the system, and the instantaneous frequency at a given point in the system is a function of the relative impedances to the rotating sources of voltage which produces the phase angle oscillation.

This consideration deserves more attention in industrial systems. It is important to understand this behavior because of the following reasons.

(1) Underfrequency relays used for load-shedding schemes may operate undesirably if they are set too high and/or have instantaneous or short-time delays. In the usual situation in industrial systems, in-plant generators and large motors are directly connected to load buses. The momentary frequency deviation or phase angle of the load bus is relatively greater here because disturbances in the industrial system are occurring