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

POWER SYSTEM PROTECTION, RELAYS

A modern electric power system is a very large and complex network consisting of generators, transformers, transmission and distribution lines, buses, reactors, capacitors, and other devices. A well-designed power system provides high-quality electric energy to the user instantly, constantly, and exactly in the amount that is needed. It would be, however, impractical or noneconomic to design and build a fault-proof power system. Thus power systems and their components need protection from natural hazards and equipment failures, as well as human error.

Power system faults in conventional fault studies (short-circuit analyses) are divided into two categories: balanced and unbalanced. Lightning, wind, ice, earthquake, fire, switching surges, resonance (or ferroresonance), trees, animals, vehicles, and humans are some of the causes of the system faults. These faults cause changes of significant magnitude in system variables at a range of the power system, such as voltages and currents, and produce sequence voltages and currents when an unbalanced fault occurs. The faults must be removed from the power system to minimize further damage to equipment and danger to people, and to maximize the continuity of service. Methods of impedance, admittance matrices and symmetrical components are applied to the fault analysis, which will provide information to protection engineer for calculation of relay settings and other uses. Power system abnormal operation conditions include transient disturbance, nonsynchronism, and so on.

Power system protection is the science and art of applying, coordinating, and setting relays. The objective of protection is to provide maximum sensitivity to faults and undesirable conditions, to clear the faulted portion (as small a portion as possible) quickly, to ensure the stability of the remaining system, while avoiding their operation on all permissible or tolerable conditions on power systems. Power system protection may be classified into two major categories: *element protection* and *system protection.* On the operating functional standpoint the two categories of protection can be further divided into *primary* protection and *backup* protection. The former is designed for speed and minimum system disruption while the latter operates with time delay and generally affects a larger portion of the system.

A protection system is normally made up of three main components: (1) *transducers,* (2) *relays,* and (3) *circuit breakers.* Transducers sense and detect system abnormalities; relays, which may be electromechanical, solid state, or computer-based, provide signals to activate the protection devices; and circuit breakers interrupt (disconnect) the circuit in the protection zone when an intolerable condition occurs in the power system.

A primary task to be undertaken for the protection system is to identify precisely the relaying requirements and the coordination criteria to be adopted. Coordination criteria include

- Instantaneous Setting Instantaneous setting is specified in terms of a threshold current above which the relay trips. The relay should be set to protect for faults on the “primary line” and should include a factor of safety to prevent against false trips for faults on the remote lines.
- Time-Delay Operation Settings These include pickup tap setting for which the allowable range of tap values must be calculated, and time dial setting.

It is difficult to specify or evaluate protective relay performance by statistical techniques. Relays are connected to power systems and energized, but they are basically inactive until a fault occurs within their operating zone. Relay performance is documented by those relays that provide direct or specific evidence of operation.

Power System Faults or Abnormal Operation Conditions

Faults. A fault-proof power system is neither practical nor economical. To ensure adequate protection, the conditions existing on a system during faults must be clearly understood. There are many reasons why faults occur in power systems. Faults can result from electrical, mechanical, and thermal failure, or any combination of these. The most common cause of power interruption is the single line-to-ground fault on a transmission line. This is followed in succession by the double line-to-ground fault, the line-to-line fault and, finally, the three-phase symmetrical short circuit. Examples of faults are illustrated in Fig. 1.

A fault represents a highly disruptive condition for the power system. Hence, if appropriate action is not taken immediately upon its occurrence, extreme damage can take place in the generators, transformers, and other connected loads of the system. Besides the enormous expense involved in repairing and/or replacing such equipment, it may also be necessary to be without electric service for a period long enough to cause discomfort. Therefore, all power systems must be equipped with strategically located circuit breakers and other switchgear, in order to disconnect sensitive equipment before irreparable damage takes place.

Relay application requires a knowledge of system conditions during faults, including the magnitude, direction, and distribution of fault currents, and often the voltages at the relay locations for various operating conditions. Among the operating conditions to be considered are maximum and minimum generation, selected lines out, line-end faults with the adjacent breaker open, and so forth. With this information, the relay engineer can select the proper relays and settings to protect all parts of the power system in a minimum amount of time.

Transient Disturbance and Stability. Transient stability is concerned with maintaining synchronism among all generators when the power system is suddenly subjected to severe disturbances such as faults or short circuits caused by lightning strikes, the sudden removal from the transmission network of a generator or tie line, or, in general, any severe shock to the system caused by a switching operation. Because of the severity and suddenness of the disturbance, transient stability analysis is focused on the first few seconds following the fault occurrence or switching mode. The brevity of the time period does offer some compensating advantages. For example, the machine variations from synchronism are small enough so that all voltage and current quantities as well as all system parameters can be used in the analysis as the known 60 Hz values. Moreover, all excitation voltages of the generators may be treated as fixed quantities.

Protective measures against transients and surges include:

- Separation This includes physical and electrical separation. For example, surges can be controlled by the discriminate application of inductance to block conduction of high-frequency transients into protected regions. Transformer isolation puts an effective common-mode barrier between segments of system.
- Suppression at the Source This includes resistor switching, parallel clamp, and suppression by termination. For example, a small capacitor offers a method of reducing input impedance at high frequency, with little effect at 50 Hz or 60 Hz or on dc. This device neither requires a higher input energy for operation nor generates heat.
- Suppression by Shielding Grounding a shield at both ends allows shield current to flow. Shield current resulting from magnetic induction will tend to cancel the flux that created it. The net effect of the shield on the signal lead is to reduce the noise level.
- Suppression by Twisting Measures that cause the signal and return leads to occupy essentially the same space minimize the effect of differential-mode coupling. Twisting a pair of leads cancels the effect of adjacent

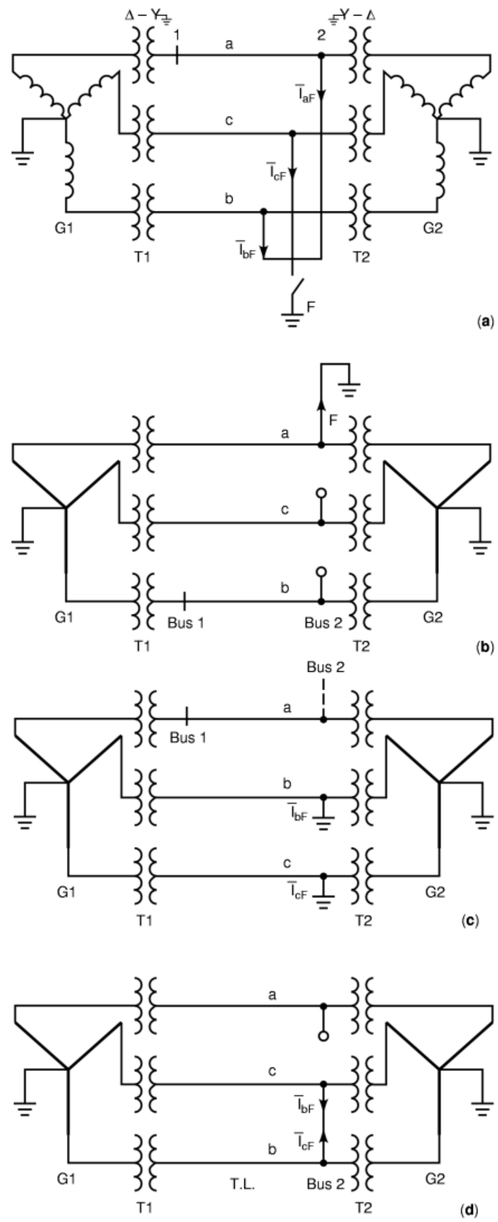

Fig. 1. (a) Three-phase fault. (b) Phase-to-ground fault. (c) Double phase-to-ground fault. (d) Phase-to-phase fault.

circuit flux. A combination of shielding and twisting effectively minimizes the influence of surges in adjacent circuits.

- Radial Routing of Control Cables All supply and return conductors should be in a common cable. This arrangement avoids the large *EMI* (electromagnetic induction) associated with the large flux loop that would otherwise be produced.

- Optical Isolators Optical isolators can provide excellent electrical separation between two circuits. The technique can be used as optically isolated input or output.

Characteristics of Protective Relay

- Reliability Reliability has two aspects: dependability and security. Dependability indicates the ability of the protection system to perform correctly when required, while security is its ability to avoid unnecessary operation during normal operation.
- Selectivity Relays have an assigned area known as the primary protection zone, but may properly operate in response to conditions outside this zone. In these cases they provide backup protection for the area outside their primary zone.
- Speed Obviously, it is desirable that the protection isolates a trouble zone as rapidly as possible. In some application this is not difficult. (A high-speed relay is one that operates in less than 50 ms.) In others, particularly where selectivity is involved, faster operation can be accomplished by more complex and generally higher cost protection.
- Simplicity A protection system should be kept as simple and straightforward as possible while still accomplishing its intended goals.
- Economy It is fundamental to obtain the maximum protection for the minimum cost, and cost is always a major factor. Protection costs are considered high when considered alone, but they should be evaluated in the light of the much higher cost of the equipment they are protecting. Relaying with computers provides a more cost-effective and reliable way for power system protection.

Components and Zones of Protection

The purpose of power system protection is to detect faults or abnormal operating conditions and to clear the faults from the system as soon as possible. To implement this purpose, relays must be able to evaluate a wide range of parameters to make decision of corrective actions. The protective relay system is connected to the ac power system through current transformers (*CT*s) or voltage transformers (*VT*s) commonly associated with the circuit breaker. At higher power system voltages each station where circuit breaker are installed has a station battery to supply direct current to the breaker trip coils, the control and protective relay circuits as required.

Components of a Protection System.

- Transducers Transducers, namely, the cts and the vts, provide insulation from higher system voltages and a reduction of the primary current and voltage quantities. The secondary is standardized for the convenience of application and relay design.
- Relays Relays are the logic elements that initiate the tripping-and-closing operation.
- Circuit Breakers Knowledge of circuit breaker operation and performance is essential to an understanding of protective relaying. It is the coordinated action of both that results in successful fault clearing. The circuit breaker isolates the fault by interrupting the current at or near a current zero. It can do this as quickly as the first current zero after the initiation of a fault, although it more often interrupts at the second or the third current zero.

Zones of Protection. All of electrical devices in a power system must be covered by their protection system. To obtain optimal selectivity between relays to relay applications, the philosophy is to divide a power system into zones in terms of power system components and power system structure. These zones are called zones of protection, which are normally bounded by their current transformers. Figure 2 illustrates a typical

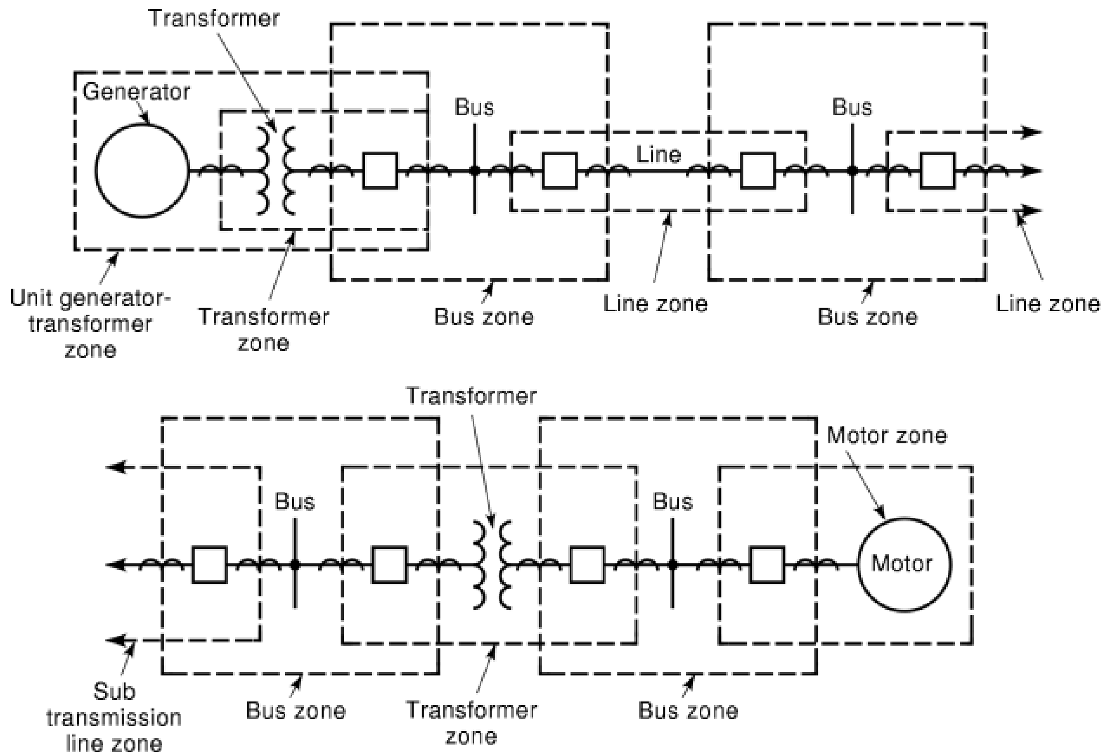

Fig. 2. Typical primary protection zones in a power system.

power system and its zones, which is divided into: generators, generator-transformers, transformers, buses, transmission and distribution lines, and motors.

The zones of protection must meet two requirements: (1) all power system elements must be covered by at least one zone. The more important elements should be included in at least two zones; (2) zones of protection must overlap to avoid the possibility of unprotected areas. The region of overlap must be limited to prevent removing a larger section of the power system from service by operating the protection belonging to both zones.

Functions of Protective Relays

Although the fundamental operating principles have not had significant changes for decades, relay design and hardware have been constantly changing. This is why protective relaying is called a constantly changing and expanding science. Changing technology—from electromechanical to discrete semiconductor, to integrated circuits, to microprocessor techniques—has enhanced the ability to solve old gnawing problems and is, in itself, in fascinating study.

References to the design and application of electronic relays for power system protection can be found in the literature from the year 1928 onwards. In 1928, Fitzerald published a scheme for pilot wire protection. Wideroe, in 1934, brought out a series of circuits for the common types of protective relays, while Loving, in 1949, published refinements to these. Macpherson, Warrington, and McConnell updated the developments up to 1948, and these were extended in later years by Barnes, Kennedy, Honey, Reedman, Dlouhy, Cahen, and Chevallier. In all these schemes, either thyratrons or thermionic tubes have been employed. None of these types has found general application for power system protection, for reasons to be discussed later. In the field of carrier current relaying, however, electronic protection with thermionic tubes has been successfully employed. Even in this field, with the heavy power supplies required for the electronic tubes, combined with the rapid development of semiconductor components, the attention has been rapidly diverted to building carrier equipment with solid-state circuits.

The art of protective relaying in power systems has assumed great importance all over the world with the tremendous expansion in interconnected power systems. There has been a demand for more reliable and advanced systems of protection. This has led to the development of solid-state or static protective relays, eliminating all moving parts. The subject of static relays originated about three decades ago (1950s). The emergence of the transistor and all other solid-state devices has given a great boost to the development of solid-state relays; and in the 1980s many of the power systems are adopting them into their overall protective systems.

The microprocessor has afforded those in protective relaying the remarkable capability of sampling voltages and currents at a very high speed, manipulating the data to accomplish a distance or over current measurement, retaining fault information and performing self-checking functions. The utilization of this new technology has also presented new challenges regarding the manner in which information is handled and manipulated.

Adaptive relay is a relay that can have its settings, characteristics, or logic functions changed on line in a timely manner by means of externally generated signals or control action. Adaptive relaying is shown to be capable of improving relaying reliability and power system security plus achieving better utilization of transmission facilities. Most of the concepts require a hierarchical computer system, involving front-line parallel processors, a substation host, and remote central processing, linked by channels that transmit data or relaying changes prior to or after a disturbance.

From the application point of view, relays can be classified as follows:

Current Relays (Fig. 3)

- Overcurrent relays
- Undercurrent relays
- Current-Balance relays
  - Overcurrent type
  - Directional type

Voltage relays (Fig. 4)

- Overvoltage relays
- Undervoltage relays
- Voltage-balance relays
  - Overvoltage type
  - Directional type

Overcurrent, undercurrent, overvoltage, and undervoltage relays are derived directly from the basic single-quantity electromagnetic attraction or induction types. The prefix "over" means that the relay picks up to close a set of "a" contacts when the actuating quantity exceeds the magnitude for which the relay is adjust to operate. Similarly, the prefix "under" means that the relay resets to close a set of "b" contacts when the actuating quantity decreases below the magnitude for which the relay is adjust to operate. The overcurrent (or overvoltage) type of current (or voltage) balance relay has one overcurrent (or overvoltage) element arranged

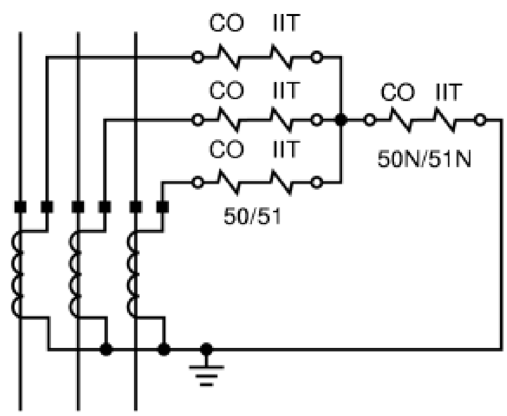

Fig. 3. Connections for an overcurrent ground relay.

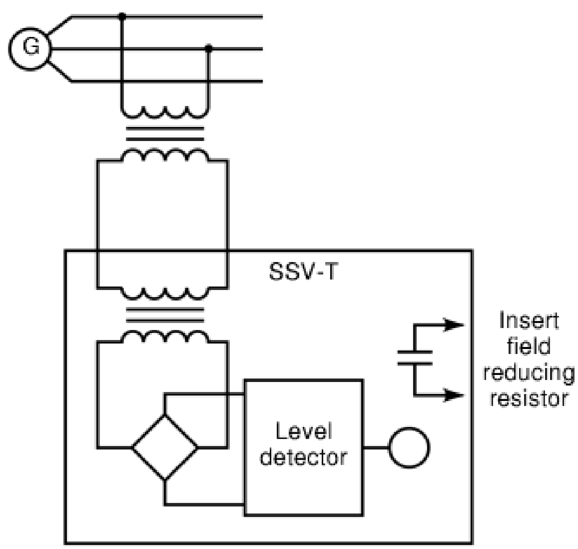

Fig. 4. Overvoltage protection for generator.

to produce torque in opposition to another overcurrent (or overvoltage) element, both elements acting on the same moving structure. The directional type of current (or voltage) balance relay uses a current–current (or voltage–voltage) directional element in which the polarizing quantity is the vector difference of two currents (or voltages), and the actuating quantity is the vector sum of the two currents (or voltages).

Directional relays (Fig. 5)

Dc directional relays

- Current-Directional Relays Used in dc power circuits, they respond to a certain direction of current flow.
- Voltage-Directional Relays These respond to a certain polarity of the voltage across the circuit or across some part of the circuit.

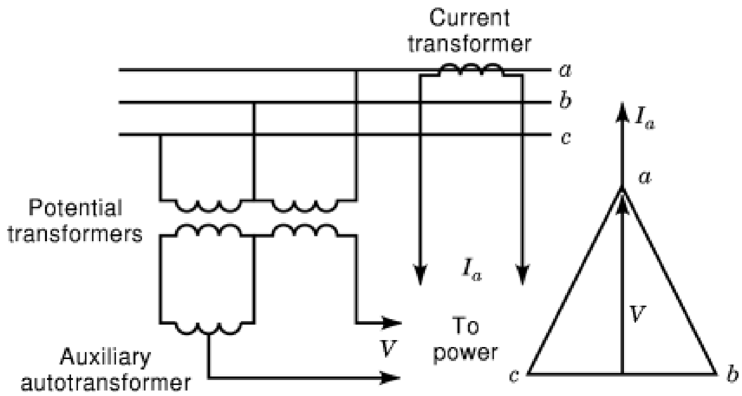

Fig. 5. Schematic of a directional relay.

- Voltage-and-Current-Directional Relays These are used to control the closing and opening of a circuit breaker in the circuit between a dc generator and a bus to which another source of voltage may be connected, so as to avoid motoring the generator.
- Voltage-Balance-Directional Relays These are used to protect a three-wire dc circuit against unbalanced voltages.
- Current-Balance-Directional Relays These are used for current balance protection of a three-wire dc circuit, or to compare the loads of two different circuits.

Ac directional relays

- Power Relays The relay characteristics are chosen such that maximum torque in the relay occurs when unity power factor load is carried by the circuit. The relay will then pick up for power flowing in one direction through the circuit and will reset for the opposite direction of power flow.
- Directional Relays for Short-Circuit Protection These are generally used to supplement other relays. They permit tripping only for a certain direction of current flow, and the other relays determine (1) if it is a short circuit that is causing the current to flow, and (2) if the short circuit is near enough so that the relays should trip their circuit breaker. Such directional relays have no intentional time delay, and their pick up is nonadjustable, but low enough so that the directional relays will always operate when their associated relays must operate.
- Directional-Overcurrent Relays These are combinations of directional and overcurrent relay units in the same enclosing case. Any combination of directional relay, inverse time overcurrent relay, and instantaneous overcurrent relay is available for phase- or ground fault protection.

Differential Relays (Fig. 6) Differential relays take a variety of forms, depending on the equipment they protect. The definition of such a relay is “one that operates when the vector difference of two or more similar electrical quantities exceeds a predetermined amount.” Almost any type of relay, when connected in a certain way, can be made to operate as a differential relay, but most differential relay applications are of the “current differential” type. The advantage of this relay is that it is less likely to operate incorrectly than a differentially connected overcurrent relay when a short circuit occurs external to the protected zone. There has been great activity in the development of the differential relay because this form of relay is inherently the most selective of all the conventional types. However, each kind of system element presents

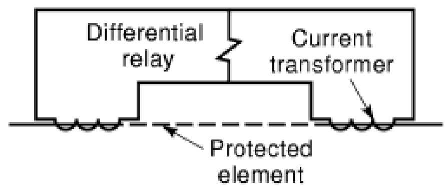

Fig. 6. A simple differential relay application.

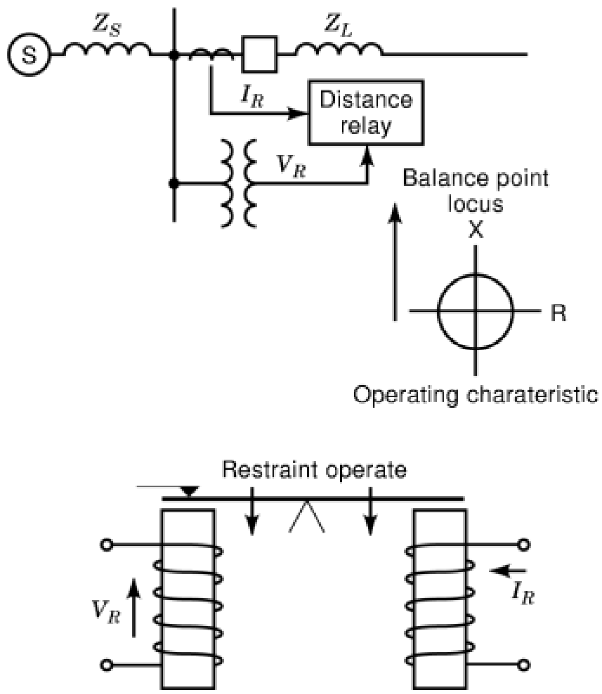

Fig. 7. A beam-type distance relay.

special problems that have thus far made it impossible to devise a differential relaying equipment have universal application.

Distance Relays (Fig. 7) Perhaps the most interesting and versatile family of relays is the distance-relay group. In distance relays there is a balance between voltage and current, the ratio of which can be expressed in terms of impedance. Impedance is an electrical measure of distance along a transmission line, which explains the name applied to this group of relays.

- Impedance-Type Distance Relay In an impedance relay, the torque produced by a current element is balanced against the torque of a voltage element. The current element produces positive (pickup) torque, whereas the voltage element produces negative (reset) torque. In other words, an impedance relay is a voltage-restrained overcurrent relay.
- Modified Impedance-Type Distance Relay The modified impedance-type relay is like the impedance-type relay except that the impedance unit operating characteristics are shifted. This shift is

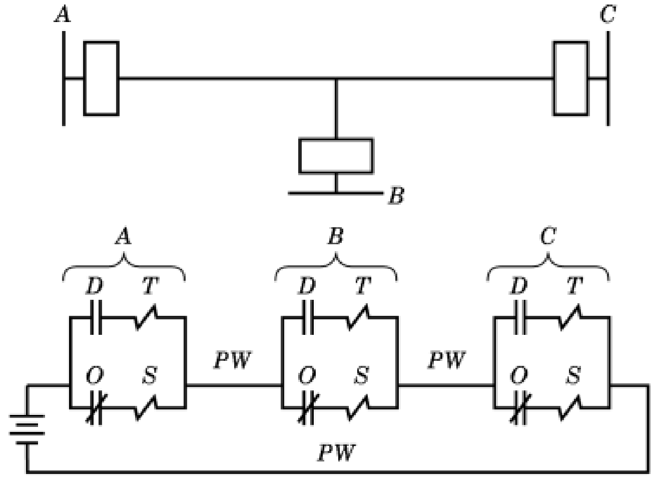

Fig. 8. Schematic of a dc wire–pilot relay.

accomplished by what is called a “current bias,” which merely consists of introducing into the voltage supply an additional voltage proportional to the current.

- Reactance-Type Distance Relay This unit has an overcurrent element developing positive torque, and an current–voltage directional element that either opposes or aids the overcurrent element, depending on the phase angle between the current and the voltage. In other words, a reactance relay is an overcurrent relay with directional restraint.

Pilot Relays (Fig. 8) Pilot relaying is an adaptation of the principles of the differential relaying for the protection of transmission line sections. The term “pilot” means that between the ends of the transmission line there is an interconnecting channel of some sort over which information can be conveyed. Three different types of such channel are presently in use, and they are called “wire pilot,” “carrier current pilot,” and “microwave pilot.” A wire pilot consists generally of a two-wire circuit of the telephone line type, either open wire or cable. A carrier current pilot for protective relaying purpose is one in which low-voltage, high-frequency currents are transmitted along a conductor of a power line to a receiver at the other end, the earth and ground wire generally acting as the return conductor. A microwave pilot is an ultra-high-frequency radio system operating above 9 MHz. The purpose of a pilot is to convey certain information from one end of a line section to another in order to make elective tripping possible.

Wire–Pilot Relays

- Tripping and Blocking Pilots If the relaying equipment at one end of the line must receive a certain signal or current sample from the other end in order to prevent tripping at one end, the pilot is said to be a “blocking” pilot. However, if one end can trip without receiving a certain signal or current sample from the other end, the pilot is said to be a “tripping” pilot.
- Ac Wire–Pilot Relaying Ac wire–pilot relaying is the most closely akin to current differential relaying. However, in modern ac wire–pilot relaying, the magnitude of the current that flows in the pilot circuit is limited, and only a two-wire pilot is required. These two features make ac wire–pilot relaying economically feasible over greater distances than current differential relaying.

Carrier-Current-Pilot Relays When a voltage of positive polarity is impressed on the control circuit of the transmitter, it generates a high-frequency output voltage. This output voltage is impressed between one

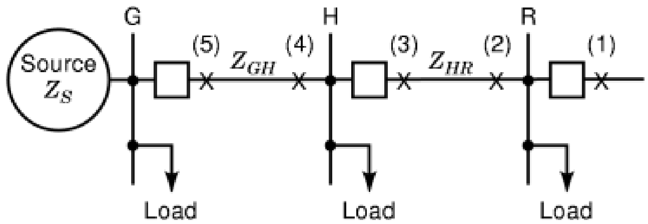

Fig. 9. A line-protection scheme for a radial feeder.

phase conductor of the transmission line and the earth. Each carrier current receiver receives carrier current from its local transmitter as well as from the transmitter at the other end of the line. In effect, the receiver converts the received carrier current into a dc voltage that can be used in a relay or other circuit to perform any desired function. This voltage is zero when carrier current is not being received.

The Microwave Pilot Relays The microwave pilot is an ultra-high-frequency radio system operating in allotted bands above 900 MHz in the United States. The transmitters are controlled in the same way as carrier current transmitters, and the receivers convert the received signals into dc voltage as carrier current receivers do.

- Phase-Comparison Relaying Phase comparison relaying equipment uses its pilot to compare the phase relation between current entering one terminal of a transmission line section and leaving another. The current magnitudes are not compared. Phase comparison provides only primary protection.
- Directional-Comparison Relaying With directional comparison relaying, the pilot informs the equipment at one end of the line how a directional relay at the other end responds to a short circuit. Normally, no pilot signal is transmitted from any terminal. Should a short circuit occur in an immediately adjacent line section, a pilot signal is transmitted from any terminal where short-circuit current flows out of the line.

Equipment Protection

Line Protection (Fig. 9). Alternating current lines are commonly classified by function, which is related to voltage level. Although there are no utility-wide standards, typical classifications are as follows:

- Distribution (2.4 kV to 34.5 kV) Circuits transmitting power to the final users
- Subtransmission (13.8 kV to 138 kV) Circuits transmitting power to distribution substations and to bulk loads
- Transmission (69 kV to 765 kV) Circuits transmitting power between major substations or interconnecting systems, and to wholesale outlet.

Most faults experienced in a power system occur on the lines connecting generating sources with usage points. Just as these circuits vary widely in their characteristics, configurations, length, and relative importance; so do their protection and techniques. There are several protective techniques commonly used for line protection:

- Instantaneous overcurrent
- Time overcurrent

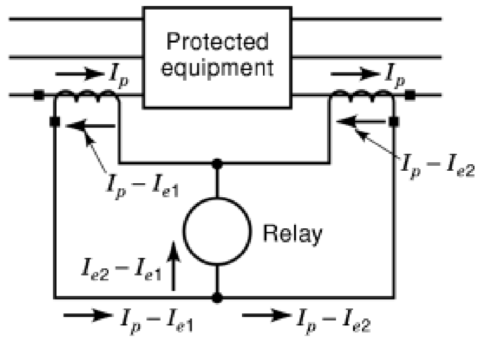

Fig. 10. The basic differential connection for generator protection.

- Directional instantaneous and/or time overcurrent
- Step time overcurrent
- Inverse time distance
- Zone distance
- Pilot relaying

Several fundamental factors influence the final choice of the protection applied to a power line:

- Type of Circuit Cable, overhead, single line, parallel lines, multiterminal, and so forth.
- Line Function and Importance Effect on service continuity, realistic and practical time requirements to isolate the fault from the rest of the system
- Coordination and Matching Requirements Compatibility with equipment on the associated lines and systems.

To these considerations must be added economic factors and the relay engineer's preferences based on his or her technical knowledge and experience.

Generator Protection (Fig. 10). Modern generators are one of the most important components in power systems. The application of protection for ac generators varies, depending on the size of the machine, the type of original mover, the station design, past practices, and so on. For the sophisticated structure of the generator, and its critical role in power systems, the protective relaying scheme against intolerable disturbances is also complex. The generator protection can be divided into the following categories:

Stator Winding Protection. This includes:

- Relays for stator ground faults
- Protection for high-resistance generator grounding (100% stator winding protection)
- Backup stator ground protection
- Abnormal detector for overheating of the stator

Field Winding Protection The brushless excitation system has been introduced, which requires that the ac exciter armature, the rectifying assembly, and the generator field winding be located on the generator shaft. Since continuous monitoring of the field circuit is not practical, a ground-detection system has been developed which checks the field circuit automatically at a given time interval or upon manual initiation.

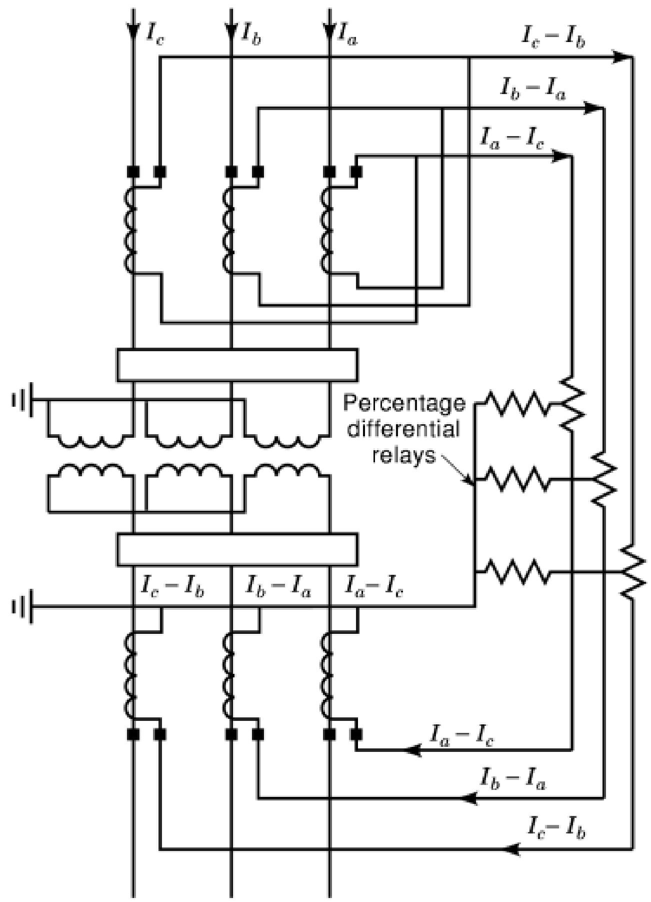

Fig. 11. Connections for percentage-differential relaying for two-winding transformer.

Generator Backup Protection Three-phase faults external to the generator zone of protection are expected to be cleared by the system protection (bus, transmission line, transformer). In the event the fault is not cleared, backup protection is applied to detect these faults and initiate tripping of the unit. This protection generally applied at the generator current transformers and is designed to "look" into the system.

Abnormal Operating Conditions These conditions include

- Under frequency
- Reverse power protection
- Overload protection
- Standstill protection

Transformer Protection (Fig. 11). Differential relays are the principal form of fault protection for transformers rated at 10 MVA and above. However, transformer differential relays are subject to several factors, not ordinarily present for generators or buses, that can cause misoperation:

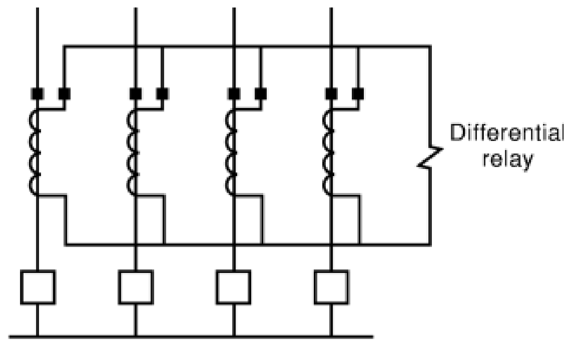

Fig. 12. Bus protection by current-differential relaying.

- Different voltage levels, including taps, that result in different primary currents in the connecting circuits
- Possible mismatch of ratios among different current transformers. For units with ratio changing taps, mismatch can also occur on the taps. Current transformer performance is different, particular at high currents.
- Thirty-degree phase angle shift introduced by transformer wye–delta connections
- Magnetizing inrush currents, which the differential relay sees as internal faults

Transformer protection is further complicated by a variety of equipment requiring special attention: multiple winding transformer banks, zig-zag transformers, phase angle regulators, voltage regulators, transformer in unit systems, and three-phase transformer banks with single-phase units. All the above factors can be accommodated by the combination of relay and current transformer design, along with proper application and connections.

Bus Protection (Fig. 12). A bus is a critical element of a power system, as it is the point of convergence of many circuits, transmission, generation, or loads. The effect of a single bus fault is equivalent to many simultaneous faults and usually, due to the concentration of supply circuits, involves high-current magnitudes. High-speed bus protection is often required to limit the damaging effects on equipment and system stability or to maintain service to as much load as possible. Differential protection is the most sensitive and reliable method for protecting a station bus. The normal practices on bus protection are:

- There is one set of bus relays per bus section.
- Use a dedicated current transformer (ct) for bus differential protection.
- Lead resistance, as well as ct winding resistance, contributes to ct saturation. Therefore, the length of secondary lead runs should be held to minimum.
- Usually, the full-ct secondary winding tap should be used. This has two advantages. It minimizes the burden effect of the cable, and leads by minimizing the secondary current and makes use of the full voltage capability of the ct.
- Normally, there is no bus relay required for the transfer bus on a main-and-transfer bus arrangement, because the transfer bus is normally deenergized and will be included in the main bus section when it is energized.
- No bus relay is required for a ring bus because the bus section between each pair of circuit breakers is protected as a part of the connected circuit.
- Special arrangements should be considered if there is any other apparatus, such as station service transformers, capacitor banks, grounding transformers, or surge arresters, inside the bus differential zone.

Reactor Protection. Both EHV transmission lines and long HV transmission lines and cables require shunt reactance to compensate for their large line-charging capacitance. This capacitance produces VAR generation that the system generally cannot absorb. In many cases, it is necessary to absorb these VAR and provide voltage control at both terminals during normal operation. High overvoltage on sudden loss of load must be limited as well. System switching and operation may require a different amount of VAR absorption and even, at times, some VAR generation. Shunt reactance for VAR control is obtained by

- Fixed shunt reactors
- Switched shunt reactors or capacitors
- Synchronous condensers

Fixed shunt reactors are generally used for EHV and long HV line and for HV cables. Switched shunt reactors or capacitors and synchronous condensers are applied in the underlining system and near load centers.

Shunt reactors vary greatly in size, type, construction, and application. The connections may be (1) directly to the transmission circuit, (2) to the tertiary winding of a transformer bank that is part of the line, or (3) to the low-voltage bus associated with the line transformer bank.

Line reactors, which are connected directly or through a disconnect switch, are a part of the transmission circuit. Circuit breakers are seldom used. The neutrals of the reactors are solidly grounded or grounded through a neutral reactor. Reactor faults require that all line terminals be open. The protective techniques commonly used for reactor primary and backup protection are:

- Rate-of-rise-of-pressure (applicable to oil units with a sealed gas chamber above the oil level)
- Overcurrent (three phase and/or ground)
- Differential (three-phase or ground only)

Capacitor Protection. Transmission lines are inherently inductive. The purpose of a series capacitor is to tune-out part or all of the transmission line inductance. In a network without series capacitors, faults are inductive in character and the current will always lag the voltage by some angle. Commonly used types of line protection can detect a fault and by operating circuit breakers clear it fast and selectively. With the series compensation of the transmission line, capacitive elements are introduced, and the network will no longer be inductive under all fault conditions. The degree of this change is dependent on the line and the network parameters, extent of series compensation, type of fault, and fault location.

The capacitive or apparent capacitive nature of the fault current may cause the line protection to fail to operate, or to operate incorrectly, unless careful measures are taken to acknowledge this problem. Due to the capacitive nature of the fault loop, a complication with respect to protection may arise both on the compensated line as well as adjacent lines. There are some practical considerations:

- For high-speed relaying of a series-compensated transmission line, the use of a pilot system is unavoidable. If directional comparison systems are used, distance elements provided with an acceptable duration of “memory” and very special logic should be available. A reverse looking unit with memory action is used to block high-speed tripping.
- If phase comparison systems are used, a relaying channel is required to transmit the information of the currents from side to side such that a phase comparison of the currents could take place.

Protective Relaying for Abnormal Phenomena

Out-of-Step (*OS*) Relaying. Ideally, fault relays should clear faults fast enough to maintain stability. Also, they should not operate on swings from which the system can recover. If the system does go out of step, it should be split by circuit breakers opening at a few preselected locations, in such a way that generation and load on each side of the split are reasonably balanced. The system should not be split so most of the generation is separated from the major system load.

- Generator Out-of-Step Relaying Generator per unit reactances have steadily increased over the years, and inertia constants have decreased as machine ratings have increased. This, in turn, has reduced critical clearing times and increased the need for the OS relaying for generators. Loss-of-field relays, equipped with directional units and undervoltage supervision, may provide a measure of OS protection for generators.
- Transmission Line Out-of-Step Relaying The prime criterion in OS tripping is to maintain a generation/load match in the islands created. If such a match were perfect, no large load shifts and load dropping would be required. Also, little or no generation would be dropped. To even approximate this ideal would, in all probability, require trip-blocking at some locations and trip-initiation at others.

Load-Shedding and Frequency Relaying. When a power system is in stable operation at normal frequency, the total mechanical power input from the prime movers to the generators is equal to the sum of all the connected loads, plus all real power losses in the system. Any significant upset of this balance causes a frequency change. The huge rotating masses of turbine-generator rotors act as repositories of kinetic energy: When there is insignificant mechanical power input to the system, the rotors slow down, supplying energy to the system. Conversely, when excess mechanical power is input they speed up, absorbing energy. Any change in speed causes a proportional frequency variation.

Unit governors sense small changes in speed resulting from gradual load changes. These governors adjust the mechanical input power to the generating units in order to maintain normal frequency operation. Sudden and large changes in generation capacity through the loss of a generator can produce a severe generation and load imbalance, resulting in a rapid frequency decline. If the governors and boilers cannot respond quickly enough, the system may collapse. Rapid, selective, and temporary dropping of loads can make recovery possible, avoid prolonged system outage, and restore customer service with minimum delay.

- Load Shedding For gradual increases in load, or sudden but mild overloads, unit governors will sense speed change and increase power input to the generator. Extra load is handled by using “spinning reserve,” the unused capacity of all generators operating and synchronized to the system. If all generators are operating at maximum capacity, the spinning reserve is zero and the governors may be powerless to relieve overloads. In any case, the rapid frequency plunges that accompany severe overloads require impossibly fast governor and boiler response. To halt such a drop, it is necessary to intentionally and automatically disconnect a portion of the load equal to or greater than the overload. After the decline has been arrested and the frequency returns to normal, the load may be restored in small increments, allowing spinning reserve to become active and any additional available generators to be brought on line.
- Frequency Relaying Frequency is a reliable indicator of an overload condition. Frequency-sensitive relays can therefore be used to disconnect load automatically. Many different types of frequency relays have been used over the years. Three general classes of frequency relays are being applied: the induction-cylinder relay, the digital relay, and the microprocessor relay.

  (1) Induction-Cylinder Relay This relay is fast and sufficient accurate for most applications. The principal of operation of the relay is based on a circuit in which the phase angle changes as frequency changes.

(2) Digital Relay This relay uses a multimegahertz counter. Zero crossing of voltage is detected, and a counter starts and continues counting until the next voltage zero. The count accumulated is indicative of the period of waveform and thus the frequency is identified.

(3) Microprocessor Relay The principle applied in the microprocessor relay is the same as that in a digital relay, but additional sophistication is included. All the self-checking provisions and examination of various failure modes are constantly achieved and alarm and lockout are an inherent part of these relays.

Reclosing and Synchronism Protection. The large majority of overhead line faults are transient and can be cleared by momentarily deenergizing the line. In fact, utility reports show that less than 10% of all faults are permanent. It is, therefore, feasible to improve service continuity by automatically reclosing the breaker after fault relay operation. For example, automatic reclosing greatly improves service in radial distribution circuits, where service continuity is directly affected by circuit interruption. High-speed reclosing on tie lines, if successful, also assists in maintaining stability.

- One-Shot Versus Multiple-Shot Reclosing Relays The desired attributes of a reclosing system vary widely with user requirements. In an area with a high level of lightning incidence, most transmission line breakers will be successfully reclosed on the first try. On the other hand, multiple-shot reclosing are warranted on distribution circuits with significant tree exposure, where an unsuccessful reclosure would generally mean a customer outage.
- Selective Reclosing The speed of tripping is a significant factor in the success of a reclosure on a transmission circuit. The faster the clearing, the less fault damage and/or degree of arc ionization, the less the shock to the system on reclosure, and the greater the likelihood of reenergization without subsequent tripping. The probability of successful reclosing then is improved if reclosing occurs only after a high-speed pilot trip. By allowing only pilot tripping to initiate high-speed reclosing, maximum success can be assured for single-shot reclosing, and many unsuccessful reclosures can be avoided.
- Synchronism Check A synchronism check relay is an element in the reclosing system that senses that the voltages on the two sides of a breaker are in exact synchronism. (An automatic synchronizer, on the other hand, initiates closure at an optimal point when the two system segments are not in precise synchronism, but have a small beat frequency across the breaker contacts.) The setting for most synchronism check relays is based on the angular difference between the two voltages and designed to minimize the shock to the system when the breaker closes.

Backup Protection

Backup relaying, which provides necessary redundancy in protective systems, is defined in the *IEEE Standard Dictionary* as "protection that operates independently of specified components in the primary protective system and that is intended to operate if the primary protection fails or is temporarily out of service."

Backup protection includes remote backup, local backup, and breaker-failure relaying. Breaker failure is defined as a failure of the breaker to open or interrupt current when a trip signal is received.

Backup protection for equipment such as generators, buses, and transformers usually duplicates primary protection and is arranged to trip the same breakers. In the event of a breaker failure, some remote line protection would isolate the fault.

In the past, backup protection for lines was provided by extending primary protection to line sections beyond the remote bus. With the advent of EHV and increased concern about both service continuity and possible breaker failures, local backup, including breaker-failure protection, has become common.

- Remote Backup Circuit breakers occasionally do fail to interrupt or trip for various reasons, and the remote terminal relays and breakers may be able to provide backup for a failed breaker. However, remote backup provides poor selectivity. It interrupts all tapped loads on the unfaulted line sections. Remote backup must also be relatively slow to give the primary relays in the remote line time to clear their fault. As the coordinating time interval is typically 0.3 s, backup times greater than 20 cycles are common. If sequential tripping is necessary, the fault-clearing time for the breaker for a remote backup must be further increased.
- Local Backup Unlike remote line protection, local backup is applied at the local station. If primary relays fail, local backup relays will trip the local breakers. If the local breaker fails, either the primary or backup relays will initiate the breaker-failure protection to trip other breakers adjacent to the failed breaker. Although local backup protection has many advantages and is widely used, it does not automatically eliminate the need for remote backup.
- Breaker-Failure Relaying Breaker-failure protection should be as fast as possible without tripping unnecessarily. This criterion is particularly important in EHV lines, where stability is critical. In applying breaker-failure protection, it is recommended that: (1) one breaker-failure circuit per breaker be applied, regardless of the bus configuration; (2) All adjacent breakers should be tripped by breaker-failure protection, regardless of fault location; (3) In all cases, all breakers tripped by the breaker-failure scheme should be locked out; and (4) a remote breaker must also be tripped by either its own relays or transfer-trip initiated by local breaker-failure protection.

Evaluation of Protective Relay Performance

Relays have been aptly named "silent sentinels." They stand on guard days and nights. They protect tremendous network and equipment. Since relays do not operate until faults occur in their protective zones, relay performance is evaluated by those relays provide direct or specific evidence of operation. It can be classified as: (1) correct operation; (2) incorrect operation, either failure to trip or false tripping; and (3) no conclusion.

Current Research

Future protective relays tend to be digital. There are many advantages for computer relays, mainly: greater reliability, economy, new functions, and trends in other subsystems.

- Relaying with Computers Computer relays can monitor themselves and, when defective, can log a service alarm at a remote location. This self-diagnostic ability is what makes them attractive to relay engineers. Most relay misoperations occur not because the protection engineers designed a faulty protection system but because the relay was in a failed state, and no one knew about it. Therefore, although one expects the computer relay to fail from time to time, just as a conventional relay does, one expects to be informed about its failure immediately and repair it. Computer relays also make possible electronic CTs and CVTs. Several functions within a substation could be combined in a relay. Redundancy in protection functions can be built up in many novel ways. Relays can be made to respond to control decisions made on a systemwide basis.
- Adaptive Relaying This is a new development in the relaying field and, quite simply, it is relaying with state vector feedback. Adaptive relaying seeks to make adjustments to the relay characteristics as system conditions change, thereby making the relay more attuned to the prevailing power system conditions. Examples can be found in out-of-step relaying. It is shown that for a system that behaves primarily as a two-machine power system, the out-of-step relay could be made more secure by applying the principle of equal area criterion.

- Relaying with Artificial Neural Networks (*ANN*s) ANNs provide a viable alternative because they can handle most situations which cannot be defined sufficiently for finding a deterministic solution. Such an approach will enjoy the advantages which are inherent in ANNs, such as excellent noise immunity, robustness, fault-tolerance, and generalization capabilities. Examples can be found in transmission line protection and transformer protection. In these examples, ANNs have been applied to inrush detection, to the calculation of tripping impedance in distance protection, and to the design and implementation of an ANN-based direction discriminator.
- Simulation and Coordination with Petri Nets (*PN*s) PNs are a flexible, visualized modeling tool capable of modeling many systems, especially discrete event systems. Examples can be found in modeling of overcurrent relaying, and in modeling of a transmission line protection relaying scheme.

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