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For her typing assistance, I would like to thank Mrs. Julie Strick.

The assistance and kindness of all incur a strong but pleasurable sense of obligation.

Montreal, P.Q.
October, 1979

C. Kouvertaris

To

my wife, Mary

for her assistance and patience

CHAPTER I

GENERAL PROTECTION PRACTICE

The purpose of any power system is to provide a continuous supply of electrical energy to its utilization equipment at a reasonable cost. The greatest hazard to this service is a short circuit caused by an insulation failure. It is necessary to interrupt the flow of current to such a failure in the shortest practical time and to remove only the faulty portion of the system without removing service to other parts of the system. The detection of faulty conditions on a power system is done by relays or fuses, commonly referred to as circuit protective devices, and the disconnection of the faulty system is done by circuit-breakers or fuses.

The over-all arrangement of relays and fuses used is commonly referred to as a protective system.

1.1 DISCONNECTION OF DEFECTIVE ELEMENTS

The elements that make up the complete system are: generators, transformers, buses, transmission lines, distribution circuits, and utilization apparatus. These elements are connected in most cases by circuit breakers and in some cases by fuses so that the opening of one or more breakers or fuses isolates an element from the rest of the system.

To maintain maximum service reliability, only those breakers or fuses should open which connect directly to a defective element. The protective devices which control the tripping of the breaker or fuses should be so co-ordinated with respect to each other as to attain reliable service. The ability of the protective system to operate so as to trip only the minimum number of breakers or fuses directly supplying the defective element is called "selectivity".

1.2 Overlapping of Protective Zones Around Circuit Breakers

The various types of relays chosen to protect the different elements of the system have known characteristics from which can be determined their range or zone of operation as applied to the system. It is highly desirable to have these zones arranged so that there exists on the system no location where an insulation failure can occur without causing the response of the proper units of the relay system. These units should in turn isolate the short circuit through the opening of the proper circuit breakers, which is best obtained by having the zones of protection overlap. Due to the construction of metal-clad switchgear, only the current transformers overlap. With this protective system arrangement, fault occuring in the common area enclosed by two protective zones cause the response of the protective relays covering each zone and the consequent opening of both sets of breakers. Such operation of more than the minimum required number of breakers is preferred over that obtained with a non-overlapping system in which certain faults can occur that fail to cause any response of the protective system and therefore can be cleared only by back-up protection or by manual operation. Overlapping protection cannot be obtained with fuses alone.

1.3 Back-Up Protection and Selectivity

The protective system should operate so as to cause minimum service interruption (Fig. 1). However, short circuits must always be isolated from the source of power supply even though this involves a complete interruption of service. It is, therefore, accepted practice to provide a protective relay system including back-up protection, which will operate not only for faults up to the next protected zone but also for faults in all of the next

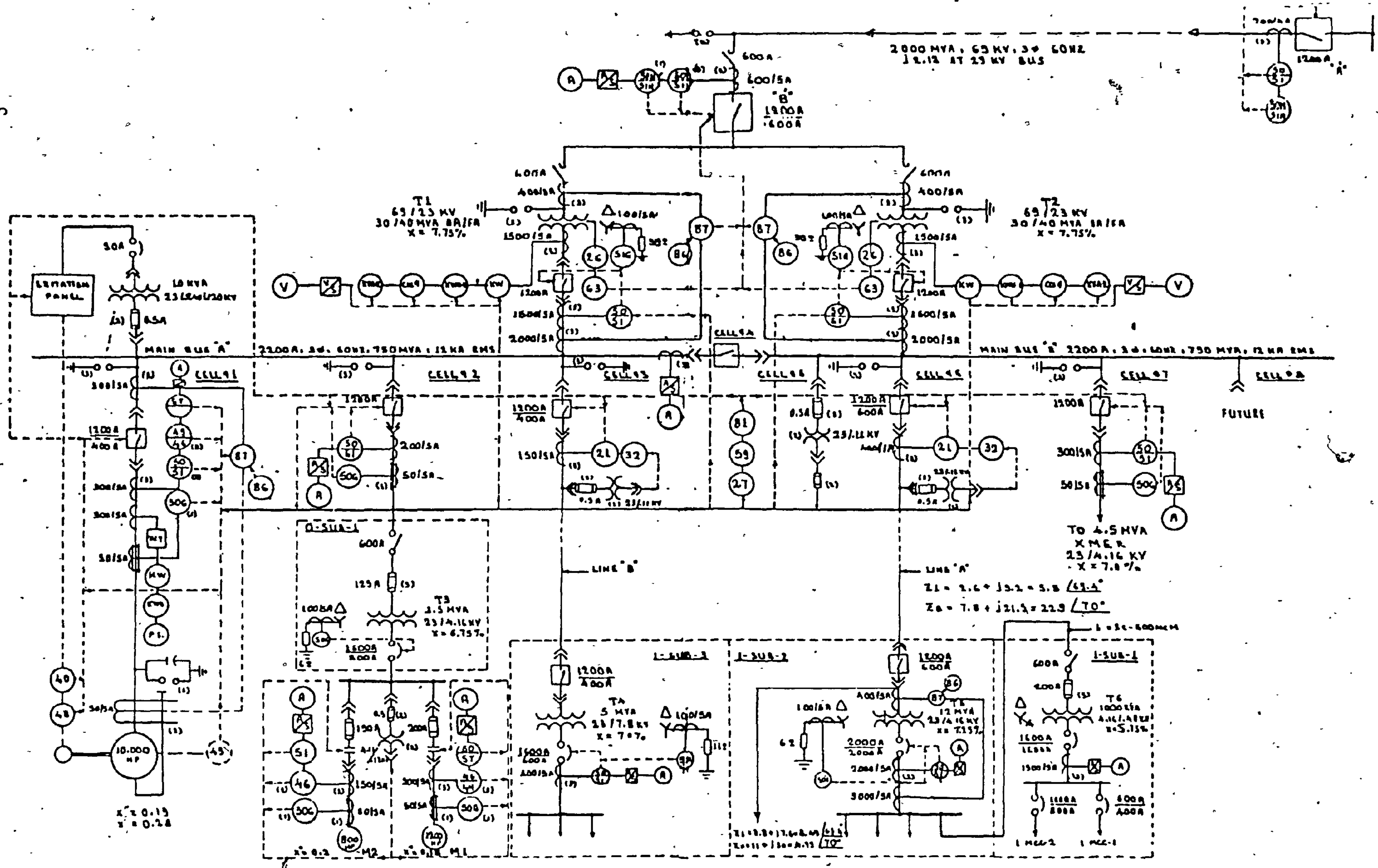


Fig. 1 — Typical single line diagram of power distribution indicating all required protective devices for back-up protection (part of power distribution for Syncrude Canada Ltd.)

zone. This back-up is generally obtained by having the protective system respond quickly for faults close by and after a longer time for the more remote faults, thus permitting selectivity with the protective equipment of adjoining system elements. By this means the system is relieved of a short circuit even though the protective equipment intended to isolate a certain system element is temporarily out of service.

1.4 METHOD OF OBTAINING SELECTIVITY

Differential protective relaying wherein relay operation is obtained when there is a difference between the vector sum of the current entering and leaving the protected elements is the most positive selective principle.

This system of relaying requires a pilot channel between the terminals of the protected element which can be used in making the current comparisons. It is limited at the present time to equipment terminating at points relatively close together.

Where a pilot channel is not available, fault locations can be indicated through the use of distance relays, wherein the relay elements respond to indicated impedance or a component of the impedance such as reactance. This ohmic indication can be used to permit relay operation only within a certain range. By using more than one operating ohmic value with varying time settings back-up protection to adjacent system elements can be obtained. Most distance relay applications permit operation below the predetermined ohmic setting only when the current flow is in one direction.

Where neither differential nor distance relays (both of which permit fast tripping for faults within their protected zone) are used, selectivity can be obtained by graded time overcurrent relays or fuses.

Directional relays may be used in combination with the overcurrent relays to prevent operation except in one predetermined direction of power flow. Instantaneous overcurrent relays set above maximum through fault current are then used in addition to the time overcurrent relays.

1.5 TRIPPING SPEED

The speed with which relays and circuit breakers or fuses operate has a bearing on:

a) the quality of service in the plant

b) the stability of the system

c) the amount of power that may be transmitted without exceeding the stability limit

d) the damage done by a short circuit and consequently the cost and delay in making repairs and loss of production

e) safety to life and property.

Service to all sections of a plant may be interrupted if the low-voltage conditions accompanying a fault are not quickly remedied.

On motor circuits, fuses and circuit breakers may open on overcurrent and synchronous motor may drop out of step. Increasing the speed of clearing faults so as to keep the principal loads on the system following a fault will greatly improve service.

The effect of faults on system stability should be investigated to determine what speed of clearing faults is necessary to keep the several generating stations in synchronism. It should be noted that the more quickly the fault is removed, the smaller is the change in phase between the synchronous machines, and consequently a larger load can be transmitted over the lines connecting these machines without exceeding the limit of stability. Fig. 2 shows in a general way the relation between relay and breaker time and the maximum power that can be transmitted. Increasing the speed of circuit breakers and relays may permit carrying greater load over existing transmission lines.

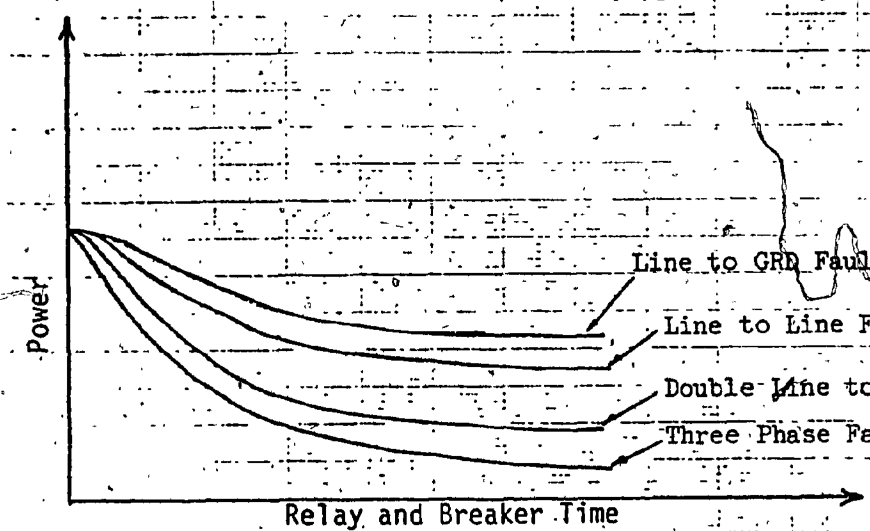


Fig. 2 — Curves Illustrating the Relation Between Relay and Breaker Time and the Maximum Power that can be Transmitted Over One Particular System Without Loss of Synchronism when Various Fault Occurs.

CHAPTER II

TYPES AND CHARACTERISTICS OF OVERCURRENT

PROTECTIVE DEVICES

The first step in designing an adequate short circuit current protective system is to select the correct devices to do the job adequately for the system involved. Some of the devices will have adjustable time current characteristics, while others, such as fuses, will have fixed characteristics. If the protective system is to function as expected to detect trouble and eliminate it with a minimum of disturbance to the system, it is essential that the devices selected have such time current operating characteristics that they can be co-ordinated into an integrated protective system.

The objective of this section is to describe the various types, characteristics, and principal uses of some of the fault-current protective devices commonly used on industrial plant electric systems.

2.1 BASIC TYPES OF SHORT CIRCUIT DETECTION DEVICES

There are three fundamental types of devices designed to detect overcurrents due to short circuit or overload somewhere in the system. The basic devices are:

i) relays
ii) direct-acting trips on circuit breakers
iii) fuses

2.2 OPERATING-TIME CLASSIFICATION OF PROTECTIVE DEVICES

All short circuit current protective relays and other devices can be classified under one of these headings:

1) Instantaneous
2) High Speed
3) Time Delay
4) Combination Instantaneous or High Speed and Time Delay.

By ASA definition, instantaneous relays are those which have no intentional time delay. Some of them operate in less than 1/2 cycle, while others may take as much as 0.1 seconds (6 cycles). Those that operate in 3 cycles or less are also classified as high speed relays.

Time delay relays may be either induction, hinged-armature, or solenoid type. Usually, the time delay is adjustable. Most of them are induction type with an inverse characteristics. That is, the relay speeds up progressively as the actuating quantity increases.

However, a few time delay relays have a substantially definite time characteristic predetermined by adjustment, and are independent of current magnitude as long as the current exceeds the pickup setting by a small amount. These are known as definite time relays.

The direct-acting trip mechanism on circuit breakers may be instantaneous, or time delay, or a combination of the two. The melting time of fuses varies from very fast to quite slow, depending on the magnitude of the short circuit current; that is, they have an inverse characteristic the same as the relays do. Some fuses are designed to give extra time delay on moderate values or overcurrent in order to ride through permissible high overloads.

2.3 RELAYS

Relays are devices installed on the system to detect trouble and complete a circuit to electrically trip their associated circuit breakers, or conductors, when necessary to isolate the faulted circuit or equipment.

Relays may be simple overcurrent devices responsive to current magnitude only, or they may have a combination of current and voltage, or current and current flow; current balance, differences in the current at two ends of a circuit, distance, etc. The majority of relays in modern power systems operate from the secondaries of current transformers and potential transformers.

Relays are more versatile and provide the best protection. Also, they can be designed to operate on only one direction of power flow to the point of fault, or locate the fault by measuring the line impedance (distance) from the relay to the trouble spot.

2.4 DISTANCE RELAYING

The basic principle of operation of a distance relay is the impedance measurement of a transmission line up to a given point.

The measurement involves the comparison of the secondary current of the C.T. equivalent to the primary fault current and a secondary voltage equal to the fault current times the impedance of the line up to the point of fault.

There are three basic types of distance relays.

a) The impedance measuring relay.

b) The admittance measuring relay (S), and

c) The reactance measuring relay.

For the operating characteristics of diatance relays, refer to various manufacturers' manuals.

2.4.1 APPLICATION OF DISTANCE RELAYS

The transmission line "A", on the system diagram shown in Fig. 1 is a typical 23 KV network supplied from a 69 kV system through two step down transformers. The following example shows the necessary calculation to check the suitability of applying distance relays to line "A" connecting substations 1-sub-2 to the metal clad switchgear cell number 6.

1. Check the setting range of the relay.

80% of line impedance = Z x 0.8 = 5.8 x 0.8 = 4.64 ohms . . . . (1)

$$Z_s = Z_p \times \frac{CT_{Ratio}}{VT_{Ratio}} = 4.64 \times \frac{400}{1} \times \frac{110}{23{,}000} = 8.87 \text{ ohms} \quad (2)$$

This value should fall within the relay setting.

2. Check the minimum volts at relay for fault at Zone 1 Reach Point.

The 30 MVA transformer impedance is:

$$Z_{1T} = Z_{2T} = 0.015 + j\,0.25 \text{ ohms} \quad (3)$$

Assuming $Z_{0T} = 1.2\ Z_{1T} = 0.018 + j\ 0.30$ ohms, (Refer to English Electric Distance Relays Manual).

The total fault current can be calculated as following.

$$Z_1 = j\ 2.12 + 0.015 + j\ 0.25 + \frac{0.8(2.6 + j\ 5.2) \times 1.2\ (2.6 + j\ 5.2)}{0.8(2.6 + j\ 5.2) + 1.2(2.6 + j\ 5.2)}$$

$$= 0.015 + j2.37 + \frac{0.96\ (2.6 + j5.2)(2.6 + j5.2)}{2(2.6 + j5.2)}$$

$$= 0.015 + j2.37 + 1.25 + j2.5 = 1.27 + j4.87 \quad (4)$$

Fault Current

$$I_{f_1} = \frac{E}{Z_L} = \frac{23000}{\sqrt{3}\ (1.27 + j4.87)} = 2640 \text{ A} \quad (5)$$

Volts at Relay = $I_{f_1} \times Z_L$ where $I_{f_1} = 2640$ A.

$$Z_L = \frac{0.8\ (5.8) \times 1.2\ (5.8)}{0.8\ (5.8) + 1.2\ (5.8)} = 2.78 \text{ ohms}$$

$$V = I_{f_1} \times Z_L = 2640 \times 2.78 = 7{,}339 \text{ volts primary}$$

Converting to phase-to-phase secondary —

$$7{,}339 \times \frac{\sqrt{3} \times 110}{23{,}000} = 60.8 \text{ volts}$$

Check with manufacturers manual for voltage reach curves.

3. Check minimum volts at relay for phase-to-phase/earth faults at Zone 1 reach point. Line Z_0 to Fault =

$$= \frac{0.8(7.8 + j21.5) \times 1.2(7.8 + j21.5)}{0.8(7.8 + j21.5) + 1.2(7.8 + j21.5)} = 0.48(7.8 + j21.5) =$$

$$= 3.74 + j10.32 \text{ ohms} \quad \ldots\ldots\ldots\ldots \quad (6)$$

From Equ. (4) and (6) we have

$$Z_1 + Z_2 + Z_0 = 2Z_1 + Z_0 = 2(1.27 + j4.87) + 3.74 + j10.32) =$$

$$= 2.54 + j9.74 + 3.74 + j10.32 = 6.28 + j20.06$$

The total earth fault resistance with one earthing resistance in service is:

$$Z_C = 3 \times 30 + 6.28 + j20.06 = 96.28 + j20.06 \text{ ohms} \quad \ldots\ldots \quad (7)$$

The fault current is:

$$I_{f_2} = \frac{3E}{Z_1 + Z_2 + Z_0 + 3N_R} = \frac{3 \times 23{,}000/\sqrt{3}}{96.28 + j20.06} =$$

$$= \frac{3 \times 13{,}279}{96.28 + j20.06} = 405 \text{ A} \quad \ldots\ldots\ldots\ldots \quad (8)$$

Volts at relay = $I_{f_2} \times Z_C$, where I_{f_2} = 405 amp and Z_C = earth loop impedance.

$$Z_C = \frac{1}{3}\left[(1.27 + j4.87) + (1.27 + j4.87) + (3.74 + j10.32) \right] =$$

$$= \frac{6.28 + j20.06}{3} = 7 \text{ ohms} \qquad (9)$$

$$V = I_{f_2} \times Z_c = 405 \times 7 = 2835 \text{ volts primary} \qquad (10)$$

Converting to secondary phase to neutral =

$$\frac{2,835 \times 110}{23,000} = 13.56 \text{ volts}$$

Check with manufacturers manual for voltage reach curves.

4. Determining the setting on the relay.

a) To set Zone 1 to cover 80% of protected line primary impedance Z_1 = 2.6 + j5.2 converted to secondary impedance.

Impedance -

$$0.8 \times (2.6 + j5.2) \times \frac{400}{1}(\text{CT}) \times \frac{110}{23,000}(\text{VT}) =$$

$$= 3.98 + j7.96 = 8.9 \angle 63.4^{\circ} \text{ ohms}$$

Reactance relay setting = 7.96 ohms

Admittance relay max. torque angle 45° line angle 63.43°

$$\text{Admittance Relay Setting} = \frac{8.9}{\cos(63.34^{\circ} - 45^{\circ})} = 9.37 \text{ ohms}$$

b) To set Zone 2 to cover the protected line plus 50% of the next line section (Fig. 1).

Primary impedance Z_1 = (2.6 + j5.2) + 50% (3.8 + j7.6) = 4.5 + j9 ohms

Converter to Secondary = $(4.5 + j9) \times \frac{400 \times 110}{23,000} = 8.6 + j17.21$

$= 19.24 \angle 63.4^{\circ}$ ohms.

Reactance Relay Setting 17.21 ohms or 217% of Zone 1.

Admittance Relay Setting $= \frac{19.24}{\cos(63.4^{\circ} - 45^{\circ})} = 20.27$ ohms

or 217% of Zone 1.

c) To set Zone 3 to cover the protected line plus 125% of the next line section.

Primary impedance = (2.6 + j5.2) + 1.25(3.8 + j7.6) = 7.35 + j14.7 ohms

Converted to secondary

$= (7.35 + j14.7) \times \frac{400 \times 110}{23,000}$

$= 14 + j28.12 = 31.4 \angle 63.4^{\circ}$ ohms

Reactance relay setting 28.12 ohms or 354% of Zone 1.

Admittance Relay Setting $= \frac{31.4}{\cos(63.4^{\circ} - 45^{\circ})} = 33$ ohms

or 354% of Zone 1.

2.5 DIFFERENTIAL RELAYS - GENERAL

Differential relays depend for their operation on the fact that when conditions are normal, the current flows into one end of a generator winding, one side of a transformer, or one end of a circuit is balanced by an equivalent current flowing out the other end; that is what goes in has to come out, if everything is in order. This makes it possible to build relays that "watch" the ingoing and outgoing currents and operate when a difference between them indicates that there is a fault inside the protected equipment or circuit.

There are three basic types of differential relays used on power systems today.

The basic relays are:

1) Generator differential relays

2) Bus-differential relays

3) Transformer differential relays.

Refer to manufacturers manual for their operating characteristics.

2.5.1 GENERATOR-DIFFERENTIAL RELAYS

As shown in Figs. 3 and 4, two current transformers of equal capacity and similar characteristics are installed in opposite ends of each generator phase winding and their secondaries are connected in series with each other and the restraining coils (RC) of the differential relay. The operating coil (OC) of the relay is connected in parallel with the two current transformer secondaries. Under normal operating conditions the same load current flows through the two current transformer primaries, and their correspondingly equal secondary currents (I_1 and I_2) circulate in the direction of the arrows through the series circuit including the restraining coils (RC) and none goes through the operating coil (OC) of the relay. When a short circuit develops inside the generator, the primary current I_{1p} is no longer equal to current I_{2p}, and current (I_F) flows through the relays operating coil (OC). If the generator is wye connected, as shown in Figures 3 and 4 and is operating alone, the fault current (I_F) is the difference between the outputs of the two current transformers; that is, $I_1 - I_2$. When the machine is carrying load, I_2 is the load current, and when it is running unloaded, I_2 is zero. If the same generator is running in parallel with other generators, I_F may equal $I_1 - I_2$ or $I_1 + I_2$. It will be $I_1 - I_2$

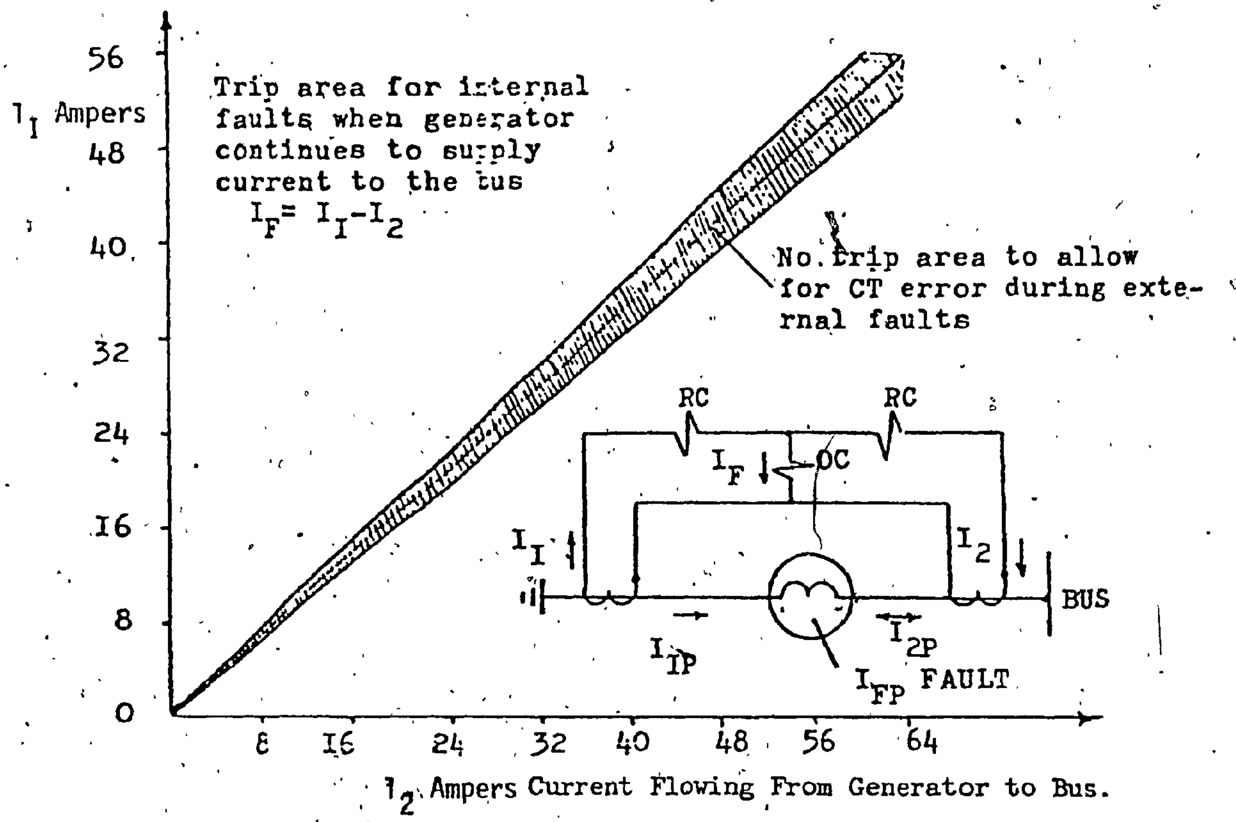


Fig. 3 — Operating Characteristics, Constant-Percent-Slope Generator Differential Relay.

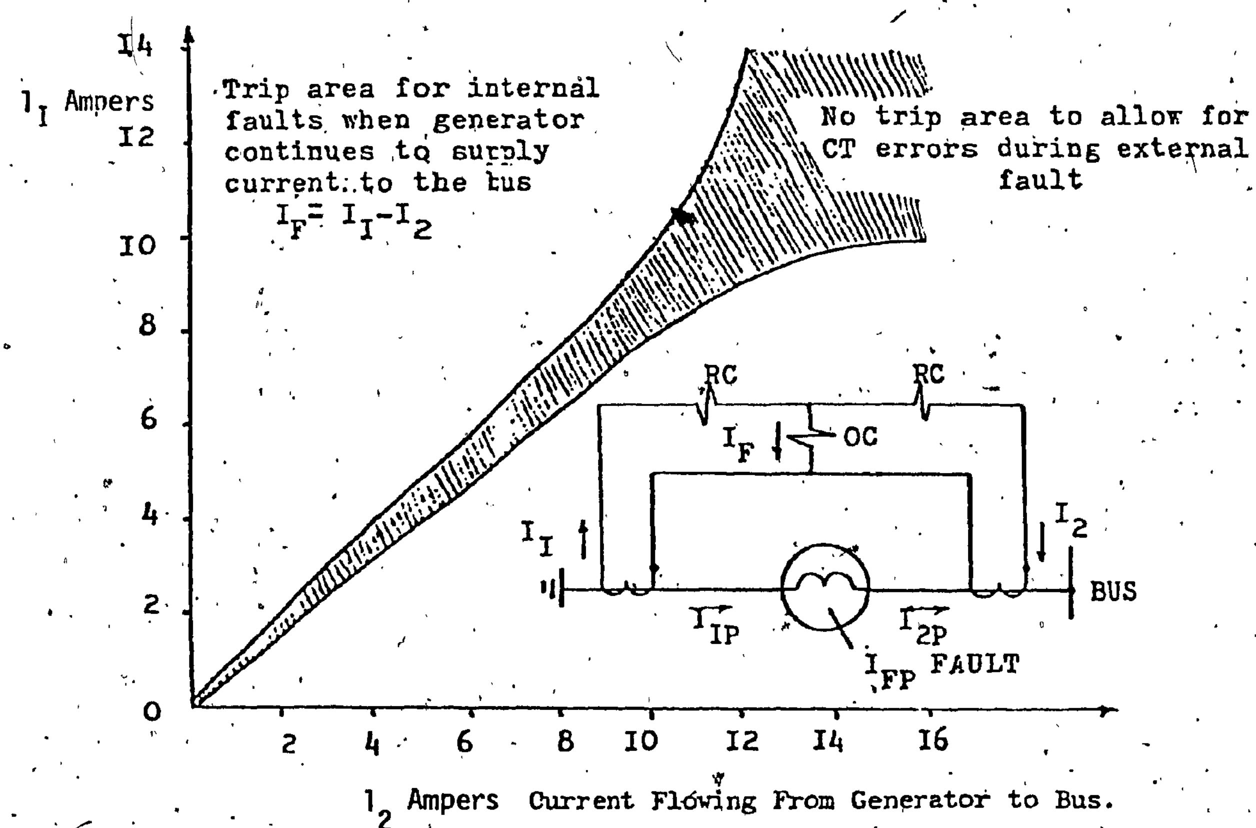


Fig. 4 — Operating Characteristics, Increasing-Slope Generator Differential Relay.

when the fault is minor and the machine continues to supply some current to the bus, and $I_1 + I_2$ for a severe fault with the other generators feeding current into the short circuit.

When the current, I_F flowing through the operating coil (OC) equals the relay's minimum pickup current, and also exceeds the current in the restraining coils (RC) by a certain percentage the relay operates to trip the generator-line and field circuit breakers through an auxiliary relay. The purpose of the slope in the two relays is to prevent false operation due to current-transformer error currents that might flow in the differential relay circuit during a severe short circuit outside the differentially protected zone. Error currents occur because no two current transformers will perform exactly alike even though made to the same specifications and from the same lot of material. If the current transformers saturate unequally, when high currents flow through them during severe short circuits on feeders their secondary currents will be unequal even though the same external-fault current flows through both current-transformer primaries. Any different in their outputs will flow through the relay's operating coil, and the relay has no way of knowing whether the current it sees indicates a fault in the generator or a "mistake" on the part of the current transformers which it should ignore.

2.5.2 TRANSFORMER-DIFFERENTIAL RELAYS

Transformer differential relays are of the constant percentage differential type. They work on the same basic principle as generator differential relays; that is, they watch to see that when current enters one winding, a corresponding amount leaves the other winding, or windings. The connections of a transformer differential relay are the same as for a generator differential relay, except that the current transformers in the leads to the two or more windings of transformers have to be of different ratios to compensate for the fact that there is different voltages in each circuit, hence, the line currents are not the same.

Transformer differential relays require more slope: that is, a greater per cent difference in the output of their current transformers, than generator differential relays do, to allow for the unbalances in current caused by transformer tap changing, current transformer saturation, and the fact that it may not be possible to have the ratio of current transformers exactly match the difference in current due to the voltage ratio. Without the extra slope, it would be necessary to readjust the relay taps whenever the tap ratio of the transformer was changed; for example, a 5 % change in transformer taps causes a corresponding change in the current in that winding, whereas the current in the other winding remains the same for a given kVA load. The currents in the different windings of transformers differ depending on the voltage ratio and, consequently, different current-transformer ratios are required.

Since it is necessary for economical reasons to use standard equipment, it is seldom possible to obtain a combination of primary and secondary current transformers that will produce exactly equal current in their secondaries for a given load, or through (external) fault conditions. Therefore, most transformer differential relays are provided with two sets of taps in their windings to permit balancing the ampere-turns in the relay elements connected to the different main transformer circuits.

2.5.3 BUS DIFFERENTIAL RELAYS

There are three varieties of relays available for differential protection of buses:

1. Ordinary time delay overcurrent relays.
2. Current actuated bus differential relays with restraining coils.
3. Voltage actuated relays.

Ordinary overcurrent relays can be differentially connected, so that they will operate on the difference between the summation of the currents entering and leaving a bus or bus section. They are not particularly well adapted for the purpose, however, because the only way to prevent their faults operation when the ratio of a current transformer breaks down due to dc and ac saturation during a severe external fault on a feeder, is to set them high in both current and time. When so set, they are too slow and insensitive to be very effective. The current actuated differential relays have restraining coils and are somewhat better than the overcurrent relays, but they are still not as effective as the voltage actuated relays. The latter are able to discriminate instantly between faults in the bus and external short circuits on feeders outside the differentially protected zone, even though one or more of the current transformers in the group become completely saturated. The voltage actuated relay is known as a differential voltage relay. It is designed for use with bushing type, or the window type current transformers used in metal-clad switchgear. The relay is connected across the paralleled secondaries of current transformers in each of the incoming and outgoing circuits (Fig. 5). Under normal load conditions, or in case of a short circuit on a feeder that does not cause current transformer saturation, the vector sum of these secondary currents is zero, and no voltage appears across the relay coil. When a bus fault occurs, the vectors sum is no longer zero and the flow of unbalanced currents creates a voltage drop across the relay causing it to operate instantly. Severe short circuits on feeders may cause current transformer saturation resultting in an unbalance in the vector sum of the currents in the paralleled current transformer secondaries and a voltage drop across them just as an internal bus fault would do. The relay will not operate falsely, in the latter case, because the voltage appearing across it for any magnitude of bus fault is enough more than that during an external feeder fault to enable it to distinguish between the two conditions, assuming that it has been properly set.

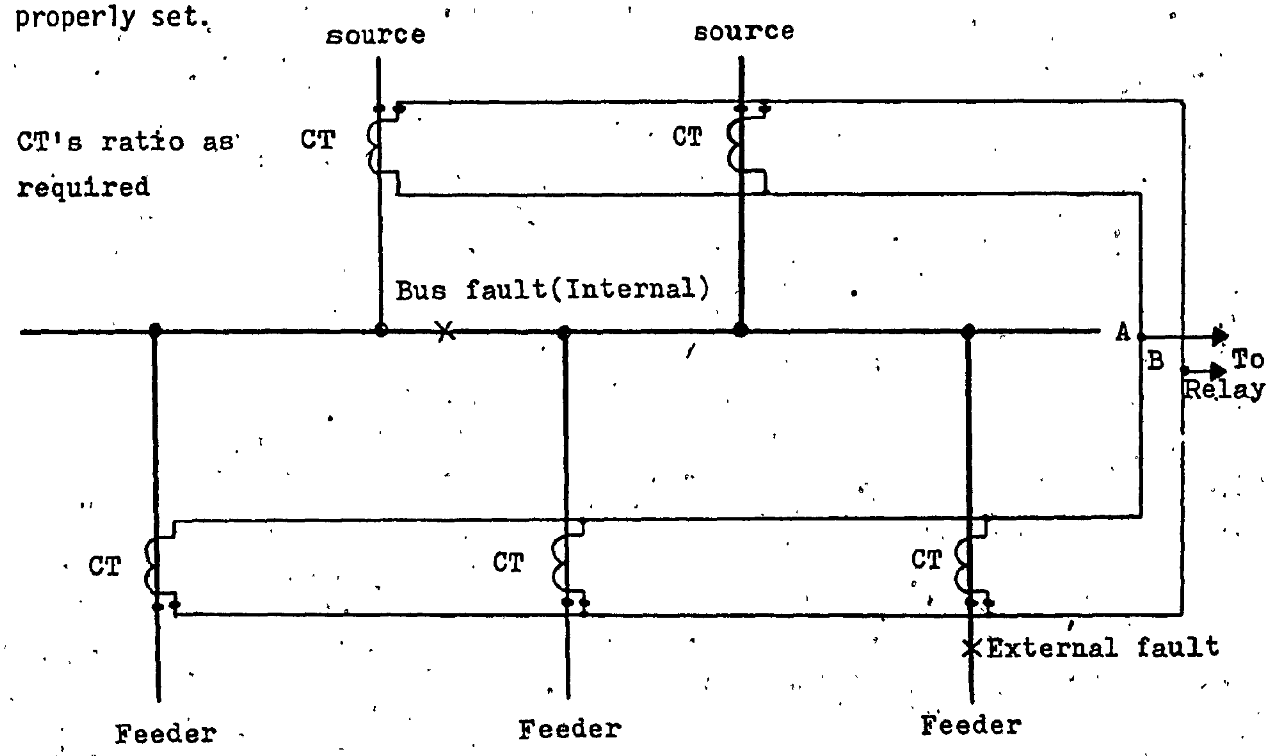


Fig. 5 — Current transformer connections for voltage actuated, bus differential relay in one phase of a three-phase circuit.

2.5.4 EXAMPLE OF SETTING DIFFERENTIAL, CURRENT BALANCE AND WIRE PILOT RELAYS

Generator and transformer differential, parallel line current balance, and wire pilot relays, operate only on faults within the zones they protect, and therefore, do not require time current co-ordination with other devices. However, some of these devices require current-tap adjustments to insure correct operation.

Generator-differential relays and current-balance relays for line protection required no adjustments of any kind.

Transformer-differential relays have current taps to permit balancing the output of the current transformers (CT_S) on opposite sides of a transformer, and to compensate for the fact that one set of the CT_S on Y-Δ or Δ-Y (to compensate for the 30 degreees phase shift), thereby multiplying the CT secondary current by 1.73. The CT_S are connected in Δ when the power transformer winding is wye connected, and in wye when the transformer is connected in Δ. Fig, 6 shows the connection for the CT secondaries in the primary and secondary of the transformer T5 in Fig. 1 and the differential relay current tap selection.

The transformer primary is delta connected so its CT secondaries are wye connected. The 4.0 ampere taps on the relay are in the CT secondaries for full load on the transformer, so the CT secondary leads are connected to them.

The transformer secondary is wye connected, so it's CT_S are delta connected which automatically multiples the 2.78 amperes in their secondaries (transformer full load output), by 1.73. The difference between the resulting 4.8 amperes and the nearest higher tap on the relay (5.0 amperes) is small enough to be taken care of by the slope in the relay's operating characteristic, so the CT secondaries are connected to the 5.0 ampere taps. As explained in Section 2.5, the slope, which is the amount by which the current in the operating coil must exceed that in the restraining coil before the relay will operate, is provided for just such contingencies at this. The combination of transformer primary and secondary current-transformers, such as 400/5 and 2000/5 could also be used satisfactorily. With this combination, the secondary current in the transformer-primary CT's would be 3.77 A as before, but the current to the relay from the delta connected transformer secondary CTs would be 4.17 x 1.73 = 7.2 A. If we select a relay with a higher-rated tap, 8.7 A, we can see that this is far above the 7.2 A available allowance in selecting the relay tap for the primary CTs in order to have satisfactory relay balance (i.e. $\frac{8.7}{7.2} \times 3.77 = 4.55$). Therefore, the proper relay taps would be 4.5 A for the primary CTs and 8.7 A for the secondary CTs.

When a choice is possible it is preferable to use CTs that will give moderately low values of secondary currents, which means lower volt-amperes (I^2Z) loss in the secondary circuits and consequently, lower burdents on the current transformers, which in turn means more sensitive relay performance.

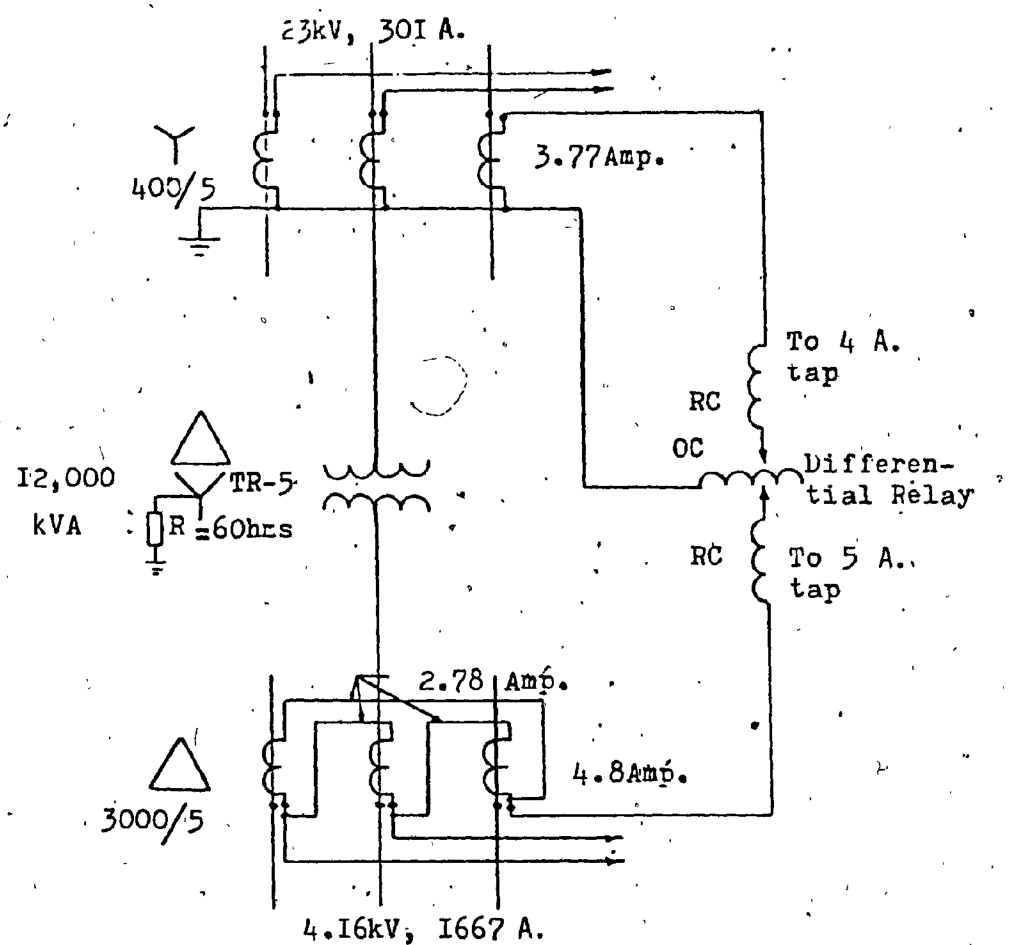


Fig. 6 — Transformer differential-relay schematic diagram for Δ-Y connected transformer showing relationship of currents in the primary circuits and the current transformer secondaries.

2.6 ac WIRE PILOT RELAYS

ac wire pilot relay protection is a modified form of current differential relaying. It is designed to provide fast phase-phase, three phase and ground fault protection of the cables, or relatively short transmission lines. In an ordinary differential relay circuit, the full output of the current transformer secondaries circulates continuously through the relay and current transformers over a set of four wires. Since the four wires must be large enough to limit the impedance sufficiently to avoid saturation trouble by overburdening the current transformers, such a system is impractical unless the current transformers are within a few hundred feet of each other. This obstacle is overcome in the ac wire-pilot protection system because the relays and auxiliary devices are designed to take just a "sample" of the current flowing in the current transformer secondaries at each end of the cable or transmission line, and then compare these samples over a pair of relatively small pilot wires. Under normal conditions or even when short circuit current flows through the line to the fault outside the protection zone (through short-circuit), the current samples match each other and the relays do not operate. When a fault occurs on the line between the relays (protected zone), the samples no longer match and the relays operate instantly to trip their respective circuit breaker.

There are two types of wire-pilot relays, one of which operates on the circulating current principle, and the other on the opposed voltage principle. In the circulating current system, current is circulating continuously through the pilot wire circuit, whereas in the opposed voltage system, no appreciable amount of current flows in the pilot wire circuit, unless there is trouble on the protected line. Fig. 7A shows an ac wire-pilot relay system operating on the opposed voltage principle. Under normal conditions with power flowing in either direction, or for through faults, the current samples at opposite ends of the line match each other and produce equal and opposite voltages in their mixing transformers and input transformers. These voltages cause current to flow in the relay polarizing (PC) and restraining (RC) coils, but since these voltages are opposed to each other, only a negligible amount of pilot wire charging current flows from each end through the relay operating coils (OC). This charging current is insufficient to operate the relays even though there is current of their polarizing coils.

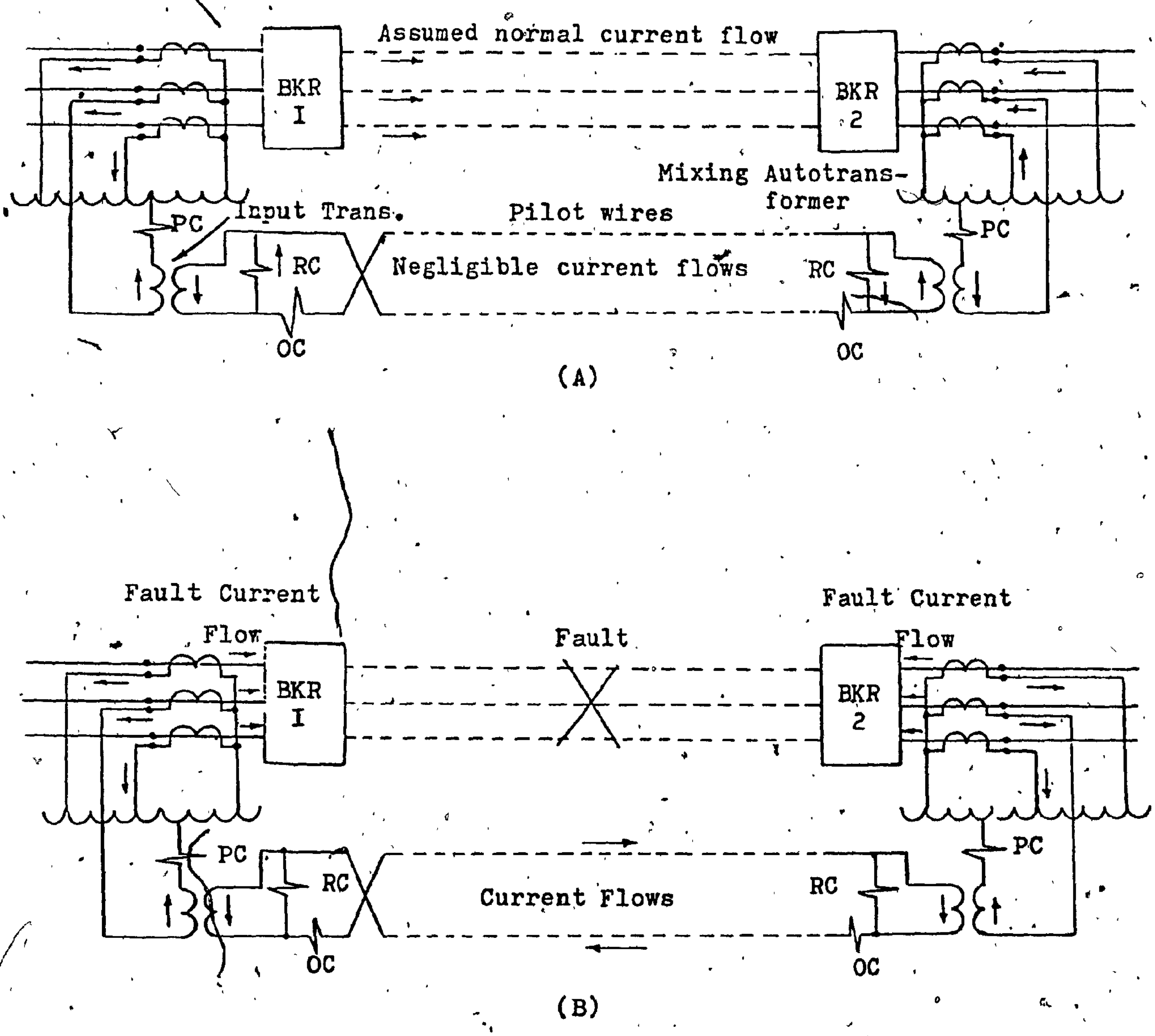


Fig. 7 — Schematic diagram of opposed voltage (A-C) wire pilot relay protection for two terminal lines.

When a fault occurs in the protection zone on a power line with generation at both ends, the sample currents produce voltages that are in series (Fig. 7B) and cause currents to flow in the pilot wires and, consequently, through the relay operating coils. Meantime, very little current flows through their relatively high impedance restraining coils (RC) and, therefore, the relays operate.

If the power source at one end of the line is shut down (assume Bkr. 2 end Fig. 7). The relay at that end will not operate because there will be no current in its polarizing coil (PC). Current would flow through the pilot wire from the other end of the line and go through the relays operating and restraining coils, but the relay could not operate without current in its polarizing coil. Usually, this is not objectionable.

However, if it is desired to have the breaker at both ends of the line tripped immediately in all cases, it is possible to send a transfer-tripping signal over the pilot wire supervisory circuit so that the relay at the power source end of the line (Bkr 1 end) can trip both breakers. ac wire pilot relaying works best on two terminal lines; that is, single circuit with no taps or branches, but it can be modified for use with some combinations of lines with branch circuits or taps. The relay system includes the necessary restraint features to prevent false operation due to current transformer errors during severe short circuit outside the protected zone.

2.7 Current Limiting and Standard Fuses

The two basic types of fuses are the current limiting, and non-current limiting or what might be termed standard fuses. Practically all fuses will melt in considerably less than 1/2 cycle on a 60-cycle basis when subjected to high values of fault current. However, the arc is a conductor and enables the current to reach its maximum crest value unless provision is made to put ~~it~~ out before the crest is attained. When such provision is made, the fuses are classified as current-limiting. Most fuses are self-protecting; that is, they are capable of extinguishing the arc for any value of current within their interrupting capacity rating limit. Current limiting fuses for motor protection, which are purposely designed to carry low values of current for considerable periods of time to permit repeated starting of joging of motors, are an exception to this rule. They are used in conjunction with a thermal relay and conductor whose function is to open the circuit on magnitudes of current so low as to require more than approximately ten seconds to melt the fuse line. Otherwise, the quartz sand in the fuse may become so hot that it cannot cool the arc enough to enable the fuse successfully to interrupt the current when the link finally melts.

Most fuses have a 'smooth', that is, a continuous melting-time curve, but some are designed to give more time on moderate overloads of two or three times fuse rating. The latter have a jog in their melting-time curves, which gives them a much longer melting time than standard fuses at moderate overloads. The purpose of this characteristic is to permit using a smaller fuse and, consequently, in some cases, a smaller switch for motor starting services. Fuse time-current operating characteristics are given in terms of the melting time for a given value of current, but unfortunately, there is no accepted industry-wide standard as to the method of showing them; that is, whether they should be plotted on the basis of short, minimum, or average, melting time, or total clearing time.

The various time current characteristics of a fuse can be calculated from the given characteristic by the simple process of adding or subtracting allowances as shown in Fig. 8. If, for example, the fuse characteristic is given in terms of minimum melting-time, the maximum melting-time can be determined by plotting another curve 20 per cent higher in current for each value of time. This 20 per cent is to allow for variation in manufacture of fuse wire. If the curves are plotted in terms of average melting time, the maximum and minimum melting times are approximately 10 per cent above and below the average. After the fuse melts, a certain length of time is required for the arc to go out and this time allowance for the particular fuse under consideration must be added to the maximum melting-time curve as shown to obtain the total clearing time for 2400 volts and above fuses. The 600 volts and below class of fuses also have an arc clearing time of somewhat shorter duration. Another factor that must be considered in determining the overall time current characteristic of a fuse for coordination purposes is the damage tolerance. This is an allowance that must be made if the fuse is used ahead of some other short circuit device. If the fault is on the load side of one of these other devices, the latter must operate and clear the fault in less than the time shown by the damage tolerance curve, in order to avoid any possibility of overheating the fuse link sufficiently to weaken it and thereby eventually cause false operation. The damage tolerance may be given in terms of current or time as shown in Fig. 8. In some cases, the damage tolerance varies and, therefore, in case of a very close co-ordination problem, specific curves for the particular fuse involved should be obtained from the manufacturer.

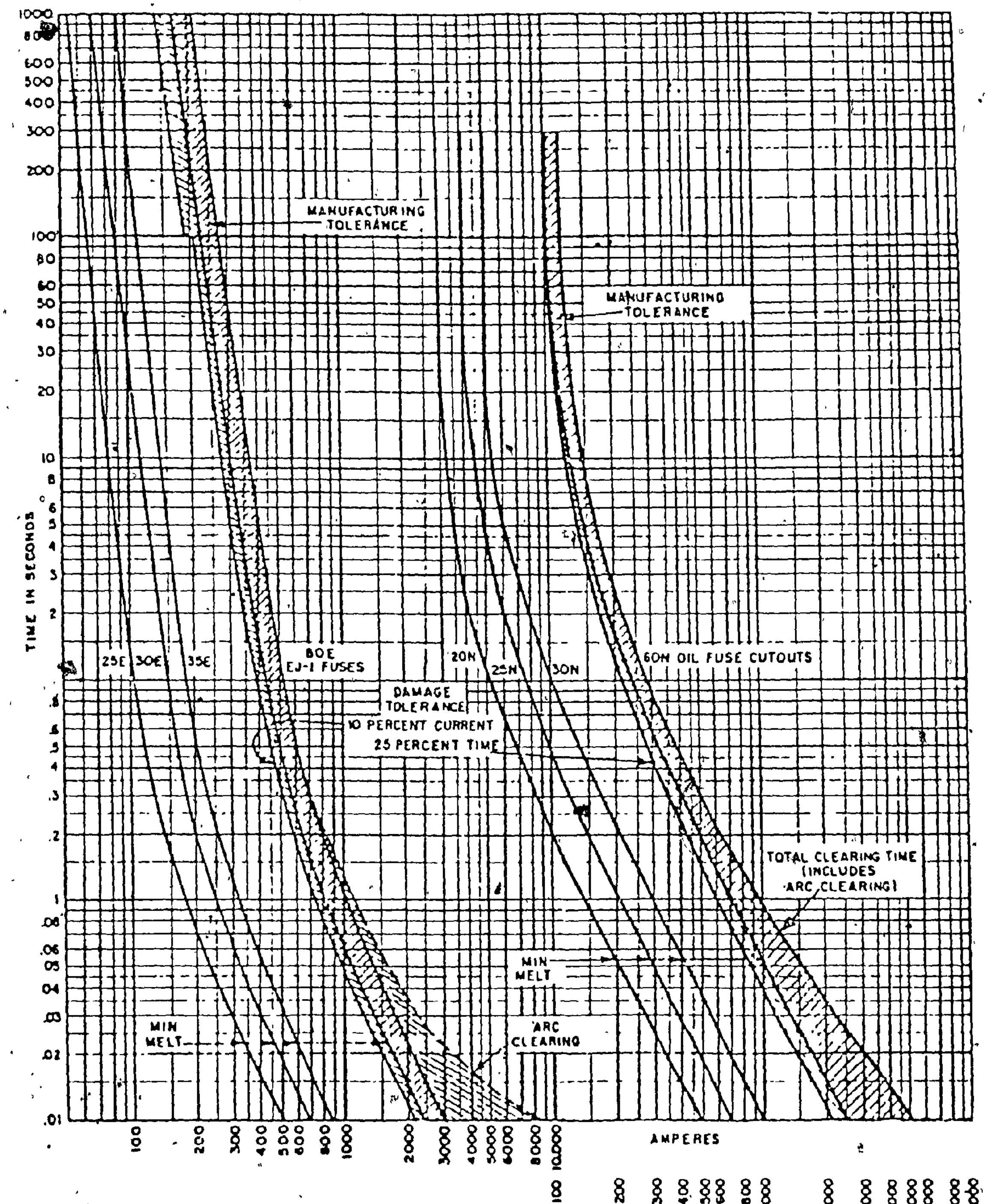


Fig. 8 — Operating time of Ej-1 current limiting fuses and oil fuse cutouts. (Photo 1150990 General Electric).

2.7.1 INTERRUPTING RATING

The basic interrupting rating of a current limiting fuse is 1.6 times the maximum (or first cycle) symmetrical value of available current the fuse shall be required to interrupt. Power-fuse interrupting abilities are sometimes alternately shown in terms of three phase MVA. These three phase MVA values are

$$\mathrm{MVA} = \sqrt{3}\left(\frac{\text{Fuse rated voltage}}{10^6} \cdot \frac{\text{Fuse inst. current}}{1.6}\right)$$

and they are based on the maximum symmetrical values of available current to which a set of fuses shall be subjected in interrrupting a three-phase short circuit at fuse rated voltage. The listed three phase MVA values must be adjusted to correspond with system base voltage before a comparison may be made with system duties from short circuit calculations. A system short-circuit duty may then be determined in either of two ways for comparison with the interrupting abilities of these fuses:

$$\text{Total RMS amperes} = \frac{1.6\ (\text{base amperes})}{X''}$$

or

$$\text{Three-phase MVA} = \frac{(\text{3-phase base MVA})}{X''}$$

where X" is the per unit value of system subtransient reactance, recognizing short-circuit contribution from synchronous and induction motors as well as from normal power sources.

2.7.2 FUSE CO-ORDINATION WITH OTHER PROTECTIVE DEVICES

In applying fuses, it is frequently necessary to choose proper ampere rating so that selective operation is provided between the fuses and other protective devices that are used on the system.

Co-ordination is based on the principle that the minimum portion of a system should be isolated in the event of a fault. Therefore, protective devices farthest from the power source should operate first. Those nearest the source should require more time to operate.

Such coordination can be determined by plotting the time-current characteristic curves of the devices involved on the same sheet of graph paper, and selecting relay settings and fuse ampere ratings so that the desired selectivity is obtained.

The following example illustrates the procedure involved in selecting a motor starter fuse, coordinated with a P&B overload relay and a vacuum contactor.

The performance of the fuse, the contactor and the overload relay must be coordinated to achieve:

1. Protection of the motor against sustained overload and stalled rotor conditions by means of the overload relay.
2. Making and breaking of the circuit by means of the contactor within the interrupting capability of the contactor.
3. Protection of the circuit by means of the fuse for fault currents above the interrupting capability of the contactor, up to the maximum fault current available.

These three conditions are necessarily inter-related and must overlap such that the fuse takes over from the contactor with sufficient margin between them for safety. The same relationship also applies between the fuse minimum interrupting current and the overload relay. Correct coordination in this respect ensures that at all times the fuse will not be required to operate on a current less than its minimum interrupting capability. The coordination of the characteristic can best be illustrated by reference to the curves shown on Fig. 9. Fig. 9 illustrates the characteristics of a 1200 HP, 4.16 kV motor (ref. to Fig. 1 motor M1), a vacuum contactor 3TL5, the operating limit of a typical P&B thermal overload relay and the characterisic of a 200A 3GA HRC, motor circuit fuse, which has been selected for this application, superimposed on the characteristics of the motor, the vacuum contactor and the thermal overload relay.

In considering this presentation, the following points are important:

a) The selected fuse permits up to two successive starts with an adequate margin of safety.

b) The overload relay will operate before the fuse on all values of overload up to motor stalling conditions. In doing so it ensures that the fuse will never be called upon to operate near or below its minimum fusing current.

c) The maximum switching capacity of the vacuum contactor is well above the value of current permitted by operation of the overload relay and permitted by the fuse in the event of a high value earth fault occurring. For lower values of earth fault, the vacuum contactor would operate normally.

To facilitate co-ordination studies minimum melting and total clearing time current characteristic curves are provided for this fuse. These curves and the time current characteristic curves of the thermal overload relay are on translucent paper from which prints can be made.

By means of these curves, fuse ratings can be selected rapidly by holding the sheet for the fuses together with similar sheets showing

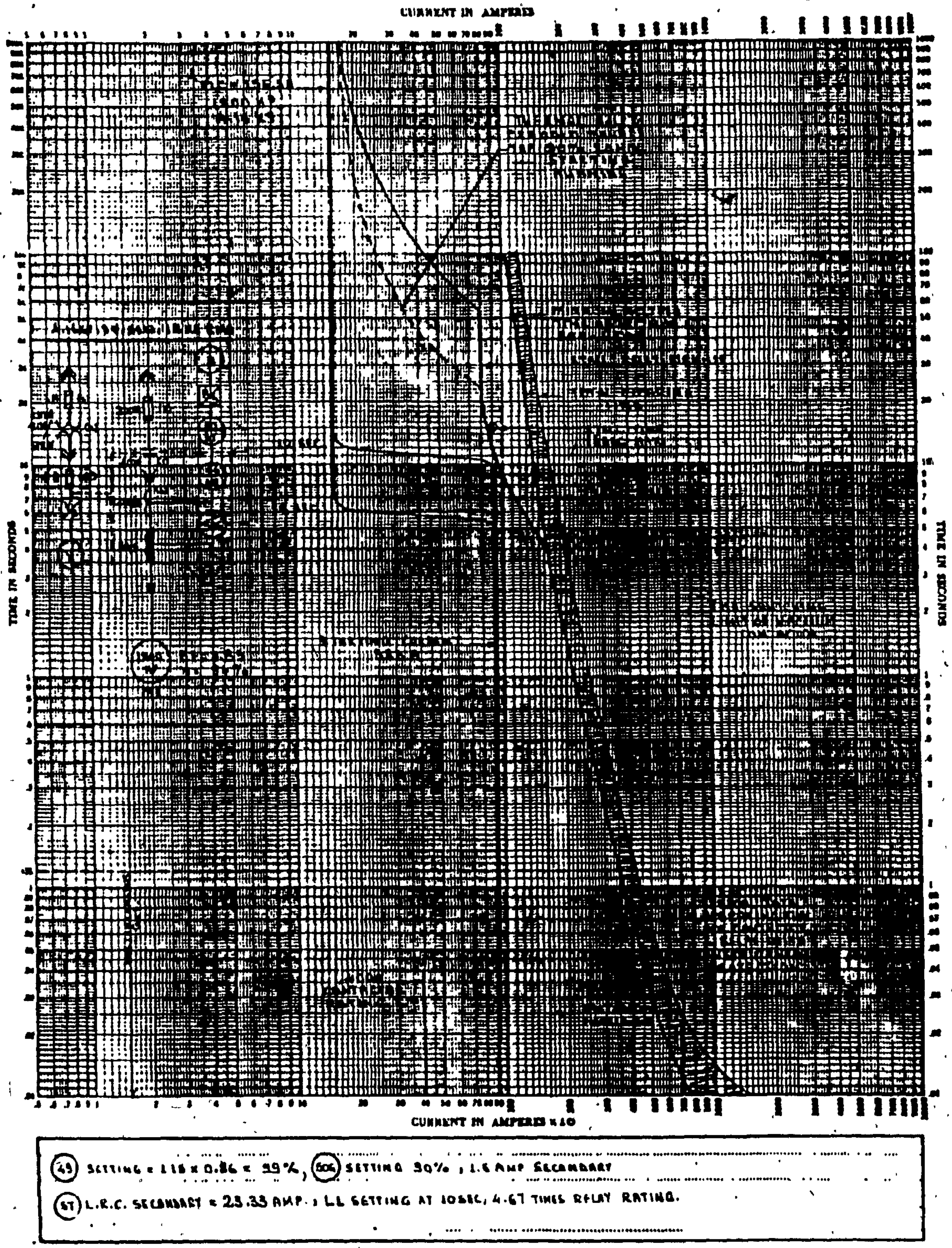


Fig. 9 — Illustration of co-ordination of fuses with vacuum contactor and overload delay.

overload relay time current characteristics on a light box, with co-ordinates matching. The fuse selected is the one for which the overload relay characteristic crosses the minimum melting characteristic at a current greater than the motor adjusted, locked rotor current. The adjusted locked rotor current is the motor manufacturer's published locked-rotor current, increased by 10 per cent.

This adjustment makes allowances for operating the motor on an electrical system where the operating voltage is at the plus tolerance above rated voltage, and for variation in motor locked rotor current due to variation in material and manufacturing tolerances. This co-ordination then protects the fuse from unnecessary operation due to motor starting, plugging, or jogging, and overload or stalling. Thus, the fuse is called on to interrupt short-circuit currents and lesser fault currents beyond the rating of the contactor, which handles all the repetitive operations and minor overloads within its rating.

2.8 CIRCUIT BREAKERS

A Circuit breaker is a device designed to open and close a circuit by non-automatic means, and to open the circuit automatically on a predetermined overload of current without injury to itself when properly applied within its rating.

Ratings are characteristic values for which circuit breakers or accessories are designed, which are assigned to them, and to which other rated values are related.

Rated values include: rated voltage, rated current, rated asymmetrical current, rated short-time current, rated interrupting current, rated interrupting capacity and rated frequency. Insulation rating is a standard term to characterize the rating of the insulation of a circuit breaker or accessory.

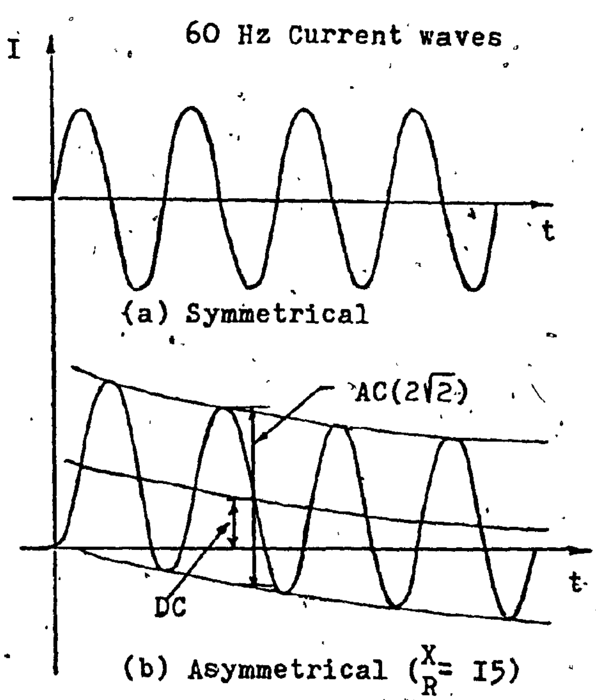
2.8.1 RATED INTERRUPTING CURRENT

Paragraph 4.6.11 of ASA C37.4-1953 identifies this current as ". . . the RMS value including the dc component, at the instant of contact separation as determined from the envelope of the current wave."

When a short circuit occurs in a power system, (or when any resistance inductance circuit is energized with an ac voltage), the current that flows will consist of two components: a steady state component as determined by the voltage and the impedance, (R+jX), of the circuit, and a dc transient component whose initial value and rate of delay are determined by the point on the voltage wave when the short circuit occurs and the relative amount of resistance and inductance in the circuit usually expressed in terms of the ratio X/R. Fig. 10 shows single-phase short circuit currents: a) symmetrical, and b) asymmetrical. The symmetrical current resulted from fault initiation at a time close to voltage crest, and the asymmetrical current from fault initiation at a time close to voltage zero. The asymmetry can, of course, occur to any degree in between a) and b). In Fig. 10b the asymmetrical current is shown with initial asymmetry or dc component, of 100%. It is completely offset with the initial dc component equal to the crest of the ac, or symmetrical, current. At any point, the total RMS, or total current can be expressed as the RMS value of the ac and dc components of current:

$$\text{Total RMS Current} = \sqrt{(\text{ac})^2 + (\text{dc})^2}$$

The current at contact separation could be asymmetrical or symmetrical, depending on when (on the voltage wave) the fault occured, and on when the contacts parted under this standard, circuit breaker application was made on the basis of the maximum total current possible at contact separation, considering X/R and the time from fault initiation to contact separation (relay time plus trip to contact separation time):



Total rms current at any instant =

$$= \sqrt{(ac)^2 + (dc)^2}$$

Fig. 10 — Single phase short circuit current waveforms.

2.8.2. INTERRUPTING CAPACITY

The symmetrical rated interrupting capacity Pa (in W) of a three pole circuit breaker is given by the following equation.

$$Pa = \sqrt{3}\, I_a U_W$$

where -

I_a - is the symmetrical rated interrrupting current (in A) as at the time of the first separation of the contacts, and

U_W - is the system recovery voltage (in V) between the conductors after interruption of the current in all poles and decay of the restricting voltage transient.

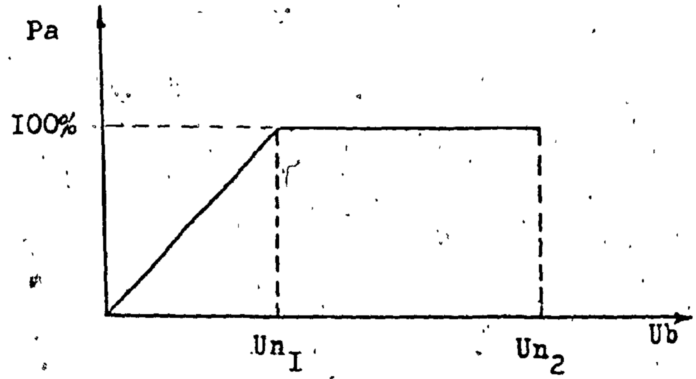
The interrupting capacity is a hypothetical value, as the two components which make it up, "rated interrupting current" and "recovery voltage", do not occur simultaneously, but consecutively. As a result of international respresentations, the rated interrupting current alone should in future be used to classify the breaking capacity of a circuit breaker.

Fig. 11 shows the interrupting capacity of a circuit breaker as a function of the operating voltage.

2.8.3 INTERRUPTING DUTY

Arc extinction in the three poles of a three-phase circuit breaker does not occur simultaneously, but consecutively in accordance with the natural current zero of the three phases. As well as this, the stress in the three poles is different with respect to maximum voltage and duration of current flow. As shown in Fig. 12, generally the first pole to clear is most heavily stressed by the increased pole recovery voltage.

The highest voltage loading, which the dielectric strength of the isolating distance must be capable of withstanding, occurs immediately after the interruption of the current, before the decay of the restricting voltage transient and is referred to as the restricting voltage e_m in V.



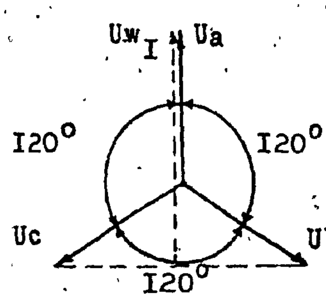
Un_I Lower rated voltage

Un_2 Upper rated voltage

Ub Operating voltage

Pa Interrupting capacity

Fig. 11 — Basic diagram of the interrupting capacity of a circuit breaker as a function of operating voltage.



Ua,Ub,Uc Phase voltages

Uw_I Pole recovery voltage at the first pole to clear after in terruption of the current and decay of restri-king voltage transient.

Fig. 12 — Voltage star before and after the interruption of the current in the pole which is first extinguished (phase A) during the interruption of a three phase short circuit.

It is —

$$e_M = U_{W_1} \gamma \sqrt{2}$$

where,

U_{W_1} - is the recovery voltage in volts at the first pole to clear as shown in Fig. 12, and γ is the amplitude factor.

Of importance for the voltage loading of the isolating distance is the time characteristic of the restricting voltage. It is determined in the single-frequency circuit by the natural frequency (f_e in Hz).

$$fe = \frac{1}{2\ t_m}$$

where t_m is the time (in s) between zero value and peak value of the restricting voltage. For the various rated voltages the following values are specified for amplitude factor (γ) and natural frequency (fe) of the restricting voltage which are to be observed when testing circuit breakers.

Rated Voltage kV	Lower —	3-6	10	15	20	25	30	45	60	110	150	220	380
	Upper —	3.6-7.2	12	17.5	24	27.5	36	52	72.5	123	170	245	420
Natural frequency kHz	A γ=1.4	10.0	7.0	5.5	4.6	4.0	3.6	2.8	2.3	1.5	1.3	1.0	0.7
	B γ=1.2	4.0	3.0	2.2	1.8	1.6	1.4	1.1	0.9	0.6	0.5	0.4	0.3

Table 1 — Natural frequencies of the restricting voltages and amplitude factors (line A for circuit breakers with a lower rated voltage of 45 KV and below. Line A or Line B for circuit breakers with a lower rated voltage above 45 KV and for a double earth fault line B).

2.8.4 MOLDED CASE CIRCUIT BREAKERS

A combination of thermal and instantaneous magnetic trip is commonly used on the molded case low voltage circuit breakers to provide time delay operation on moderate overcurrents, and instantaneous operation on high magnitude short circuit currents. In some cases, the thermal element only is used.

The thermal characteristic is usually nonadjustable in the field, but the instantaneous trip is available in adjustable or nonadjustable construction. Fig. 13 shows the ac time-current tripping characteristic curves of the nonadjustable thermal trips in combination with adjustable instantaneous trips for the various ratings available in a 600-ampere frame size molded case breaker.

It will be noted that the minimum tripping time curve of the time delay thermal device is the same for all ratings; whereas, the maximum tripping time curve varies with the current rating of the trip unit. Arc clearing time is included in both the time delay and instantaneous trip curves.

The instantaneous trip on the 600-ampere frame size breaker is adjustable from 2.6 to 10 times normal in seven uniformly spaced steps, including the "HI" and "LO" position. The number of steps varies with different breaker design and frame size.

There are some molded case breakers with adjustable in the field thermal and electromagnetic instantaneous trip. Fig. 14 shows the time-current characteristics of the 3VS56 to 3VS66 molded case breakers with adjustable thermal and instantaneous trip.

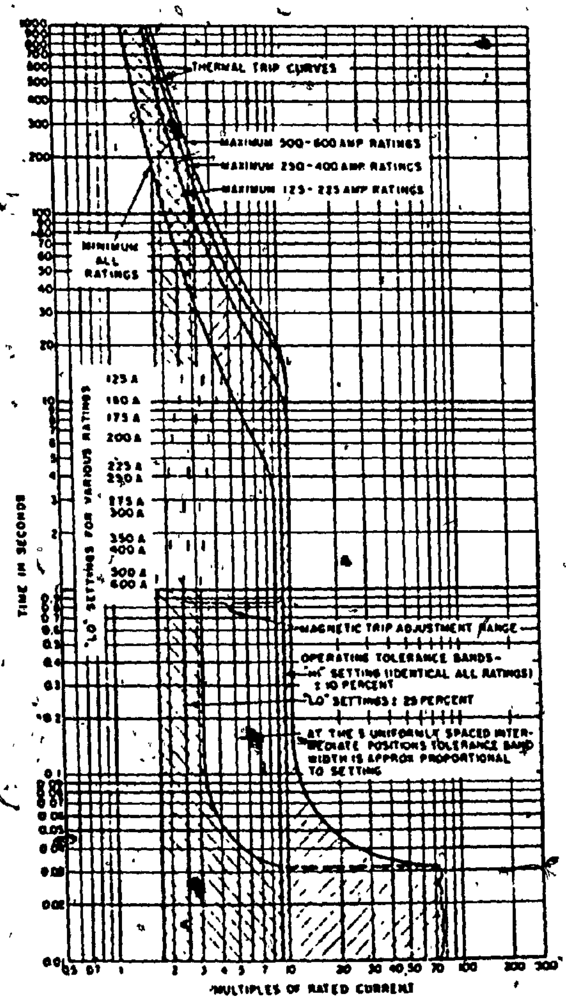


Fig. 13 — Time current characteristic curves for thermal magnetic, 600A frame size molded case circuit breaker, General Electric.

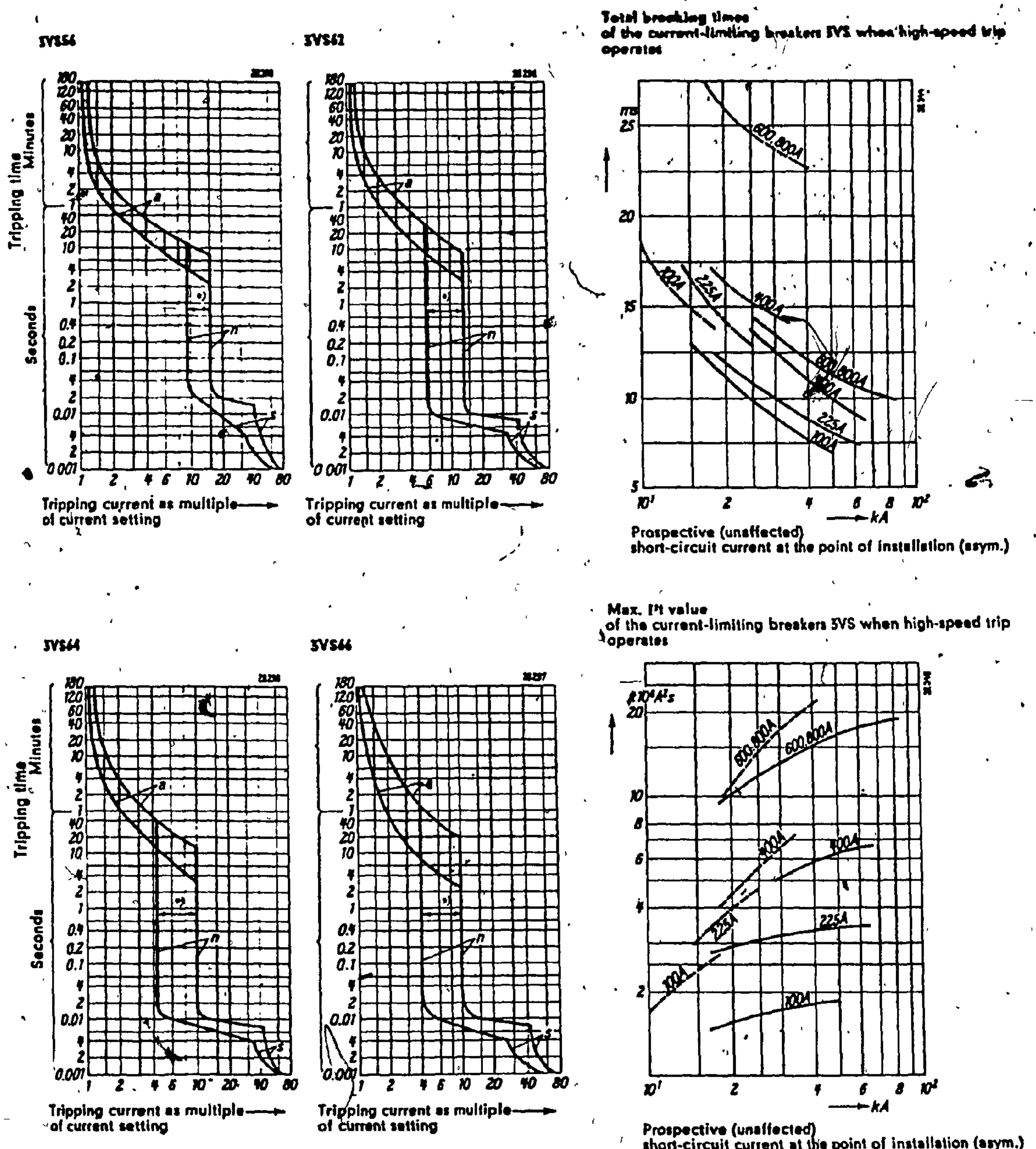


Fig. 14 — Time current characteristic curves for adjustable thermal and electromagnetic overcurrent release for 100A to 800A frame size molded case circuit breakers, Siemens Type 3VS.

* *setting range*
a) delayed thermal overcurrent release
n) instantaneous electromagnetic overcurrent release
s) high speed tripping feature characteristic as multiple of maximum rated breaker current.

2.8.5 DIRECT ACTING TRIP DEVICES FOR LOW VOLTAGE CIRCUIT BREAKERS

The direct acting trip devices of low voltage circuit breakers (600 volts and below) are of electromagnetic, hinged armature construction actuated by the flow of current through coils in series with the circuit.

Short circuit protection is provided by magnetic forces suddenly overcoming spring restraint. A separate adjustable unit is required for each circuit breaker frame size.

Three tripping devices are provided on each three phase breaker. They can be built with instantaneous and long or short time delay trips. These different trips can be used in a variety of combinations: 1) instantaneous 2) long and short time delay 3) instantaneous and long or short time delay 4) instantaneous and both long and short time delay. Although direct acting trip devices have been applied to low voltage circuit breakers for many years, they do have some inherent disadvantages. The trip point will vary, depending on age and severity of duty, and they have a limited calibration range. Because the trip characteristic curve of electromechanical devices has a very inverse shape with a somewhat unpredictable broad operating band (Fig. 15), coordination of tripping with other devices is sometimes difficult.

The current setting of the long time delay trip devices in Fig. 15 is adjustable in the field, and they have pick-up setting calibrated at 80 - 100 - 120 - 140 and 160 percent of the trip coil rating. They can also be set at any intermediate value between these calibration points.

When selecting breakers and making settings it should be borne in mind that the trip coil rating is the maximum continuous current that the unit can carry.

For example, a 1600 A trip set at 100% will operate at the same

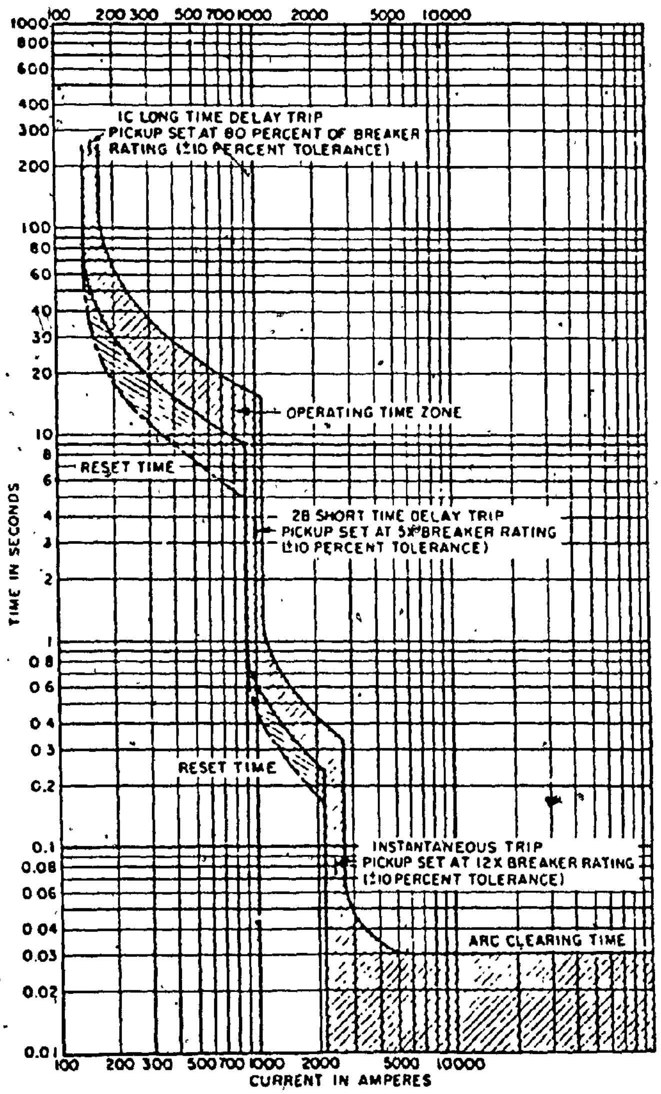


Fig. 15 — Time current characteristic curves for low voltage, 200A air circuit breaker with long and short time delay and instantaneous trip. (Photo General Electric).

value of current as a 1000 A trip set at 160%, but their continuous current ratings are quite different. The purpose of a setting higher than continuous rating is to enable the trip mechanism to ride through short duration peaks such as motor starting loads.

The current setting of the short time delay trip devices is also adjustable and they can be obtained with calibrations anywhere in the range of 3 to 10 times the trip coil rating, as long as the desired maximum setting is not more than 2 1/2 times the minimum setting. Instantanous trips, when supplied, are generally adjustable in the field. The standard trips are usually calibrated in the range of 4 to 12 times the pick up setting.

2.8.6 STATIC TRIP DEVICES

Static trip devices on power circuit breakers operate from a low current signal generated by current transformers in each phase. The output from the current transformers is fed into a static trip unit which evaluates the incoming signal with respect to its calibration setpoints and acts to trip the circuit breaker if preset values are exceeded. The static trip devices are available with ground trip protection in addition to phase protection.

The most important advantages of static trip devices are the shape of the trip characteristic curve, which is a straight line throughout its working portion having a very narrow and predictable operating band and the much easier calibration procedure.

2.8.7 EXAMPLE OF COORDINATION BETWEEN PRIMARY FUSE AND SECONDARY MAIN CIRCUIT BREAKER OF UNIT SUB-STATION 1

The transformer TR-6 on the secondary unit substation 1-Sub-1 is 1000 kVA, DRY-TYPE, 4160/480V Delta primary, wye secondary, solid grounded with 200 MVA short circuit capacity on the primary.

The secondary full load current is —

$$I_{S_{FL}} = \frac{1000}{\sqrt{3} \times .48} = 1204 \text{ A.}$$

The selected main secondary circuit breaker is Siemens Type LA with static-trip device 1600 A frame and 1600 A tripping transformer. Refer to time current characteristics curves (Fig. 16) for LA type circuit breakers and to coordination curves sheet, Fig. 17. From the coordination curves, Fig. 17, we can see that an air switch with current limiting fuse type CL-14-200A is satisfactory for primary transformer protection. The secondary feeder breakers LA-600A and LA-1600A are selected with tripping transformers 400A and 800A and their long time pick-up settings are 400A and 700A accordingly.

The first step for drawing the time-current characteristic curves of Fig. 17 is to select the largest fuse which both protects the transformer for a bolted secondary fault at the terminals and carries transformer magnetizing inrush current.

The total clearing time curve of this fuse must pass through or to the left of the point representing the maximum time that the assumed delta-wye transformer can safely withstand a bolted secondary short-circuit according to the American standards. This point is obtained if the primary short circuit current is multiplied by 0.58 to allow for a single-phase line to ground short-circuit on the delta-wye transformer.

$$\text{Primary Short Circuit Current } I_{P_{SC}} = \frac{1000000}{0.0575 \times \sqrt{3} \times 4160}$$

$$= 2416 \text{ A.}$$

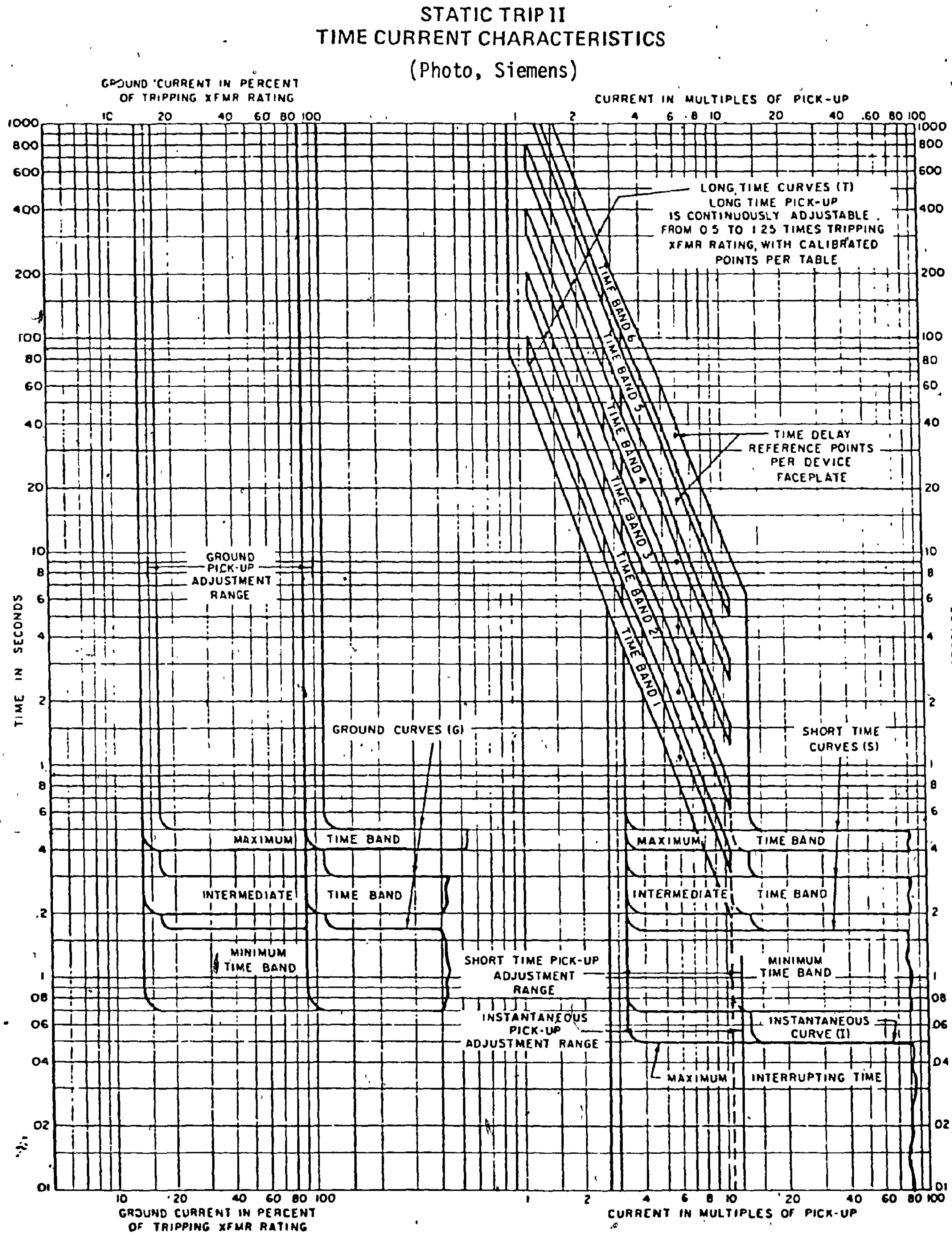


Fig. 16 — Time current characteristic curves of LA type air circuit breaker.

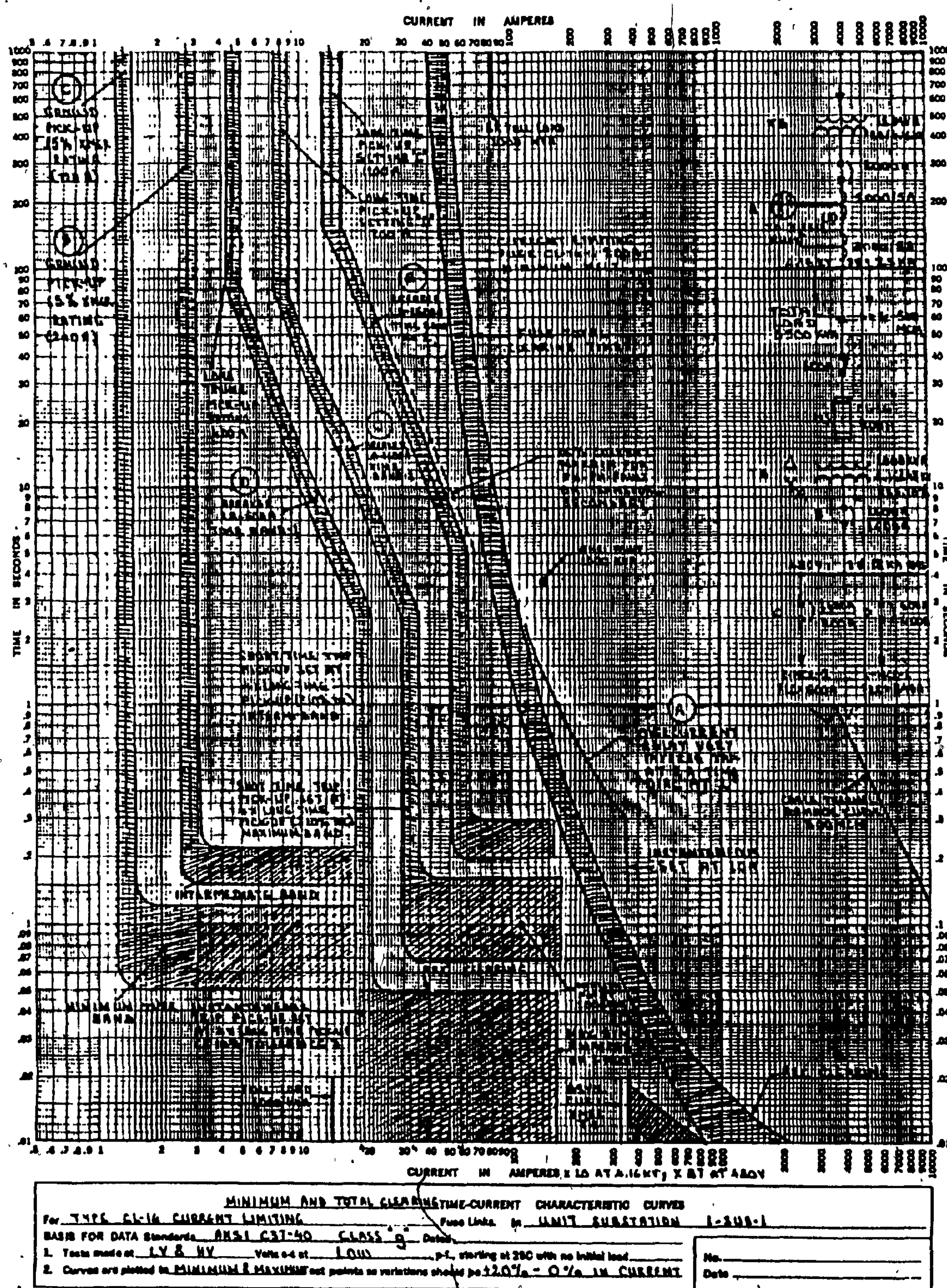


Fig. 17 — Coordination of unit substation 1-Sub-1 with primary feeder very inverse time overcurrent relay HFC-53.

per ASA Standard - C52.12-08.112. The transformer must withstand for 4 seconds 2416 x 0.58 = 1402 amp.

The fuse short-time characteristic curve must pass to the right of the point, 12 times transformer full load current at 0.1 seconds, to permit transformer magnetizing-inrush current to flow without blowing or damaging the fuses. The trip rating of the main secondary feeder breaker should be selected so that in no instance does its characteristic curve (plus the 16 percent margin for the line to line secondary short circuit) overlap the fuse short time curve.

The 6 times full load current of the transformer shall be indicated on the coordination curves according to CSA Standards.

The medium voltage feeder overcurrent relay pick-up should be less than 834A (6 x full load primary current of the 1000 kva transformer) and more than 4800 x (480/4160) x 1.16 = 643 amp. where 4800 A is the short time pick-up of the transformer main secondary breaker. Since this setting will also protect the cable supplying the substation the lowest possible pick-up should be selected, and it shall be also coordinated with the protective devices on the other feeders connected to 4.16 kV bus.

The total connected load on the 4.16 kV bus is 5.500 kva. The corresponding current on the secondary of the CT is —

$$5,500 \times 5/2000\ (1.732 \times 4.16) = 1.91\ \text{A}$$

Therefore, the standard 2A tap is used. The corresponding current in the primary circuit is —

$$2 \times 2000/5 = 800\ \text{A}$$

The instantaneous element is set above the available asymmetrical short circuit current on the 480V bus so that it does not trip for 480V faults. This is,

$$18000 \times (480/4160) \times (5/2000) \times 1.6 = 8.5\ A$$

Therefore, the instantaneous is set at approximately 10A.

CHAPTER 3

PROTECTIVE DEVICES FOR CIRCUITS BETWEEN UTILITY AND INDUSTRIAL PLANT POWER SYSTEMS

3.1 SCOPE OF THIS SECTION

This section discusses the application of relays and other protective devices between the utility company and the industrial plant of Fig. 1. The discussion covers only devices that are involved directly or indirectly in the protection of the circuit between the utility and the industrial system.

3.2 BASIC CIRCUIT ARRANGEMENT AND RELAYING REQUIREMENTS

The circuit shown in Fig. 1 is a radial feed with the utility system being the only source of power or fault current.

In a radial feed system the relaying system is normally designed on the basis that fault current can only flow from the utility into the industrial plant. The rare exception to this would be where there were some very large, very high inertia load synchronous motors in the industrial plant. Such motors could conceivably contribute a substantial amount of fault current for a considerable period. A relatively long duration of current flow, would be possible because the power factor of short circuit current is very low (unless there is a considerable amount of line resistance involved). Consequently, there would be very little kW component to slow the motors down and stop their operation as generators. The fault protective relaying for such a system would be the same as for an industrial plant with load generation. Induction motors also act as generators during an external short circuit, but the major part of their contribution dies out so quickly that it is unnecessary to provide reverse current relaying for them.

There is a source of short-circuit current at both ends of the line when there is local generation, hence the protective relaying must be able to determine whether the fault current is flowing into or out of the industrial plant, and operate selectively in either case. Normally, there is no difficulty in accomplishing the desired objective, but special attention is needed when:

1. The tie circuit is of high capacity and the magnitude of fault current from the industrial plant generators is low due to the size and/or number of generators in use.
2. Provision is made for the industrial plant to supply a substantial amount of power to the utility system at certain times.
3. Modernizing the relaying for an industrial plant with a high-capacity utility-system tie, a small amount of existing generating capacity, and planning for a major expansion of generating capacity.

In Condition 1, the required high-current rating of the current transformers in the tie circuit might make it difficult to obtain the desired degree of sensitivity with ordinary overcurrent relays when current flows from the industrial plant generators into a fault in the utility tie or system.

In Condition 2, the impedance of the tie circuit may be so high that the current flowing into a fault at its far end may not be enough greater than the reverse flow of load current to enable ordinary over-current relays to distinguish between them. This same problem arises when relaying a line from a remote industrial engineering station with a varying number of machines in use.

When Condition 3 is involved, the high-capacity tie requires large line CT's, and there may be such a big difference between the magnitude of present and future fault-current contributions from the industrial plant generators as to necessitate installations of low-current-rating relays initially and subsequently replacing them with relays of higher capacity.

3.3 PHASE FAULT RELAYS

Three-phase fault relays and a ground fault relay provide adequate protection against the several types of faults that can occur on circuits protectable by plain overcurrent relays. The three phase overcurrent relays are usually the #50/51 (refer to Appendix 'B' for relays function and defin-ition) and the ground fault relay is the 50 G.S. for instantaneous protection or 51N for time delay protection.

3.4 CO-ORDINATION OF UTILITY AND INDUSTRIAL PLANT RELAY TIME CURRENT SETTING

Many industrial plants are quite large and complex and have almost as many steps of protective devices as there are in a utility system. This creates one of the problems involved in relaying the connections between utility and industrial-plant power systems. The reason is, that as far as the utility is concerned, the industrial plant's incoming-line breaker is the 'end of the line', whereas it is just the beginning of the industrial's protective relaying system. This problem is simplified when there are transformers in the tie circuit. Transformers usually introduce enough impedance in the circuit to limit the maximum asymmetrical fault current on their secondary sufficiently to permit setting an instantaneous device on the transformer primary so that it will operate only for faults in the transformer. The ability to use such an instantaneous relay makes it possible for the utility to start a new timing sequence at this point.

There will be cases, however, when the transformer capacity is so large that its impedance will not limit the secondary fault current enough to permit using such an instantaneous relay on the utility side. A similar condition arises when the utility supplies the industrial plant at utility-substation voltage with no transformation at the industrial end. In either case, the utility-system overcurrent relays have to be slowed down to co-ordinate with the industrial relays. If this is undesirable because of the effect on other utility-system relays, some other type of protection such as distance or pilot relays must be used.

Since the many variables involved affect both industrial and utility-system operation, the selection of protective devices for the connection between the two systems should be discussed co-operatively by engineers from the utility, the industrial plant, and the manufacturer supplying the equipment. Such cooperation will prevent the possibility of installation of equipment in the industrial plant that is incompatible with that in the utility system.

3.5 Bus Fault and Feeder Back-Up Protection

The phase overcurrent instantaneous and time delay relay #50/51 and the ground overcurrent relay #50N/51N in the incoming utility circuit provide adequate protection for the circuit arrangement shown in Fig. 1. This type of bus fault protection is usually used in most metal-clad switchgear installation. If maximum protection is desired, bus differential relays must be added.

3.6 Transformer Differential Protection

Transformer differential relays #87 are recommended for all main power transformers and sometimes for large unit substation transformers when there is a primary circuit breaker available which can be tripped in case of transformer faults. Refer to Section 2.5.4 for setting transformer differential relays.

3.7 Transformer Neutral Relay

The time delay, ground fault relay #51G, shown in the transformer neutral connection in Fig. 1 provides: (1) back-up for other #51N ground relays on the industrial system and the transformer differential relay #87 during transformer ground faults and (2) the only protection for ground faults on the bus when there is no bus-differential relay.

3.8 Phase and Ground-Fault Relays at Utility and Industrial Ends of the Line

Both instantaneous and time delay phase (#50/51 and ground fault (#50/51N) overcurrent relays will be used in practically all cases at the utility end of the supply line (A in Fig. 1).

Similar relays would normally be used at the industrial plant end of the line also if there are transformers with primary circuit breakers in the line as in Fig. 1. When there are no transformers, only time delay relays can be used.

If the line is long enough, its impedance will limit the current for faults near the industrial plant to values that will not operate the relays at A, thus making it possible to co-ordinate instantaneous as well as time-delay relays at A and B. This provides direct indication of fault location. If there is not enough current difference to give selective tripping of the instantaneous relays, both sets of relays would operate for severe faults in the transformer primary. In that case, location of the fault would have to be determined on the basis of whether one relay (A) or both sets of relays (A and B) operated. If both operated, the trouble would be in the transformer, whereas if only A relays operated, it would indicate line trouble.

Instantaneous phase-fault relays could not be used at B and have co-ordination between them and the plant relays without the benefit of the transformer impedance.

Instantaneous ground fault relays #50N can be used on the primary of transformers connected to solidly grounded systems as shown in Fig. 1. The reason for this is that the maximum ground fault current on such a system is so much greater than the asymmetrical transformer magnetizing current inrush that a #50N relay has plenty of "elbow room" when set high enough to avoid false tripping. The same is not on resistance grounded systems, therefore instantaneous ground fault relays are not recommended on them unless a ring type CT is used.

The phase fault relay #50/51 can also be used on the secondary of transformers with primary circuit breakers but this is generally not considered sufficiently important to justify the extra cost and the necessary slower setting on the #51 relay on the primary of the transformer, particularly when there is a transformer differential relay.

The ground fault relay #51N in secondary of transformer with primary circuit breakers is optional. The reason is that back up relay #51G adequately protects the system against ground faults and operation of either relay will (1) shut a radial feed plant down, or (2) cut off the utility supply to a plant with local generation.

The only reason in having a #51N in the transformer secondary is to be able to differentiate automatically between ground faults in the plant, and in the transformer secondary circuit.

3.9 UNDERFREQUENCY RELAY

If the power company has high speed (15-20 cycle) automatic reclosing on the circuit breaker in the line to an industrial plant with synchronous motors or generators, or large induction motors (over 200 H.P.), an underfrequency relay #81 is recommended to prevent re-energizing the motors out of phase when the line is reclosed. The relay should be connected to trip the main breaker.

An Underfrequency relay is also recommended as a means of opening the utility-tie circuit breaker and disconnecting non-essential load to prevent complete collapse of its power system when an industrial plant with inadequate local generating capacity loses its utility-system power supply.

CHAPTER 4

APPLICATION OF RELAYS FOR MISCELLANEOUS FEEDERS BUS, AND LINE PROTECTION

This Chapter covers the application of relays and other devices for the protection of the miscellaneous feeders, buses, tie circuits, and lines involved in an industrial power system, exclusive of the connection to a utility system. The various protective functions and the devices used to accomplish them will be discussed in greater detail in the following chapters.

4.1 RELAY PROTECTION FOR GENERAL-PURPOSE RADIAL FEEDER

3 - devices #50/51, overcurrent, (4/16 A) time delay and (20/80 A) instantaneous phase fault relays.

1 - device #51N, overcurrent, (0.5/2.0 or 1.5/6.0 A) time delay, residually connected, ground fault relay.

3 - conventional current transformers.

An instantaneous ground fault relay device #50G, (0.5/2.0 A) can be used on a feeder if there are no other ground-fault relays on its load side with which it must co-ordinate, e.g., a feeder supplying only transformers.

4.2 DIRECTIONAL-OVER CURRENT PHASE FAULT RELAYS

Directional, time and instantaneous or time overcurrent devices #67 are recommended at the industrial plant: (1) when there are two radial-feed circuit operating in parallel as line "A " and "B " in Fig. 1; (2) when there is a source of power at both ends of the circuit. In Case (1) both sets of #67 relays see the same current, but the directional feature prevents operation of the relay in the healthy line. They must be set at least one time step faster than the non-directional #51 relays, which provide plant protection. In Case (2), the #67 relays operate for fault current flowing from the industrial generators into the utility system, and the #51 relays operate on fault current flowing from the utility into the industrial system. The #51 relays are set slower than the #67 relays.

CHAPTER 5

EQUIPMENT PROTECTION

Various devices, each with a specific protective function to perform, are required to properly protect power equipment in the event of short circuit and other abnormal or undesirable operating conditions.

Following is a description of the various functions to be performed for the protection of rotating machines and transformers.

5.1 SYNCHRONOUS SPEED INDICATOR

Device #13 indicates that the machine has attained the speed at which field should be applied. For unloaded start synchronous motors Device #13 is an overcurrent relay connected to a line current transformer. It picks up on motor starting current and drops out when the starting current drops abruptly between 95 and 100 per cent speed, causing the field contactor to close.

For a loaded start synchronous motor, Device #13 is a slip frequency relay which operates when the percent slip in the field circuit (motor-rotor) has reduced to a value which indicates that the machine has attained the desired percentage of synchronous speed.

5.2 AUTOMATIC SYNCHRONIZING FOR GENERATORS

Device #25 sometimes required to close the generator circuit breaker, in order to avoid the possibility of damaging the machine by accidentally connecting it to the bus out of phase during manual synchronizing. The usual procedure is to connect the contacts of the synchronizing relay in series with the generator circuit breaker control switch, and allow the relay to give the circuit breaker closing signal, as soon as the operator has brought the on-coming machine into synchronism with the bus by manual control of the prime mover's governor.

5.3 SYNCHRONOUS MOTORS, SQUIRREL-CAGE INDUCTION MOTORS, TRANSFORMERS WINDING PROTECTION.

Device #26 is used to protect the windings of squirrel cage or synchronous motors from overheating, particularly if the motor is stalled, and the winding of large power transformers for extended overload condition.

It is standard practice to include Device #26 to give thermal protection to the rotors of loaded start synchronous motors. The protective equipment consists of the relay, a reactor, and resistor. The latter are connected in the motor's field discharge resistor circuit with the relay heater element paralleling them.

5.4 UNDERVOLTAGE PROTECTION

Every ac motor, with the exception of essential service motors, should have protection against undervoltage on at least 1 phase during both starting and running.

Undervoltage protection is not recommended for essential service station auxiliary motors as it is preferable to let them re-accelerate automatically following a voltage disturbance. Such protection might be desirable, however, on other 'essential service' drives if automatic restart was desirable for some reason. Device #27 operates on single phase, line-line voltage. On medium voltage equipment the undervoltage device is connected to the secondary of a potential transformer or the control power transformer. On some low voltage equipment the device is connected direct to line voltage and in others a potential transformer is used. Undervoltage protection should be time delay for motors rated 2200 volts and above.

In the case of motors rated 600 volts and below controlled by magnetically held in contactors, the undervoltage release is automatically supplied by the dropping out of the contactor when voltage fails or drops to an excessively low value.

5.5 Loss of Field Protection – Synchronous Motors and Generators

Loss of field protection is recommended for synchronous motors and for generators rated 10,000 kVA and larger. In the case of the synchronous motor, the relay prevents: (1) stator overheating due to the high current the motor would draw while trying to carry load without field excitation, and (2) rotor overheating that would result if the motor continued to run without excitation, i.e. as an induction motor.

The purpose of the relay on generators is to protect both the generator and the system. If a synchronous generator loses field it will continue to operate as an induction generator excited from the other machines on the system. When this happens, the generator rotor overheats dangerously in a short time, due to the slip frequency current induced in the rotor.

5.6 Phase Current-Balance Protection

Device #46 is recommended in circuit breaker starters to protect large motors against single phase (open circuit) operation.

The rotor of a large motor will overheat rapidly due to the flow of negative phase-sequence current in the event of single phase or badly unbalanced 3-phase operation.

The line current operated overload relays (Device #49) are depended upon for protecting small and medium size motors, for both of these conditions. These relays are relatively slow, however, and the economic value of large motors justifies better protection in the form of current balance relays. These are recommended for induction and 0.8 PF synchronous motors over 1500 HP, and for 1.0 PF synchronous motors over 1750 HP.

5.7 Instantaneous and Time Delay Over-Current Phase-Fault Protection for Motors

The flow of short circuit current is usually accompanied by arcing with consequent damage to insulation and punching of a machine. Hence, the short circuit current should be interrupted as quickly as possible without shutting down unfaulted equipment unnecessarily. Motors are farthest from the power source, hence short circuits in them can be interrupted instantaneously (for all current magnitudes greater than asymmetrical starting current) by means of simple overcurrent relays, as well as differential relays. An instantaneous relay cannot be set any lower because it would prevent the motor from starting, and also would trip on the current which the motor could feed into an external short circuit for which the motor circuit should not be interrupted.

Practically, this means that instantaneous operation of an overcurrent protective device is permissible for currents greater than approximately twice symmetrical full voltage, locked rotor motor starting current.

Time delay, phase fault protection, is theoretically desirable on medium-voltage circuit breaker type motor starters, because it is possible to set a standard induction relay to operate in a fraction of a second on phase fault currents just above the symmetrical locked rotor starting current. This is possible because such relays are not affected by the dc component of motor starting or feedback current, as the instantaneous #50 relays are.

5.8 INSTANTANEOUS OVER-CURRENT GROUND FAULT PROTECTION FOR MOTORS.

A sensitive, instantaneous, ground fault relay, Device #50G, is standard equipment in all medium voltage motor starters. This protection is provided by a 0.5/2.0 A , instantaneous relay connected to the secondary of a ring-type current transformer encircling all-phase conductors. When all phase conductors pass through one CT, the fluxes created by the positive and negative phase sequence current neutralize each other and only zero sequence ground fault current appears in the current transformer secondary. There can be no **dc** saturation error currents because the dc components of assymetrical phase currents cancel each other.

A ground relay supplied from a ring type CT can be more sensitive than a residually-connected ground relay because the rating of such CT's is independent of load current, whereas the current transformers for a residually-connected relay must be large enough to carry it.

An instantaneous ground fault relay #50N supplied by residually-connected CT's cannot be set low enough on resistance grounded systems to be of much value without risking false operation due to error-currents caused by CT saturation by the dc component of motor starting and external fault current.

CHAPTER 6

BASIS OF RATING ac SHORT CIRCUIT PROTECTIVE DEVICES

The background of the circuit breaker rating structures and other protective devices as well as the basic characteristics of short circuit currents must be understood to enable the engineer to select the proper rotating machine reactances and multiplying factors for the dc component to determine the short circuit current magnitude for checking the short circuit current duty, on a particular device, such as momentary duty or interrrupting duty.

6.1 POWER CIRCUIT BREAKER RATING BASIS

The standard Magne-blase circuit breakers as used in metal-clad switchgear will be used here to explain power circuit breaker ratings. The same fundamental principles apply to all other high voltage power circuit breakers.

The power circuit breaker rating structure is complicated because of the time of operation of the circuit breakers when a short circuit occurs.

The few cycles needed for the power circuit breaker to open the circuit and stop the flow of short-circuit current consist of the time required for: (1) the protective relays to close their contacts; (2) the circuit breaker trip coil to move its plunger to release the circuit breaker operating mechanism; (3) the circuit breaker contacts to part and (4) the circuit breaker to interrupt the short-circuit current in its arc chamber. During this time, the short-circuit current produces high mechanical stresses in the circuit breaker and in other parts of the circuit (Fig. 18). These stresses are produced almost instantaneously in phase with the current, and vary as the square of the current. Therefore, they are greatest when maximum current is flowing.

During the time from the inception of the short circuit until the circuit breaker contacts part, the current decreases in magnitude because of the decay of the dc component and the change in motor reactance. Consequently, the current that the circuit breaker must interrupt, four or five cycles after the inception of the fault, is generally of less magnitude than the maximum value of the first loop.

The fact that the current changes in magnitude with time has led to the establishment of two bases of short-circuit current ratings on power circuit breakers: (1) the momentary rating or its ability to close against and withstand mechanical stresses due to high short-circuit current, and (2) the interrupting rating or its ability to interrupt the flow of short-circuit current within its interrupting element.

6.2 WHAT LIMIT APPLICATION OF POWER CIRCUIT BREAKERS ON SHORT CIRCUIT DUTY BASIS

Insofar as applying power circuit breakers on an interrupting duty basis is concerned, it can be seen from the following table that there are four limits, none of which should be exceeded. These must all be checked for any application.

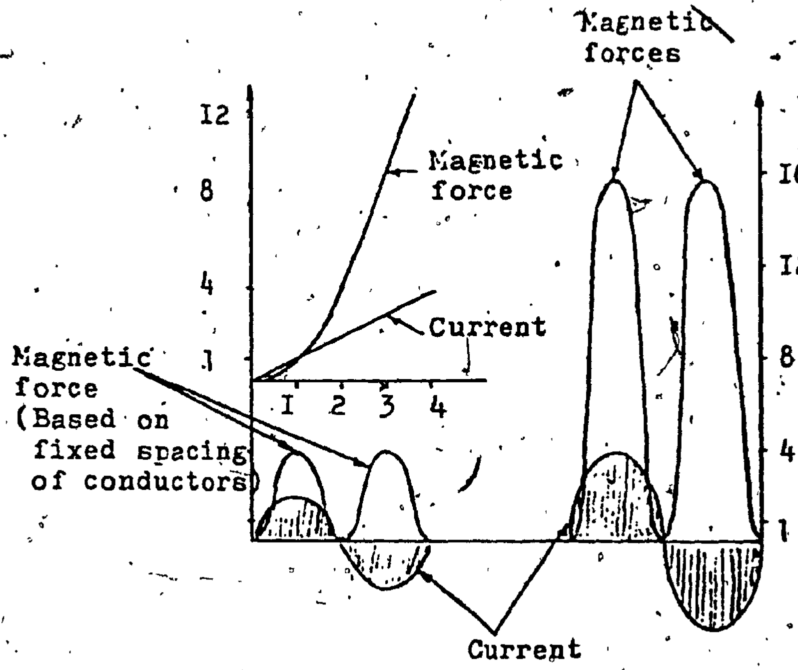


Fig. 18 — Short circuit stresses vary as the square of the time.

I	2	3	4	5	6	7	8	9	I0
				Insul. Level		I200-2000 A Current Rat. A		250 MVA Inter. Rating	
				Withstand Test		Short Time		RMS Total A.	
	Rated kV	Maximum Design kV	Minimum Operating kV of Rated MVA	Low frequency RMS kV	Impulse Crest kV	Momentary	4 sec.	At rated Voltage.	Max. Rating
AM4,I6 250	4,I6	4,76	3.85	I9	60	60 kA	37.5kA	35 KA	37.5KA

Table 2 — Typical ASA circuit breaker rating schedule, none of which should be exceeded. These must all be checked for any application.

1. Operating voltage: This value should never at any time exceed the limit of column 3, Table 2, i.e., the maximum design voltage.

2. Interrupting MVA: This should never be exceeded at any voltage. This limit is significant only when the operating voltage is between the limits of columns 3 and 4, Table 2. It is not significant when the operating voltage is below the limit of column 4, Table 2, because maximum interrupting Ampers limit the MVA to values less than the MVA rating.

3. Maximum interrupting rating amperes: This should never be exceeded even though the product of this current times the voltage times the square root of three is less than the interrupting rating in mva. This figure is the controlling one insofar as interrupting duty is involved when the voltage is below that of column 4, Table 2 (minimum operating voltage at rated MVA).

4. Momentary current: This should never be exceeded at any operating voltage. Modern power circuit breakers generally have a momentary rating in rms amperes of 1.6 or more times the maximum interrupting rating in rms amperes. As a result, where there is no short-circuit current contribution from motors, a check of the interrupting duty only is necessary. If this is within the circuit breaker interrupting rating then the maximum short-circuit current, including the dc component, will be within the momentary rating of the circuit breaker.

Where there is short-circuit contribution from motors, the momentary rating of the circuit breaker may be exceeded, before the interrupting rating is exceeded in a given circuit. Whenever there are motors to be considered in the short-circuit calculations, the momentary duty and the interrupting duty should both be checked.

6.3 High Voltage Fuses Rating Basis

High voltage fuses are either of the current limiting type, Fig. 19, which opens the circuit before the first current peak, or of the non-current limiting type which opens the circuit within one or two cycles after the inception of the short circuit. For standardization purposes, all fuse interrupting ratings are on the basis of maximum rms current that will flow in the first cycle after the short circuit occurs. This is the current that will flow if the fuse did not open the circuit previously, i.e. fuses are rated in terms of 'available short circuit current'.

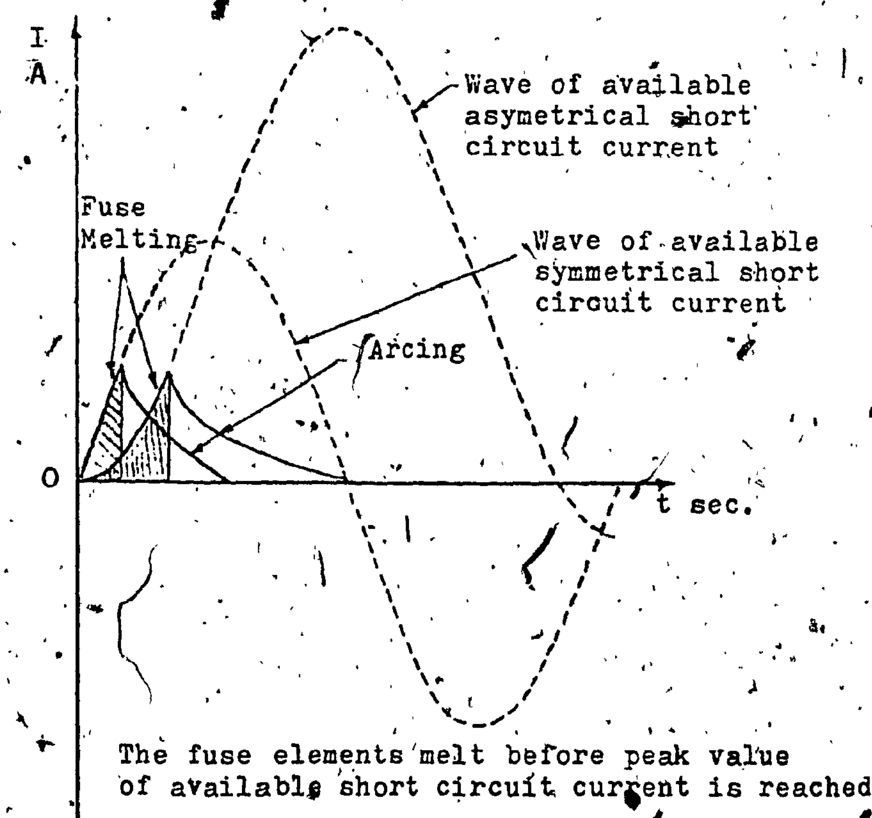


Fig. 19 — Explanation of current limiting action of fuses.

To determine the available short-circuit current at the first cycle for the application of high-voltage fuses, factor the subtransient reactances of all generators, induction motors, synchronous motors, and utility sources and allow for the maximum dc offset. The multiplying factor for allowing for dc offset is 1.6, the same as for allowing for dc component when determining the momentary duty on a power circuit breaker.

The interrupting rating of fuses in amperes is exactly parallel, insofar as short-circuit current calculations are concerned, to the momentary rating of power circuit breakers.

The ampere interrupting rating of high-voltage fuses is the only rating that has any physical significance. For the sake of simplicity of application, some fuses are given interrupting ratings in three-phase kVA. The three-phase kVA interrupting rating has no physical significance, because fuses are single-phase devices, each fuse functioning only on the current which passes through it.

These three-phase kVA ratings have been selected so they will line up with power circuit breaker ratings. This line-up permits applying power circuit breakers and high-voltage fuses on exactly the same basis as far as short-circuit current calculations are concerned. For example, a high-voltage fuse rated 150 MVA and a power circuit breaker rated 150 mva can be applied on the basis of the same short-circuit current calculations. Of course, the application voltage must be factored in each case. Hence, only one set of short-circuit calculations is necessary for applying breakers or fuses rated on a three-phase, mva basis.

6.4 Calculation of A.C. Short-Circuit Duty

Several steps precede actual calculating work, and this work sometimes commands a large part of the time devoted to a study. The first step is to obtain or create an accurate one line diagram of the system showing the types and ratings of all components and the manner in which they are interconnected. The diagram will also indicate all devices or locations in the system where the short circuit duty is to be determined. Another step is to identify the kinds of short circuit duties to be derived because these must conform with the rating bases of the kind of equipment being checked. The kinds of short circuit duties also determining which of alternating values of certain machine reactances will be used. A further step is to establish which switching units are to be considered open and which closed. Equivalent network manipulations provide the means of investigating maximum or minimum duties.

6.5 Short Circuit Current as a Function of Time

An accurate rms current expression as a function of time can be written in a form based on an envelope concept of an actual oscillographic current. This expression includes three fundamental-frequency ac terms and a single dc term. Each ac current term is itself an integral-cycle rms value. The three ac terms are considered to be in phase and their arithmetical sum is the value of the ac component of the total current. All but the steady-state ac term are of transient nature and decay to zero exponentially.

The short-circuit current (I_{ac}) then has the following composition of ac and dc components:

$$I_{ac} = (I'' - I')\,\varepsilon^{-t/T''} + (I' - I_{ss})\,\varepsilon^{-t/T'} + I_{ss}$$

$$= \left(\frac{E''}{Z''} - \frac{E'}{Z'}\right)\varepsilon^{-t/T''} + \left(\frac{E'}{Z'} - \frac{E}{Z_{ss}}\right)\varepsilon^{-t/T'} + \frac{E}{Z_{ss}}$$

and
$$I_{dc} \leqq \sqrt{2}\ \frac{E''}{Z''}\,\varepsilon^{-t/T_s}$$

If resistance can be neglected, the above components will have these forms that are more readily evaluated:

$$I_{ac} = \left(\frac{E''}{X''} - \frac{E'}{X'}\right)\varepsilon^{-t/T''} + \left(\frac{E'}{X'} - \frac{E}{X_{ss}}\right)\varepsilon^{-t/T'} + \frac{E}{X_{ss}}$$

and
$$I_{dc} \leqq \sqrt{2}\left(\frac{E''}{X''}\right)\varepsilon^{-t/T_s}$$

Certain symbols in the above expressions have the following meanings:

t = elapsed time to the midpoint of the desired integral cycle

T'' = subtransient time constant in seconds

T' = transient time constant in seconds

T_s = dc time constant in seconds

The included magnitude of direct current represents a wave with full initial offset. Lesser amounts of the dc component (to as little as zero value) can be present depending on the point in the voltage wave at which the short circuit takes place.

Fig. 20 illustrates the early part of a fully offset sustained short-circuit current. Also shown are the usual four components (three a-c parts and a single dc part) with realistic proportions indicated by the following numerical expressions of integral cycle rms currents:

Subtransient rms = $.6e^{-t/0.03}$

Transient rms = $.6e^{-t/2.0}$

Steady state rms = 1.0

dc = $3.11e^{-t/0.04}$

During any particular integral cycle of the short circuit current, the effective value of current can be approximated by taking the square root of the sum of the squares of the values of the ac and dc components at the mid-cycle time.

$$I_{sc} = \sqrt{(I_{ac})^2 + (I_{dc})^2}$$

The ac components of current in an electric circuit is correctly expressed as $E/|Z|$, where:

$$|Z| \quad \sqrt{X^2 + R^2} = X\sqrt{1 + (R/X)^2}\ .$$

The factor $\sqrt{1 + (R/X)^2}$ is seen to be the ratio $|Z|/X$ and is consequently the ratio of current calculated with resistance neglected to current calculated with resistance included. This factor is plotted against the circuit (X/R) ratio in Fig. 21 and shows large errors of calculation by neglecting resistance if the ratio (X/R) is low, but negligible errors (less than 3% ~~if~~ the (X/R) ratio is greater than 4.0.

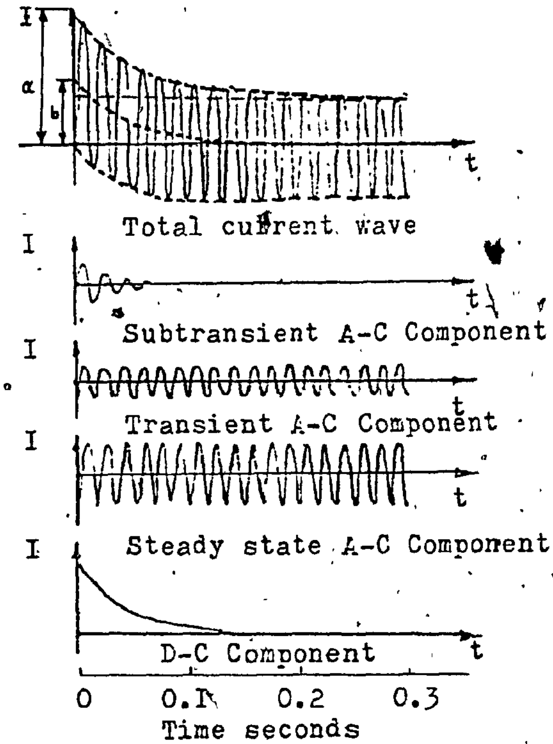


Fig. 20 — The a.c. short circuit current and its components with particular relative magnitude.

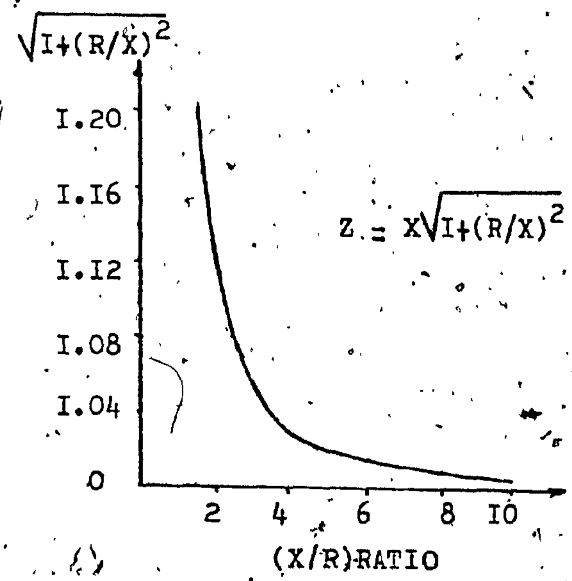


Fig. 21 — Increase in calculated current caused by neglecting resistance is indicated by the expression $\sqrt{1 + (R/X)^2}$ which is the ratio of current calculated with resistance neglected to current calculated with resistance included.

Circuit (X/R) ratios are typically higher than 4.0 in short circuit calculations work, and it is therefore customary to ignore resistances in the impedance networks.

The system component most likely to have low (X/R) and significant resistances, are the conductors (cables, buses, or open-wire lines). In such cases when the (X/R) ratio is less than 4.0, a calculation with the component impedance included will provide a more accurate estimate of short circuit current.

6.6 FIRST CYCLE CURRENT

The first cycle current is generally the greatest in magnitude and for this reason is used to measure mechanical strength limits. It also serves to define interrupting duty of fast operating interrupters as fuses and low voltage circuit breakers. Setting t = 0 in the current expression presented in the previous section gives the following results:

$$I_{ac} = E''/X''$$

and

$$I_{dc} = \sqrt{2}\,E''/X''$$

If the ac and dc components remained unchanged, the first cycle total rms current of the completely offset wave would be:

$$I_{sc} = \sqrt{(E''/X'')^2 + (2\,E''/X'')^2} = \sqrt{3}\,(E''/X'')$$

Only a small change in the ac component of current will occur during the first cycle but a relatively large change will take place in the dc component. Practical multipliers, differing from the $\sqrt{3}$ value, have been standardized in the simplified calculating procedures.

6.7 PREPARATION OF IMPEDANCE DIAGRAM

For the single line diagram of Fig. 1 there can be several impedance diagrams differing in that they display different characteristic impedances for some system components. The majority of short circuit calculations employ the positive sequence network only, but still may require different impedances in the same or generally similar diagrams to establish the duties for different type of components. An example of this is checking the duty for applying a power circuit breaker at a given point in the system. Initial or subtransient impedances (reactances) would be selected for checking the momentary duty, while certain other values would be used in checking the interrupting duty where the calculated current would be representative of the actual current magnitude a few cycles after fault inception. The proper reactances to select under the standard calculating procedures for various classes of interrupting devices are given by ASA and shown in Table 3.

Unbalanced-fault calculations involve the negative and the zero-sequence networks as well as the positive sequence. The duties from unbalanced faults are not often critical industrial systems, and seldom require careful evaluation. Impedance values shall be expressed in terms of one of several possible units. Throughout this section for uniformity and simplicity, impedances will represent per unit values on an assigned three-phase reference kVA base.

6.7.1 TRANSFORMERS

Conversion of % X_T to a per unit value on the study kVA base is accomplished as follows:

$$X = \frac{(\%\ X_T)}{100} \times \frac{(\text{Study Base kVA})}{\text{Transf. rated kVA}}$$

Type of Short-Circuit Duty & Kinds of Equipment	Syn. Generator	Syn. Motors	Ind. Motors	Multiplying Factor to be Applied to Calculated Sym. Value
Interrupting duty power circuit breaker 8 cycles to 2 cycle	Subtransient	Transient	Neglect	1.0 to 1.4
Momentary duty power circuit breaker	✓	Subtransient	Subtransient	1.6
Inter. Duty Power Circuit Breaker	✓	✓	✓	1.0
Interrupting Duty Molded Case Circuit Breakers	✓	✓	✓	1.0
Interrupting Duty Fuse Above 1500 V	✓	✓	✓	1.6
Interrupting Duty L.V. Fuse	✓	✓	✓	1.0
Interrupting Duty L.V. Motor Controlled	✓	✓	✓	1.25

Table 3 — Machine reactances with multiplying factors used in simplified calculations of short-circuit duty.

6.7.2 TRANSMISSION LINES AND CABLES.

With reactance known in ohms per phase (Ω/ϕ), the desired per unit value on the study base kVA is obtained as follows:

$$X = \frac{(\Omega/\phi)(\text{Study Base kVA})}{1000(\text{kV})^2}$$

6.7.3 ROTATING MACHINES

It is the effect of the spinning rotor which creates many peculiarities to the machine reactance. A terminal short-circuit causes the contributed circuit from the rotating machine to be initially high (controlled by X''). The current will thereafter decay to a much lower value or to zero. In synchronous machines the presence of induced currents in the main excitation winding only would account for an intermediate current (controlled by X').

To convert the machine reactances to per unit on the study base we use the same rule that applies for transformers. The following guides can be used in determining the machine rated kVA.

Kind of Machine	Three-Phase Rated kva
Any	$\frac{E_R\ I_R \sqrt{3}}{1000}$ (exact)
Induction motor and 0.8 PF syn. motors	1.0 x rated HP (approx.)
1.0 PF syn. motors	0.8 rated HP (approx.)

6.8 SYMMETRICAL CURRENT CALCULATION

With impedance diagrams at hand, a specific electrical network with a single driving voltage and a short circuit connection is defined.

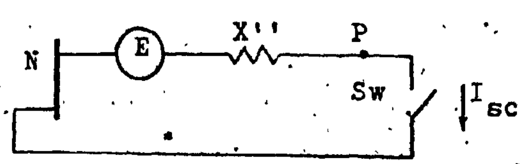
The problem now is one of calculating a single equivalent impedance to the point of short circuit. The most common procedure involves combining two impedances in series or in parallel. With diagram impedances expressed in per unit, the computed current will also be in per unit on the assigned reference base ($I_{PU} = E_{PU}/Z_{PU}$). Multiplication of this result by base current will convert the anser into amperes. If the duty is desired in PU kVA rather than current, the result comes from the expression $(E_{pu})^2/Z_{pu}$. The product of this value and base kva gives short circuit kVA.

6.8.1 THREE PHASE BOLTED FAULT

Three-phase bolted values of short-circuit current are the most basic reference quantities and in a large number of studies will be the only quantities needed. In almost all cases, knowledge of the three-phase bolted-fault values will be wanted. Accordingly, this case is singled out for independent treatment. Furthermore, the steps involved in the solution of this case will set the pattern to be used in other cases.

First-cycle Current (X'' Network): For mechanical-stress considerations, momentary-current checks, and interrupting duty for fuses and other fast interrupters, the first-cycle currents are sought. This current is calculated from the subtransient impedance network in which each circuit branch is represented by its subtransient reactance (X'').

Viewed from a particular fault point, the entire impedance network can be resolved into a single-impedance circuit as illustrated below.



complete detailed impedance diagram as the one shown in Fig. 22.

3) Maximum load current on all circuits including the starting-current requirements of major motors.

4) Manufacturers' characteristic time current performance curves of the relays, trip coils and fuses to be coordinated.

5) Any special overcurrent protective requirements, such as those stipulated by CSA standards and NEC, or dictated by load characteristics.

6) Any special overcurrent protective device setting requirements stipulated by the public utility company with which the industrial plant may be interconnected.

7) Manufacturers' curves showing current transformer performance with varying multiples of short-circuit current in their primaries and varying secondary burdens.

7.2 Short Circuit Current Needed for the Operation of Protective Relays

1) Instantaneous plunger type relays. These relays are responsive to direct current and to alternating current and are fast enough to operate on the first half-cycle of fault current. Therefore, their operating current will be the initial asymmetrical fault current contributed by all rotating machines calculated on the basis of its subtransient reactance (X_d''). Use a 1.6 multiplier to obtain the magnitude of the asymmetrical current.

2) High Speed Induction-type Relays. Since these relays operate in three cycles or less, and induction relays in general are not affected by D-C, the initial asymmetrical I''_d fault current may be used as their operating current.

3) Time Delay Relays. The devices of this class are too slow to be appreciably affected by the very short duration I_d'' portion of the fault current. Therefore, the initial symmetrical I_d' current can be used as their maximum operating current. Those time-delay devices that can operate in about 0.1 second (6 cycles) or less are an exception to the rule, but they are usually the first in a series (farthest from the power source); hence, any reduction in their operating time due to neglecting the effect of the small subtransient portion of the current simply increases the time margin between them and the devices nearer the power source.

7.3 CURRENT SETTING OF RELAYS AS AFFECTED BY THEIR FUNCTION

When the short circuit currents are all calculated, the next step in a relay coordination study is to select the time-current settings for the various adjustable devices starting at the load end of each circuit and working back toward the power source. The current settings must be high enough to carry normal load swings, and yet low enough to be sure the device will operate positively on the minimum expected short circuit current.

Also, the settings should conform to CSA rules, where the latter are applicable.

Minimum current is the magnitude of current calculated with minimum power supply available and assuming a solid short circuit with no allowance for current limitation due to impedance in the fault itself, for example, arc-resistance. Normally, there will be ample margin between the minimum short-circuit current level and the relay setting dictated by the maximum permissible load. Occasionally, that will not be true, as in the case of two or more high reactance generators whose total output is transmitted over a single line. Such possibilities should be recognized and provided for when designing the protective system by specifying devices, such as distance relays, that do not depend on current magnitude alone for operation and selectivity.

The following general rules serve as guides in determining the minimum relay current settings that will not trip on permissible load currents.

7.3.1 RELAYS ON TRANSFORMER FEEDERS.

The CSA Standard C22.1, Article 26, states that the time delay overcurrent relays on a feeder for a single transformer should be set not more than 2.5 times the full load rating of the transformer for units without secondary circuit breakers, and up to six times transformer full load current if there is a secondary circuit breaker and the transformer reactance is not more than 0.075 per unit, but only four times if the transformer reactance is between 0.075 and 0.10 per unit. The fact that the standard permits it, however, does not mean that the relays should always be set at these upper limits. For example, if the transformer load is a diversified one with no relatively large motors whose starting current might be the limiting item, a relay current setting of 1.5 times transformer rating may be sufficient. Ordinary time delay overcurrent relays are too slow to be operated by the transformer magnetizing current inrush.

When several transformers are connected to one feeder, a relay current setting corresponding to 1.5 times the total full load rating of the several transformers should be enough to clear load swings except in those cases having large individual motors. However, the setting selected should meet the CSA standard requirements.

When each transformer has its own primary fuse or circuit breaker protection, the main primary feeder relays may be given the lowest current setting that will coordinate with the transformer primary fuses without regard to the individual transformer ratings. An instantaneous relay in the primary circuit of a single transformer with an instantaneously tripped secondary breaker should be set a little above the asymmetrical I''_d current it will see during a three-phase fault close to the transformer secondary. This is usually high enough to prevent relay operation on transformer magnetizing inrush and will coordinate.

If a transformer primary feeder breaker trips when the circuit is energized during installation tests, and there is no fault, the instantaneous-relay's current setting should be increased just enough to prevent relay operation on the magnetizing inrush. The minimum setting of the instantaneous relay on a feeder supplying several transformers will usually be dictated by the need for riding over their total magnetizing current inrush. This will be in the neighborhood of 10-15 times normal. Such a setting would be high enough to prevent tripping the main feeder breaker with a solid secondary fault on one of the transformers and full load on the others.

7.3.2 RELAYS ON SINGLE MOTOR FEEDERS

Instantaneous and time delay relays may be used on single motor control circuits as:

1. Locked or stalled rotor protection
2. Stator short circuit protection
3. Substitute for stator thermal relay.

Separate relays should be used for these functions, because the proper time current setting for one function is usually unsuitable for the others.

The type 2E time delay static relay, shown in Fig. 23, when used as protection against stalled-rotor trouble, should be set so that it will ride through normal starting current with a reasonable margin for variation in starting time, and yet operate in time to protect the rotor against dangerous heating in case the rotor stalls. There are numerous possible combinations of the current setting that would accomplish this objective, but each of them will make the relay too slow to provide acceptable short-circuit protection.

One point that should be kept in mind when setting the Type 2E relay for locked rotor protection is that the percent of the time dial setting should be selected such as, the starting time will be below the maximum stalling time and above the starting time of the motor. The time setting range of the relay is from 5 - 40 sec. The percentage of the current setting of the 2E relay is determined from the ampere-turns of the relay, the full load current and the CT's ratio.

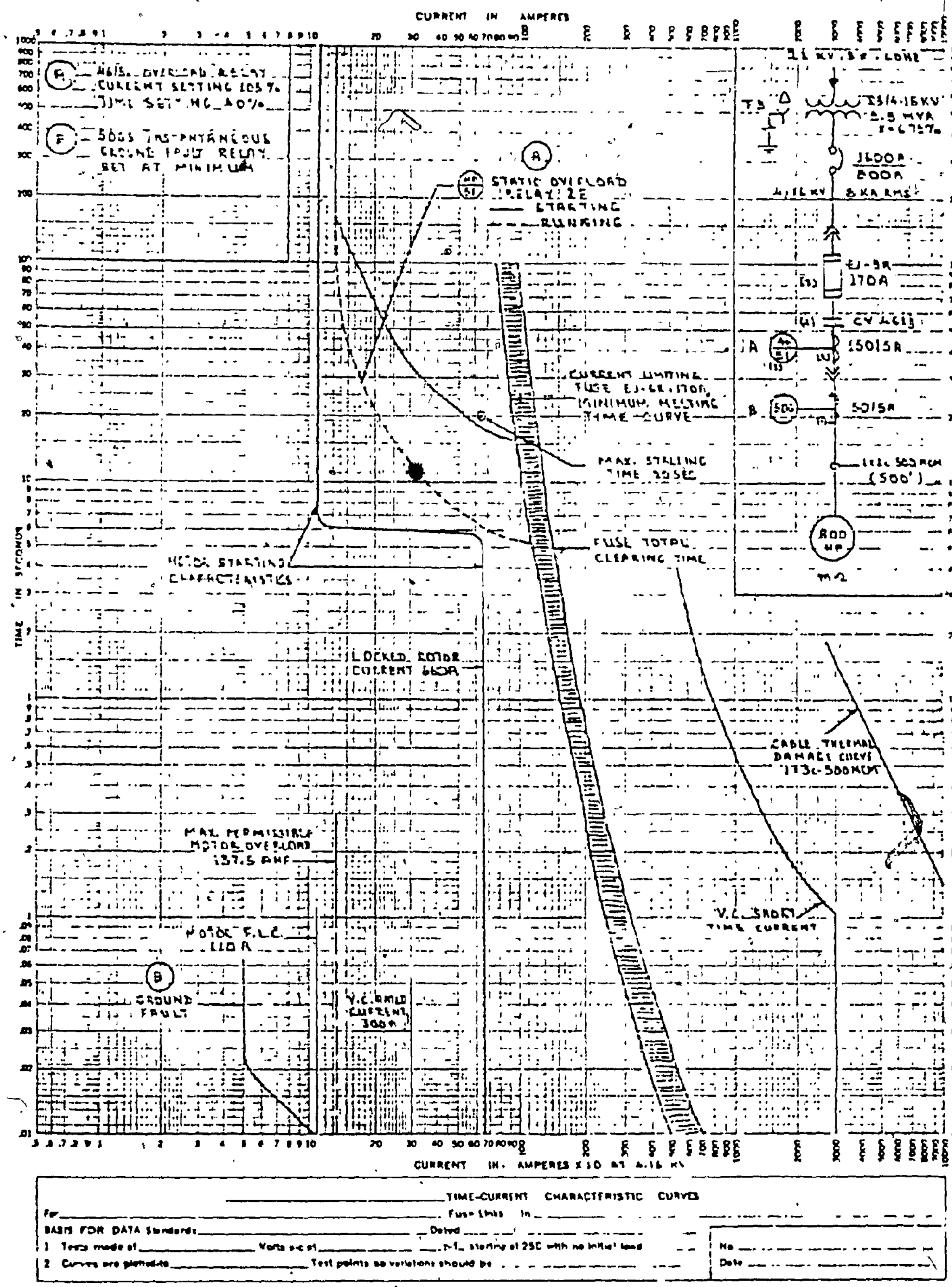


Fig. 23 — Illustration of 2E Relay Setting for Motor Protection on the M.V. Starter M_2 of Fig. 1.

The current setting of the HFC51 or HFC53 time delay relay when used to provide short circuit protection on a single motor feeder should preferably be above the motor's locked rotor starting current, because such relays are much too fast to ride through any appreciable amount of motor starting current.

Plunger type, instantaneous relays, are commonly used to provide fast short circuit protection in case of a fault in the motor or its leads. These relays should not operate on the current which their motor will contribute to a fault elsewhere on the system, that should be cleared by some other breaker and relay combination.

Since they are fast enough to operate in the first half-cycle and also are affected by the D-C component, they should be set slightly above the asymmetrical I''_d current their motor can supply to an external fault. The symmetrical component of this current can be calculated from the motor's I''_d or estimated on the basis that it is approximately 20 per cent higher than the motor's locked-rotor starting current. For example, if the instantaneous relay HFC50 had to be used for the motor M2 (Fig. 1) 800 HP, 0.8 PF, 0.93 EFP. with full load current 111 amp. the instantaneous relay in the feeder to it should be set at about 35 amp.

That setting is based on the fact that the motor could contribute $111/0.2 \times 1.6 = 888$ amperes asymmetrical I current to the fault on the other circuit.

The corresponding current in the secondary of the 150/5 CT's is 29.6 amperes, and the difference between this and the suggested 35 amperes setting is to allow for variation in the setting and performance of the relays. Such setting affords satisfactory protection for faults in the motor, since the fault current from the rest of the system is many times such a motor relay setting.

7.3.3 RELAYS ON INCOMING LINES AND FEEDERS WITH MISCELLANEOUS LOADS

The minimum setting of a time-delay overcurrent relay on an incoming line, or a feeder with miscellaneous load which may include large motors, should be just above the total of the starting current of the biggest motor plus full load on the other circuits unless it is intended to start more than one motor at time by manual control, or the motor controls are so designed that the motors would restart automatically when the circuit is re-energized following an outage. In the case of widely fluctuating loads, such as those encountered in steel mills, the relay current setting should be high enough to allow for peak loads on some of the motors as well as starting the largest one.

Instantaneous relays cannot be used on currents where there are other instantaneous relays with which they must coordinate, unless there is sufficient circuit impedance in the form of transformers or overhead lines between them and the other relays to reduce the fault current that the other relays work on to a value too small to operate the main-circuit relays. This problem is discussed in more detail later in this chapter under the heading of "Co-ordination of Relay in Series". If they can be used, they should be set a little above the total initial asymmetrical I''_d current which all the motors on these circuits could contribute to a short circuit elsewhere on the system. This setting should be checked against the expected magnetizing current of any transformers on the circuit to be sure that it exceeds it.

7.3.4 RESIDUALLY CONNECTED GROUND-FAULT RELAYS

Residually-connected ground relays (Fig. 24) are connected in the Y of the secondaries of the 600/5A line transformers of the incoming line of Fig. 1. They will see only the unbalanced residual (zero phase sequence) current flowing during ground faults. It should be noted, however, that third harmonic currents, due to CT saturation, will flow in residually-connected relays and may be the cause of false operation in unusual cases, as discussed below.

Since no current flows in a residually-connected relay under normal load conditions, it can be set at much lower current levels than phase relays can. This characteristic permits sensitive operation on ground faults, which are the most common variety. Such relays are normally rated 0.5 to 2.0 amperes, or 1.5 to 2.0 amperes. These relays will operate satisfactorily over their entire tap range when connected to high-accuracy current transformers, but they may not on the 0.5 ampere tap when connected to the low-turn-ratio taps of some bushing current transformers. This is due to the fact that the bushing current transformer ratio breaks down due to the high volt-ampere burden imposed by the relay on the low-current tap. If a check of the bushing current transformer performance curves with the expected volt-ampere burden indicates that the relay may not operate, it will usually be possible to obtain satisfactory operation by using a higher current tap on the relay or bushing current transformer, or both.

Ground-fault-relay current and time settings are handled in the same manner as for phase-fault relays. However, the ground-fault current will usually be of different magnitude than the phase-fault current, and it may not appear in all parts of the system since all transformers except grounded Y-Y units block its flow.

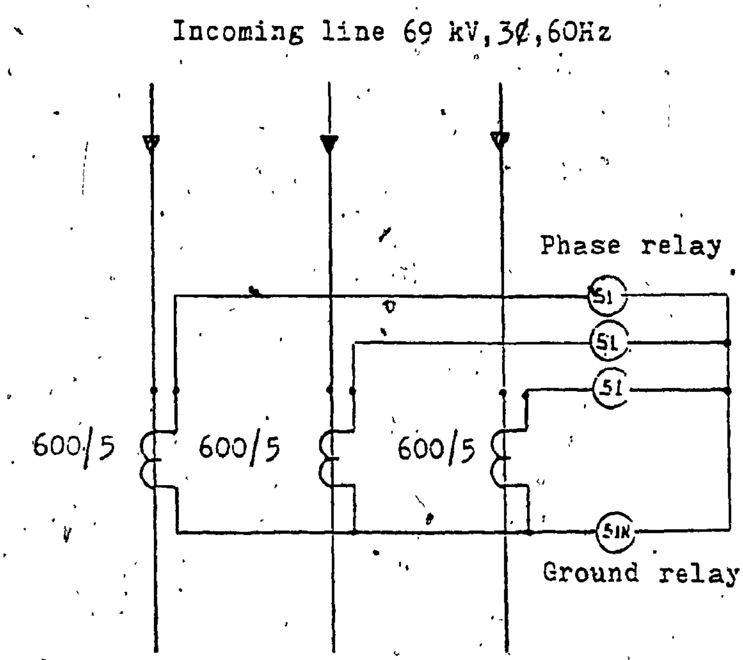


Fig. 24 — Typical diagram of residually connected ground fault relay 51N of the incoming line of Fig. 1.

Usually, ground-fault relays can be set to operate faster than the phase relays at the same location. For example, the phase relays on the incoming line of Fig. 1 must have enough time delay to coordinate with other phase overcurrent protective devices on the main transformer secondary; whereas, a residual current ground relay on the primary side of the same transformer would not see fault current in the secondary system unless the transformer was Y-Y connected and grounded. Therefore, a primary circuit ground relay on a Δ-Y transformer would not have to coordinate with a secondary-circuit device and could be set for minimum time delay.

Residually-connected ground relays are subject to possible false operation due to current transformer error currents during severe phase faults. This possibility is due to the fact that the D-C component of the fault current, differences in volt-ampere burden, and slight variation in characteristics will cause current transformers to saturate unequally during severe phase-phase or three-phase short circuits. This may cause a sufficient amount of unbalanced current to flow in the Y of residually connected current transformers to operate ground relays having the low current settings. One solution to the error current tripping problem is to design the system to have sufficient ground fault current to insure positive tripping with the ground relays set above the expected maximum current transformer error-current.

However, available data regarding current transformer saturation indicates that the possible magnitude of error currents caused by unequal saturation due to differences in their burdens, plus the differences permissible under manufacturing tolerances, may be quite substantial. Consequently, this solution might require increasing the ground fault current to very high values, and therefore causing much greater damage during a ground fault.

The other, and seemingly better way, is to keep both the magnitude of the ground-fault current, and the current setting of the ground relay at a minimum consistent with positive relay operation, and prevent false operation by timing the ground relay to be selective with any phase relays on its load side. This, of course, raises the question as to which causes more damage — high ground-fault current and less sensitive relay pickup with minimum relay operating time, or less ground-fault current and a more sensitive, but perhaps one-time-step (0.4 second) slower relay setting. It is a difficult question to answer, but it seems reasonable that the odds are in favor of the latter combination.

Residually connected instantaneous ground relays are not recommended on resistance grounded systems because it is exceedingly difficult, if not impossible to set them so that they will operate on the limited ground fault current and not operate falsely on error currents and transformer magnetizing current.

7.3.5 GROUND FAULT RELAYS IN SERIES WITH TRANSFORMER OR GENERATOR NEUTRAL

It is general practice to connect a final backup ground relay to a current transformer in the transformer or generator neutral earth connection. A low current relay and a current transformer, whose rating is 25 or 30 per cent of that of the neutral grounding resistor, is the combination generally used.

This combination affords good sensitivity and protection, and is permissible since current flows in the neutral of a balanced, three-phase, three wire circuit only during a line to ground fault.

The relays usually furnished for this purpose are capable of being set slow enough to permit the flow of ground-fault current up to the thermal limit of the neutral grounding resistor, when there is one. Some users set the neutral relays to do that. Since it is fairly general present-day practice to use 2-second rated resistors, the relay would be set for 1 to 2 seconds in such cases.

Another method of setting the neutral relay is to time it to co-ordinate with the other ground relays on the system; that is, one time step slower. This seems preferable, since experience indicates that if a relay or circuit-breaker trip is going to work at all, it will do so in its scheduled time. Hence, any more delay than the normal coordination time between relays simply means more damage caused by the continued flow of ground-fault current. Incidentally, it should be borne in mind that the generator or transformer-neutral relay is the only protection for main-bus ground faults if there is no bus differential relay.

The neutral-lead ground relay is normally used to shut the system down as a last resort in the event that a ground fault has not been removed by some other relay.

7.4 How to Select Relay Current Tap and Time Dial Settings

In Fig. 25 there are two examples how to use a relay's family of curves to (1) determine the operating time of an overcurrent relay with a specified time dial and current tap setting when a given amount of fault current flows through it, and (2) select a suitable current tap setting for the relay in a particular circuit and then find the time dial setting needed to give a specified operating time for a given amount of short circuit current.

Example 1 : Required to find the operating time of the relay 51 on Cell No. 2 of Fig. 1.

1. Relay is a very inverse time 12HFC53 with 1-12 amp Tap
2. Fault current is 2080 amperes symmetrical
3. Relay is set on its 5 amp tap and 2 time dial.
4. Relay is connected to a 200/5A (40/1) current transformer.

First, determine the multiples of relay tap setting represented by the fault current. The current transformer (CT) ratio is 40/1 so there

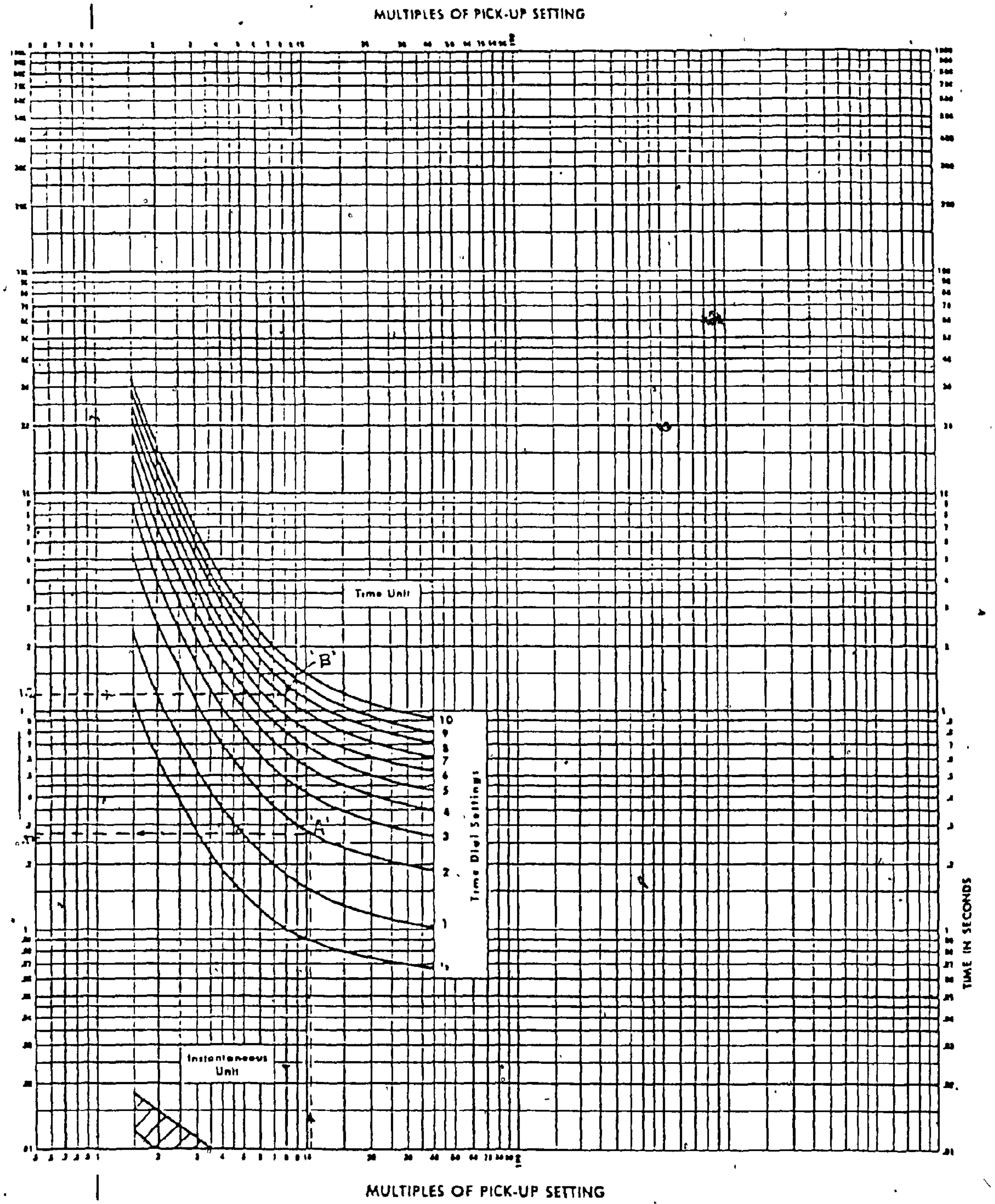


Fig. 25 — How to Use Relay Time-Current Curves (HFC 53 Very Inverse Time Relay).

will be 2080/40÷52 amperes in the CT secondary and relay coil. This is 52/5 = 10.40 multiples of the relays 5 amp tap or pick-up setting. Now enter the relay's family of time current curves at 10.4 multiples of tap setting and follow the arrows vertically to point A where the current ordinate intersects the interpolated 2 time dial curve, and then go horizontally to the time scale and read the operating time, which is 0.275 sec.

Example 2: Required to find the relay time dial and current tap setting, of the relay 51 connected on the secondary of the main power transformer T1 in Fig. 1, and it must meet the following conditions:

1. Relay is a very inverse time with 0.5- 6 amp tap
2. Maximum load current on the circuit is 1004 amperes
3. Relay is connected to 1500/5 (300/1) current transformer
4. Fault current is 12,000 amperes symmetrical
5. Desired relay operating time is 1.2 sec.

First, decide on the relay tap setting to use. The maximum full load current is 1004A so the CT secondary current will be 1004/300 = 3.35 amperes.

Since this is the maximum current the transformer can deliver with fan cooling, a 5.0 amperes tap would allow sufficient margin for relay operational variations. This tap setting corresponds to the CT's 1500 amperes primary rating, so the relay will see 12000/(300x5) = 8 multiples of relay tap setting. Now enter the chart in Fig. 25 at the desired time of 1.2 sec and follow the arrows horizontally to the intersection (point B) with the vertical line starting at 8 multiples of tap setting. The point dial curve passing through the point of intersection (curve 7 in this case) is the desired time dial setting.

7.5 IMPORTANT RULES FOR COORDINATION OF TIME DELAY RELAYS

The time current characteristics of relays are represented by families of single line curves (see Fig. 25), whereas the time current curves of direct acting time delay trips and fuses include the necessary allowance for overtravel, manufacturing tolerance, etc. Since their operating characteristics are shown by single lines, it is necessary to make a time allowance between relays operating in series with each other, so that they will operate in the correct sequence. A time margin of 0.4 seconds with maximum three phase fault current flowing is sufficient to afford satisfactory selectivity between induction overcurrent relay settings. This margin allows 0.13 second circuit breaker opening time (8 cycles), 0.1 second relay overtravel, and a safety factor of 0.17 second to cover manufacturing variations.

When two time delay relays are set to coordinate properly at the maximum expected value of three phase fault current, they will be selective on lower values provided (1) they have the same shape time-current curves, and (2) the current setting of the slower relay is equal to, or preferably slightly higher, than that of the faster relay.

This rule is applicable for all three phase faults and for line-line faults except when there is a wye-delta or delta wye transformer in the circuit between the relays or other devices being coordinated.

When choosing between two combinations of current tap and time-dial settings, either of which will give the desired operating time on maximum fault current, the combination with the lower current and higher time dial setting is usually preferable. The reason is that a relay with the latter setting will be more sensitive and faster on low values of fault current.

7.6 Important Rules for Coordination of Instantaneous Relays

The only way to make instantaneous, electromagnetic attraction-type relays and direct acting trips to coordinate is to select a current setting tha will prevent operation of the device nearest the power source, (relay A, Fig. 17) on the maximum asymmetrical current the other device (Breaker B, Fig. 17) will see during a fault on its load side.

This is necessary because such devices respond to both ac and dc components of fault current and operate immediately whenever the current in the circuit exceeds their setting. Therefore, there must be sufficient impedance in the circuit between instantaneous devices in series to create the necessary current differential.

If this objective cannot be obtained, one of the devices must be made inoperative, or omitted initially if selective operation is desired. Usually, a transformer's impedance is sufficient to permit coordinating instantaneous devices on opposite sides of it. For example, an instantaneous relay #50 on the primary of a transformer will coordinate with an instantaneous trip on the secondary circuit breaker (Fig. 17) provided the primary circuit's current transformers are not too small. If the ratio of the current transformers is too low, their secondary current will be so high during a transformer secondary fault that the 20/80 amperes instantaneous relay normally supplied on switchgear equipment (or the new type 6/250 amperes instantaneous relay), could not be made selective with the instantaneous trips on the secondary breaker.

Instantaneous relays can sometimes be coordinated at opposite ends of high-voltage (2400V and above) cable of overhead lines (Fig. 1 incoming line) of the length likely to be found in industrial plant power systems. In many cases, however, the circuit impedance will be too low to cause the necessary current differential.

Circuit impedance is much more effective in reducing the magnitude of fault current in low voltage circuits (600 volts and below), and therefore it is usually possible to coordinate the operation of instantaneous devices at opposite ends of such circuits.

7.7 EFFECT OF CURRENT TRANSFORMER A-C SATURATION ON RELAY PERFORMANCE

The breakdown in current transformer ratio due to saturation may affect relay operation. Industrial plants often have some relatively small feeders operating which may be subjected to high levels of short circuit current. Consequently, some of the current transformers in such plants may be subjected to short circuit currents as high as 200 times their rating, and multiples of 50 to 100 times current transformer rating will be quite common. When subjected to such magnitudes of fault current, most current transformers will saturate, and then their accuracy breaks down. The extent of this breakdown in current transformer ratio depends on the volt-amperes burden imposed by the impedance of the relays, instruments and leads connected to their secondaries, and the multiples of rated primary current imposed on them. The available data is not conclusive, but it appears that their ratio can break down to the extent that only a fraction of the theoretically correct secondary current will be available for relay operation as shown in Fig. 26.

For example, the particular current transformer, whose characteristics are shown, would deliver about 49 multiples of rated secondary

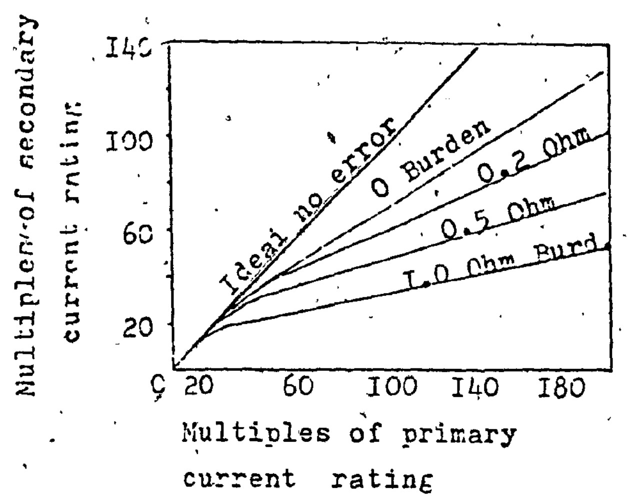


Fig. 26 — Approximate performance of type js-1 400/5 to 800/5 current transformers with varying secondary burdens and primary overcurrents.

current with a primary current input of 100 times its rating and a burden of 0.5 ohms, which would be the approximate burden imposed by an IAC51 relay plus an ammeter and the panel wiring. The burden of relays, meters and instruments is usually given in terms of resistance and impedance with reactance the principal factor.

The effect of current transformer saturation should be considered when making close settings between relays connected to CT's subjected to high values of fault current, and having substantially different ratings and secondary burdens.

To illustrate the effect of CT saturation on phase relays, assume an HFC53 relay set at 16 amperes tap and 4 time dial connected to a CT with a burden of 1.0 ohm and the characteristic shown by Fig. 26. If the current was 100 times the CT primary rating, the secondary output, as shown by the curve of Fig. 26, would be only 32 times normal and the relay would see only ten times its tap setting instead of 32 times based on perfect CT performance.

The effect of CT saturation can be ignored in setting the majority of industrial plant relays, because even though the CT secondary output is drastically reduced, there will still be sufficient current to cause the relays to operate on the flat portion of their curves, so that the reduction in operating time will be negligible.

7.8 ALLOWANCE FOR FAULT CURRENT DECREMENT IN SETTING OVER-CURRENT RELAYS

It is usually permissible on industrial plant systems to ignore the slowing down effect of the fault-current decrement when selecting time current settings for devices that are expected to operate in not over approximately 0.6 seconds after the short circuit occurs. In such cases, the settings are made on the basis that the short circuit current is maintained at the initial symmetrical transient or subtransient current value. depending on the characteristics of the protective device involved. However, those devices having longer time settings, such as the generator and main feeder overcurrent relays, are usually affected sufficiently by the reduction in operating current due to generator decrement.

The problem in setting a generator external-fault backup protection relay is to select time-current setting that will make it selective with the feeder relays, and also enable it to distinguish between fault currents, and permissible high overload currents on the generator. The recommended current setting is between 2.0 and 2.5 per unit of generator full load rating if there is a generator voltage regulator, and 1.5-2.0 per unit if there is no regulator. The reason for the difference in setting is that, as shown in Fig. 27, the short circuit current output of a generator with a voltage regulator decays to a steady-state value of 2-3.5 times normal depending on generator characteristics, but without a regulator, the steady state fault current would be less than twice normal. In the case shown in Fig. 27, the generator fault current decayed to 2.75 times normal with the regulator in use and 1.75 times without the regulator.

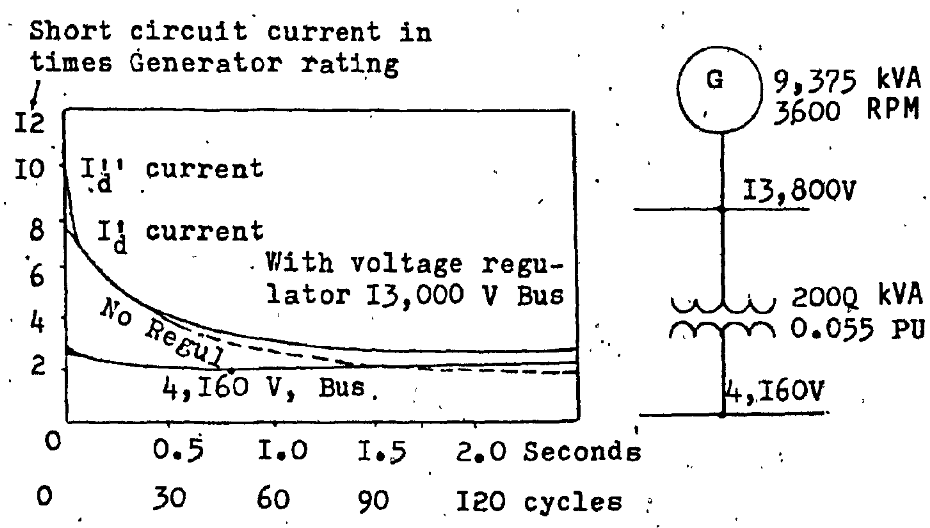


Fig. 27 — Decrement curves of short circuit current from 9375 kva generator for faults on own bus, and on 4160 bus fed through transformer.

7.9 Effect of Wye-Delta and Delta-Wye Connected Transformers on Overcurrent Protective Device Co-Ordination

A wye-delta or delta-wye connected transformer causes a 30 degree shift in the phase relationship of the fault current on opposite sides of it. In the case of three-phase faults, this does not affect overcurrent protective devices, because the currents in the three phases on each side of the transformer are still equal in magnitude. In the case of phase-phase faults, however, the currents on opposite sides of the transformer are in phase, but the current in the faulted phase will be only 0.866 per unit of three phase fault current on that side of the transformer, whereas the current on the unfaulted side will be equal to three phase fault current (1.0 per unit of it) in one phase while only half that much flows in the other two phases. Therefore, the overcurrent device in one phase of the transformer will see 1.0/0.866 = 1.155 per unit of the current that the device in the faulted side sees and, therefore, will operate faster in proportion. This relative decrease in operating time of the device on the unfaulted side may be sufficient to prevent selective operation of devices on opposite sides of the transformer, unless allowance is made for it. As shown in Fig. 17, it is a very simple matter to make the necessary allowance when coordinating a secondary main breaker tripping mechanism with a transformer primary fuse or relay on a radial feed transformer. First, locate the breaker operating band in the normal manner on the basis of its pickup setting, then move it 0.16 per unit in current to the right and coordinate the primary and secondary devices on the basis of the new boundary. The other set of transformer-primary and secondary devices in the faulted phase will see current in the ratio of 0.5/0.866 of three phase fault current. This does not create any problem, however, because the current unbalance speeds up the transformer secondary device with respect to the primary device, and therefore increases the time margin between them.

There is no phase shift in delta-delta or wye-wye transformers. Hence the current in the primary of a radial feed transformer during a secondary line to line fault will be 0.866 per unit of that during a three-phase secondary fault. Therefore, the relays on the primary should be coordinated with those on the secondary fault on the basis of three phase fault current.

CONCLUSION

In this paper the use, selection and application of protective devices in power distribution systems were demonstrated.

The selection of the number of steps, of short circuit protective relaying was determined by many considerations, including degree of desired selectivity, type of equipment to be protected and kind of industrial process.

Specific knowledge of the system and its requirements is needed to make this decision and thus no general rule can be made to cover all situations.

The differential and distance relays are not co-ordinated with the other short circuit protective devices, and their operating time is normally less than 0.1 sec. (6 cycles).

Solid state relay to relay co-ordination time interval is determined by the breaker clearing time plus a safety factor. In applications where electromechanical relays are used, two additional factors must be considered: Overtravel, and back-up relay reset time.

Instantaneous ground fault protective devices used on all secondary feeders are set at minimum. However the primary transformer neutral resistor ground fault protection is a time delay relay in order to co-ordinate with the down-stream ground fault devices.

In general the cost of the protective devices is approximately five to ten percent of the cost of the equipment they would be protecting. This is a small price to pay for protection against serious damage.

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7) Protective Relays Catalogue. by Siemens Canada Ltd.

8) Protective Relays Catalogue. by General Electric Co. Ltd.

9) "Are Your Circuit Breakers Equal to Their Job?", by D.L. Beeman and W.C. Huening - G.E. Publication GER-679-A.

10) ASA Power Circuit Breaker Standards C37,4, C37,5, C37,6 , C37,7, C37,8, C37,9, C37.11 and C37.12.

11) Calculation of Electric Power Systems Short Circuits During the First Few Cycles, AIEE Committee Report. Trans. Power Appl. & Systems. Vol. 75, 1966.

Appendix A

SELECTION AND COORDINATION OF PROTECTIVE DEVICES FOR MARINE GENERATION AND DISTRIBUTION POWER SYSTEMS

Marine Switchboard - General

The marine switchboard is described in this chapter for the control and protection of three (3) 800 kw, 390V, 3-phase, 50 Hz ship's service generators for individual or parallel operation. One 1500 kw shaft generator for single operation and all outgoing sub-circuits at 390V, 3-phase and 220V 3-phase 50 Hz.

Equipment to be built to DNV requirements and other regulations listed on Table 4.

Isolating switches (no current) to be fitted on bus-bars, to separate the generation selections from the essential and important distribution sections. The non-important section to be isolated at the preferential tripping breaker.

All distribution circuits should be protected molded case circuit breakers calibrated for 50°C ambient temperature.

All circuit breakers above 100A size to be plug-in type and to have sufficient interrupting capacity to meet classification rules.

1.1 Ship's Service Switchboard

The equipment included in this switchboard shall incorporate the following for the three main generators 800 kw, 390V, 3 pH, 50 Hz.

1. Main generator air circuit breaker, 43 kA rms, interrupting capacity at 500V, 2000 amp frame, 3-pole, electrically operated, draw out type, complete with LTD, STD and instantaneous overcurrent trips, auxiliary switches and undervoltage trip.
2. Combined overcurrent and reverse power relay.
3. ac ammeter and ammeter selector switch to read the current of each phase of generator.
4. Polyphase wattmeter (red line at 764 kW).
5. Kilowatthour meter.
6. Hour counter.
7. Governor motor control switch with spring returns.
8. Voltmeter and voltmeter selector switch.
9. Circuit breaker control switch.
10. Circuit breaker 'open' indicating light (white) and circuit breaker 'closed' indicating light (green).
11. Contactor, 2-pole, 220V, ac for generator space heater, The contactor would be interlocked with the generator circuit breaker to ensure that the heater is switched 'off', when the generator is in service.
12. Indicating light (blue) to indicate generator space heater is 'on'.
13. Current transformers, potential transformers and control transformers for metering.

1.2 SHAFT GENERATOR

Description generally as for the 3 main generators except:

1. Generator and circuit breaker to be 3000 A frame.
2. No reverse power relay and governor motor control switch to be provided.

1.3 COMMON EQUIPMENT TO SHIP'S SERVICE GENERATORS

1. 3 ground indicating lights and ground switch.
2. 1 ground detection monitoring instrument.
3. 1 preferential tripping breaker.
4. 1 voltage and frequency monitoring instrument.

1.4 SYNCHRONIZING EQUIPMENT

1. 1 synchronoscope.
2. 1 synchronizing switch, for paralleling ship's service generators and shaft driven generator.
3. 2 clear synchronizing lights (dark synchronizing).
4. 2 voltmeters.
5. 2 frequency meters.
6. 1 manual/auto switch for synchronizer.
7. auto synchronizing and load sharing instrument.
8. necessary switches, transformer, control relays, timers, etc.

1.5 SHORE SUPPLY

1. 1 molded case brk. 400A frame. 25 kA rms interrupting capacity at 390 V complete with undervoltage coil and auxiliary switches.
2. 1 ammeter and ammeter selector switch.
3. 1 voltmeter and voltmeter selector switch.
4. 1 polyphase watthour meter.
5. an electrical interlock system between the shore, the shaft, and the diesel generator breakers to be provided so that the shore breaker cannot be closed when any of the shaft or diesel generator breakers are in 'closed' position or vice-versa.

1.6 390 V Distribution

1. Total of 36 molded, case circuit breakers 100 a.f. to 600 a.f. for essential, important and non-important distribution as per attached single line diagrams, Fig. 28.
2. Ammeter and selector switch for single phase reading for essential and important service feeders as per single line diagram.

1.7 220 V Distribution

1. Total of 21 molded case circuit breakers 100 a.f. 22 kA rms interrupting capacity for essential and non-important services.
2. Three ground indication lights and ground switch.
3. Ground detection monitoring instrument.

1.8 Automation of the Electric Power Plant

The production of electric power shall be done by three 800 kW diesel generators capable of functioning in parallel and by one 1500 kW shaft driven generator for single operation, paralleling of shaft generator with diesel generator and vice-versa to be possible for a very short period of time to avoid black-out during transfer time.

Automatic load dependent start and stop of diesel generators and fully automatic synchronizing, parallelling and load sharing to be provided. Automatic start to standby generator to be provided in case of:

a. high voltage
b. low voltage
c. low frequency
d. overload
e. shutdown of working generators

Autostart of two generators to be provided in case of failure of the shaft generator.

Manual start stop shall also be possible from electrical control room during normal operation or locally at the engine in emergency.

Interlocking scheme to be provied so that the bow thruster operation will only be possible when the three diesel generators run in parallel.

Preferential tripping circuit to be incorporated in the system to prevent overloading of generators in case of failure of a paralleling unit or of the shaft generator.

2. PROTECTION PRACTICE FOR MARINE EQUIPMENT

The same protection principle discussed in the previous chapters of this paper are also applied to several electrical equipment used in a marine switchboard. In IEC publication 144, of August 1970, Section DIN-40050, Sheet 1, indicates the degree of protection for marine equipment.

Table 4, following, gives the minimum degree of protection for some marine classification societies.

Marine Classification Societies	Country	Equipment to be installed	Type of Equipment: Switch-Boards	Measur. Instrum.	SWGR & Control Gear	Transformers
ABS	USA	In service, engine and boiler rooms, in steering gear compartment.	IP 12	IP 23	IP 23 IP 12[1]	IP 13
BY	France	On deck, in open control stations	IP 56[2]	IP 56	IP 56	-
GL	W. Germ.					
LRS	United Kingdom	In the wheelhouse	IP 23	-	IP 23	-
NV	Norway	In the radio and chart room	IP 23	-	-	-
PRS	Poland					
RINa	Italy	In the crew's quarters	IP 23	-	-	-
USSR	USSR	In sanitary rooms, in the galley and store rooms	IP 44	-	-	IP 44

Table 4 — Minimum degree of protection for marine equipment.

[1]For items developing a large amount of heat.

[2]Waterproof distribution boxes.

2.1 OVERPOWER AND UNDERPOWER PROTECTION

Occasionally, it is necessary to limit the amount of power sent over a line in a particular section.

Such a need arises, for example, in the ship's generating station having it own local load. The generators have enough capacity to supply the ship load when the generators run in parallel. In case of failure of a paralleled unit or of the emergency generator an overpower relay is used to trip the preferential tripping breaker to prevent overloading the generator(s). An underpower relay may be used, to disconnect one or more generators if the load falls and remain below a given value.

3. APPLICATION OF PROTECTIVE DEVICES FOR ac GENERATORS

This section covers the application of protective devices for the protection of ship's service generators. Relay protection for generators varies widely depending on many factors. The protective devices discussed in this section are recommended as standard equipment for the rating and class of generators listed on the single line diagrams.

3.1 OVERSPEED

Overspeed protection is recommended for all prime mover driven generators. However, such protection is usually part of the prime mover or its speed governor. It shuts down the prime mover and also disconnects the generator from the ac system.

Opening the generator breaker prevents overfrequency operation of load connected to the system and prevents possible injury to the prime mover due to its being motorized by the generator on power taken from the system.

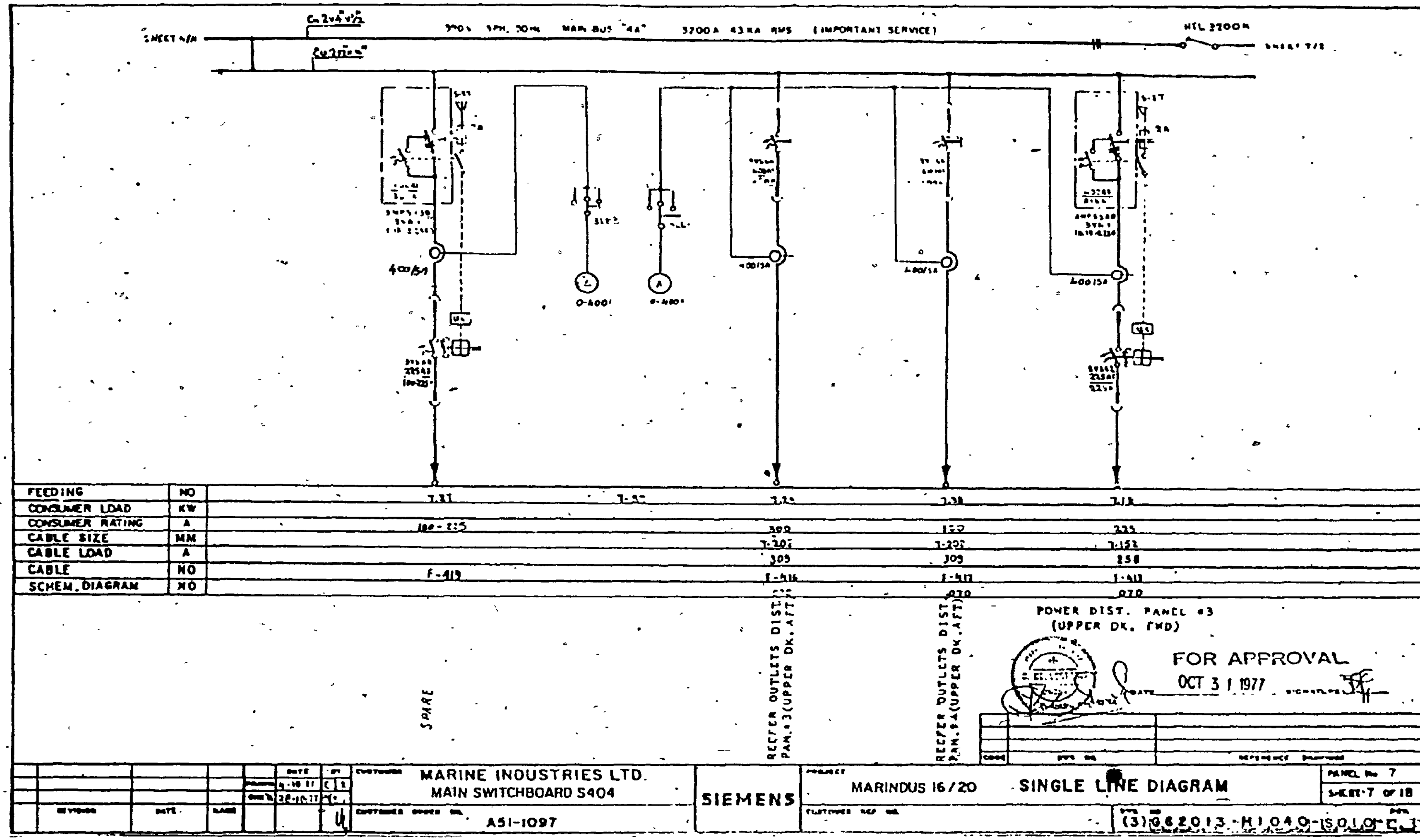

Fig. 28 — Typical single line diagram for 390V distribution of marine main switchboard 5404.

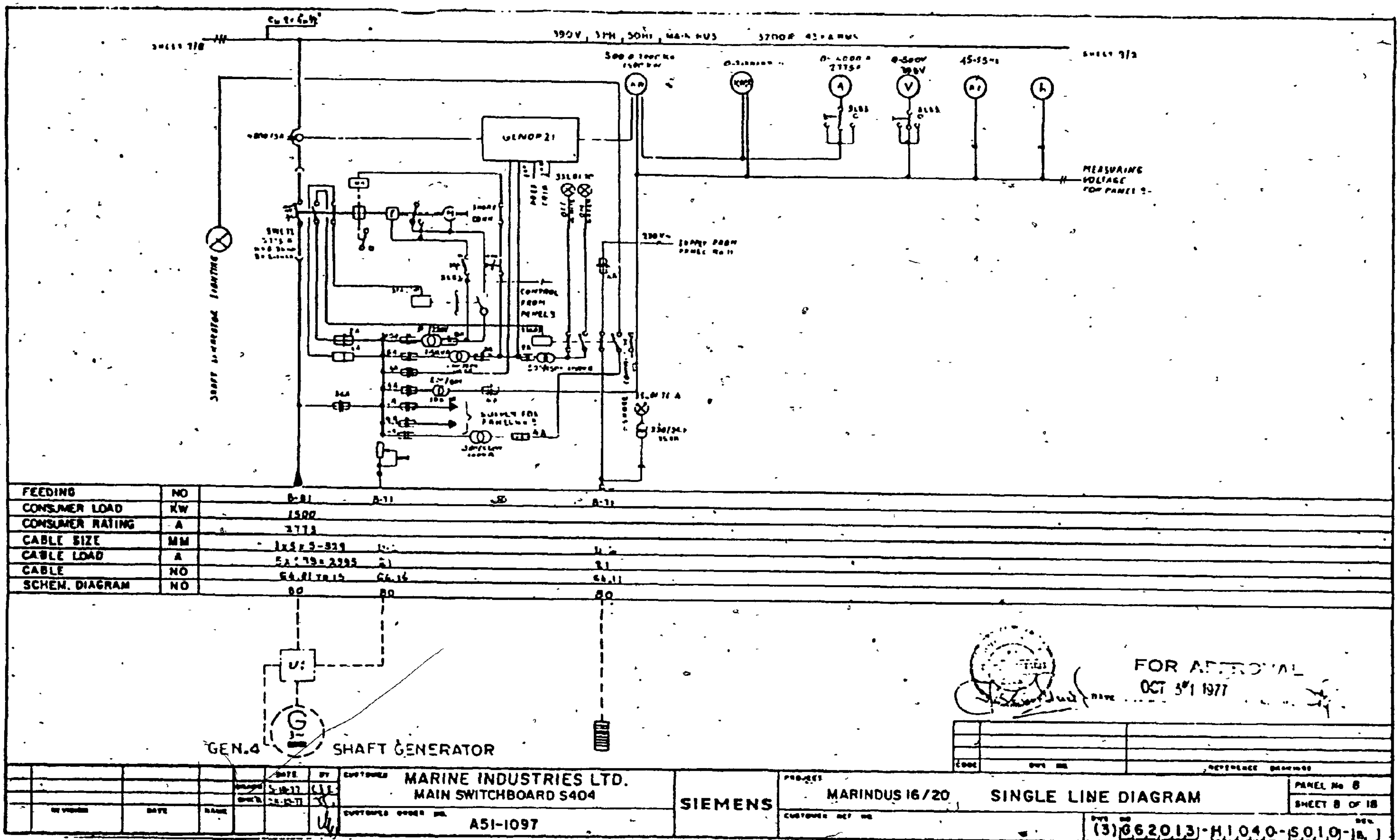

Fig. 29 — Typical single line diagram of shaft generator.

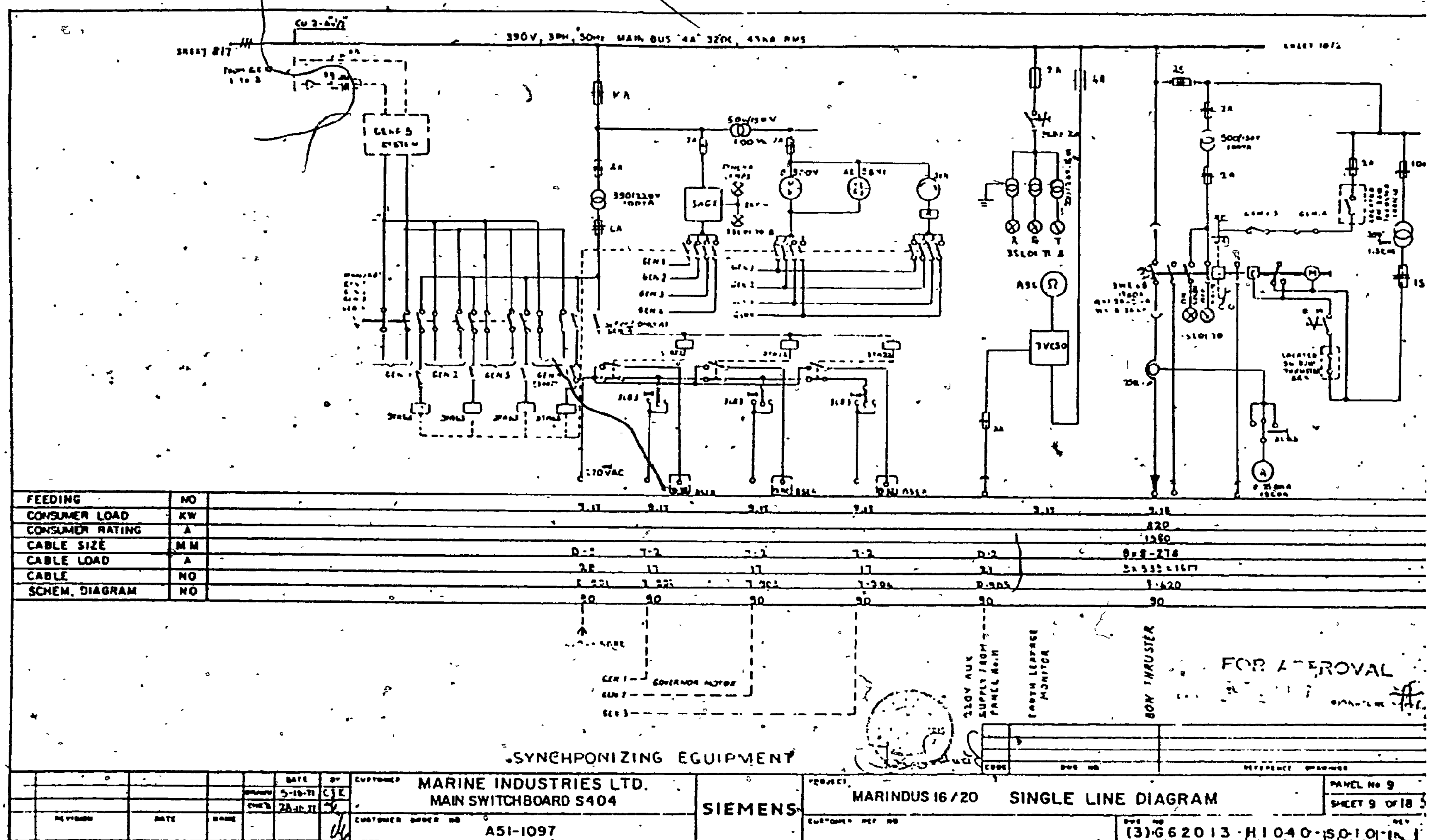

Fig. 30 — Typical single line diagram of synchronizing equipment.

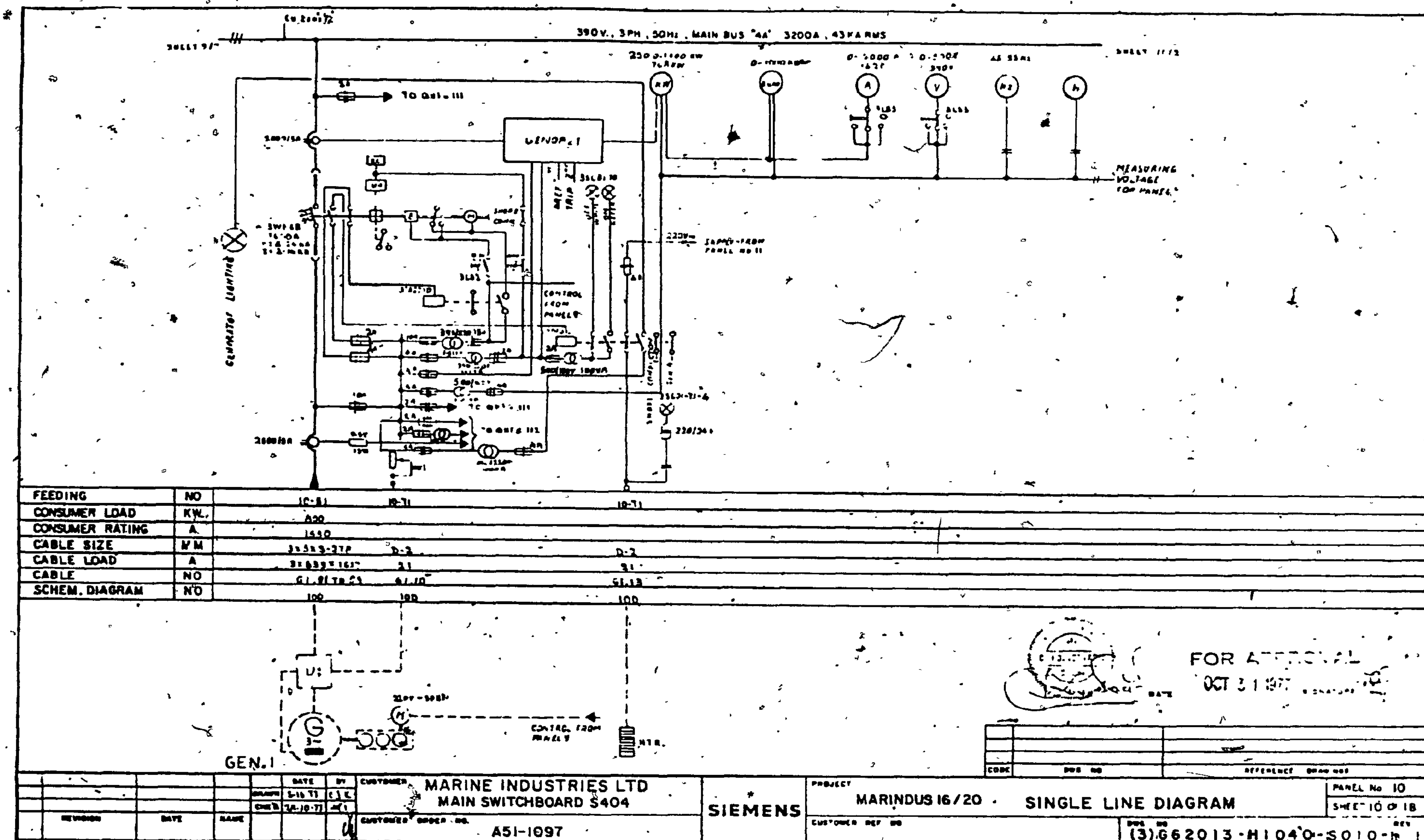

Fig. 31 — Typical single line diagram of ship service generator 1-3.

3.2 AUTOMATIC GENERATING STATION

Figs. 29-31 of the single line diagrams shows the equipment required for manual operation of the three diesel generators and one shaft alternator. For automatic generating stations we use the same equipment as attended stations but have the following additional units for auto-synchronism, speed machine, load sharing, automatic start and stop, and emergency shutdown devices.

3.2.1 TRANSFORMER UNIT QHFG 112.

This unit is an adaption unit between the synchronizing and load sharing unit QHFG 102. It enables direct connection to the generator and main busbars, giving voltage supply and reference voltages for load measuring. The presence of this voltage is checked by one relay giving an internal alarm to the central unit. The two transformers enable direct connections to the generator and main bus bar.

3.2.2 SYNCHRONIZING AND LOAD SHARING UNIT QWFG 102.

In combination with the transformer unit QHFG 112, the following functions are provided:

1. Synchronizing of the generators with the main bus-bars, i.e., bringing the generator voltage in phase with the main bus bar voltage.
2. Load sharing between connected generators.
3. Frequency sustentation, keeping the frequency constant independent of the load.
4. Overload alarm with an opening contact function intended for the general alarm system. The output stage is designed for a speed-setting motor on an integrating governor.

The output signal is on-off, parallel to the manual increase-decrease switch. Power supply is taken from the three-phase generator via transformer unit QHFG 112.

3.2.3 BASIC UNIT QHFG 101

The basic unit has the following functions:

1. Start and stop program.
2. Manual start and stop.
3. Start and connection of diesel generator on the occurrence of a black-out.
4. Monitoring of eight channels programmable for external sensors or internal circuits for indication of:

   4.1 starting failure
   4.2 synchronizing failure
   4.3 overspeed
   4.4 low frequency
   4.5 high voltage
   4.6 low voltage
   4.7 prelubrication failure
   4.8 other fault (only for external sensor)

   All channels are programmable for critical (direct stop) or no critical function and individual delay 0-15 sec. There are three potential free contacts intended for the general alarm system with the following functions:

   - opens at initiated alarm.
   - opens at initiated internal alarm.
   - opens at running engine.

5. Prelubrication system programmable for intermittent 5 min/hour or continuous service when the engine is not running.
6. Synchronizer, giving closing order to the generator circuit breaker when frequency and phase conditions are fulfilled. The synchronizer can also be activated via an external contact.

The output control stages have the following functions:

6.1 Intermittent activation of the starting air valve until the ignition speed has been exceeded.

6.2 Activation of pre-excitation at start until voltage has been obtained.

6.3 Activation of fuel limitation program at start until normal speed has been reached.

6.4 Tripping of circuit breaker when an order is issued.

6.5 Activation of the stop solenoid when a stop order is issued.

6.6 Closing of the circuit breaker by the synchronizer or on the occurrence of a black out.

6.7 Activation of prelubrication program.

3.2.4 RELAY UNIT QHFG 111.

The basic unit QHFG 101 has seven output stages capable of driving a load of 0.3A at 24V. Most control devices required more current or different voltages. The relay unit QHFG 111 has eight 24V DC relays and two transformers. The relay contacts are rated 250V, 5A and are provided with extinguishing devices. For normal application the control valves for starting and stopping will be supplied by a separate 24V D.C.

3.2.5 CENTRAL UNIT QHFG 104.

The load of each generator is measured in the QHFG 102 unit as described on paragraph 3.2. These individual signals are added in the central unit and the sum gives information about the load on the main bus bar. Adjustable level detectors determine at which busbar load a generator shall start or stop. According to the starting sequence, selected with push buttons at the front start and stop orders are distributed to the QHFG 101 units.

These orders are delayed one minute in order to prevent actions initiated by temporary load variations. The delay will be bypassed when a fault occurs on a running set, overload is detected or a controlled load is requested.

The unit also determines whether or not the number of connected sets is sufficient to cover the required load under normal conditions.

In this case a signal to the QHFG 101 unit will permit a set with a noncritical fault to be disconnected and stopped. This signal will also permit a requested controlled load to be connected. In the central unit the loads of the connected sets are added and thus the total load of the main busbar is known. Start and stop orders are determined by means of level detectors measuring on that total load.

In the case of three sets the level detector for start of the second set may be adjusted to a load corresponding to 80% of the first set. Then there is 20% in reserve until overload. Assuming that 20% reserve is suitable for this plant, then start of the third set will be adjusted to 180% or 90% on each of the connected sets.

Another assumption may be that the load normally fluctuates with 20% of one generator capacity. Then the stop levels can be adjusted to 60% and 160% respectively. After executing these stop orders the load of the remaining sets will be 60% and 80% indicating a profitable utilization of the plant.

The sets of a ship can be rated differently which is of no consequence but in the following respects:

— the power reserve in kw may differ according to the sequence and the connected sets.

— The setting of the heavy load control has to be calculated on the basis of the lowest rated set..

The following Figs. 32-34 show the interconnection of the equipment described in paragraph 3.2 as well as start-stop levels of load variation.

3.3 Motoring of Prime-Mover by Its Generator

Anti-motoring protection is required on all steam and gas-turbine driven generators and internal-combustion engine driven generators. The Genop-21 senses the reverse power in one phase and emits selective tripping commands when the set limits are exceeded, thus disconnecting the generator.

The reverse power monitoring is achieved by means of a converted d.c. current proportional to voltage, which is amplified and evaluated by a limit monitor. The associated potentiometer is adjustable from 1 to 20% reverse power, refered to 5A respectively, 1 A active current.

The output signal of the limit monitor, which is indicated by a light-emitter diode, is forwarded to an output relay through a time delay unit (adjustable from 1 to 5 sec) thus tripping the generator breaker. Auxiliary relays with floating throw contacts are coupled to the output signals for signalling and tripping.

3.4 Generator Overload Protection

The Genop 21 is an electronic device of high accuracy for the thermal protection of three phase generators. It senses the generator current in all three phases, and emits selective tripping commands when the set limits are exceeded, thus disconnecting —

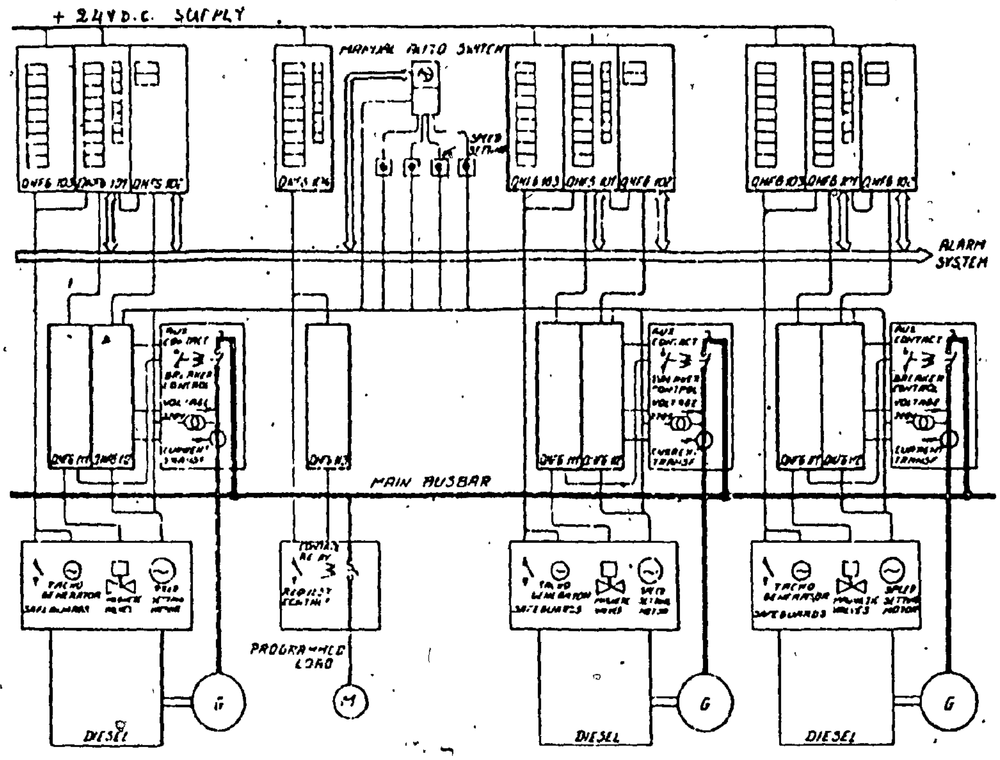

Fig. 32 — Generator lay-out of the GENA-S automatic control system for the three service generators.

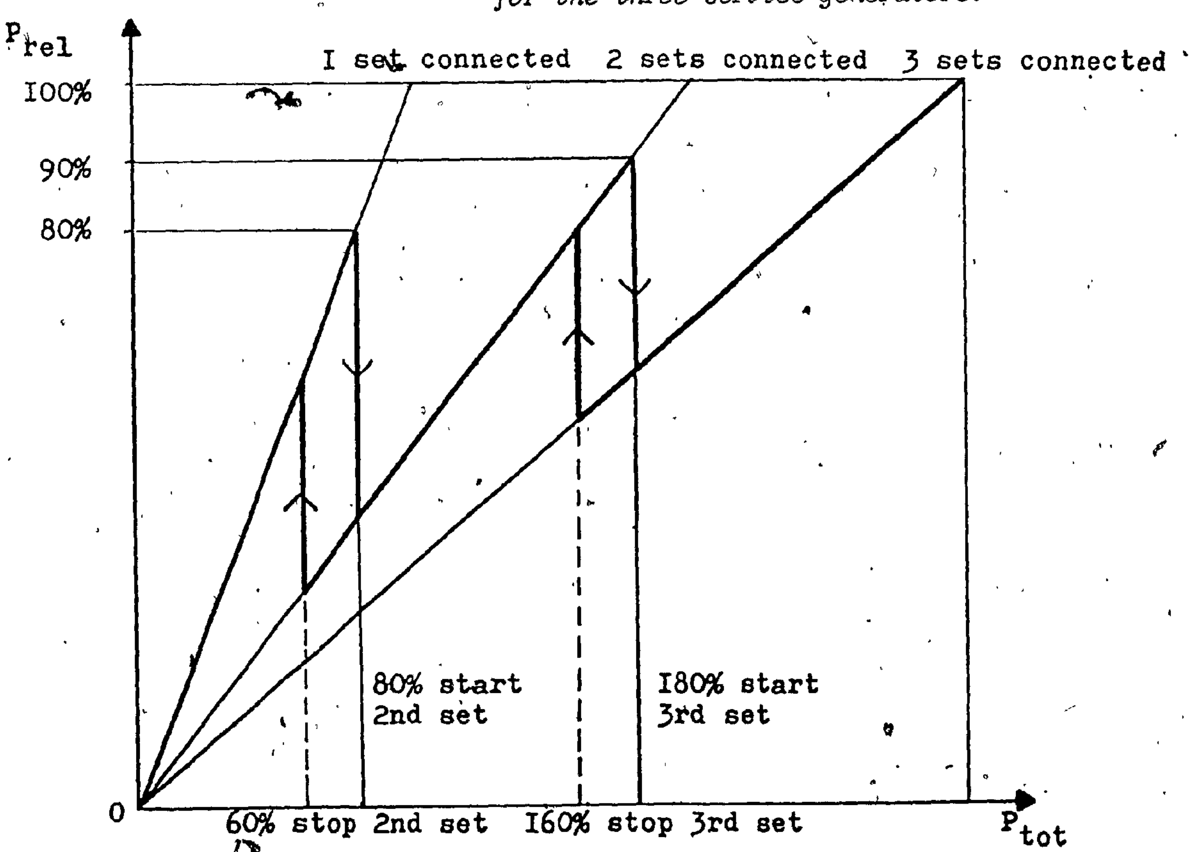

Fig. 33 — Start and stop levels of load variations.

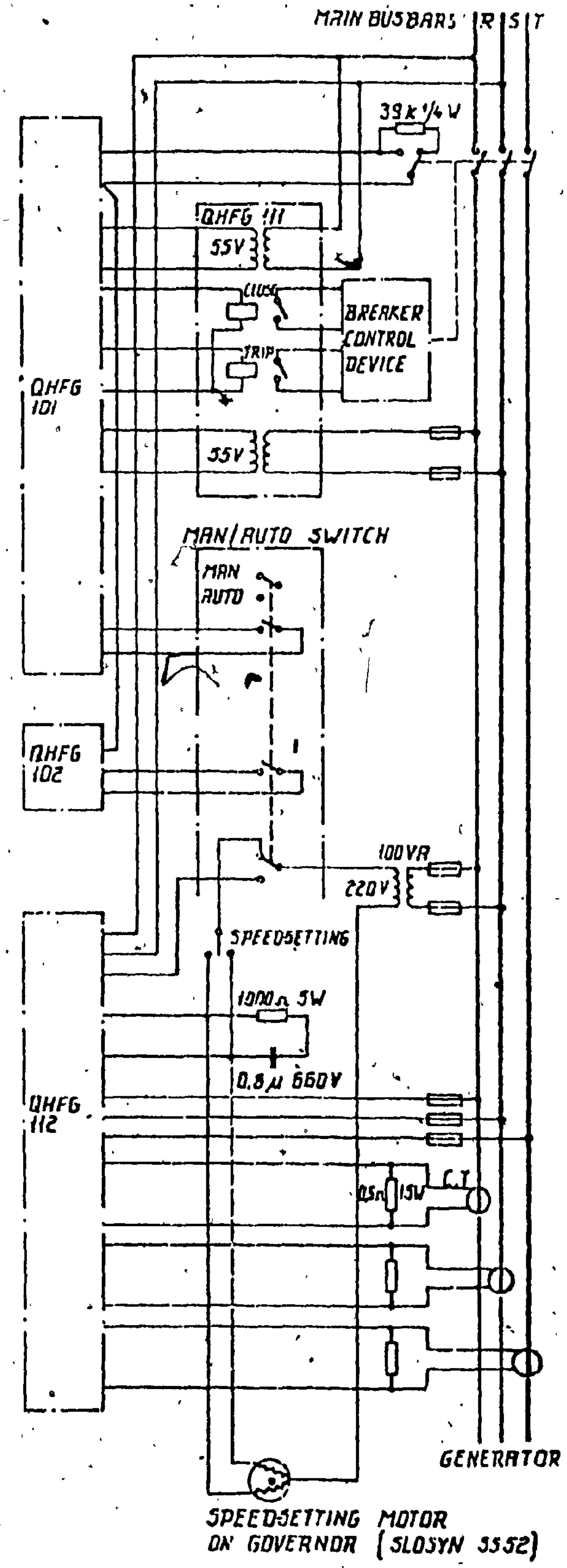

Fig. 34 — Connections in main switchboard.

1) The non-important load in two groups.

2) The generator.

The terminals provided for overcurrent signals can also be used for giving starting signals to another generator set in automatically controlled marine power supply plants.

The instrument consists of three current steps I_1, I_2, I_3 each adjustable from 2 to 7A respectively and are converted into d.c. voltage proportional to the current. The highest of the three voltages is fed to the differential limit monitors. These compare the d.c. voltage from the current sensor with the rated value. As soon as the limit value is exceeded, the respective light-emitting diode lights up. Simultaneously three adjustable time relays T_1, T_2, and T_3 are fed, which then give a signal to an output relay after the delay has elapsed. If the current drops back below the limit while the delay time is elapsing, no signal is given to the output relay. During instantaneous response of the higher current steps I_2 and I_3, the time delay of the appropriate lower current steps I_1 and I_2 is reduced to 5 sec. and the applicable output signal is given correspondingly sooner.

3.5 Ground-Leakage Monitor

Non-grounded a.c. systems of more than 43V must incorporate facilities for monitoring the insulation resistance.

The ground-leakage monitor, 7VC50 on Fig. 30 both measures and monitors the insulation resistance of the ship's electrical supply system. Because the entire shipp's supply system has to be monitored continuously, the 390V and 220V network have its own ground leakage monitor.

The monitor is connected to the ship's supply system via a transformer incorporated in the unit and monitored by the unit. The supply tapped off from the transformer is rectified, smoothed and stabilized to 36V.

The measuring circuit is connected to one phase of the network to be monitored, and to ground or to the ship's hull. The circuit is closed via the insulation resistance of the network. The insulation resistance is steplessly adjustable with calibrated position 2.5, 25 and 250 kΩ. If the resistance drops below the preset level, an output relay picks up. The change-over contact of this relay can be used for visual or audible signalling.

A light emitting diode indicates the fact that the monitor is ready for service and also that the resistance level is above the preset value. In the event of the supply failing or the insulation resistance dropping below the setting, a signal is initiated by the output relay as described above. A separate measuring instrument, which is calibrated in KΩ between 0 and infinity, permits the insulation resistance of the particular network to be monitored continuously.

3.6 General Comments

The short circuit protective devices discussed in Chapter 1 through Chapter 7, provide fast, sensitive, and inherently selective protection for transformers, motors and generators for various types of faults in industrial power plants. The relative merits of the different protective devices and their method of operation are discussed at length in these chapters. Hence, this discussion is avoided here since many of these protective devices are applied to marine generation and distribution systems.

In Appendix A, we briefly discussed some special applications of protective devices designed to meet the requirements for marine application such as the GENA-S power plant control system. The GENA-S system is designed to meet the special requirements for marine applications with regard to necessary functions and environmental conditions.

The GENA-S system offers a number of combinations, from a simple automatic standby system to a complete control system for up to four generator sets, of which one may be a turbo generator set.

The system is designed to meet the requirements of the classification socieites listed in Table 4.

Appendix B

ANSI Protective Device Designations[18]

1. *Master Element* is the initiating device, such as a control switch, voltage relay, float switch, etc. which serves either directly or through such permissive devices as protective and time-delay relays to place an equipment in or out of operation.

2. *Time-Delay Starting or Closing Relay* is a device that functions to give a desired amount of time delay before or after any point of operation in a switching sequence or protective relay system, except as specifically provided by device functions 48, 62, and 79.

3. *Checking or Interlocking Relay* is a relay that operates in response to the position of a number of other devices (or to a number of predetermined conditions) in an equipment, to allow an operating sequence to proceed, or to stop, or to provide a check of the position of these devices or of these conditions for any purpose.

4. *Master Contactor* is a device, generally controlled by device function 1 or the equivalent and the required permissive and protective devices, that serves to make and break the necesssary control circuits to place an equipment into operation under the desired conditions and to take it out of operation under other or abnormal conditions.

5. *Stopping Device* is a control device used primarily to shut down an equipment and hold it out of operation. [This device may be manually or electrically actuated, but excludes the function of electrical lockout (see device function 86) on abnormal conditions.]

6. *Starting Circuit Breaker* is a device whose principal function is to connect a machine to its source of starting voltage.

7. *Anode Circuit Breaker* is a device used in the anode circuits of a power rectifier for the primary purpose of interrupting the rectifier circuit if an arc-back should occur.

8. *Control Power Disconnecting Device* is a disconnecting device, such as a knife switch, circuit breaker, or pull-out fuse block, used for the purpose of respectively connecting and disconnecting the source of control power to and from the control bus or equipment.

NOTE: Control power is considered to include auxiliary power which supplies such apparatus as small motors and heaters.

9. *Reversing Device* is a device that is used for the purpose of reversing a machine field or for performing any other reversing functions.

10. *Unit Sequence Switch* is a switch that is used to change the sequence in which units may be placed in and out of service in multiple-unit equipments.

11. Reserved for future application.

12. *Over-Speed Device* is usually a direct-connected speed switch which functions on machine overspeed.

13. *Synchronous-Speed Device* is a device such as a centrifugal-speed switch, a slip-frequency relay, a voltage relay, an under-current relay, or any type of device that operates at approximately the synchronous speed of a machine.

14. *Under-Speed Device* is a device that functions when the speed of a machine falls below a predetermined value.

15. *Speed or Frequency Matching Device* is a device that functions to match and hold the speed or the frequency of a machine or of a

[18] From ANSI C37.2-1970, Manual and Automatic Station Control, Supervisory, and Associated Telemetering Equipments

system equal to, or approximately equal to, that of another machine, source, or system.

16. Reserved for future application.

17. *Shunting or Discharge Switch* is a switch that serves to open or to close a shunting circuit around any piece of apparatus (except a resistor), such as a machine field, a machine armature, a capacitor, or a reactor.

NOTE: This excludes devices that perform such shunting operations as may be necessary in the process of starting a machine by devices 6 or 42, or their equivalent, and also excludes device function 73 that serves for the switching of resistors

18. *Accelerating or Decelerating Device* is a device that is used to close or to cause the closing of circuits which are used to increase or decrease the speed of a machine.

19. *Starting-to-Running Transition Contactor* is a device that operates to initiate or cause the automatic transfer of a machine from the starting to the running power connection.

20. *Electrically Operated Valve* is an electrically operated, controlled or monitored valve used in a fluid line.

NOTE: The function of the valve may be indicated by the use of the suffixes in Section 2-9.4.

21. *Distance Relay* is a relay that functions when the circuit admittance, impedance, or reactance increases or decreases beyond predetermined limits.

22. *Equalizer Circuit Breaker* is a breaker that serves to control or to make and break the equalizer or the current-balancing connections for a machine field, or for regulating equipment, in a multiple-unit installation.

23. *Temperature Control Device* is a device that functions to raise or lower the temperature of a machine or other apparatus, or of any medium, when its temperature falls below, or rises above, a predetermined value.

NOTE: An example is a thermostat that switches on a space heater in a switchgear assembly when the temperature falls to a desired value as distinguished from a device that is used to provide automatic temperature regulation between close limits and would be designated as device function 90T.

24. Reserved for future application.

25. *Synchronizing or Synchronism-Check Device* is a device that operates when two ac circuits are within the desired limits of frequency, phase angle, or voltage, to permit or to cause the paralleling of these two circuits.

26. *Apparatus Thermal Device* is a device that functions when the temperature of the shunt field or the amortisseur winding of a machine, or that of a load limiting or load shifting resistor or of a liquid or other medium, exceeds a predetermined value; or if the temperature of the protected apparatus, such as a power rectifier, or of any medium decreases below a predetermined value.

27. *Undervoltage Relay* is a relay that functions on a given value of undervoltage.

28. *Flame Detector* is a device that monitors the presence of the pilot or main flame in such apparatus as a gas turbine or a steam boiler.

29. *Isolating Contactor* is a device that is used expressly for disconnecting one circuit from another for the purposes of emergency operation, maintenance, or test.

30. *Annunciator Relay* is a nonautomatically reset device that gives a number of separate visual indications upon the functioning of protective devices, and which may also be arranged to perform a lockout function.

31. *Separate Excitation Device* is a device that connects a circuit, such as the shunt field of a synchronous converter, to a source of separate excitation during the starting sequence; or one that energizes the excitation and ignition circuits of a power rectifier.

32. *Directional Power Relay* is a device that functions on a desired value of power flow in a given direction or upon reverse power resulting from arc-back in the anode or cathode circuits of a power rectifier.

33. *Position Switch* is a switch that makes or breaks contact when the main device or piece of apparatus which has no device function number reaches a given position.

34. *Master Sequence Device* is a device such as a motor-operated multi-contact switch, or the equivalent, or a programming device, such as a computer, that establishes or determines the operating sequence of the major devices in an equipment during starting and stopping or during other sequential switching operations.

35. *Brush-Operating or Slip-Ring Short-Circuiting Device* is a device for raising, lowering, or shifting the brushes of a machine, or for short-circuiting its slip rings, or for engaging or disengaging the contacts of a mechanical rectifier.

36. *Polarity or Polarizing Voltage Device* is a device that operates, or permits the oper-

ation of another device on a predetermined polarity only, or verifies the presence of a polarizing voltage in an equipment.

37. *Undercurrent or Underpower Relay* is a relay that functions when the current or power flow decreases below a predetermined value.

38. *Bearing Protective Device* is a device that functions on excessive bearing temperature, or on other abnormal mechanical conditions associated with the bearing, such as undue wear, which may eventually result in excessive bearing temperature or failure.

39. *Mechanical Condition Monitor* is a device that functions upon the occurrence of an abnormal mechanical condition (except that associated with bearings as covered under device function 38), such as excessive vibration, eccentricity, expansion, shock, tilting, or seal failure.

40. *Field Relay* is a relay that functions on a given or abnormally low value or failure of machine field current, or on an excessive value of the reactive component of armature current in an ac machine indicating abnormally low field excitation.

41. *Field Circuit Breaker* is a device that functions to apply or remove the field excitation of a machine.

42. *Running Circuit Breaker* is a device whose principal function is to connect a machine to its source of running or operating voltage. This function may also be used for a device, such as a contactor, that is used in series with a circuit breaker or other fault protecting means, primarily for frequent opening and closing of the circuit.

43. *Manual Transfer or Selector Device* is a manually operated device that transfers the control circuits in order to modify the plan of operation of the switching equipment or of some of the devices.

44. *Unit Sequence Starting Relay* is a relay that functions to start the next available unit in a multiple-unit equipment upon the failure or nonavailability of the normally preceding unit.

45. *Atmospheric Condition Monitor* is a device that functions upon the occurrence of an abnormal atmospheric condition, such as damaging fumes, explosive mixtures, smoke, or fire.

46. *Reverse-Phase or Phase-Balance Current Relay* is a relay that functions when the polyphase currents are of reverse-phase sequence, or when the polyphase currents are unbalanced or contain negative phase-sequence components above a given amount.

47. *Phase-Sequence Voltage Relay* is a relay that functions upon a predetermined value of polyphase voltage in the desired phase sequence.

48. *Incomplete Sequence Relay* is a relay that generally returns the equipment to the normal, or off, position and locks it out if the normal starting, operating, or stopping sequence is not properly completed within a predetermined time. If the device is used for alarm purposes only, it should preferably be designated as 48A (alarm).

49. *Machine or Transformer Thermal Relay* is a relay that functions when the temperature of a machine armature or other load-carrying winding or element of a machine or the temperature of a power rectifier or power transformer (including a power rectifier transformer) exceeds a predetermined value.

50. *Instantaneous Overcurrent or Rate-of-Rise Relay* is a relay that functions instantaneously on an excessive value of current or on an excessive rate of current rise, thus indicating a fault in the apparatus or circuit being protected.

51. *AC Time Overcurrent Relay* is a relay with either a definite or inverse time characteristic that functions when the current in an ac circuit exceeds a predetermined value.

52. *AC Circuit Breaker* is a device that is used to close and interrupt an ac power circuit under normal conditions or to interrupt this circuit under fault or emergency conditions.

53. *Exciter or DC Generator Relay* is a relay that forces the dc machine field excitation to build up during starting or which functions when the machine voltage has built up to a given value.

54. Reserved for future application.

55. *Power Factor Relay* is a relay that operates when the power factor in an ac circuit rises above or falls below a predetermined value.

56. *Field Application Relay* is a relay that automatically controls the application of the field excitation to an ac motor at some predetermined point in the slip cycle.

57. *Short-Circuiting or Grounding Device* is a primary circuit switching device that functions to short-circuit or to ground a circuit in response to automatic or manual means.

58. *Rectification Failure Relay* is a device that functions if one or more anodes of a power rectifier fail to fire, or to detect an arc-back, or on failure of a diode to conduct or block properly.

59. *Overvoltage Relay* is a relay that functions on a given value of overvoltage.

60. *Voltage or Current Balance Relay* is a relay that operates on a given difference in voltage, or current input or output, of two circuits.

61. Reserved for future application.

62. *Time-Delay Stopping or Opening Relay* is a time-delay relay that serves in conjunction with the device that initiates the shutdown, stopping, or opening operation in an automatic sequence or protective relay system.

63. *Pressure Switch* is a switch which operates on given values, or on a given rate of change, of pressure.

64. *Ground Protective Relay* is a relay that functions on failure of the insulation of a machine, transformer, or of other apparatus to ground, or on flashover of a dc machine to ground.

NOTE: This function is assigned only to a relay that detects the flow of current from the frame of a machine or enclosing case or structure of a piece of apparatus to ground, or detects a ground on a normally ungrounded winding or circuit. It is not applied to a device connected in the secondary circuit of a current transformer, or in the secondary neutral of current transformers, connected in the power circuit of a normally grounded system.

65. *Governor* is the assembly of fluid, electrical, or mechanical control equipment used for regulating the flow of water, steam, or other medium to the prime mover for such purposes as starting, holding speed or load, or stopping.

66. *Notching or Jogging Device* is a device that functions to allow only a specified number of operations of a given device, or equipment, or a specified number of successive operations within a given time of each other. It is also a device that functions to energize a circuit periodically or for fractions of specified time intervals, or that is used to permit intermittent acceleration or jogging of a machine at low speeds for mechanical positioning.

67. *AC Directional Overcurrent Relay* is a relay that functions on a desired value of ac overcurrent flowing in a predetermined direction.

68. *Blocking Relay* is a relay that initiates a pilot signal for blocking of tripping on external faults in a transmission line or in other apparatus under predetermined conditions, or cooperates with other devices to block tripping or to block reclosing on an out-of-step condition or on power swings.

69. *Permissive Control Device* is generally a two-position, manually-operated switch that, in one position, permits the closing of a circuit breaker, or the placing of an equipment into operation, and in the other position prevents the circuit breaker or the equipment from being operated.

70. *Rheostat* is a variable resistance device used in an electric circuit, which is electrically operated or has other electrical accessories, such as auxiliary, position, or limit switches.

71. *Level Switch* is a switch which operates on given values, or on a given rate of change, of level.

72. *DC Circuit Breaker* is a circuit breaker that is used to close and interrupt a dc power circuit under normal conditions or to interrupt this circuit under fault or emergency conditions.

73. *Load-Resistor Contactor* is a contactor that is used to shunt or insert a step of load limiting, shifting, or indicating resistance in a power circuit, or to switch a space heater in circuit, or to switch a light or regenerative load resistor of a power rectifier or other machine in and out of circuit.

74. *Alarm Relay* is a relay other than an annunciator, as covered under device function 30, that is used to operate, or to operate in connection with, a visual or audible alarm.

75. *Position Changing Mechanism* is a mechanism that is used for moving a main device from one position to another in an equipment; as for example, shifting a removable circuit breaker unit to and from the connected, disconnected, and test positions.

76. *DC Overcurrent Relay* is a relay that functions when the current in a dc circuit exceeds a given value.

77. *Pulse Transmitter* is used to generate and transmit pulses over a telemetering or pilot-wire circuit to the remote indicating or receiving device.