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PROTECTION OF ELECTRICAL EQUIPMENT
SINGLE PHASING AND RELATED FAULTS

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Motors, switchgear, transformers, buss-work, and in fact, all electrical equipment is vulnerable to serious failures due to single phasing. Single phasing is the loss or electrical breakdown of one phase of a three-phase circuit. If undetected the simple failure grows and can cause a large loss of equipment. The degree of protection needed is the subject of some controversy. Economy is one factor influencing how much protection is justified. Nevertheless more serious consideration is needed in view of the number of losses caused by single phasing.

Protection against single phasing is dependent on more than one protective device. Fundamental methods of protection as well as some of the newer protective devices are discussed in this data sheet.

CAUSES OF SINGLE PHASING

Causes of a single phase condition on a 3-phase circuit include a blown fuse, a broken utility line, a contact failure, a grounded conductor, or an open thermal element, Unless properly installed protective devices operate, the result can be overheating, arcing, fire, and burning out of windings, or a chain reaction of electrical failures.

SINGLE PHASING OF MOTORS

An ‘‘open phase’’ on a polyphase system (i.e. motors on the system have available only a single-phase power) will lead to trouble. If one line (phase) to a three-phase motor opens while it is running, the motor may continue to run - but as a single-phase unit. In this condition, the motor itself tends to maintain the voltage in all three phases but current flow in the other two phases is higher than usual. This current will be greater than 1.73 times normal current, with maximum flow of current dependent upon motor efficiency and power factor (Fig. 1). The poorer the power factor or lower the efficiency, the greater the current flow during a single phase condition.

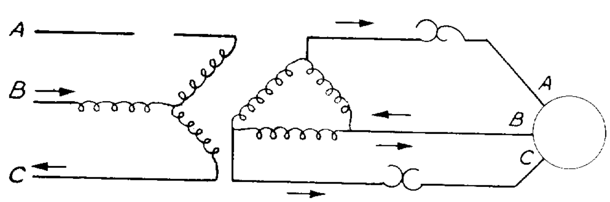


Fig. 1. An open circuit in a primary leg can cause severe unbalance of current in a secondary circuit. Current in the unprotected leg could be twice that in the other two.

A running motor may stall if carrying more than 35% of its rated load when single phasing occurs. More frequently it continues to run as a single phase motor with part of its winding drawing excessive current. This current, if measured by an overload relay, will trigger the relay to disconnect the motor before it is damaged.

OVERLOAD RELAYS

Many standard motor starters have overload relay protection in only two of the three lines (phases) since this arrangement usually will detect single phasing in most circumstances. There are conditions in which the excess current flows only in one line, and there is a 33% probability that this will be the unprotected leg. An overload relay properly applied in each of the three phases would eliminate this probability.

SINGLE PHASING WITH OTHER CONNECTED LOADS ON SAME FEEDER

If on the same feeder there is more than one connected load, the voltage generated by the transformer action in the open phase will supply power to these single phase loads. This results in heavier current flow through the connected two phases. It is only a matter of time until excessive overheating will cause burning out of the winding and damage to connected wiring and switchgear.

Since the ‘‘dead’’ single phase will always generate at a voltage close in potential to the supply voltage, any phase-failure device which is wholly dependent on voltage alone will not open the circuit.

UNBALANCED VOLTAGES AND CURRENTS

The use of single-pole interrupters in polyphase power distribution systems has resulted in an increasing number of motor failures because of inadequate protection against overheating caused by unbalanced phase currents.

The balanced relationship between phases becomes distorted if there is a single phase-to-ground, phase-to-phase, or two-phases-to-ground fault. Any one of these faults cause voltage variations and unbalanced currents. The current and voltage can vary widely dependent upon the system and type and location of the fault.

It is too often assumed that if a system has fuses in each of the three phases of the power line and each motor is properly protected with a thermal relay, protection is adequate in the event of single phase operation. Even if a three-phase undervoltage relay is installed in the system, it cannot be assumed that the voltage triangle will collapse or the unbalance of the three voltages will be sufficient under single phase operation to cause the relay to operate. The voltage triangle does not in many cases collapse, because, even with one phaseout, the connected motors will continue to run on a single phase supply, and will operate like a generator trying to maintain a sufficiently balanced three-phase voltage (Fig. 2.)

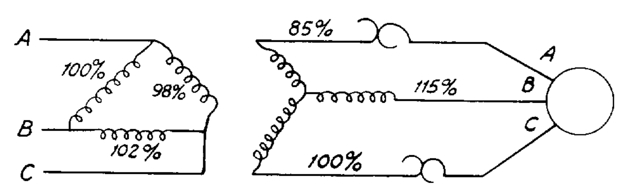


Fig. 2. Effect of unbalance of primary voltage showing effect on secondary voltage.

With the same transformer connections, if primary voltages are unbalanced, a small unbalance of 2% in primary voltage can cause a 15% unbalance in motor current. In many cases the primary unbalance voltage can go well in excess of 2%.

When motors are supplied from transformers connected delta-wye or wye-delta and have isolated neutrals, an open circuit (i.e. single phasing) in a primary leg can cause severely unbalanced current in the secondary circuit. The current developed in one of the motor legs could be twice that in the other two and could result in burning out of the winding if not properly protected. While this transformer connection is common, malfunction of the other electric equipment usually signals an open phase before motors are damaged in attended locations.

An example of this is where the circuit may consist of two three-phase motors, of differing horsepower or, a three-phase motor and a substantial single phase load connected to the same three-phase circuit. With an ‘‘open phase’’, excess current can develop which may remain undetected until failure occurs unless adequate protective devices are available (Fig. 3).

UNBALANCED PHASE LOADING OF GENERATORS

Extensive damage to the fields of alternating current generators can occur due to unbalanced loads in the three phases. When the loads are balanced on a three-phase generator, a fundamental of magneto-motive force (MMF) is generated that moves at synchronous speed with respect to the rotor. But when the phases become unbalanced, two fundamentals of MMF are generated, only one of which moves in the same direction. The backward-moving MMF moves at twice the normal speed with respect to the rotor, and in a 60-cycle machine eddy currents at 120 cycles would be induced in the surface of the windings.

Depending upon the amount of unbalance and the resistance in the circuit, the induced currents can cause overheating and burning at the point of contact between the retaining ring and the rotor wedges. The

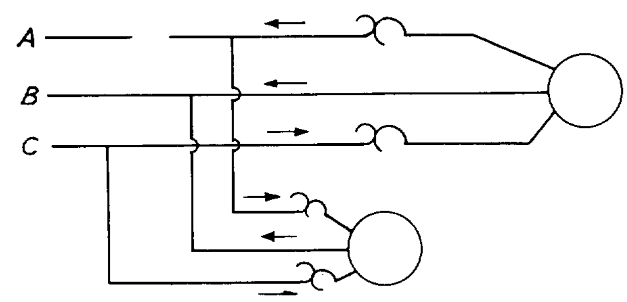


Fig. 3. Two 3-phase motors of unequal horsepower or a 3-phase motor and connected single phase load may be connected to the same load. With an open line, current interchange can result in an excessive current in the unprotected phase.

overheating may also cause a change in grain structure of the retaining ring and the wedge ends which in turn result in weakening of these parts. Occasionally the retaining ring may burst and rupture the case while the machine is in operation.

BASIC FAULT PROTECTION FOR MOTORS AND MOTOR CIRCUITS

Protection against single-phasing and related faults may start with first providing basic protective devices. Without the necessary basic protection, other protective devices cannot function satisfactorily to recognize faults in the system.

FUSES

The standard fuse. The standard fuse, lacking a builtin time lag, cannot handle a 700% starting current and at the same time give the required running overload protection. If the requirement is only for short circuit protection, then the standard fuse is satisfactory.

The time-lag fuse. The time-lag fuse is used for both overload and short circuit protection. Careful selection of size is necessary for reliable protection against short circuit or ground. This is governed by the full load current rating of the motor. Fuses are in themselves one of the causes of single-phasing since a blown fuse can create single-phasing in a three-phase circuit. It is therefore important that other protective features be incorporated in the circuit.

The dual-element fuse. The dual-element fuse is a special fuse incorporating two elements one of which has the speed of response required for short circuit protection and the other will provide running overcurrent protection for the motor windings with enough time delay to handle the motor starting current

THERMAL TRIP DEVICES

Thermal overload relays are installed in the motor controller to provide the required running overcurrent protection for the motor. Where circuit breakers are used for protection of the motor branch circuit, they are equipped with thermal time delay trips to provide the required overload protection for the conductors and a magnetic trip for instantaneous tripping on short circuits.

Thermal trips. Thermal trips are of the melting alloy or bimetallic type and are widely used as protection against single-phasing and motor overload. The development of heat due to current flow through a series sensing device will actuate a toggle and trip the controller circuit breaker. If the thermal protection is limited to only two of the three phases of the controller, protection against single phasing is not complete since there is a 33% probability that the overload will occur on the unprotected leg.

THERMAL PROTECTION

Overheating of a rotating machine’s windings due to single-phasing or other causes can be prevented by measuring or sensing the temperature of the winding directly, instead of using a current relay. Temperature-sensitive switching elements (Fig. 4) are inserted into the winding overhang or the slots of the stator in each phase, before the winding is impregnated with varnish. When the predetermined temperature limit is exceeded, the resistance of the thermistor probe rises steeply and, being connected in series with the relay, de-energizes the circuit. (Fig. 5).

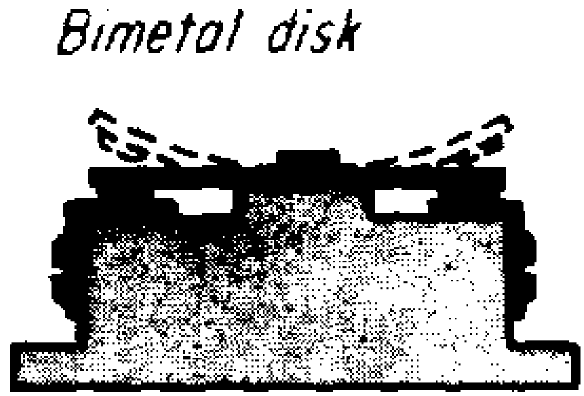


Fig. 4. Some protective devices that react to winding temperature. These inherent protectors have been improved to give faster, more accurate response to temperature of the windings. Lower illustration shows thermistor temperature detectors of normal design.

Thermistor probes are available in several different temperature ratings and may be used in a motor with the high temperature setting connected to actuate a relay which causes the motor to shut down, and with the low temperature setting connected to sound an alarm before critical temperature is reached.

Protection against single phasing on motors is critical when the unit is lightly loaded. The rated current must not be exceeded, in any case, so that the winding will not be damaged. In delta connections, one phase of the motor may be overloaded, although the rated supply current is not exceeded. For such cases, the protection needed is a thermal relay combined with a single-phase protective device, which would automatically alter the tripping characteristic of the relay as soon as one phase fails. With measuring elements in the winding, the winding temperature is measured direct and single-phase protection is provided.

Motors 1500 hp and Above. During assembly, temperature detectors should be embedded as an integral part of the windings. These detectors should be connected to protective devices which will shut down the motor when detected temperature is higher than the nameplate data for a 40°C ambient.

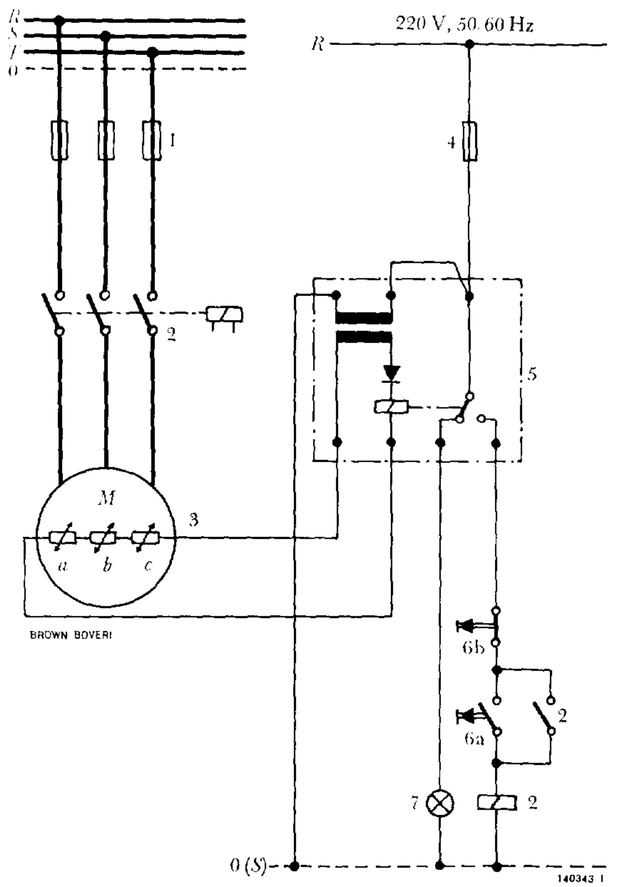
RECOMMENDED PROTECTION AGAINST SINGLE UNBALANCE IN THE CIRCUIT AND RELATED FAULTS

Balance Relays. Current balance relays are used to detect unbalance in the three line currents and are considered satisfactory means of protection against single phase operation.

When phase current becomes unbalanced, as in the case of failure in one phase, the phase balance relay contacts close and actuate the tripping circuit for the breaker or starter.

For a current balance relay to protect against single phase operation, the continuous rating of the current balance relay must be equal to or greater than the maximum total load current, while at the same time, the operating point of the relay must be low enough to protect the smallest installed motor. The current balance relay will protect a single unit (motor or generator) against unbalanced phase currents but is not sensitive enough to protect a system of motors.

Current balance relays are expensive and their application has been limited because an installation of fuses, breakers, and thermal elements has usually been considered satisfactory and more economical to protect rotating electric equipment.



1 = Main fuse
2 = Contactor
3 = Protected motor with measuring elements *a*, *b*, *c*
4 = Control fuse
5 = Control relay
6a = "ON" button
6b = "OFF" button
7 = Fault indicator lamp

Fig. 5. Basic circuit diagram for a drive with thermistor protection.

The negative-sequence voltage relay. The negative-sequence voltage relay will detect when the three line voltages are unbalanced and will protect motors against single phasing. It operates by detecting the presence of negative sequence voltage during an unbalanced condition of the circuit. When the three line voltages in a three-phase system become unbalanced, a negative sequence voltage appears which can be detected to actuate a relay designed for that purpose.

The relay operation is instantaneous but may be installed with a time delay so that the breaker would not be tripped during a system transient. (See Fig. 6 for suggested location system.)

The relay could also be used to actuate an alarm which would alert the operator to the unbalanced power circuit.

Ground Fault Sensor or Interrupter. At certain fault current values in polyphase circuits, only one fuse may blow. A single phase condition then exists, and the usual overload protective devices provided may not operate because of the low level fault current. If due to arcing to ground, the fault condition could continue until destruction of equipment takes place.

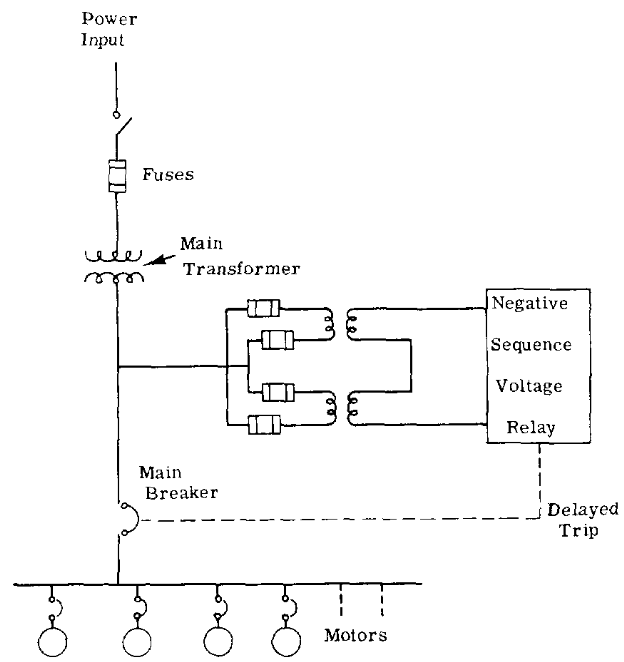


Fig. 6. Negative sequence relay for motor protection.

Sensitive, fast acting protective devices are needed that are not affected by phase-to-phase currents but instead will react to a phase-to-ground current. Because an arcing fault is nearly always between phase and ground (even if the fault originates from phase-to-phase, it will always involve ground), a protective device which would respond to phase-to-ground current is required for protection against this condition. Such a device is the ground sensor or ground-fault interrupter. This device may be used with either a time delay relay or with an instantaneous relay. An instantaneous relay would be used on circuits to ungrounded transformer windings or single loads while a time delay relay with the ground sensor would be more applicable on motor control centers or unit substations.

The ground fault sensor or interrupter consists of a current-sensing device known as ground fault sensor that operates in combination with a solid state switch or a relay which may incorporate time delay features to reduce nuisance tripping. This is generally known as a differential-type ground fault interrupter in which the transformer core encircles all the circuit conductors, including the neutral if there is one (Fig. 7). Under normal conditions the vector sum of the three phase currents passing through the core is zero, but when a ground fault develops, an unbalance occurs and an output signal proportional to the ground fault is produced which initiates the operation of the circuit breaker.

Some of the known ground fault sensor devices available on the market are the General Electric *Power Sensor,* O.Z. Electrical Manufacturing Company (Div. of General Signal) *Hi-Z Ground Fault Sensor,* and I.T.E. *Ground Shield* system. The Rucker Company and Federal Pacific Electric Company also have developed ground fault control devices.

SURGE PROTECTION FOR MOTORS

Surge protection is recommended for high voltage motors. This is most important where the cable to the motor is over 100 ft. long. In such cases a surge could develop on shutting off the motor, with damage by overstressing to the first few turns of the winding.

A sudden circuit disturbance can cause a transient voltage or surge to be produced that will result in failure to an unprotected motor.

Any programming surge protection must provide for switching surges as well as lightning surges. This requires proper system grounding, adequate shielding, and the use of lightning arrestors and surge capacitors.

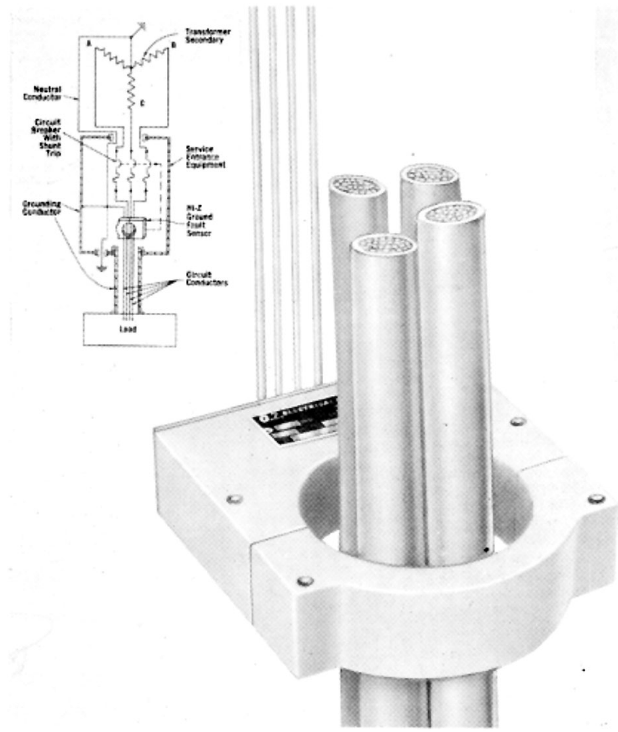


Fig. 7. One commercially available differential-type ground fault interrupter, the Hi-Z Ground Fault Sensor installed around all circuit conductors.

Motors Needing Recommended Protection Against Faults.

Horsepower Rating	*Voltage Rating*
500 - 1499	5000 and higher
1500 - 2999	2200 and higher
3000 - and above	At all voltages

Where the initial investment is high, direct measurement of winding temperatures is usually justified. This is accomplished by means of resistance-type measuring elements, usually of platinum wire, laid in the stator slots and connected to a simple bridge circuit.

Grounding protective relays and differential relays are also recommended for the protection of large motors.

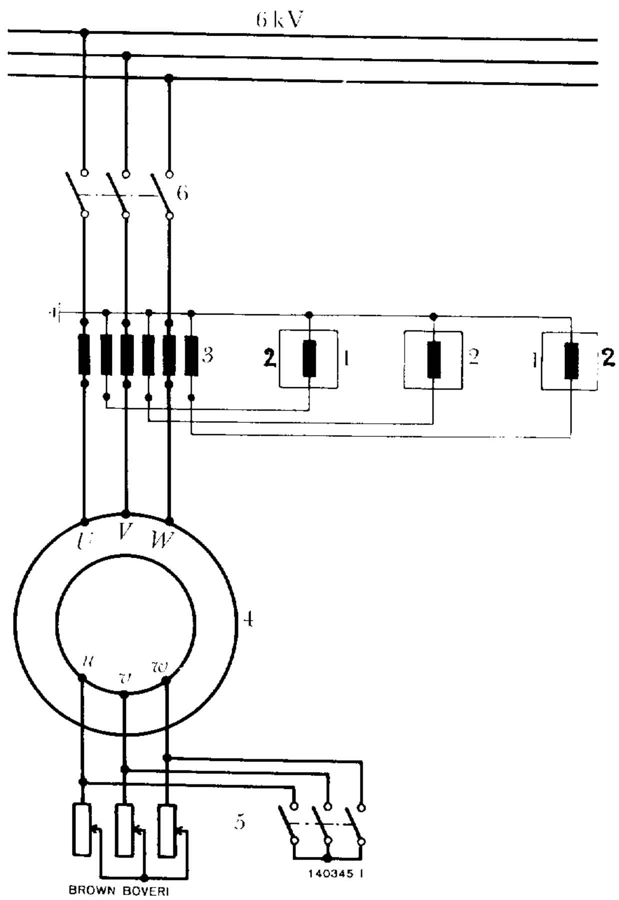
Single Large Motor Operation (500 hp and over). If one large motor is being operated directly from an individual wye-delta or delta-wye transformer, a third overload relay is recommended (Fig. 8).

Larger rotating equipment needs special protection from surges and other faults. The cost of the initial installation and its importance to protection more than justifies the small expense of added protection.

RELATED CONDITIONS THAT AFFECT ELECTRICAL PROTECTION

There are different problems and relationships in a plant depending on whether or not the distribution system is grounded or ungrounded.

Grounded Systems. In grounded systems, phase-to-ground faults produce currents which if of sufficient magnitude will cause the operation of neutral overcurrent relays. These relays automatically detect the fault, determine which feeder has faulted, and initiate the tripping of the correct circuit breakers to deenergize the faulted portion of the system without interruption of service to other portions. When the fault current is flowing, relaying will take place to trip the appropriate circuit breaker and prevent serious damage at the point of the fault.



1 = Instantaneous overcurrent relay (short-circuit protection)
2 = Thermal relay (overload protection)
3 = Current transformer
4 = Motor
5 = Rotor starter
6 = Main switch

Fig. 8. Simple protection of a relatively large high-voltage motor.

Ungrounded Systems. In ungrounded systems, a phase-to-ground fault produces relatively insignificant values of fault current but often produces dangerous overvoltage. In a small installation the ground fault current due to normal leakage and capacitance of the system may be well under 1 ampere, while at a large plant with miles of cable it may produce not more than 20 amperes of ground fault current. These currents will not cause operation of the usual overcurrent protective devices to remove the fault because devices are not sensitive enough to the ground faults which are complex and of various distributive capacitance.

The argument for the use of an ungrounded system is that even if an arcing ground occurs, there is an advantage in maintaining continuous service for the entire system including the faulted phase-to-ground area. Against this advantage must be balanced such problems as operating with an unknown and unsafe condition and a continuing over-stressing of insulation of the unfaulted phases.

Sustained arcing faults in low voltage apparatus are often initiated by a single-phase fault to ground which results in extensive damage to switchgear and motor control centers.

A low voltage arcing fault will often travel through an entire bus structure until it reaches a point where the heat from the arcing causes ignition of combustible materials. The result is the cascading development of a fault of such magnitude that unless adequate interrupting capacity is available, the result is complete destruction.

This is due to the failure of the standard protective devices, such as fuses or circuit breakers, to recognize the fault because the resistance of the arc and impedance in the fault circuit are such that sufficient current cannot flow to operate these devices soon enough to prevent the damage. In numerous cases the installed protective devices do not operate at all.

PROTECTION AGAINST SUSTAINED ARCING FAULTS

The overcurrent protective elements utilized in low voltage systems are generally in the form of a series trip device in two or three phases of a circuit breaker. Other protection may be provided by fuses.

These elements are usually rated or set high enough so as not to have unnecessary power interruption under normal steady state and transient load conditions. It is important that they not be set higher than absolutely necessary in order to give adequate protection.

One rule of thumb on the settings of instantaneous elements of low voltage feeder breakers is that they should not be higher than four to six times the overload setting, and the settings of instantaneous elements of secondary breakers not greater than the feeder breaker. If settings are higher, an arcing fault will not be recognized by the breaker. At lower settings it is more likely that an arcing fault will be detected.

Phase-to-neutral arcing faults for the grounded neutral system are more critical to detect as a result of the very limited magnitude of fault current. There are a number of ground fault sensing devices available which actuate a shunt trip of the circuit breaker. This is a recommended method of detecting a low magnitude phase-to-ground arcing fault. In most cases this is an additional expenditure and not always justifiable from the plant’s point of view. However, it is a justifiable expense in view of the problem which is encountered with any related phase-to-ground arcing fault.

A ground detector which operates as an electrical fault ground detector and locator is recommended for ungrounded distribution systems. This device is often used with an indicator and alarm.

All noncurrent-carrying metal enclosures for energized conductors or equipment should be grounded in order to prevent above-ground potentials on this equipment and to provide a low resistance path for fault currents to cause operation of protective devices.

PROTECTION AGAINST SINGLE PHASING FROM INCOMING POWER LINES AND TRANSFORMERS

If the power is being purchased, adequate protection against single phasing should be provided at the utility end of the tie line. This should consist of three distance relays* or three time overcurrent relays.

If a utility tie line and plant generators are both tied into the plant system, protection becomes more complicated. Reverse power and power directional relays with supplementary instantaneous and time delay relays are recommended.

Transmission Lines. Overhead ground wires protect transmission lines by intercepting direct lightning strokes and by providing a low resistance for the stroke current. They also protect against induced strokes by increasing the capacitance between conductors and ground, and thereby reducing the voltage from conductor to ground. Lines of low insulation strength are more susceptible to induced voltages which are of sufficient magnitude to produce flashover.

On a direct lightning stroke, the voltage across the insulation is reduced by coupling between conductors and overhead (static) ground wires. The more (static) ground wires there are and the closer their location to the conductors, the greater is the chance of intercepting a direct lightning stroke and directing the high voltage safely to ground.

Transmission lines can be considered adequately shielded if they are placed below the (static) ground wire so that they lie within an imaginary tent the peak of which is the ground wire which forms an angle with 20° between the protected line and a plumb line through the ground wire.

For some horizontally arranged single circuit lines and for double circuit lines, two overhead ground wires are needed for complete shielding.

Each heavy lightning surge that is not properly dissipated will result in stressing of a transmission line or travelling into the transformer or other areas of the distribution system.

Transformers. A single-phase condition can develop on the primary side of the incoming transformers due to a broken transmission line, a blown fuse, or phase failure within the transformer.

At the substation where the incoming tie line is fed into the primary side of the plant transformers, the use of 3-phase overcurrent relays and ground overcurrent relays are recommended for phase and ground fault protection.

Protection for the power transformer banks in unattended locations should include thermal protection for each phase. The thermal device should also be connected to an external relay to assure complete disconnection of the fault if it occurs in any one phase, thereby protecting the transformer from further damage. In attended stations arrangements should include an audible alarm if overheating occurs.

Protection of the transformer at the main substation should include overcurrent relays of the directional type and reverse time and instantaneous relays on the primary side to secure selective tripping with other protective devices on the system. Differential relays are also advised for large transformers (50000 kva and above) for fast protection against internal faults in either winding, and directional relays on the secondary side for fast selective tripping (Fig. 9).

Directional relays are designed to operate only when current in the circuit flows in a given direction. Two types are available: the directional overcurrent type and the directional product type. Either type may be used for the detection of short circuits, but the directional product type must be used for directional ground fault protection. (Fig. 10).

*A distance relay measures line impedance between fault location and relay location. It is used on incoming utility lines as an instantaneous or inverse-time delay relay, and gives required back-up protection for the main substation.

NATIONAL ELECTRICAL CODE.

Protection against single phasing is specifically covered in the National Electrical Code (NFPA No. 70-1971) in Part C of the Code’s Article 430. Table 430-37 of the National Electrical Code specifies that three running overcurrent units shall be used where three-phase motors are installed unless protected by other approved means.

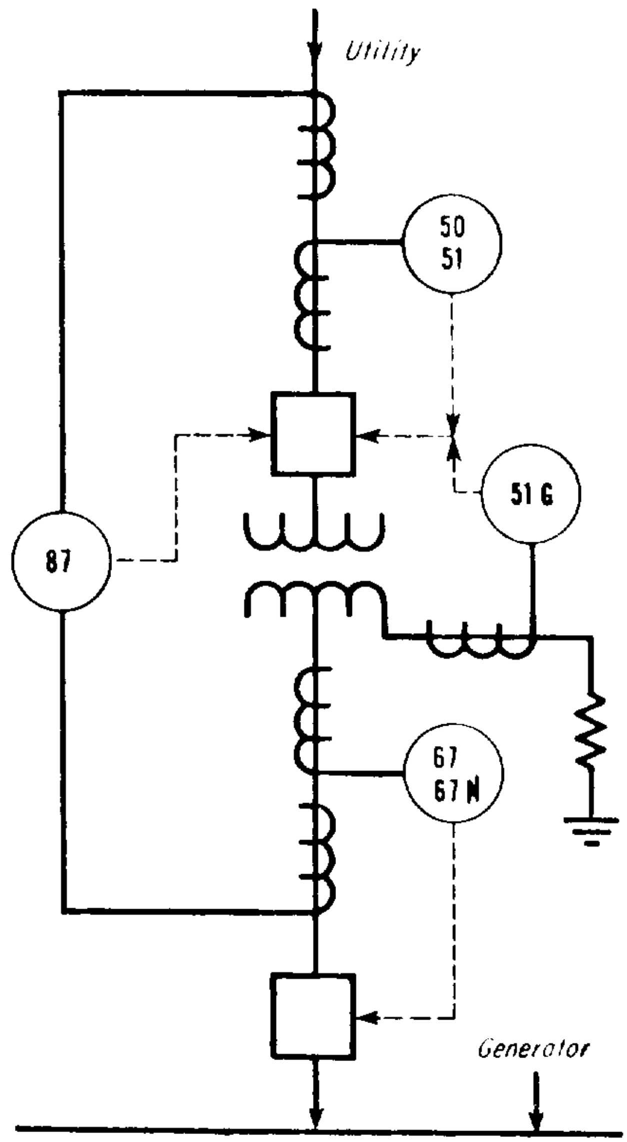


Fig. 9. Main substation protection for transformer and incoming line, using overcurrent, differential, directional, and ground relays. Overcurrent relays, inverse time (51) and instantaneous (50), protect the primary of the transformer. A time-delay overcurrent ground relay (51G) is connected in the transformer neutral circuit. On the secondary side, directional relays (67) and (67N) apply to both phase and ground. A differential relay (87) is also used.

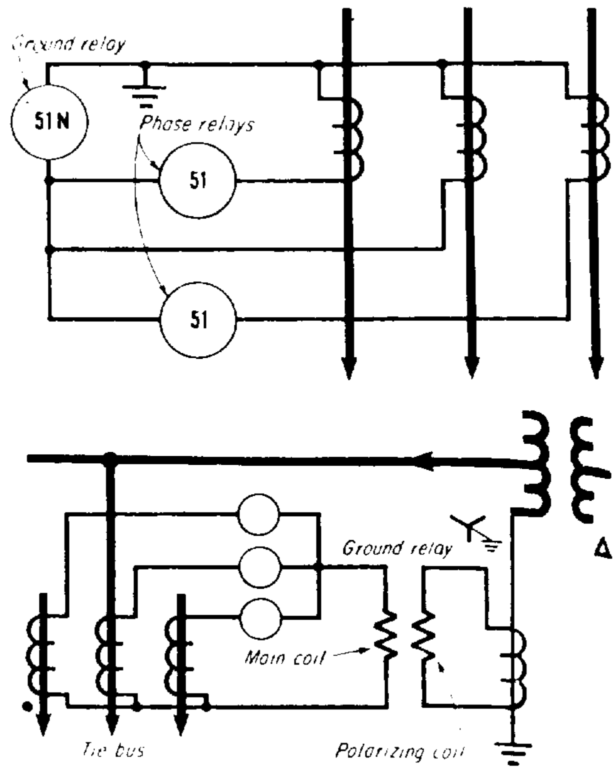


Fig. 10. (Upper) Example of a simple hookup of directional relays, suitable for many systems. This gives phase short-circuit, and ground protection by a relay connected in ct neutral. (Lower) Directional ground relaying is shown polarized by current value for operation on flowing ground current (arrows).

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