PROTECTION AND COORDINATION OF AUXILIARY SYSTEMS FOR LG-3 POWERHOUSE

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ABSTRACT

PROTECTION AND COORDINATION OF AUXILIARY SYSTEMS FOR LG-3 POWERHOUSE

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Almost any electrical power distribution system will function smoothly under steady-state conditions. A properly designed system, however, will provide protection for all system components under fault conditions while also providing selective fault clearing. The fault conditions should be established and short-circuit calculations must be made for all possible fault points in the system. Based on calculated fault currents, all system protective devices must be applied and coordinated properly to achieve a coordinated power system.

The first part of this report attempts to provide a sufficient coverage of each phase of the subject in order to enable a good understanding of the basic principles. In the second part of the report a real life example is presented as studied by the author.

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INTRODUCTION

1. INTRODUCTION

All power systems, whether they be utility, industrial, commercial, or residential, have the common purpose of providing electric energy to the utilization equipment as safely and as reliably as is economically feasible. The relative importance of economic, reliability, and safety considerations may vary somewhat with the type of system, but all three elements must be taken into consideration in any good system design, and certain minimum safety and reliability requirements must be satisfied.

If the designer needed to consider only normal operation, his task would be relatively easy. He could assume that there would be no equipment failures, no operating mistakes, and no "acts of God" such as floods, fires, or lightning strokes. But in practice a design based solely on normal operational requirements would be totally inadequate and would inevitably result in intolerable equipment outages.

The function of system protection and coordination is to minimize damage to the system and its components and to limit the extent and duration of service interruption whenever equipment failure, human error, or "acts of God" occur on any portion of the system. Economic considerations and the choice of system components will determine the degree of system protection and coordination which can be feasibly designed into a system. Failure to design into a system provisions for protection and coordination sufficient to satisfy at least the minimum system safety and reliability requirements will inevitably result in unsatisfactory performance. In the following, the proper selection, application and coordination of that group of components which constitute system protection for industrial plants and commercial establishments is considered.

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FUNDAMENTALS OF A-C SHORT-CIRCUITS

2.1 NATURE OF SHORT-CIRCUIT CURRENTS

Electric power systems are designed to be as fault free as possible through careful system and equipment design, as well as proper installation and maintenance. However, even with these precautions, faults do occur. Some causes are: loose connections; voltage surges; deterioration of insulation; accumulation of moisture, dust and contaminants; the intrusion of metallic or conducting objects, and a large assortment of "undetermined phenomena".

When a short circuit occurs on a power system, several serious and possibly disastrous conditions develop:

1. Short-circuit current flows from various sources to the fault location.

2. At the fault location, arcing and burning can occur.

3. Components carrying the short-circuit currents are subject to thermal and mechanical stresses.

4. System voltage drops in proportion to the magnitude of the short-circuit current. Highest voltage drop occurs at the faulted location.

It is clear from the above that if a protective scheme is to be effective, its protective devices - circuit breakers and fusible switches - must clear the fault, or in other words must interrupt the maximum short-circuit current which can flow for a fault at the device location. This short-circuit current is known as the "available" short-circuit current.

2.2 SOURCES OF SHORT-CIRCUIT CURRENTS

In order to determine the magnitude of short-circuit currents all sources of short-circuit should be considered and the impedance characteristics of these sources should be known.

There are four main sources of short-circuit current:

1. Generators. When a short-circuit occurs on the circuit fed by a generator, the generator continues to produce voltage because the field excitation is maintained and the prime mover (turbine, diesel engine, water wheel, or other) drives the generator at normal speed. The generated voltage produces a short-circuit current of a large magnitude that flows from the generator to the short-circuit location. This flow of short-circuit current would only be limited by the impedance of the generator and the circuit between the generator and the short-circuit location.

2. Synchronous motors. Synchronous motors are constructed much like generators; they have a field which is excited by d.c. current and a stator winding in which a.c. current flows.

They normally draw a.c. power from the line and convert it to mechanical energy. During a system short-circuit, the voltage is reduced and the motor slows down and stops delivering energy to the mechanical load. But the energy stored in the inertia of the load and the rotor drives the synchronous motor, which then acts as generator and delivers short-circuit current for many cycles after the short circuit has occurred.

3. Induction Motors. The field of the induction motor is produced by induction from the stator, rather than from a d.c. winding. As long as voltage is applied to the stator the rotor flux remains normal but if the external source of voltage is suddenly removed, as in the case of a short-circuit, the rotor flux cannot change instantly. Because the rotor flux cannot decay instantly and the stored energy in the inertia of the rotating parts drives the motor, a voltage is generated in the stator winding. This causes current to flow to the short-circuit until the rotor flux decays to zero. Since there is no sustained field current in the rotor to provide flux as in

the case of a synchronous machine, the short-circuit current decays in a few cycles. However this short-circuit current lasts long enough to affect the momementary duty on circuit breakers and the interrupting duty on devices that open within one or two cycles after a short-circuit.

4. Electric Utility Systems. The electric utility system or the supply transformer are often considered a source of short-circuit current. Strictly speaking, this is not correct because the utility system or supply transformer merely delivers the short-circuit current from the generators. Transformers merely change the system voltage and magnitude of current. The short-circuit current delivered by a transformer is determined by its secondary voltage rating and impedance, plus the impedance of the generators and the utility system to the terminals of the transformer and the impedance of the circuit from the transformer secondary terminals to the short-circuit location.

Fig. 2.1 depicts the four basic sources of short-circuit current.

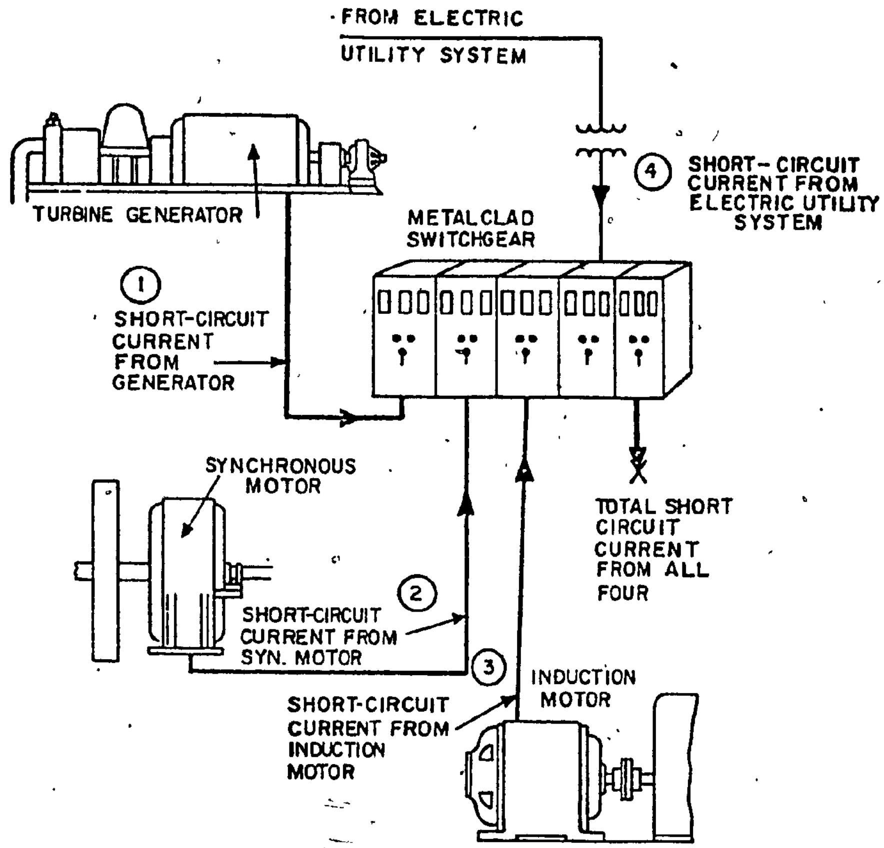


Fig. 2.1 Sources of short-circuit current

2.3 VARIATION OF SHORT-CIRCUIT CURRENT WITH TIME

The impedance of a rotating machine consists primarily of reactance which is not one simple value as for a transformer or a piece of cable, but is complex and variable with time. For example, if a short-circuit is applied to the terminals of a generator, the short-circuit current starts out at a high value and decreases exponentially to a lower steady-state value sometime after the initiation of the fault. Since the field excitation voltage and speed have remained relatively constant within the short interval of time considered, the reactance of the machine may be assumed to have changed with time, to explain the change in the current value.

Expression of such a variable reactance at any instant requires a complicated formula involving time as one of the variables. For simplification, three values of reactance are assigned to generators and motors for the purpose of calculating short-circuit currents at specified times. These values are called the subtransient, transient and synchronous reactances and are described (1) as follows:

1. Subtransient reactance (X''_d) is the apparent reactance of the stator winding at the instant the short-circuit occurs, and it determines the current flow during the first few cycles after the short-circuit.

2. Transient reactance (X'_d) determines the current, following the period when the subtransient reactance is the controlling value; it is effective up to one-half second or longer, depending upon the design of the machine.

3. Synchronous reactance (X_d) determines the current flow after a steady state condition is reached. It is not effective until several seconds after the short-circuit occurs, and thus it is seldom used in calculating fault currents. However it is useful for relay-setting studies.

The same designation as described for a generator is used to express the variable reactance of a synchronous motor. However, numerical values of the three reactances X''_d, X'_d and X_d will often be different for motors than for generators. For the induction motors there is no sustained field current in the rotor to provide flux. Thus the short-circuit current decays in a few cycles and therefore the only reactance assigned to the induction motors is the subtransient reactance X''_d. This value will be about equal to the locked-rotor reactance and thus the initial value of short-circuit current is approximately equal to the locked-rotor starting current.

2.3.1 SYMMETRICAL AND ASYMMETRICAL CURRENTS

The words "symmetrical" and "asymmetrical" describe the shape of the a.c. waves about the zero axis. If the envelopes of the peaks of the current waves are symmetrical about the zero axis, they are called symmetrical current envelopes. If they are not symmetrical about the zero axis, they are called asymmetrical current envelopes.

Most short-circuit currents are asymmetrical during the first few cycles after the short-circuit occurs, but in a few cycles gradually become symmetrical. An oscillogram of a typical short-circuit current is shown in fig. 2.2

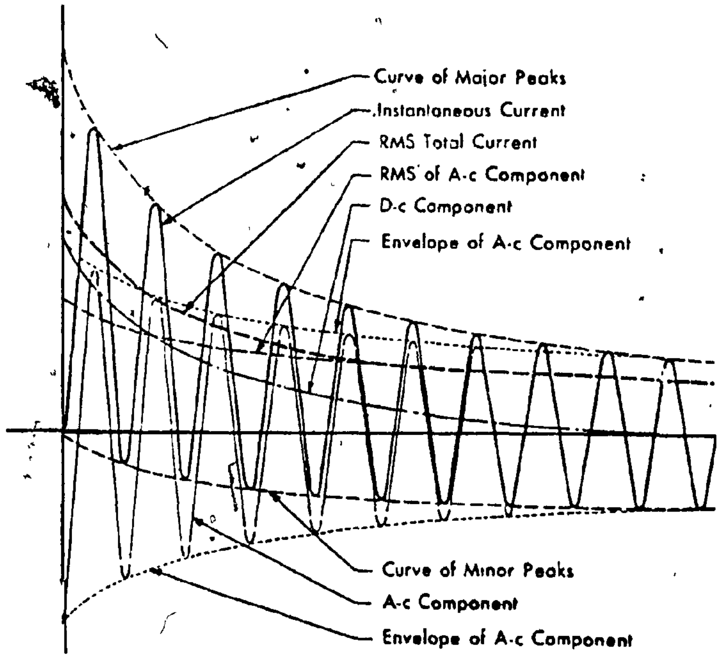


Fig. 2.2 Oscillogram of a typical short-circuit

The power factor of a short-circuit is determined by the series resistance and reactance of the circuit, (from the fault back to and including the source or sources of the short-circuit).

In ordinary power circuits, the resistance of the circuit is low compared with the reactance of the circuit. Therefore, the short-circuit current lags the source voltage by approximately 90 degrees.

If a short-circuit occurs at the peak of the voltage wave in a circuit containing only reactance, the short-circuit current will start at zero and its sine wave, which must be 90°degrees out of phase with the voltage, would be totally symmetrical about the zero axis.

If a short-circuit occurs at the zero point of the voltage wave, the current will start at zero but cannot follow a sine wave symmetrically about the zero axis because the current must lag behind the voltage by 90 degrees. This can happen only if the current is displaced from the zero axis as shown in Fig. 2.3.

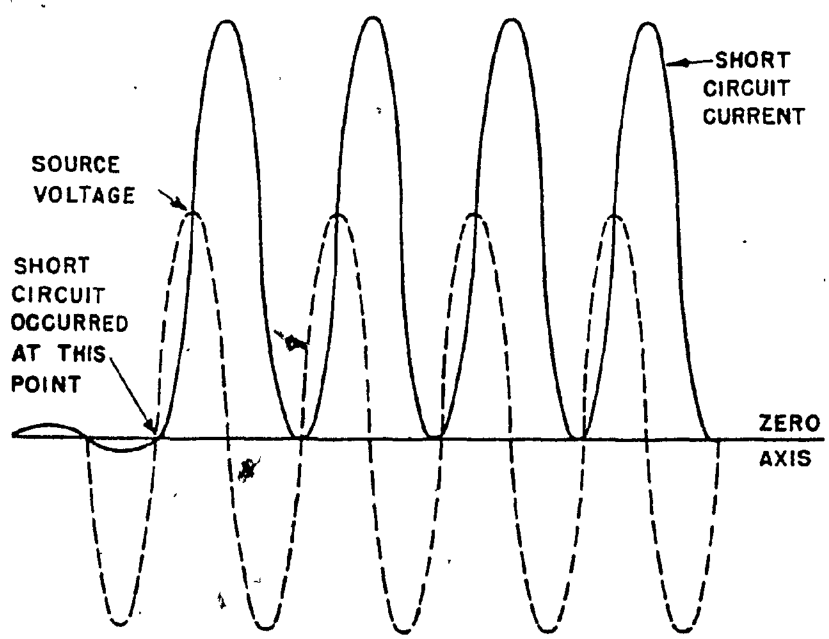


Fig. 2.3 Asymmetrical current and voltage in a zero power-factor circuit.

Specifically a maximum asymmetry (offset from zero axis) will occur at a time angle of $90^{\circ}+\theta$ where tan θ equals the reactance-to-resistance ratio of the circuit. The short-circuit current will be symmetrical when the fault occurs 90° from that point on the voltage wave.

Asymmetrical currents are analyzed in terms of two components, a symmetrical a.c. current and a d.c. component. The sum of the symmetrical alternating current and the direct-current at any instant is equal to the asymmetrical wave at the same instant. This can be observed in Fig. 2.2. It should be understood that the d.c. component referred to here is generated within the a.c. system with no external source of direct current being considered.

Calculation of the precise rms value of an asymmetrical current at any time after the inception of a short-circuit could be very involved. However simplified methods have been involved whereby the d.c. component is accounted for by simple multiplying factors. The multiplying factor converts the rms value of the symmetrical a.c. wave into rms amperes of the asymmetrical wave including a d.c. component. Fig. 2.4 shows the multiplying factors for various X/R ratio.

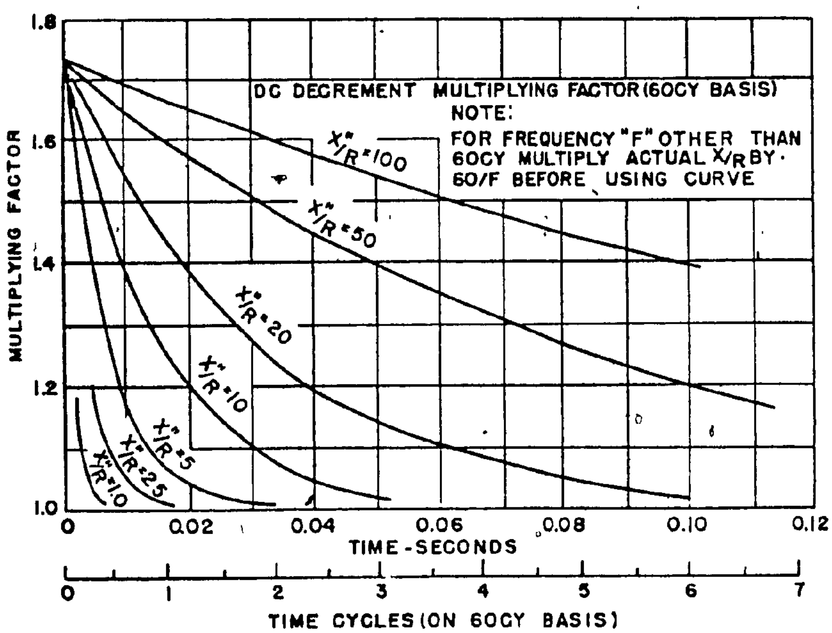


Fig. 2.4 Charts showing multiplying factors to account for decay of d.c. component for various X/R ratio of circuits.

Summarizing we can repeat that the total symmetrical short-circuit current usually has several sources. This is illustrated in fig. 2.5 where it can be seen that the total short-circuit current decays with time (bottom of fig. 2.5).

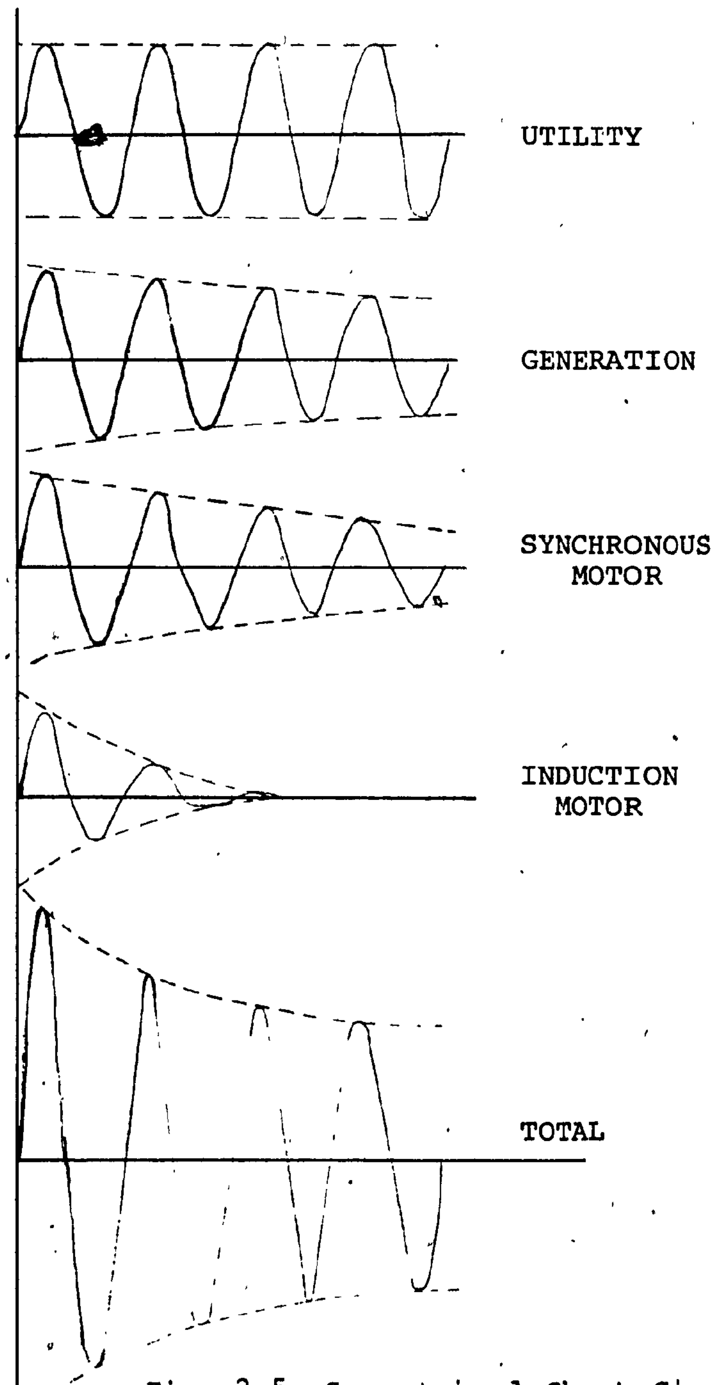


Fig. 2.5 Symmetrical Short-Circuit Currents from Four Sources Combined into Total

It can also be observed that the magnitude of short-circuit current is highest at the first half cycle after short-circuit and is of lower value a few cycles later.

Also the magnitude of the first few cycles of the total symmetrical short-circuit current is further increased by the presence of the d.c. component. This d.c. component offsets the a.c. wave and, therefore, makes it asymmetrical. In all circuits containing resistance, the d.c. component will also decay (to zero) as the energy represented by the d.c. component is dissipated as I^2R loss in the resistance of the circuit. The rate of decay of the d.c. component is a function of the resistance and reactance of the circuit. In practical circuits, the d.c. component decays to zero in one to six cycles.

It is this total asymmetrical short-circuit current, that must be determined for short-circuit protective-device application. The problem of doing this has been simplified by standardized procedures to a point where to determine the rms asymmetrical current one need only divide the line-to-neutral voltage by the proper impedance and then multiply by a proper multiplying factor. A table indicating those multiplying factors is included as table 5.

3

THE DETAILS OF SHORT-CIRCUIT CALCULATIONS

3.1 INTRODUCTION OF FAULT CURRENT CALCULATION PROCEDURE

In most cases where the fault currents are to be determined, the process can be briefly described in five basic steps. Later sections of this chapter will expand on each of the steps, as required, but it is felt that at this point an overview of the complete process would be advantageous.

Step 1: System one-line diagram

The system one-line diagram is fundamental to short-circuit analysis. It should include all significant equipment and components and show their interconnections. A one-line diagram is defined as "a diagram that shows, by means of single lines and graphic symbols, the course of an electric circuit or system of circuits and the component devices or parts used therein".(2)

Step 2: Location of faults

A decision on fault locations and type of short-circuit current calculations should be taken, based on type of equipment being applied. The variation of system operating conditions required to display the most severe duties should be considered. Bus numbers or suitable identification should be assigned to the fault locations.

Step 3: Development of the equivalent circuit (Impedance diagram)

The one-line diagram should be re-drawn but the information for the circuit elements should be converted into equivalent impedances. This circuit should include all sources of short-circuit current. To simplify calculations, many small motors can be grouped and treated as a single impedance.

Step 4: Solving for symmetrical currents

Step 3 should have reduced the complete circuit to a single equivalent impedance (Z) connected to the point of the short-circuit. Thus the current (I) for that point is calculated from Ohm's law: $I = \frac{E}{Z}$. This short-circuit current is the symmetrical a.c. component of the actual short-circuit current that may flow in the circuit.

Step 5: Applying multiplying factors

In step 4 the calculation yields a symmetrical, rms value of fault current. There is, in addition to the symmetrical a.c. component of the current, a d.c. component in the total current wave which produces an offset or asymmetry and decays to zero in a few cycles. This asymmetry is taken into account in the short-circuit current calculation by multiplying calculated symmetrical current by an offset multiplier. Finally, when these currents are calculated, they can be used on time-current co-ordination plots.

3.2 USING THE ONE-LINE DIAGRAM IN FAULT CURRENT CALCULATIONS

Preparation of a one-line diagram is the first step in making a short-circuit and relay co-ordination study. This diagram should show all sources of short-circuit current and other significant circuit elements.
For demonstrating the principles involved a typical system (shown in fig. 3.1) is considered. The following comments can be made to clarify the necessary data elements.

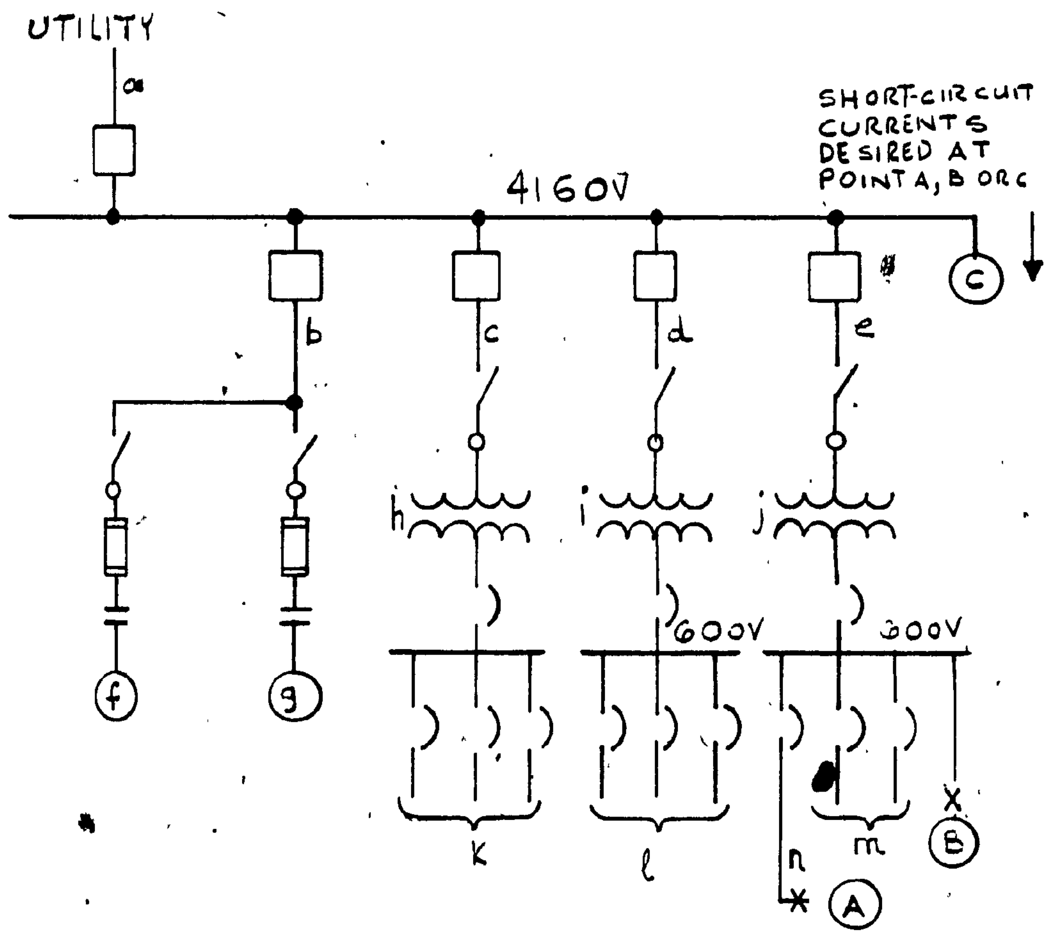


Fig. 3.1 Typical one-line diagram

3.2.1 INCOMING SUPPLY LINES

The most common power supply encountered in co-ordination studies is the electric utility source. Utility system engineers keep accurate records of the short-circuit capability throughout their system. In the absence of specific available short-circuit kVA, the kVA or MVA interrupting rating of the incoming line circuit breaker can be used to establish a conservative value of impedance to represent the utility system in the short-circuit calculation.

3.2.2 GENERATORS

Inspection of generator nameplates should yield the kVA rating of the generator or the kilowatt rating and power factor of the machine. The per unit impedance (X''_d) is not often a part of nameplate data. Knowing the type of machine (wound rotor or salient pole) and rotational speed, typical values of the X''_d reactance can be obtained from available tables (Table 1).[17]

	X''_d	X'_d
Turbine Generators		
2 pole (3600 rpm)	.09	.15
4 pole (1800 rpm)	.15	.23
Salient Pole Generators with damper windings		
12 poles or less (600 rpm or more)	.16	.33
14 poles or more (514 rpm or less)	.21	.33
Synchronous Motors		
6 pole (1200 rpm)	.15	.23
8-14 pole (514 - 900 rpm)	.20	.30
Synchronous Condensers	.24	.37
Synchronous Converters		
600 V direct current	0.20	-
250 V direct current	0.33	-
Individual Induction motors, usually above 600 V	0.17	-
Groups of motors, each less than 50 hp, usually 600 V and below	0.25	-

NOTE: Synchronous motor kVA bases can be found from motor horsepower ratings as follows:

for 0.8 pf motor - kVA base = hp rating
for 1.0 pf motor - kVA base = 0.8 x hp rating.

Table 1. Typical reactance values for Induction and Synchronous machines

3.2.3 INDUCTION AND SYNCHRONOUS MOTORS

As in the case of generators, the X''_d reactance is seldom given on the nameplate. The best way to determine X''_d is to inspect the nameplate for a code letter, horsepower rating, speed and power factor (for synchronous machines). The code letter is defined in the National Electrical Code (Section 430) and a list of code letters is reproduced here as table 2.

Code Letter	Kilovolt-Amperes per Horsepower with Locked Rotor
A	0 - 3.14
B	3.15 - 3.54
C	3.55 - 3.99
D	4.0 - 4.49
E	4.5 - 4.99
F	5.0 - 5.59
G	5.6 - 6.29
H	6.3 - 7.09
J	7.1 - 7.99
K	8.0 - 8.99
L	9.0 - 9.99
M	10.0 - 11.19
N	11.2 - 12.49
P	12.5 - 13.99
R	14.0 - 15.99
S	16.0 - 17.99
T	18.0 - 19.99
U	20.0 - 22.39
V	22.4 - and up

Table 2 Locked Rotor indicating Code Letters

For each code letter there is a corresponding kVA per hp at locked rotor. The reciprocal of this value is X''_d to be used in the short-circuit calculation.

Another way of calculating X''_d is by dividing full load current by locked rotor current.

Finally if none of the above methods can be used, by simply knowing hp, r/min and power factor (if synchronous) X''_d can be determined from table 1.

For the low voltage motors and for short-circuit calculation purposes only, the total connected horsepower on the bus should be considered and the equivalent reactance should be assumed. But for relay co-ordination of all the various motors in the low voltage bus, each motor feeder needs to be identified with its full load and starting current.

3.2.4 REACTORS

Some systems have current limiting reactors for the purpose of reducing short-circuit current levels between two interconnected buses. The impedance information for a current limiting reactor is often a percent voltage drop and a continuous current rating. This information can be used to obtain a system per unit reactance for the one-line impedance diagram. The most useful number on the nameplate is the Ohms per phase of the reactor.

3.2.5 TRANSFORMERS

For transformers, the significant information should include: (1) the high and low voltage ratings of the windings. (2) the percent impedance and (3) the winding connection, all of which can be found on the nameplate. Winding connection means that the high and low voltage windings are connected in wye or delta. If they are in wye, it should be noted if they are solidly grounded, grounded through a resistor, or isolated from ground. (For typical reactances see table 3).

Per Unit Reactance on Transformer kVA Rating *

Primary Voltage Rating	Bank kVA (Three-Phase or 3 Single-Phase) 25-100	100-500	Above-500
2400/4160 V	(.015-.018)	.050	.055
13.8 kV	(.015-.025)	.050	.055
46 kV	-	.060	.065
69 kV	-	.065	.070

* Use manufacturer's specified values if available.

Table 3 Typical Reactances of transformers

3.2.6 CABLES

All points in the system are interconnected by various types of electrical conductors. These may be single-phase or three-phase cables, buses or open wire construction. Often these circuit elements add a significant amount of impedance into the circuit and have a bearing on the short-circuit current delivered to a certain point. The required data are:

(1) the length of the cable circuit;

(2) the type of cable (single or three conductor);

(3) voltage rating;

(4) conductor type and size in MCM or AWG number;

(5) interlocked armor cable, lead sheathed or shielded cable;

For open wire construction the significant parameters are:

(1) the voltage rating of the circuit;

(2) the length of the circuit;

(3) the conductor spacing;

(4) conductor type (copper or aluminum);

(5) size (AWG or MCM).

From this information the resistance and reactance of these interconnecting links can be determined from various tables and charts. See table 4 for typical cable reactances.

AWG or MCM	In Magnetic Duct or Armor						In Nonmagnetic Duct or Armor					
	Nonshielded 600 V & 5 Kv			Shielded 5 Kv & 15 Kv			Nonshielded 600 V & 5 Kv			Shielded 5 Kv & 15 Kv		
	R	X	Z	R	X	Z	R	X	Z	R	X	Z
8	.811	.0577	.813	.811	.0658	.814	.811	.0503	.812	.811	.0574	.813
8 (solid)	.786	.0577	.788	.786	.0658	.789	.786	.0503	.787	.786	.0574	.788
6	.510	.0525	.513	.510	.0610	.514	.510	.0457	.512	.510	.0531	.513
6 (solid)	.496	.0525	.499	.496	.0610	.500	.496	.0457	.498	.496	.0531	.499
4	.321	.0483	.325	.321	.0568	.326	.321	.0422	.324	.321	.0495	.325
4 (solid)	.312	.0483	.316	.312	.0508	.317	.312	.0422	.315	.312	.0495	.316
2	.202	.0448	.207	.202	.0524	.209	.202	.0390	.206	.202	.0457	.207
1	.160	.0436	.166	.160	.0516	.168	.160	.0380	.164	.160	.0450	.166
1/0	.128	.0414	.135	.128	.0486	.137	.127	.0360	.132	.128	.0423	.135
2/0	.102	.0407	.110	.103	.0482	.114	.101	.0353	.107	.102	.0420	.110
3/0	.0805	.0397	.0898	.0814	.0463	.0936	.0766	.0346	.0841	.0805	.0403	.090
4/0	.0640	.0381	.0745	.0650	.0446	.0788	.0633	.0332	.0715	.0640	.0389	.0749
250	.0552	.0379	.0670	.0557	.0436	.0707	.0541	.0330	.0634	.0547	.0380	.0666
300	.0464	.0377	.0598	.0473	.0431	.0640	.0451	.0329	.0559	.0460	.0376	.0596
350	.0378	.0373	.0539	.0386	.0427	.0576	.0368	.0328	.0492	.0375	.0375	.0530
400	.0356	.0371	.0514	.0362	.0415	.0551	.0342	.0327	.0475	.0348	.0366	.0505
450	.0322	.0361	.0484	.0328	.0404	.0520	.0304	.0320	.0441	.0312	.0359	.0476
500	.0294	.0349	.0456	.0300	.0394	.0495	.0276	.0311	.0416	.0284	.0351	.0453
600	.0257	.0343	.0429	.0284	.0382	.0464	.0237	.0309	.0389	.0246	.0344	.0422
750	.0216	.0326	.0391	.0223	.0364	.0427	.0197	.0297	.0355	.0208	.0332	.0389

The resistance values are based on tinned Class B stranded-copper conductors (unless otherwise specified) at 60 cps and at 75 C.

The inductive reactance values are at 60 cps and are either positive- or negative- sequence values.

Multiply resistance values by 1.64 to obtain resistances for equivalent aluminum conductors.

Table 4 Three-conductor cables-Impedance L-N in Ohms/1000 ft

3.2.7 MISCELLANEOUS DEVICES

In short-circuit study work the impedance added to the system by the circuit breakers, contactors, fuses, current transformers, and other circuit elements are taken as zero in short-circuit calculations. These devices usually add such a small amount of impedance that their effect can be neglected. Nevertheless in certain calculations at low voltages where very large current capacities are available, the impedance added by these elements may be significant enough to warrant inclusion in the calcutions. In most industrial systems however, this will not be required.

3.2.8 LOADS WHICH DO NOT CONTRIBUTE TO SHORT-CIRCUIT

There are a few types of loads which do not contribute to short-circuit current fault levels. Among these are lighting loads, furnace loads, and rectifiers. Included in the rectifiers are all types of the static power conversion packages. Banks of capacitors do not contribute significantly to short-circuit current magnitudes and are normally neglected in the calculations.

3.3 TYPES OF POWER SYSTEM FAULTS

Faults or short-circuits can occur on a three-phase power system in several ways. The protective device or equipment must have the ability to interrupt or withstand any type of fault which can occur. The basic types of faults will be described, but it should be noted that the basic fault calculation for the selection of equipment and for the application of short-circuit protective devices is the bolted three-phase fault calculation. The current magnitude of all the other types of faults is normally a fraction of the three-phase short-circuit current.

The most straight-forward and most common mode of analysis is by the utilization of symmetrical components. The parameters used in the equations to follow (4), (5), (6), (7), are defined as follows:

I is the rms value of the symmetrical a.c. phase current flowing into the fault;

V_f is the rms value of the a.c. voltage to ground at the fault prior to the occurrence of the fault;

Z_1, Z_2, Z_o are the positive, negative, and zero sequence impedances of the system viewed from the fault;

Z_f is the fault impedance associated with a given type of fault (See fig. 3.2)

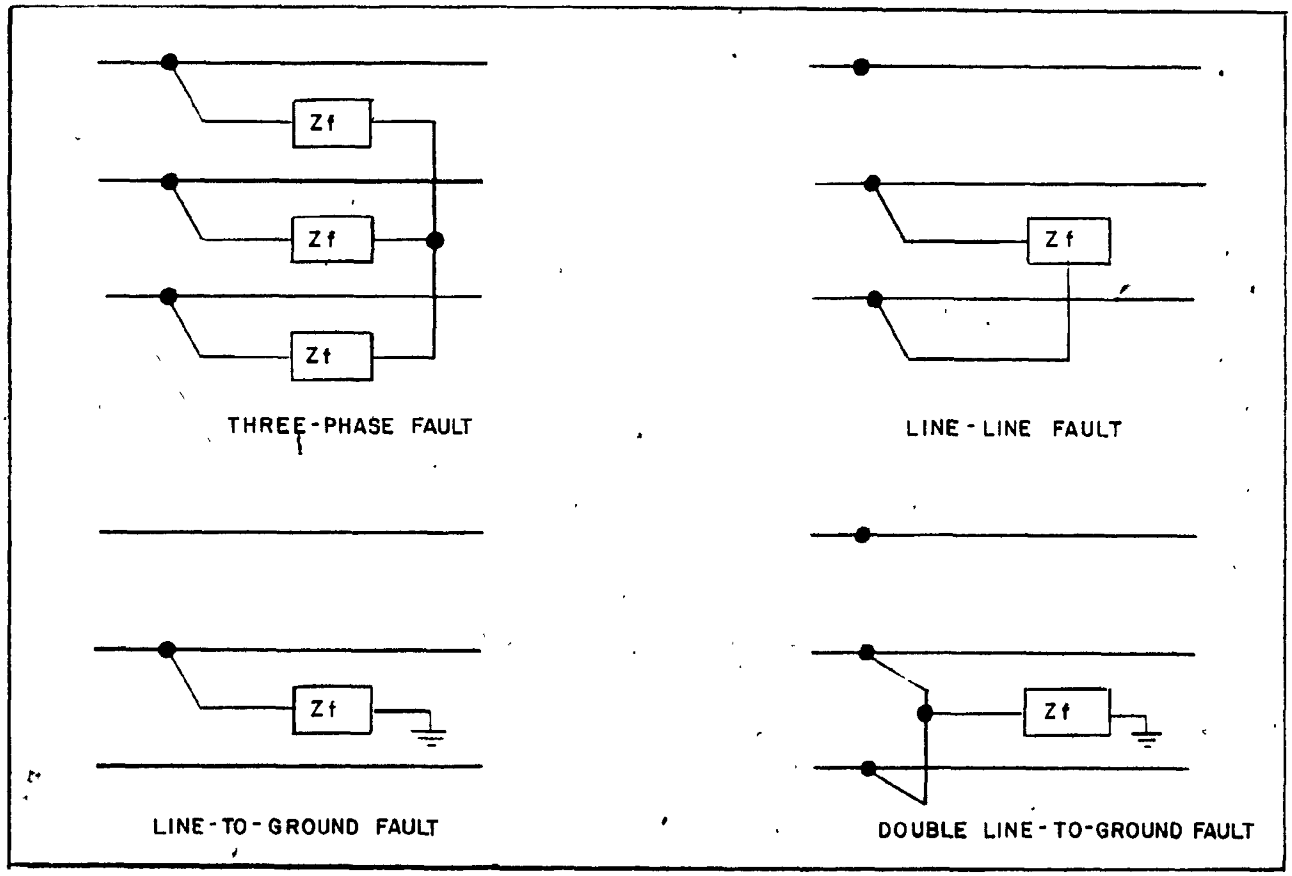


Fig. 3.2 Fault impedance Convention for equations (3.1) through (3.5).

3.3.1 THREE-PHASE BOLTED FAULTS

A three-phase bolted fault describes the condition where the three conductors are physically held together with zero impedance between them just as if they were bolted together. While this type of fault condition is not the most frequent in occurrence, it generally results in maximum short-circuit values and for this reason is the basic fault calculation in commercial and industrial power systems.

The three-phase short-circuit condition represents a balanced three-phase short-circuit on the system. Thus the positive sequence impedance is only needed. The equation expressing this fault current is:

$$\left| I \right| = \left| \frac{V_f}{Z_1 + Z_f} \right| \qquad (3.1)$$

3.3.2 LINE-TO-LINE BOLTED FAULTS

In most three-phase power systems, the levels of line-to-line bolted fault currents are approximately 87% of three-phase bolted fault currents, but this calculation is seldom required because it is not the maximum value.

This type of fault involves only the positive and negative impedance. The equation expressing the fault current is:

$$\left| I \right| = \left| j \frac{\sqrt{3}\ V_f}{Z_1 + Z_2 + Z_f} \right| \qquad (3.2)$$

3.3.3 LINE-TO-GROUND BOLTED FAULTS

In solidly-grounded systems, line-to-ground bolted fault current is usually equal to, or less than a three-phase bolted fault current. Sometimes it is significantly lower than the three-phase bolted fault current due to the high impedance of the ground-return circuit (that is, conduit, busway enclosure, grounding conductor, and building steel).

Line-to-ground fault calculations are seldom necessary in solidly-grounded, low-voltage industrial and commercial power systems. In resistance-grounded, medium voltage systems (2.4-13.8 kV) the resistor is generally selected to limit ground fault current to a value ranging between 400 to 2000 amperes. Line-to-ground fault magnitudes on these systems are determined primarily by the resistor itself and a line-to-ground short-circuit calculation is generally not required. Positive, negative and zero sequence impedances are involved in this type of fault. The equation expressing the line-to-ground fault current is:

$$|I| = \left| \frac{3V_f}{Z_1 + Z_2 + Z_o + 3Z_f} \right| \qquad (3.3)$$

3.3.4 DOUBLE LINE-TO-GROUND FAULTS

The occurence of this type of fault is rather limited, ranging between 4% - 9%.[9] The magnitude of the short-circuit current is a fraction of the bolted three-phase short-circuit current and thus this type of calculation is again not needed.

The double line-to-ground fault current is expressed as:

$$\left| I \right| = \left| j \sqrt{3}\, V_f \frac{Z_o + 3Z_f - aZ_2}{Z_1 Z_2 + (Z_1 + Z_2)(Z_o + 3Z_f)} \right| \tag{3.4}$$

and in the other phase associated with this fault

$$\left| I \right| = \left| j \sqrt{3}\, V_f \frac{Z_o + 3Z_f - a^2 Z_2}{Z_1 Z_2 + (Z_1 + Z_2)(Z_o + 3Z_f)} \right| \tag{3.5}$$

3.3.5 ARCING FAULTS

In calculating the maximum current it is assumed that the fault is a zero-impedance (bolted) fault with no current-limiting effect due to the fault itself. However, it should be recognized that actual faults particularly in low voltages systems often involve arcing, which reduces the fault current magnitude by inserting the impedance of the arc into the circuit. Although the current magnitudes may be very low in relation to three-phase fault currents, they do cause major problems. To protect the electrical systems against those problems specialized protection is required known as ground fault protection. Methods of providing ground fault protection are extensively treated in chapter 5.0.

3.4 SELECTION OF LOCATION OF SHORT-CIRCUIT AND SYSTEM CONDITIONS FOR MOST SEVERE DUTY

The selection of the location where short-circuit current magnitudes should be calculated is very important. In many studies all buses are considered faulted. The maximum short-circuit current will flow through a circuit breaker, fuse, or motor starter when the short-circuit occurs at the terminals of the breaker, etc. (Fig. 3.3). These devices, if properly applied, should be capable of opening the maximum short-circuit current that can flow through them. Thus, only

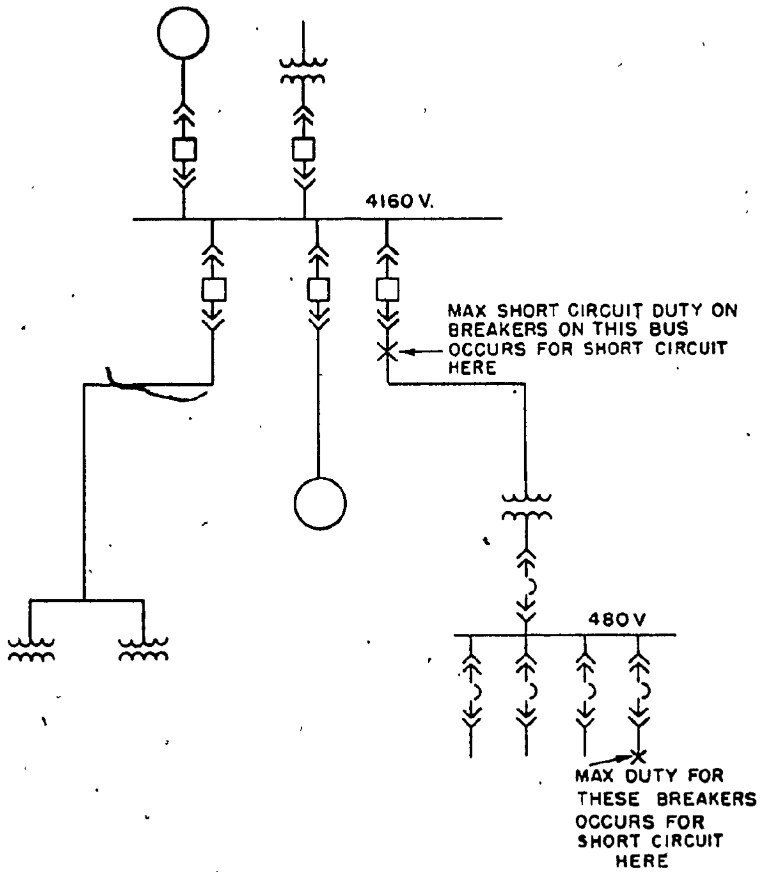


Fig. 3.3 Location of faults for maximum short-circuit duty on circuit breaker.

one short-circuit location (at the terminal of the device) need to be considered for deciding or checking the duty on a given circuit breaker, fuse, or motor starter. It is sometimes quite difficult to predict which of the intended or possible system conditions should be investigated to reveal the most severe duties for various components. Future in-plant or in-building expansions will probably raise short-circuit duties in various parts of the power system so that future expansions must also be considered initially.

The most severe duty usually will occur when the maximum concentration of machinery is in operation and all interconnections are closed. The conditions most likely to influence the critical duty include:

(1) Which machines and circuits are to be considered in actual operation?

(2) Which switching units are to be open or closed?

(3) What future expansions or system changes will affect in-plant or in-building short-circuit currents?

3.5 DEVELOPMENT OF EQUIVALENT CIRCUIT

The one-line diagram shown in fig. 3.1 can be redrawn as a preliminary equivalent circuit as shown in fig. 3.4 using the collected information converted into equivalent impedances for the circuit elements. These impedances are to be expressed on a common base to simplify calculations which will follow. Where exact impedances cannot be determined from equipment nameplate information, it is sufficiently accurate to use known impedances of similar equipment.

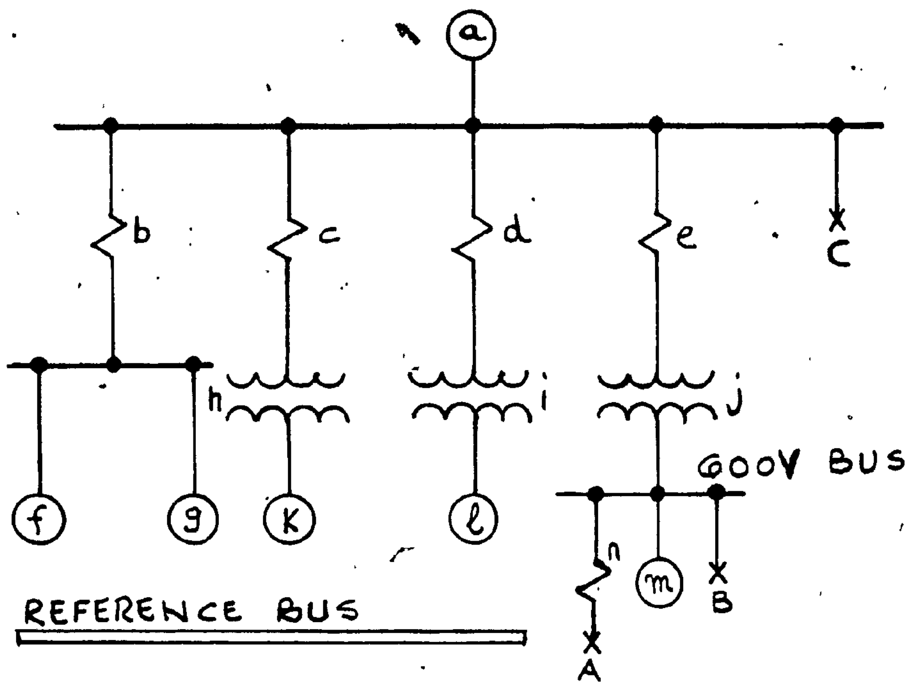


Fig. 3.4 Preliminary equivalent circuit

This circuit should include all sources of short-circuit current. The utility supply and in-plant generators (if any) will be the major sources of short-circuit current to any fault. But electric motors which are normally a load in the system are also sources of short-circuit current. It is not necessary to detail the equivalent circuit down to every load connection. Many small motors are frequently grouped and treated as a single impedance to simplify calculations. (This is illustrated in fig. 3.4 by the motor groupings identified as K, l and m).

The next step is to add to this "preliminary" circuit an imaginary "source" or "reference" bus (shown in fig. 3.5) from which all sources of short-circuit current will emanate. This bus is also known as "Zero Voltage" bus or "Zero" bus. Now the connections from each current source to the reference bus can be drawn (shown as dotted lines in fig. 3.5).

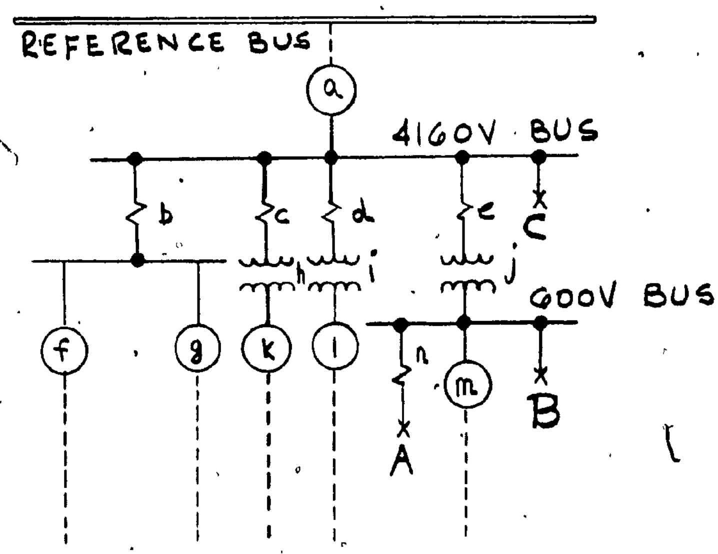


Fig. 3.5 Preliminary equivalent circuit

This preliminary equivalent circuit can now be redrawn into the format of figure 3.6; the ultimate equivalent circuit which can be used for the short-circuit calculations.

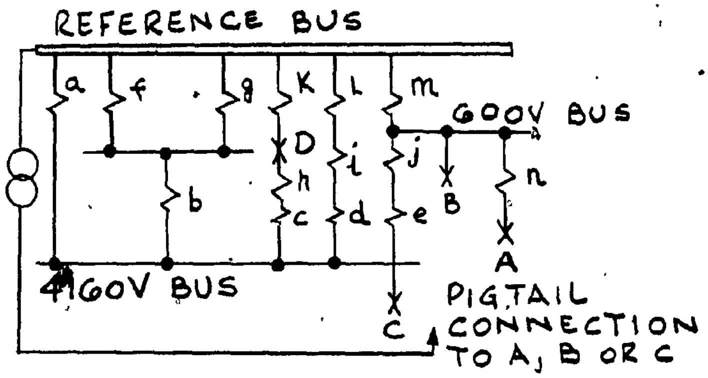


Fig. 3.6 Equivalent circuit for calculations

To determine the short-circuit current at point A, B, or C we can connect the «pig-tail» to point A, B or C, respectively. If some other point in the system is to be faulted also, it may be required to again re-draw the equivalent circuit for clarity. For example, if it is necessary to calculate the short-circuit current level at the secondary of transformer «h» the pig-tail should be connected to point D and figure 3.7 results as the ultimate equivalent diagram.

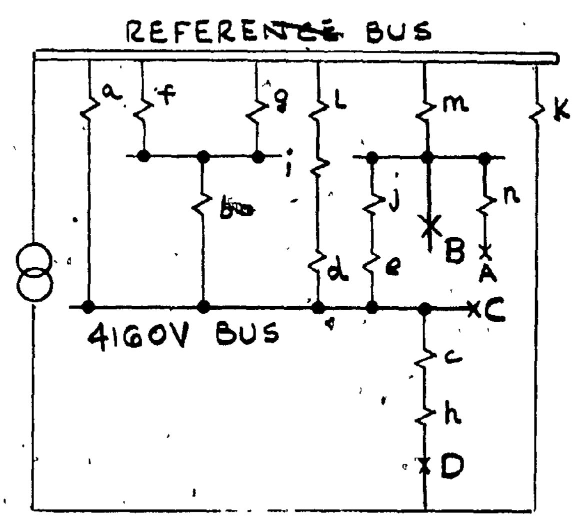


Fig. 3.7 Equivalent circuit for fault at point D

3.6 DETERMINATION OF SHORT-CIRCUIT CURRENTS

After the impedance diagram is finalized, the short-circuit currents can be determined. This can be accomplished by longhand calculation, network analyzer or computer techniques.

In general, the presence of closed loops in the impedance network, such as might be found in a large industrial plant high-voltage system, and the need for short-circuit duties at many system locations will favor using a network analyzer or digital computer from an economic and time saving standpoint. Simple radial systems, such as those used in most low-voltage systems, can be easily resolved by longhand calculations although digital computers can yield significant time saving, particularly when short-circuit duties at many system locations are required and when resistance is being included in the calculation.

A longhand solution requires the combining of impedances in series and parallel from the source driving voltage to the location of the fault being calculated to determine the single equivalent network impedance. The calculation to derive the symmetrical short-circuit current is $I = \frac{E}{Z}$ where E is the system driving voltage and Z is the single equivalent impedance. Now if this symmetrical short-circuit current is multiplied by the applicable multiplying factor from table 5 the asymmetrical short-circuit current can be found. Depending upon the choice of the final multipliers, they can be compared with the short-circuit ratings of the protective devices in the system. For example a low voltage breaker has just one short-circuit rating - the interrupting current rating on its nameplate. But a medium or high-voltage breaker has two - the allowable momentary current and the allowable interrupting current or kVA. The short-circuit current calculated at the point of application should never exceed the short-circuit rating or ratings of the device to be applied.

Equipment	Type of Short-circuit Rating	Machine Reactances to Use: Synchronous Generators	Machine Reactances to Use: Synchronous Motors	Machine Reactances to Use: Induction Motors	Multiplying Factor to be Applied to Calculated Symmetrical Value*: General Case†	Multiplying Factor to be Applied to Calculated Symmetrical Value*: Special Case†
L-V Power Circuit Breakers L-V Molded-case Circuit Breakers L-V Motor Controllers (Incorporating Fuses or Molded-case Circuit Breakers) L-V Fuses L-V Busway Bus Bracing in L-V Switchgear L-V Switchboards L-V Motor-control Centers L-V Panelboards	Symmetrical Amperes Available	Subtransient (X")	Subtransient (X")	Subtransient (X")	None	
Power Circuit Breakers (above 600 volts) with Rated Interrupting Times of 8 cycles (Refer to the Total Current Rating Basis—ASA C37.6—1964)	Interrupting--Symmetrical Amperes or MVA Available	Subtransient (X")	Transient (X)	Neglect	1.0	1.1
	Momentary—Asymmetrical Amperes Available	Subtransient (X")	Subtransient (X")	Subtransient (X")	1.6‡	1.5‡
Fuses and Fused Cutouts (above 1500 volts)	Interrupting—Asymmetrical Amperes Available	Subtransient (X")	Subtransient (X")	Subtransient (X")	1.6¶	1.2¶

Table 5 Multiplying factors used in calculation of short-circuit duty (ANSI-C37.5 - 1953)

4

PROTECTIVE DEVICES CHARACTERISTICS AND SETTINGS

4.1 GENERAL DISCUSSION

Proper selection and adjustment of short-circuit protective devices will enable the power system designer to achieve maximum circuit and equipment protection consistent with the requirements of service continuity. It is the intent of this section to provide basic information for the protection and coordination devices normally found in industrial power systems. The general nature of their time-current characteristics is illustrated and the information required to carry out a coordination study is identified.

In general, all of the devices discussed here are responsive to current. The response time, that is, the time to operate, varies with the magnitude of current flow. This is generally true whether the device is a relay, low voltage breaker, molded-case circuit breaker, or a fuse. The response time is long in the low current region and becomes progressively more rapid at higher current levels, with the upper limit for some devices being a response which is almost instantaneous (two to three cycles or less) from the inception of the fault current.

The spectrum of currents to be dealt with can be divided in three levels:

1) Load current, extending up to 100% of the full load current and including mild (115-125%) overload conditions.

2) Overcurrent level, extending up to the locked-rotor current for a motor or to the short-time overload peaks sustained by some types of equipment. They are produced by a demand for current greater than normal full load but not involving a short-circuit condition.

3) Short-circuit level, extending to ten times full-load current of the device and higher.

4.2 TYPES OF PROTECTIVE DEVICES

4.2.1 THERMAL OVERLOAD RELAYS IN MOTOR STARTING CONTACTORS

These relays are used in both low-voltage and medium-voltage equipment. Their function is to sense the current to the load, and, in case of an overcurrent condition, open a contact and permit the contactor to drop out, thus de-energizing the motor. As it can be seen from figure 4.1, these relays provide coverage up to 10 or 20 times full-load current. Above these levels, a short-circuit device, such as a fuse or circuit-breaker is expected to provide the required protection. (A complete discussion of this will follow up in the section of combination devices).

The information required for coordination should include:

1) The current rating of the contactor.

2) The current rating of the thermal-overload sensing device (often less than the rating of the contactor, but chosen to match the motor's full-load current).

3) The interrupting capability of the circuit breaker.

4) The characteristic curve for the thermal overload device.

Usually the overload relays carry a non-adjustable current rating, thus they must be selected to match load characteristic.

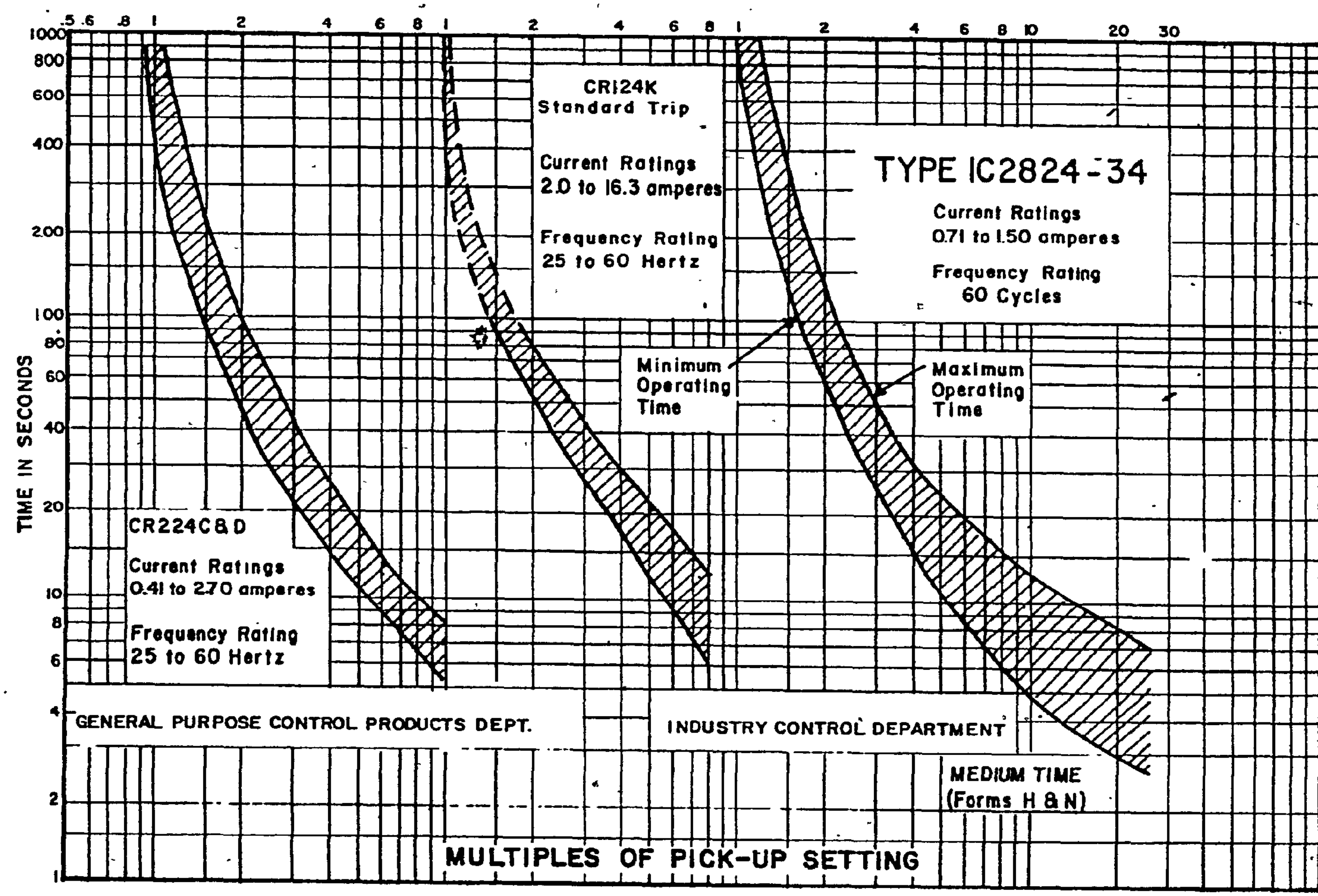


Fig. 4.1 Typical thermal-overload Relay characteristics

4.2.2 MOLDED CASE CIRCUIT BREAKERS AND LOW VOLTAGE POWER CIRCUIT BREAKERS

The molded-case circuit breaker tends to be applied in the smaller current ranges and is generally found in panelboards, distribution switchboards, and as a part of combination motor starters in motor control centers and other similar packaged equipment. Their current capability can reach up to 2,500 amperes, and they are sometimes used as the transformer secondary breaker.

The low-voltage power circuit breaker is generally used in heavy-duty industrial applications, as a transformer secondary breaker and feeder breakers for transformers from 500 to 3000 kVA, in load-center transformer applications and finally as starters for low-voltage motors (150-350 hp range). The information required for coordination of both of these types of breakers should include:

1) The full-load ampere rating of the breaker frame size.

2) The ampere rating of the trip coil in the breaker (which could be less than the ampere rating of the breaker frame).

3) The range of adjustment on the long-time portion of the characteristic curve.

4) The range of adjustment on the short-time portion of the characteristic curve (if any).

5) The range of adjustment on the instantaneous unit pickup.

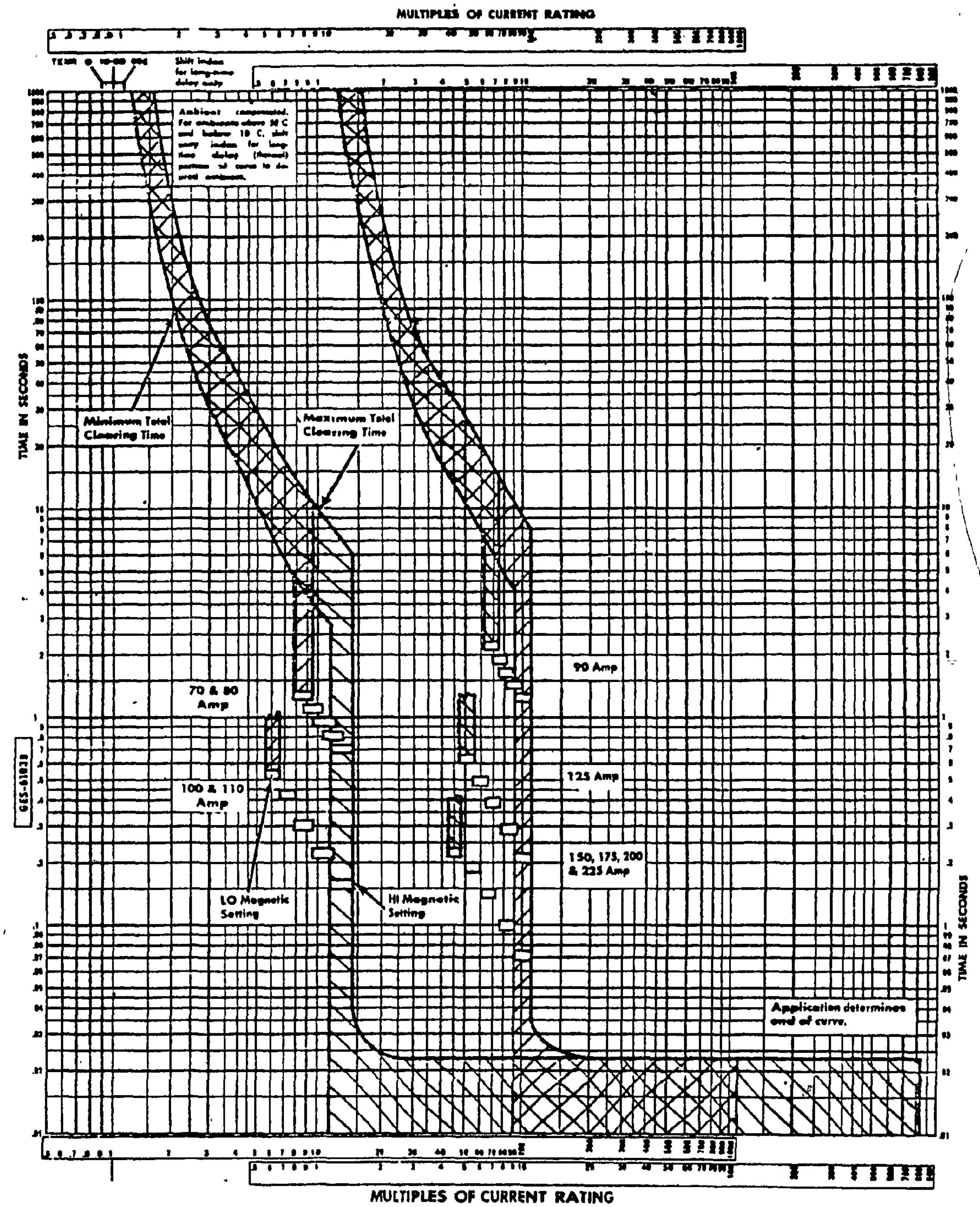
6) The maximum interrupting rating of the breaker,

7) A time-current characteristic curve.

Typical characteristic curves for these types of breakers are shown in Figs. 4.2 and 4.3.

4.2.3 FUSES

There is a wide variety of fuses available for application to power circuits, both in the low-voltage and medium-voltage range. A fuse is a non-adjustable device and thus the characteristic is fixed by the rating of the device itself. In addition to the continuous current rating, fuses also have an interrupting



GENERAL ELECTRIC

Current Ratings
70, 80, 90, 100, 110, 125, 150, 175, 200 and 225 amperes
Voltage Ratings
600 volts a-c (250 volts d c)
Frequency Rating
60 Hertz

MOLDED-CASE CIRCUIT BREAKER

F 225 LINE

Types TFJ, THFJ (150A Max.), TFK, THFK
Long-time Delay and Instantaneous
Time-current Curves

GES-6103B

Adjustments

Long-time delay thermal trip: not adjustable
Instantaneous magnetic trip: continuously adjustable, factory set on HI.
Blocks show trip range at marked points on instantaneous dials.

CIRCUIT PROTECTIVE DEVICES DEPT., PLAINVILLE, CONN

Fig. 4.2 Molded Case Circuit Breaker Characteristics

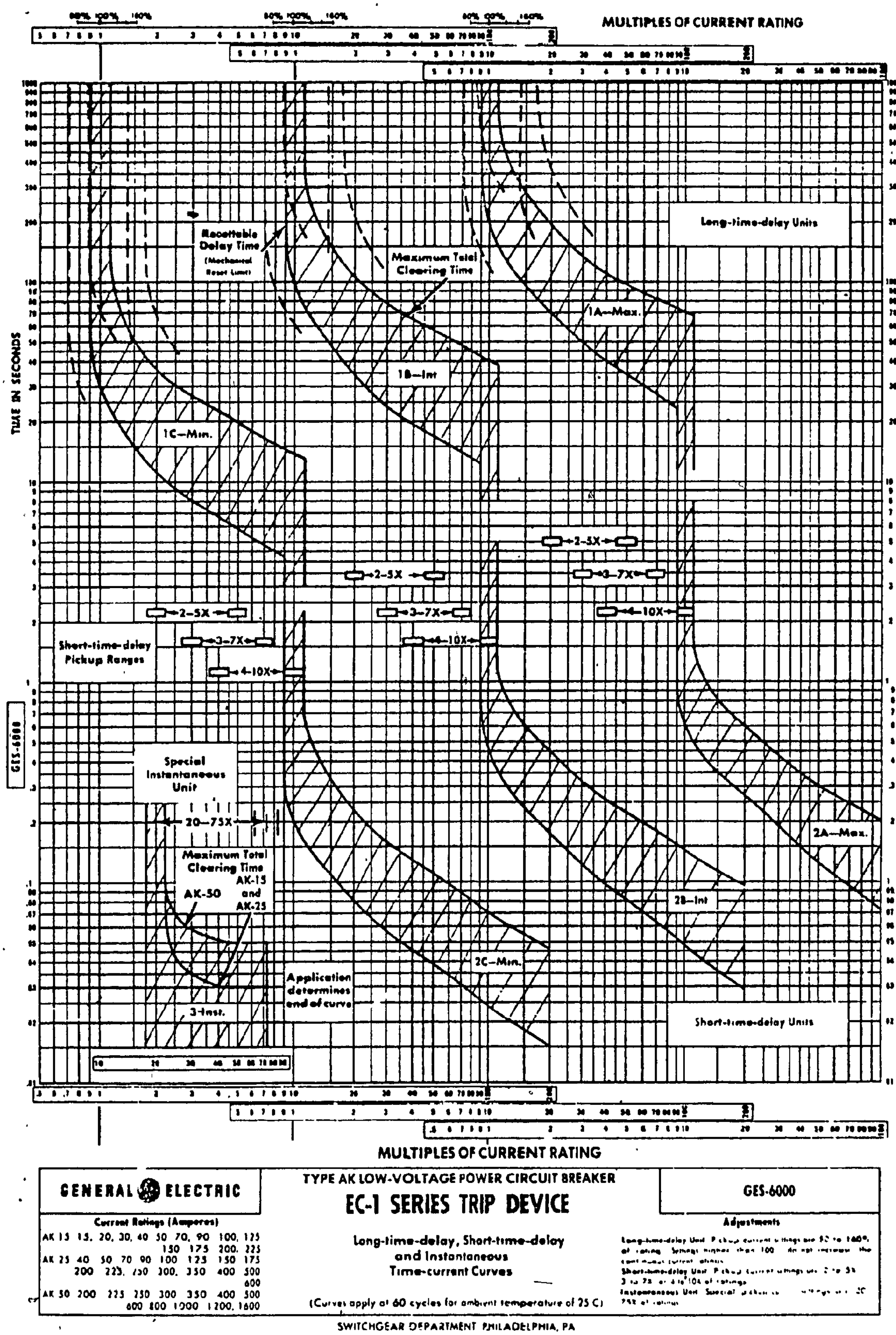


Fig. 4.3 Low-Voltage Power Circuit Breaker Characteristics

rating. In addition some fuses are classified as current-limiting. This indicates that they can be applied in combination with contactors and molded-case circuit breakers to provide high-level short-circuit protection to a branch circuit. The information required for a coordination study of the fuse device should include:

1) The continuous current rating.

2) Its characteristic curve.

3) Its assigned interrupting-current capacity.

Typical characteristic curves for types of fuses are shown in Figs. 4.4. and 4.5.

4.2.4 COMBINATION DEVICES

Sometimes a fairly large transformer can be the source of power to a low-voltage bus, resulting in large available short-circuit current. The various contactors and circuit breakers may have small load current requirements, and being small devices, they have lesser short-circuit interrupting ratings. The protection against a short-circuit in the event of a fault on an upstream

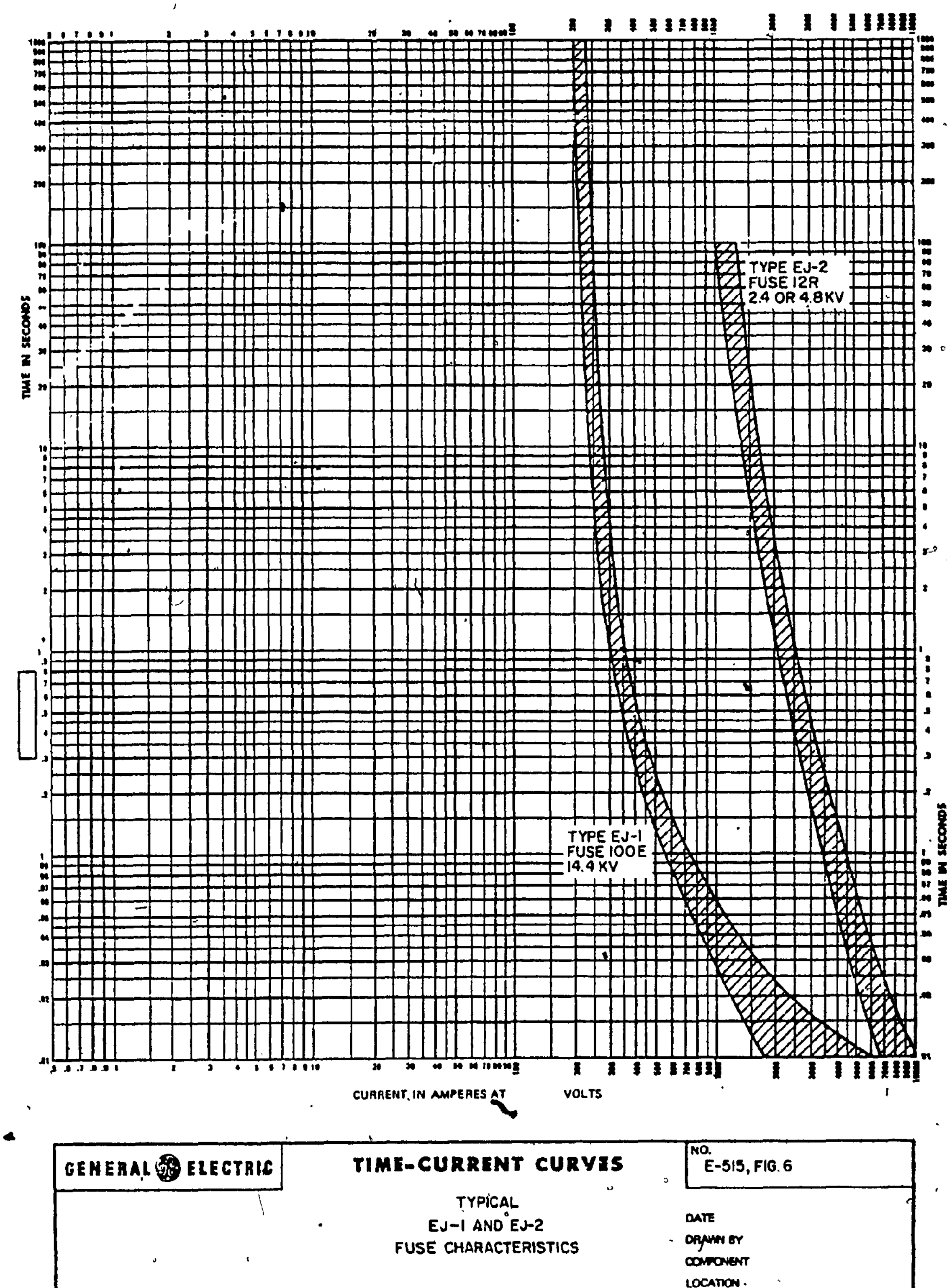


Fig. 4.4 High Voltage Fuse Characteristics

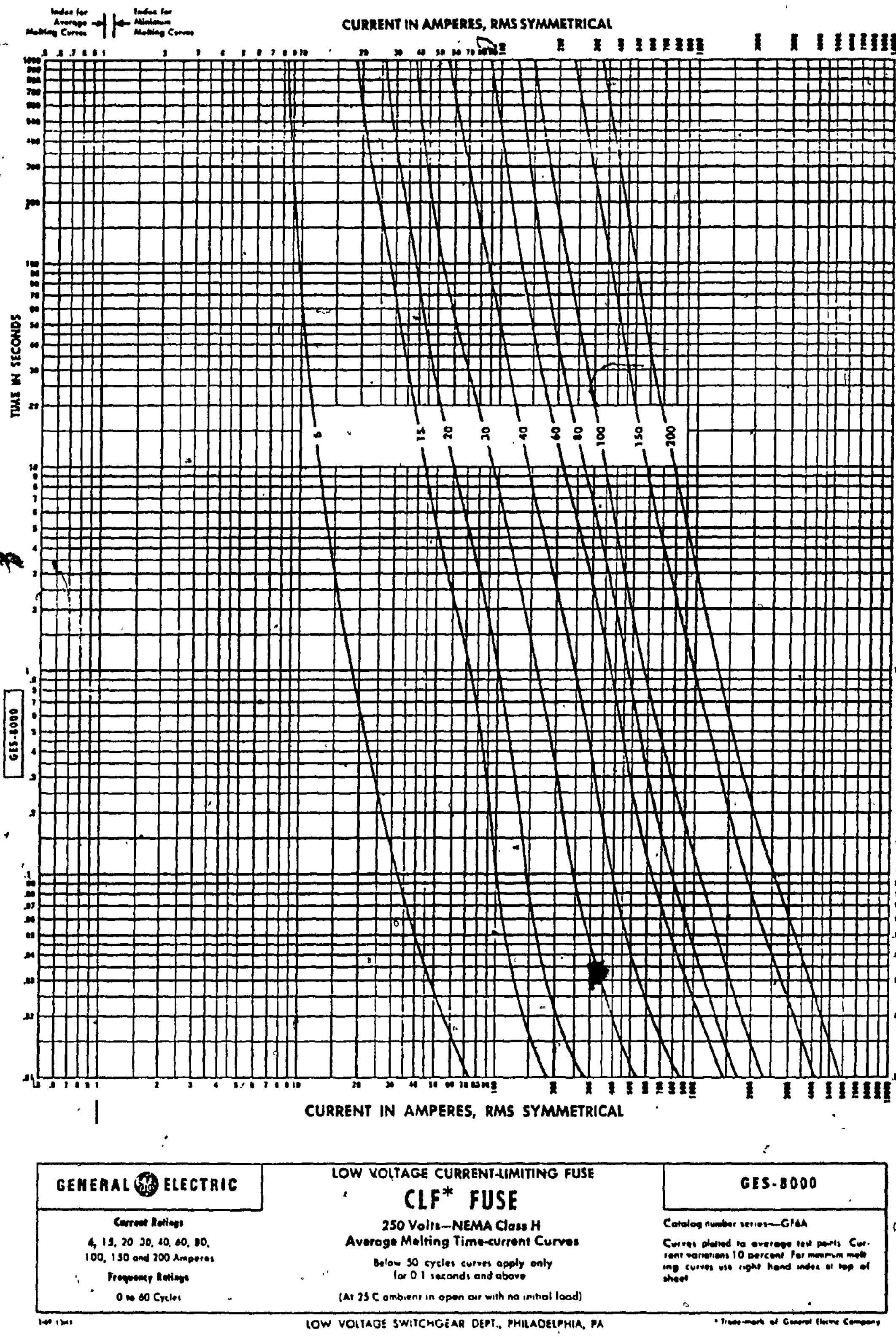


Fig. 4.5 Current limiting fuse characteristics

location, is provided by a fuse (often a current-limiting one. - The current-limiting fuse will operate before the current reaches the peak value of its first major loop -).

The information required for these combination devices, to be represented on the coordination plot should be:

1) The rating of the overload relay and its characteristic curve or (if used) the rating of the long-time device in the circuit breaker and its characteristic curve.

2) The rating of the fuse and its characteristic curve.

3) The assigned interrupting rating of the combination device.

Time-current characteristics for typical combination devices are shown in figs. 4.6 and 4.7.

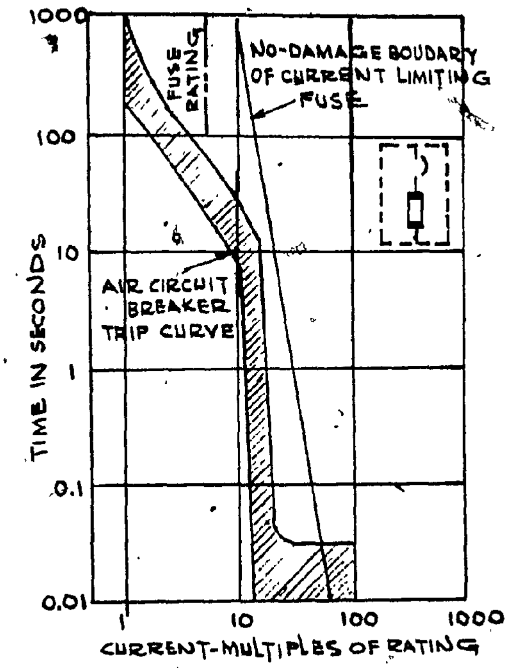


Fig. 4.6 Typical Combination devices characteristics, Current limiting fuse with Low-Voltage Power Circuit Breaker

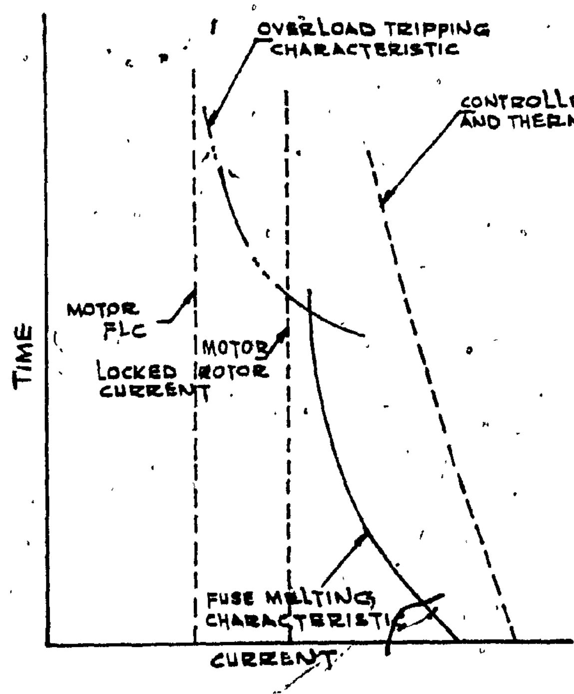


Fig. 4.7 Typical Combination devices characteristics, fuse with overload relay.

4.2.5 PROTECTIVE RELAYS

Another protective device encountered in coordination studies of medium and high-voltage systems is the protective relay. The protective relay gains the information it needs to locate a fault in the form of currents and voltages from instrument transformers (CT'S and PT'S) located on the specific portion of the power system being protected. This information is then relayed in the form of a tripping impulse to the circuit breakers, which isolate the defective apparatus by interrupting the flow of current from all sources.

There is a wide variety of protective relays available. Since it is virtually impossible to cover them all in the context of this report, an attempt will be made to introduce the ones that are most commonly used for the protection of systems we are mostly concerned, namely low and medium voltage.

4.2.5.1 TYPES OF RELAYS

A protective relay could be of the electromagnetic type or of the solid-state type. The operating elements for the electromagnetic relays could be of the magnetic attraction type (plunger, hinged armature), or the induction type (disk or cup). Sketches of the basic constructions are shown in figures 4.8 to 4.12. It should be noted that the magnetic attraction types can be used with either alternating or direct current quantities. The induction type can only be used with alternating current quantities since torque is developed in a movable rotor in the same way that it is produced in an induction type motor.

The term static relay normally means that the measuring part, e.g. time delay circuit of a time-lag relay, is built up of static components such as resistors, capacitors, etc. When certain requirements are fulfilled the measuring circuit gives an output signal to the output stage. This output stage can be a semiconductor such as a thyristor, but usually it is an electromechanical auxiliary relay, whose contacts actuate those circuits where the operation of the static relay is required. The definition is, therefore, in the latter case, somewhat inadequate, as the static relay contains moving parts in the form of armature and contacts, etc. in an auxiliary relay.

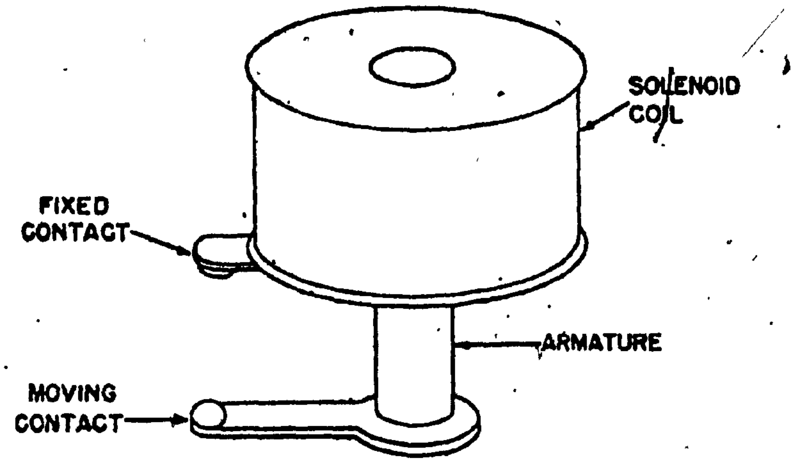


Fig. 4.8 Plunger construction

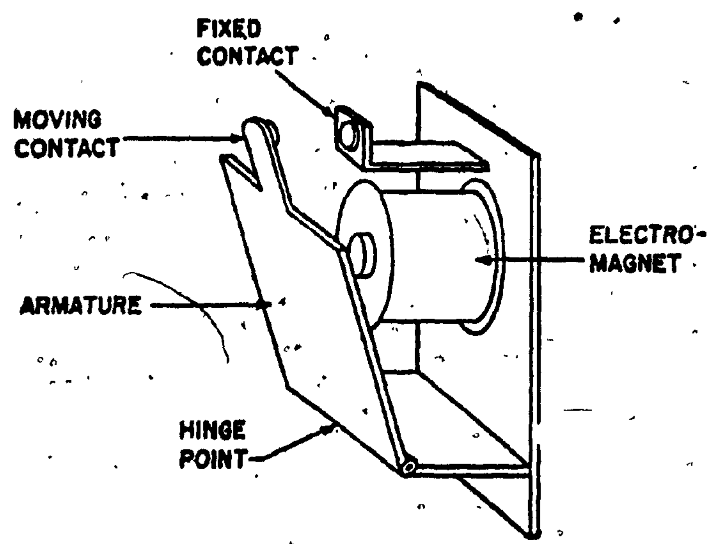


Fig. 4.9 Hinged armature construction

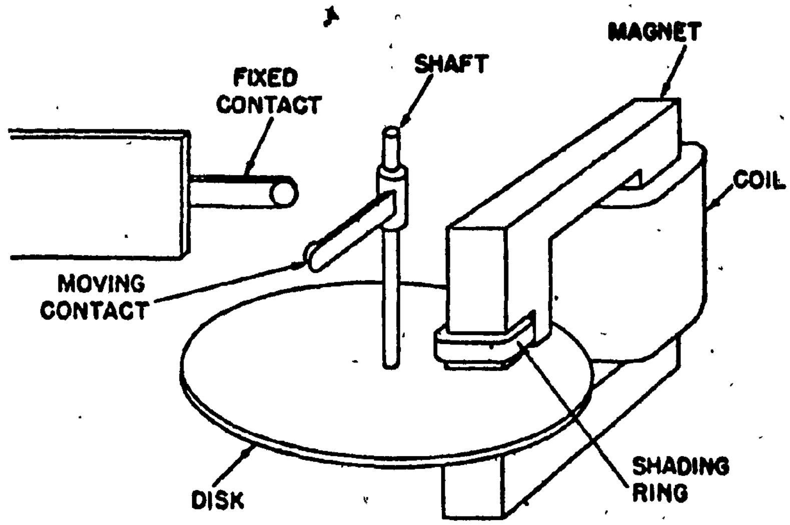


Fig. 4.10 Shaded pole induction disk

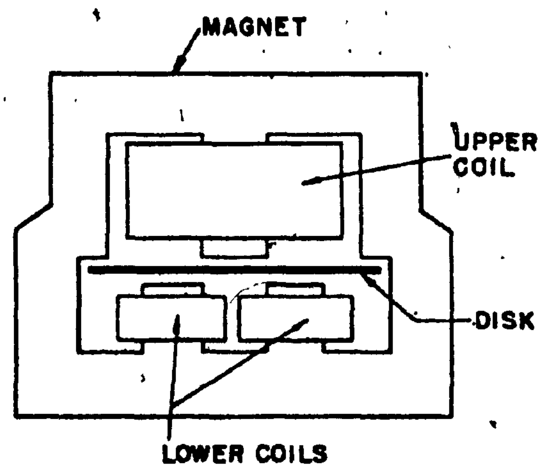


Fig. 4.11 Wattmetric induction disk

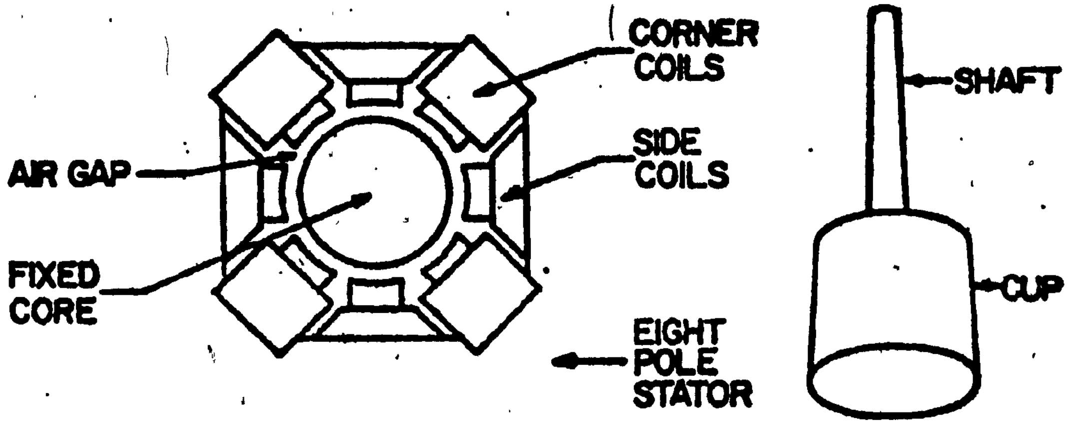


Fig. 4.12 Induction cup construction

Static relays have been of interest during the past twenty years. However, it is only during the past five or ten years that the manufacture of such relays has increased substantially. The reason for this increase is that the reliability of the static components, especially all the semi-conductors used in the static relays, has increased to such an extent that it is advantageous to design the measuring elements in the protective relays with the static components. Even the pricing of the static components has been favorable and one can assume that a further reduction in price can be expected, especially for the integrated circuits, which have come to be used as building blocks in the relays.

4.2.5.2 STATIC VERSUS ELECTROMECHANICAL RELAYS

The static relays compared to the corresponding electromechanical relays have many advantages and a few disadvantages. Among the advantages, the following can be mentioned:

a) Reliability: The reliability of a relay and especially of a protective relay is of fundamental importance. If a relay does not operate or operates when uncalled for there may be disastrous consequences. Due to the precision manufacture, and the careful and regular maintenance of the electromechanical relays these relays have high reliability as compared to many other electromechanical apparatus. Static relays should, however, have still better reliability especially since the moving parts have been almost completely eliminated.

The reliability of the static relays is totally dependent on the reliability of the individual static components. It is therefore important to choose these with great care and to design the relay in such a way that the number of components is reduced to a minimum. Some components such as switches and potentiometers which have shown to have the lowest reliability should be chosen with great care.

b) <u>Power consumption in the measuring circuits</u>: Power consumption in the measuring circuits of the static relays is generally much lower than for the electromechanical equivalents. Current relays with 1 mW power consumption are quite common. Low power consumption makes it possible to use smaller and thus cheaper current transformers.

c) Shock and vibration sensitivity: Most of the components, including the auxiliary relays used in the output stage, are relatively insensitive to vibrations and shocks. The risk for unwanted trippings is therefore less when static relays are used than when electromechanical equivalents are used.

d) Operating times etc: As the fault MVA level increases, the operating times become of prime importance for relays which are included in short-circuit protections. Static relays lacking moving parts in the measuring circuits permit drastic decreases in operating times to low values which are impossible to obtain with the conventional electromechanical relays.

Static relays also have certain disadvantages as compared to their electromechanical equivalents. Among these the following can be named:

a) Auxiliary voltage requirements: This disadvantage is in most cases of little importance as the auxiliary voltage normally can be obtained from the station battery which is ordinarily required for other purposes.

b) Voltage transients: Short duration voltage "transients" caused for example, by breaker and isolator operations in switchyards, by breaking of relay contacts in the control circuits etc. can cause malfunction or damage to the static relays if no special measures are taken. Such special measures can consist of including filter circuits in the relay or screening the cables connected to the relays.

c) Temperature dependence: The semi-conductors are affected by the ambient temperature. The amplification factor of a transistor, the forward voltage drop in a diode etc., changes when the temperature is changed. In order for the measuring accuracy of the relay not to be affected appreciably, the individual components in the circuits are used in such a way that a change in the characteristic data of the components does not affect the characteristic data of the relay. These requirements can be easily met in relay designs by means of temperature compensation, use of digital measuring technique etc. Nearly as good temperature properties can thus be obtained for the static relays as for the electromechanical relays within the temperature limits the relays are required to work (-5°C to +40°C).

d) Price: The price of the static relays today is generally somewhat higher than the equivalent electromechanical types. The difference is, however, decreasing gradually and it can be expected that the static types will be cheaper in a few years. The prices for the semi-conductor components have been reduced during the past years and a further reduction is expected. As the sales of the static relays are increasing, and hence the series production, there is every reason to be optimistic and expect that the price for the static relays will be more and more favorable.

The above mentioned advantages and disadvantages are some of the most important for the static relays. Naturally many other factors such as dimensions, weight etc. can be evaluated and compared.

4.2.5.3 OVERCURRENT RELAYS

It is necessary to trip a circuit breaker when more than a certain amount of current flows into a particular portion of a power system. Thus an instantaneous overcurrent characteristic, either the plunger type, or the hinged-armature type, or the induction-cup type or the solid-state type should be used. When it is desired to have more time-delay for purposes of coordination with other protective relays, the induction disk type, or static type-employing RC time-lag networks - can be used. In the induction disk type time-delay is achieved by a permanent magnet arranged to produce an induction drag on the disk.

There are three most commonly used shapes for the time overcurrent characteristics which differ by the rate at which the time of operation of the relay decreases as the current increases. These curve shapes, shown in fig. 4.13 are called "inverse", "very inverse", and "extremely inverse".

Information required for these devices to be represented on the coordination plot include:

1) The type of relay.

2) The ampere tap range of the relay (typically 4-16 or 1.5-6 amperes).

3) The instantaneous overcurrent attachment if the relay is so equipped (typically 10-40 or 20-80 amperes).

4) The time current characteristic curves.

It should be mentioned that a time overcurrent relay with a long-time range and an instantaneous range is really two relays incorporated into one enclosure. A long-time overcurrent and instantaneous characteristic is displayed in fig. 4.14 for a representative type relay.

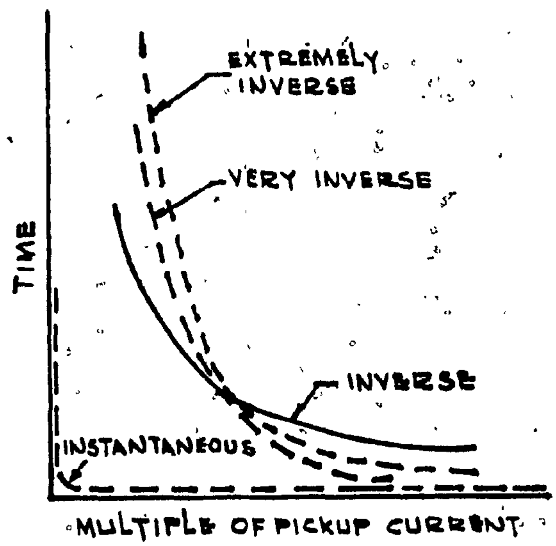


Fig. 4.13 Time current characteristics

4.2.5.4 DIRECTIONAL RELAYS

Directional relays are required for applications where it is desirable to allow tripping for current flow in only one direction. The directional relay can be produced in either the induction cup or the wattmetric

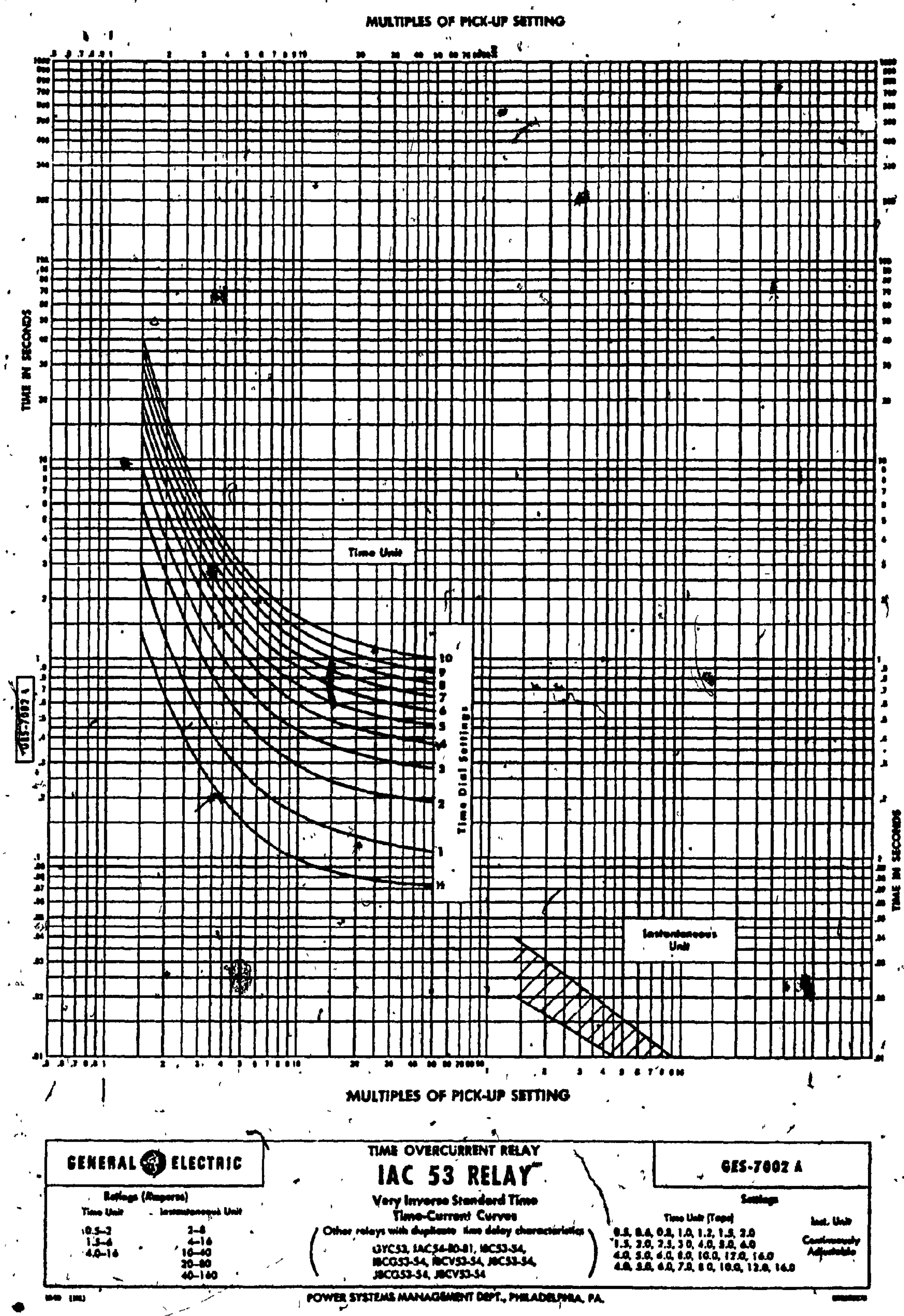


Fig. 4.14 Induction disk overcurrent relay with very inverse characteristic

induction disk construction. One winding may be energized by the circuit voltage to "polarize" the unit - that is, to predetermine the direction of current flow for which the unit is to operate by providing a reference quantity. The other winding may then be energized by the desired current. Current flow in the operating direction will produce a torque to close the contacts, but current flow in the reverse direction will produce a torque to restrain the unit or to hold the contacts open. A sensitive directional unit will operate for a very small value of the actuating quantity when the polarizing quantity is the normal rated value; its function is only to recognize the proper direction. With the addition of restraint, the directional unit can perform a measuring function. An example of this type of unit is the directional over-current relay. Both the sensitive type and the measuring type can be made to operate instantaneously or with some purposely-introduced time delay.

Sometimes, a directional unit may be polarized by some reference current instead of a voltage. An example of this type is a directional overcurrent unit for protection against short-circuits involving ground. In this case, the reference current can be obtained from a current transformer connected in the neutral of the grounded transformer bank.

4.2.5.5 CURRENT BALANCE RELAYS

In situations where it is desirable to trip a breaker whenever there is an abnormal change in the division of current between two circuits, a current balance relay may be applied. A current balance relay may use the hinged armature, induction disk, or the induction cup construction. Such a relay has two torque-producing elements actuated by currents obtained from the two circuits. One element produces operating torque tending to open the contacts. The ratio in percent of the operating current to the restraining current to cause the relay to operate is called the percent "slope" of the operating characteristic. The relay also requires a minimum current to operate when the current in the restraining element is zero.

4.2.5.6 DIFFERENTIAL RELAYS

All the previously described relays have the common characteristic of adjustable settings to operate at a given value of some electrical quantity such as current, voltage, frequency, power, or a combination of current and voltage or current and phase angle. There are other fault-protection relays which function by virtue of

continually comparing two or more currents. One of them is the differential relay which actually is the most selective relaying principle. It is achieved by a certain connection of current transformers, and almost any type of relay may be used. Current transformers are put in all of the connections to the system element to be protected, and their secondaries are connected in parallel to a relay operating coil. So long as current flows normally through the protected system element, the current transformer secondary currents merely circulate between the current transformers, and no current flows through the relay coil. But should a short-circuit occur in the protected system element, a difference current will flow in the relay coil and cause the relay to trip all of the breakers in the circuits connected to the faulty element. Differential protection may be applied to any section of a circuit and is used extensively to protect motors, generators, buses and transformers against internal faults.
It detects internal faults immediately and is not affected by overloads or faults outside the differentially protected section.
Fig. 4.15 shows the differential principle applied to one phase winding of a generator. Here, a current balance relay is used to provide what is called «percentage differential» relaying.

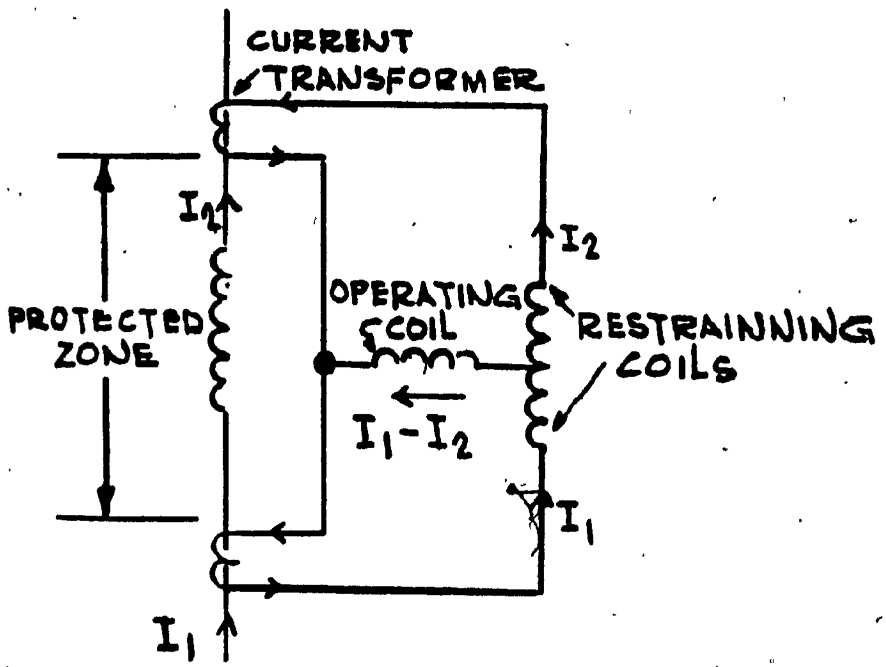


Fig. 4.15 Differential Circuit Connections

The two sets of current transformers are connected in parallel to the operating coil, as previously described. In addition, the current from each current transformer is made to flow through a restraining coil. The purpose of the restraining coils is to prevent undesired relay operation, should current flow in the operating coil as a result of current transformer errors. (Error in ratio, or slight variation in manufacture etc). Use of differential relays for transformer protection presents certain problems (Magnetizing inrush,differing voltage ratios,phase shift between H & X terminals) that can be solved by using harmonic restraint coils, auxiliary transformers and proper C.T. connexions as described in chapter 6.

5

GROUNDING PRACTICES & GROUND-FAULT PROTECTION CONSIDERATIONS

5.1 GENERAL CONSIDERATIONS

The problem of whether or not a system neutral should be grounded, and how it should be grounded, has sometimes not had the complete understanding and engineering analysis which it deserves. As a consequence the grounding of many systems has been based on past experience or opinion; and therefore system grounding practice is found to vary widely on existing industrial power systems.

Historically, power system designers had preference for the ungrounded systems due to an apparent higher degree of service continuity. But accumulated operating experience indicates that the overvoltage incidents associated with ungrounded operation diminish the useful life of insulation in such a way that electric circuit and machine failures occur more frequently than they do on grounded systems. On the other hand, solidly grounded systems exercise the greatest control of overvoltages but result in higher magnitudes of ground-fault current. This necessitates the use of a fast and reliable ground-fault protection scheme. Indeed, today modern technology offers many elaborate ground-fault protective schemes. For the sake of completeness all present grounding practices would be at least mentioned, but more weight will be given to the grounding methods related to ground-fault protection.

5.2 CHARACTERISTICS OF UNGROUNDED SYSTEMS

The term "ungrounded system" is used to identify a system in which there is no intentional connection between the system conductors and ground. However, any practical system is "capacitively grounded" since there exists a capacitive coupling between the system conductors and ground.

When the neutral of a system is not grounded, it is possible for destructive transient overvoltages, of several times normal, to appear from line - to - ground during normal switching of a circuit having a line - to - ground fault. Tests have shown that overvoltages may be developed by repeated restriking of the arc during interruption of a line - to - ground fault, particularly in low voltage systems. Experience has also shown that these overvoltages may cause insulation failures at locations other than at the point of fault. Thus, a line - to - ground fault on one circuit may result in damage to equipment and interruption of service on other circuits.

In an ungrounded system, a ground fault on one line causes full line - to - line voltage to appear throughout the system between ground and the two unfaulted lines. This voltage could be as high as 73% above normal.(1). The insulation will usually be adequate to withstand this overvoltage as long as it is not maintained for a long time. Under this line - to - ground fault a very small ground fault current will flow through the system. It has a magnitude of a few amperes to 25 amperes which in general is not enough to actuate protective devices.(1) This particular inability of the one line - to - ground fault to actuate the protective devices is considered as the sole advantage of the ungrounded system. The system can be permitted to continue in operation until it is convenient to locate the fault without interfering with production. If the fault is not cleared in time and a second fault occurs in the same circuit as before or on another circuit, the resulting line - to - line fault will actuate relays or circuit breakers and can trip either one or both circuits.

5.3 ADVANTAGES OF SYSTEM NEUTRAL GROUNDING

The advantages of operating an industrial power system grounded compared with operating it ungrounded may be one or more of the following:

1. Reduced operating and maintenance expense.
2. Reduction in magnitude of transient overvoltages.
3. Improved lightning protection.
4. Simplification of ground fault location.
5. Improved system and equipment fault protection.
6. Improved service reliability.
7. Reduction in frequency of faults.
8. Greater safety for personnel.

The relative weight of these advantages varies with system voltage classes and to a lesser degree with installation conditions. Some additional advantages of grounded systems are:

1) Low impedance system neutral grounding allows the use of grounded neutral lightning arresters. This gives better lightning protection.

2) Better protection can be obtained in a grounded neutral circuit because differential relay protection of motors, generators and transformers is improved in grounded neutral systems.

3) Slightly lower system costs can sometimes be obtained because cables designed for grounded-neutral service are appreciably less expensive than those designed

for ungrounded neutral service for: 1) systems at 13.8 kV and above and 2) systems where automatic ground fault relaying is used.[1]

4) It has been the experience of operators who have used both grounded and ungrounded neutral systems that the failure rate is substantially lower and the time the system is out of service less on the grounded neutral system. This results from the fact that transient overvoltages are reduced to safe values on a grounded neutral system. This reduction of overvoltages will increase the life of electric insulation and thus service interruptions will be minimized.

There are several methods by which a power system can be grounded. Figure 5.1 illustrates the commonly used grounding methods. Each method is named in accordance with the nature of the external circuit from system neutral to ground.

5.4 CLASSIFICATION OF SYSTEM GROUNDING

The types of system grounding used in industrial and commercial power systems are:

1) Solid grounding.
2) Reactance grounding.
3) Ground fault neutralizers.

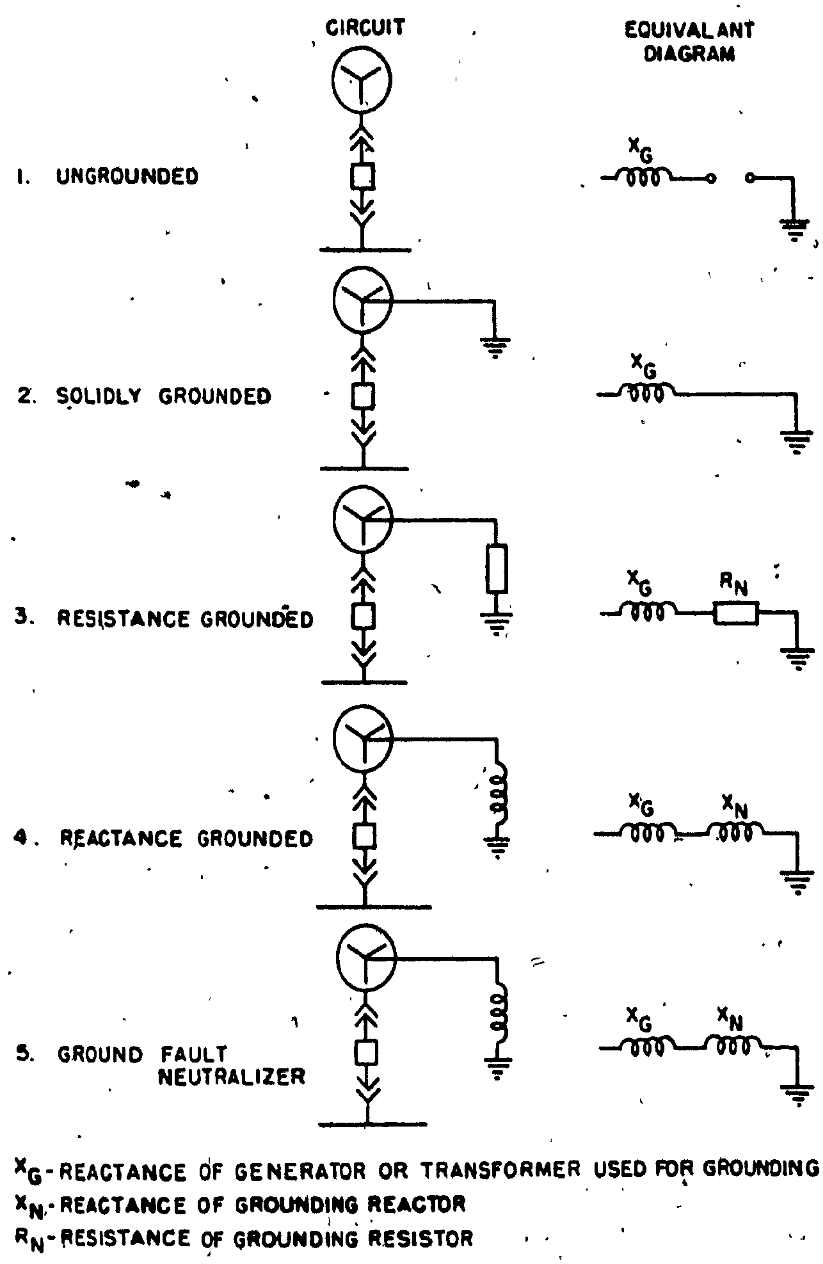


Fig. 5.1 System-neutral circuits and methods of grounding

4) Line grounding.
5) Mid-phase grounding.
6) Low-resistance grounding.
7) High resistance grounding.

Each type of grounding has advantages and disadvantages, and there is no general acceptance of any one method. Factors which influence the choice include:

1) Voltage level of power system.
2) Transient overvoltage possibilities.
3) Type of equipment on the system.
4) Required continuity of service.
5) Caliber and training of operating and maintenance personnel.
6) Methods used on existing systems.
7) Availability of convenient grounding point,
8) Code requirements.
9) Cost of equipment, including protective devices and maintenance.
10) Safety, including fire and shock hazard.
11) Tolerable fault damage levels.
12) Effect of voltage dips during faults.

It should be mentioned that in most industrial systems solid, low and high resistance grounding methods are almost exclusively used. These three methods offer themselves to the use of ground-fault protection devices.

Line and mid-phase grounding have been used in the past but they are rarely encountered in new industrial installations.

Grounding through reactance or through ground-fault neutralizers is used in special applications. For example, reactance grounding is used with low-voltage generators and ground-fault neutralizers are used primarily on systems above 15 kV consisting essentially of overhead transmission lines.(1)

5.4.1 SOLIDLY GROUNDED SYSTEMS

A power system is solidly grounded when a generator, power transformer or grounding transformer neutral is connected directly to the station ground or to the earth.

Solid grounding cannot be considered a zero impedance circuit since the reactance of the grounded generator or transformer is in series with the neutral circuit. If the reactance of the generator or transformer is too great, the objectives sought in grounding, namely freedom from transient overvoltages, will not be achieved. Thus it is necessary to determine how solidly the system is grounded.

A ground-fault current of 25% to 100% of the three-phase current would assure us of good solid grounding and would prevent the development of transient overvoltages. This may mean that the rms ground-fault current could be in the order of 10,000 to 40,000 A.

On low voltage systems (600 V, and less) solid grounding is commonly used. The neutral is usually obtained at the wye point of the transformer. Upon occurence of a fault, a large ground fault current is available to operate the series trip devices, which one normally furnishes on most low voltage interrupters, or to blow the fuses so that prompt fault clearing is achieved. Solid grounding is also the most common method at voltages above 13.8 kV. At those voltages the advantages associated with solid grounding (better lightning protection, more sensitive relaying, reduced line hardware and equipment costs) become more and more significant and for those reasons virtually all utility systems are solidly grounded.

The disadvantage of using solid grounding includes the fact that ground-fault currents are often of high magnitude, and thus are very destructive, unless interrupted within a few cycles. This almost immediate interruption, deenergizes the affected circuit. The forced outage is unacceptable in some applications where continuity of service is very important.

5.4.2 LOW-RESISTANCE GROUNDING

In resistance grounding, the neutral is connected to ground through one or more resistors.

When a single line - to - ground fault occurs on a resistance-grounded system, a voltage appears across the resistor (or resistors), nearly equal to the normal line - to - neutral voltage of the system. The resistor current is equal to the current in the fault. Thus the current is practically equal to line - to - neutral voltage divided by the number of ohms of resistance used. Thus resistors have a voltage rating equal to line - to - neutral voltage and a current rating equal to the current which flows when this voltage is applied to the resistor. In this method, when the above-mentioned resistor rating is used, the line - to - ground voltages which exist during a line - to - ground fault are nearly the same as for an ungrounded system (except transient overvoltages).

A system properly grounded by resistance is not subject to destructive transient overvoltages. For resistance-grounded systems at 15 kV and below such overvoltages will not ordinarily be of serious nature unless the resistance is so high as to limit the ground-fault current to a small fraction of 1% of the system three-phase fault current (i.e. to less than the system charging current).

Usually the magnitude of the grounding resistance is selected to allow sufficient current for ground-fault relays to detect and clear the faulted circuit. The value of resistance depends on the type of relaying and the amount of motor windings which can be protected.

Systems grounded through resistors as described in this section should use lightning arresters for ungrounded-neutral circuits, where lightning arresters are required.

The reasons for limiting the current by resistance neutral grounding are as follows:

1) To reduce burning and melting effects in faulted electric equipment such as switchgear, cables and rotating machines.

2) To reduce mechanical stresses in circuits and apparatus carrying fault current.

3) To reduce electric shock hazards to personnel, caused by stray ground-fault currents in the ground return path.

4) To reduce the momentary line-voltage dip occasioned by occurence and clearing of a ground-fault.

5.4.3 HIGH-RESISTANCE GROUNDING

This method of grounding employs a neutral resistor of higher ohmic value than that which would be selected for a low-resistance-grounding application. This means that the steady-state line - to - ground voltage of the unfaulted phases during a ground fault would be closer to full line - to - line value than in the case of low-resistance grounding.

Properly applied, high-resistance grounding limits transient overvoltages resulting from repetitive occurence of a line - to - ground fault to values which are comparable to those found in a lower-impedance type of grounding.

The ground-fault current usually associated with high-resistance grounding is but a few tenths of 1% of system three-phase fault current.[1]. However, proper application of this grounding method results in a value of ground-fault current, which is equal to or greater than the system three-phase charging current. As in the case of the ungrounded system, this ground-fault current is not enough to actuate overcurrent protective devices, and thus immediate tripping does not occur. This allows the operation to continue with the ground-fault until a more favorable moment for circuit outage arrives. Sensitive relaying is required with high-resistance grounding because of the low ground-fault currents involved. It is important to allow sufficient ground-fault current to flow to compensate for the capacitive charging current of the system which otherwise could trigger transient overvoltages during switching or other changing circuit conditions. This current should not be less than the measured or calculated capacitive charging current of the existing and projected system.

5.5 ARCING FAULTS - NATURE AND PROBLEMS

It has been mentioned earlier that there are basically two types of faults: (1) bolted and (2) arcing. So far concern has been shown to the first. In this section, time will be spent on the second type of fault, namely arcing fault.

Arcing ground fault currents are commonly caused by insulation failure, loose connections, construction accidents, debris, etc. Although the current magnitudes may be very low in relation to the three-phase fault currents, they do cause major problems such as the interruption of electrical power, destruction of electrical equipment and associated hazards to personnel. Arcing faults have been responsible for damage to virtually all types of electrical equipment, regardless of manufacturer or mode of operation.

The energy released during an arcing fault is localized and can be so intense that it can vaporize copper or aluminum conductors and surrounding steel enclosures. In order to understand how much damage results from these currents we will try to determine a level of "acceptable" damage to the equipment. Controlled experiments have been carried out by various manufacturers to establish the amount of damage caused by various values of current flowing for definite periods of time. In a paper presented to the IEEE in 1967 [16] a theory was suggested as to how to measure the damage done by arcing faults. This method was quickly picked up by other manufacturers and seems to be becoming a popular rule of thumb for a damage scale. The theory suggests that arcing damage varies directly as the current magnitude, the voltage of the arc and time. From this fact, a strictly empirical equation was developed, as shown below:

$$\text{Arc Energy (kW-cycles)} = \frac{I * AV * t}{1000}$$

where I = Ground fault current in Amperes

AV = Approximate Arcing voltage = 100 Volts for a 600 Volts system

t = time in cycles the fault persists before extinguishing itself or being cleared by a protective device.

From the controlled experiments carried out this kW-cycle parameter has been related to the amount of damage. The following table (15) shows the effect of various values of arc energy and the amount of damage they can produce.

Arc Energy (kw - cycles)	Amount of Damage
100	The location of the fault can be identified by close inspection - there will be spit marks on the metal and some smoke marks.
2000	If there is no damage then the equipment can usually be restored by painting smoke marks and repairing punctures in the insulation.
6000	Minimal amount of damage results but fault may more easily be located.
10,000	The fault will probably be contained by the metal enclosure - # 10 gauge steel.
20,000	The fault will probably burn through a single thickness enclosure and spread to other sections of thef equipment.
Over 20,000	Considerable destruction in proportion to the let-through energy.

In order to get an appreciation of the tremendous amounts of energy released and the considerable resulting damages the following elementary case will be considered. Consider a protective device operating on an inverse time characteristic. A normal setting could be 100% long time with instantaneous setting at 4 times. With these settings an overload current of three (3) times normal could take up to 60 seconds to trip the protective device. In other words if the protective device were a 1600 Ampere breaker, it would be possible to have a ground fault current of 4800 Amperes flowing for a full minute. Thus:

$$\text{Arc Energy} = \frac{4800 * 100 * 60 * 60}{1000} = 1{,}728{,}000 \text{ kW-cycles}$$

It should be noted that the time of current flow is controlled by two factors, i.e. the time delay setting of the ground protection relay and the opening time of the breaker that is clearing the fault. Thus it can be seen that if the relay is delayed too long or the opening time of the breaker is excessive then the kW cycle value could reach a high level which would be unacceptable from a damage point of view.

5.5.1 MAGNITUDE OF ARCING FAULT CURRENTS

When designing an electrical power system maximum fault conditions are always considered. Also, when determining the equipment interrupting capacity requirements, maximum fault currents are taken into consideration. Phase protective devices which are normally set for the load conditions are expected to achieve selective tripping but avoid nuisance tripping. However, under arcing conditions, short-circuit levels may be at their minimum levels and the phase protective tripping devices may be insensitive to these low-level fault currents since they are set to meet load requirements. It has been said earlier that the determination of those low-level fault currents is necessary in determining protection schemes. Exact minimum values of arcing ground current are difficult to compute precisely for several reasons:

1) Results are influenced by the geometry, spacing, environmental and supply circuit characteristics.

2) Current wave shape is generally irregular with a harmonic content.

3) Current is frequently discontinuous.

We have seen earlier that, mathematically, the general expression for a line - to - ground fault current in a three-phase system in symmetrical component parameters is:

$$I_f = \frac{3V_{L-N}}{Z_o + Z_1 + Z_2 + 3Z_g} \qquad (5.1)$$

Where I_f = line - to - ground fault current

V_{L-N} = line - to - neutral voltage

Z_1 = positive sequence impedance

Z_2 = negative sequence impedance

Z_o = zero sequence impedance

Z_g = ground return impedance

This mathematical expression does not consider the effects of the voltage drop due to the arc in an arcing fault condition, but expresses a bolted-to-ground condition. Due to the voltage drop across the arc, the resultant ground-fault current may be considerably lower than the bolted-ground fault current. This reduction can be accounted for by a multiplier K which relates the arcing to bolted-ground-fault current as follows:

$$I_f \text{ arcing} = K \frac{3V_{L-N}}{Z_1 + Z_2 + Z_o + 3Z_g} \qquad (5.2)$$

Values of K are given in table reproduced below[17], [18]

TYPE OF FAULT	NOMINAL SYSTEM VOLTAGE		
	575 V	480 V	208 V
Single Phase (L-G)	0.40	0.38	0
Single Phase (L-L) *	0.85	0.74	0.02
Three Phase	0.94	0.89	0.12

Table 6: Factor relating Arcing to bolted-ground fault currents

* These type faults do not involve ground. They are included as matter of interest.

Those values are used only in low-voltage systems since the effect or arc voltage is significant in comparison with the driving voltage. It is also important to remember that this calculation procedure for determining the ground-fault current is only an approximation. The minimum fault current value is dependent on actual system conditions at the time of fault. Typical conditions that would increase the system impedance and thereby cause a lower ground-fault current than that calculated would be:

a) Installation changes that depart from design, such as greater conductor spacings (phase-to-phase and/or phase-to-ground) or ground-return path alterations (ground conductors, bonding jumpers, etc.).

b) Operating conditions such as opening of one phase to the transformer primary, changes in the ground-return path due to loose connections, open-ground conductors, etc.

5.5.2 SOLUTIONS TO THE ARCING FAULT PROBLEMS

Solutions to the arcing-fault problem involve a two-pronged approach.

1) Minimize the probability of arcing fault initiation by:

a) Careful attention to system design and to the settings of protective devices.

b) Selecting equipment that is isolated by compartments within grounded metal enclosures.

c) Selecting equipment with draw-out, rack-out, or stab-in features, thereby reducing the necessity of working on energized components.

d) Providing proper installation practices and supervision.

e) Protecting equipment from unusual operating or environmental conditions.

f) Insisting on a thorough clean up immediately before initial energization of equipment to remove construction debris, such as wire clippings, misplaced tools, etc.

g) Executing regular and thorough maintenance procedures.

h) Maintaining daily good house-keeping practices.

2. Sense and remove the arcing fault quickly (within cycles on a power frequency base) so that damage is minimal, thus allowing relatively rapid restoration of power after the damage is repaired. To remove the arcing fault current promptly from the system, protective devices with the following characteristics are required:

a) Sensitivity to detect low-level ground-fault current magnitudes.

b) Speed to operate within cycles to remove the fault from the system.

c) Selectivity to provide coordination with other protective devices so that a minimum portion of the system is shut down under ground-fault conditions.

d) An adjustment and setting of each protective device which can be tailored to the specific system.

5.6 METHODS OF GROUND FAULT DETECTION

The ground-fault current can be monitored either as it flows out to the fault or on its return to the neutral point of the source transformer or generator. When monitoring the outgoing fault current, the currents in all power conductors are monitored either individually, or collectively. When monitoring the return fault current only the ground-fault return conductor is monitored. Caution is required to help assure that the returning ground-fault current bypasses the outgoing monitoring current transformer, but does not bypass the current transformer monitoring the returning ground-fault current.

Ground-fault responsive devices can consist of a static voltage relay and matched current sensors or an overcurrent relay (electro-magnetic or static) using any properly rated standard window-or bar-type current transformer. The relay pick-up level is adjustable and the relay may be equipped with an adjustable time-delay feature. Operation of the relay activates a trip mechanism on the interrupting device. Selectivity is achieved through a time delay and/or current setting. Zone selectivity can be achieved by using a differential scheme.

5.6.1 RESIDUAL GROUND FAULT PROTECTION

The ground current is measured by current transformers which are interconnected in such a way that a ground relay responds to a current proportional to the ground-fault current. The basic residual scheme is shown in fig. 5.2. Although this scheme is frequently applied in medium voltage applications, is hardly ever used at low-voltage levels because of the need for current transformers, (3 for the 3-wire systems and 4 for 3-phase 4-wire systems). Due to unequal saturation of the current transformers residually connected relays cannot have sensitive settings.

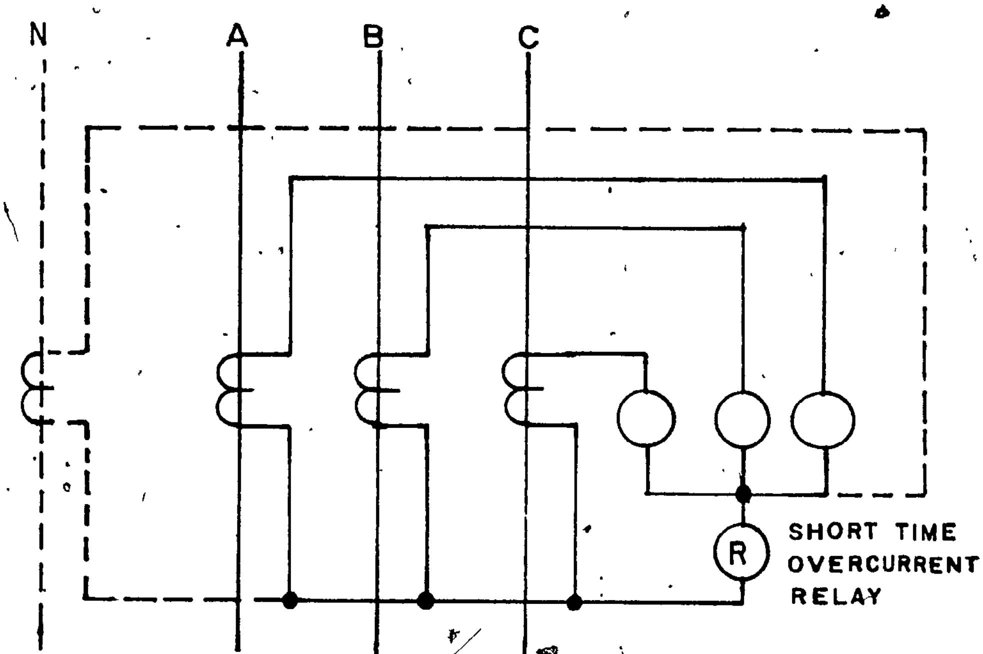


Fig. 5.2 Residually Connected Ground Relay

5.6.2 CORE BALANCE OR GROUND SENSOR PROTECTION

Ground-sensor protection is provided by a combination of a window- or donut-type current transformer, which surrounds all 3 or 4 outgoing conductors and a specifically matched relay, with either instantaneous and/or time delay characteristics.

Under normal conditions, all current flows out and returns through the current transformer. When a ground fault occurs, the ground fault current returns through the equipment grounding conductor (and possibly other paths) bypassing the current transformer. The flux produced in the current transformer core is proportional to the ground fault current, and a proportional current flows in the ground relay circuit. The principle of the core balance current transformer circuit is shown in fig. 5.3. By properly matching the current transformer and relay, ground-fault detection can be made as sensitive as the application requires.

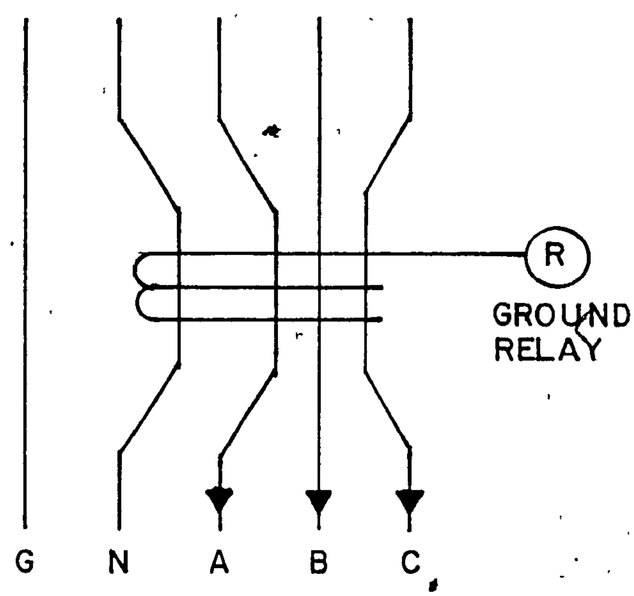


Fig. 5.3 Ground-sensor protection. Relay is insensitive to balanced 3-phase load currents.

5.6.3 GROUND RETURN PROTECTION

Ground-fault currents must return to the transformer neutral to complete the circuit. The most reliable application of this principle is in the transformer neutral connection to ground. A current transformer installed in this location will sense all ground currents returning to the source transformer. (Fig. 5.4). Operation of this ground-return relay indicates that the ground-fault may be on the bus, in the transformer winding, or on its extension to the line terminals of the main secondary breaker. To provide the proper protection, the relay should be wired to trip the main secondary breaker and to start a timer so that in approximately five to ten cycles after breaker operation, if the fault is still sensed by the ground-return relay, the timer will signal the transformer primary protector to trip. Application of this form of protection in locations other than the transformer neutral-to-ground connection must be carefully coordinated to assure that the ground sensor relay will sense all or most of the ground return current.

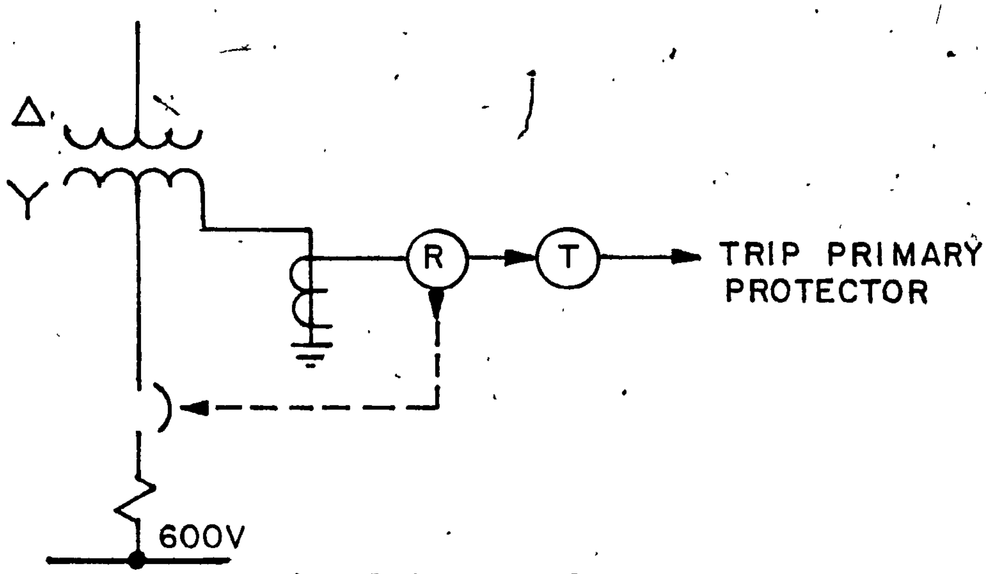


Fig. 5.4 Transformer neutral ground fault protection.

5.6.4 GROUND DIFFERENTIAL PROTECTION

Ground differential relaying is effective for main bus protection since it has inherent selectivity. With the differential scheme (Fig. 5.5), core-balance current transformers are installed on each of the outgoing feeders and another smaller current transformer is placed in the transformer neutral connection to ground. This arrangement can be made sensitive to low ground-fault currents without incurring tripping for ground-faults beyond the feeder current transformers. All current transformers must be very carefully matched to prevent improper tripping for high-magnitude faults occuring outside the differential zone.

Bus differential protection protects only the zone between current transformers and does not provide backup protection against feeder faults.

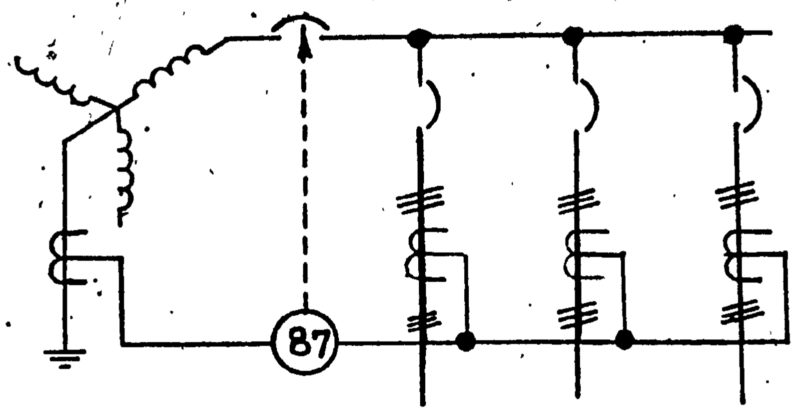


Fig. 5.5 Ground Differential Scheme

6

PROTECTION OF MAJOR EQUIPMENT

6.1 TRANSFORMER PROTECTION

6.1.1 GENERAL DISCUSSION

Proper protection is important on transformers of all sizes, even through they may be some of the simplest and most reliable components in any power distribution system. The following table 7,(8) depicting results of a certain study, indicated that although transformers had the lowest failure rate per year, the average out-of service time per transformer failure was very high.

System Component	Average Failures per Year	Average Hours per Failure	Average Forced Hours Downtime per Year
Electric utility power supply	0.963	2	1.93
Power cables (per 1000 circuit ft)			
underground, nonleaded conduit	0.0397	36	1.43
above ground, nonleaded conduit	0.0252	44	1.11
Drawout metal-clad circuit breakers			
600 V and below	0.0163	25	0.41
above 600 V	0.0104	79	0.82
Transformers (primary below 15 kV)	0.0076	253	1.92

Table 7 - Reliability of Major System Components

Protection is achieved by the proper combination of system design and protective devices. Protection should be designed to include:

(1) Protection of the transformer from harmful conditions occurring on the system to which the transformer is connected.

(2) Protection of the electric system from the effects of transformer failure.

(3) Detection and indication of conditions occurring within the transformer which might cause damage or failure. Those are the so-called "incipient" faults.

The system and devices should be selected to provide protection in each of the above areas. Some devices will include more than one of these areas in their protective operation.

Failure of a transformer can be caused by any number of internal or external fault conditions. The following table 8,[9] indicates the percentage failure rates corresponding to each type of fault.

TYPES OF FAULTS	TYPICAL %
Windings	50%
Tap changer	20%
Bushing failure	15%
Terminal board failures	7%
Core failures	3%
Miscellaneous	5%

Table 8 - Typical failure rates

Transformer failures, other than from physical or environmental reasons, are caused by three distinct undesirable conditions, namely overloads, short circuits, and overvoltages.

6.1.2 OVERLOAD THERMAL PROTECTION

An overload will cause a rise in the temperature of the various transformer components. If the final temperature is above the design temperature limit, deterioration of the insulation system will occur, causing a reduction in the useful life of the transformer.

Protection against overloads consists of both load limitation and overload detection.

The major load limitation that can be properly applied to a transformer is one that corresponds to transformer temperature. By monitoring the temperature of the transformer, overload conditions can be detected. A number of monitoring devices which mount on the transformer are normally used for alarm or to initiate secondary protective device operation. They include the following:

a) Liquid temperature indicator: The liquid temperature indicator is the most common transformer temperature sensing device. It measures the temperature of the insulating liquid at the top of the transformer. Since the hottest liquid rises to the top of the tank, its temperature reflects the temperature of the transformer winding and is related to the loading of the transformer.

This device is normally equipped with one to three contacts which operate at preset temperatures, initiating first or second stage cooling and alarm or load reduction on the transformer.

b) <u>Thermal Relays:</u> Thermal relays are used to give a more direct indication of winding temperatures than the liquid temperature indicator. As shown in fig. 6.1 a current transformer, mounted on a transformer bushing, supplies current to the thermometer bulb heater coil which contributes the proper heat to closely simulate the transformer hot spot temperature.

Thermal relays are used more often on transformers 10 MVA and above than on smaller transformers.[(10)]

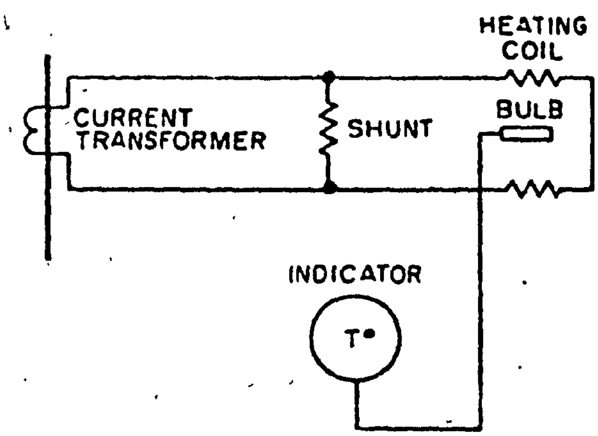


Fig. 6.1 Thermal or winding temperature Relay

c) <u>Hot-Spot Temperature Equipment:</u> It is similar to thermal relays but in order to sense the hot spot temperature it utilizes the Wheatstone bridge method. This principle is demonstrated in fig. 6.2. It should be mentioned that the hot spot temperature of the transformer is not actually measured, but rather simulated.

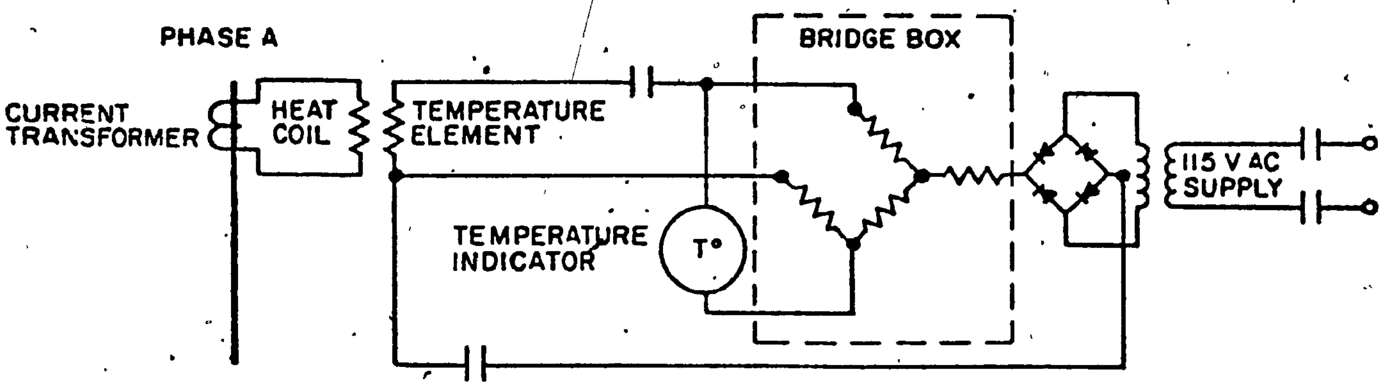


Fig. 6.2 Hot-spot temperature indicator

d) Forced-air Cooling: By utilizing auxiliary forced-air cooling equipment, one can increase the capacity of a transformer by 15 to 33 percent of base rating, depending upon transformer size and design.[10]

6.1.3 SHORT-CIRCUIT CURRENT PROTECTION

In addition to thermal damage from prolonged overloads, transformers are affected by internal or external short-circuit conditions.

Protection of the transformer against both internal and external faults and overloads should be as rapid as possible to reduce damage to a minimum. However, this may be restricted by selective co-ordination system design and operating procedure limitations.

There are several sensing devices available which provide varying degrees of short-circuit protection. The devices sense two different aspects of a short-circuit. The first group of devices sense the formation of gases consequent to a fault and are used to detect internal faults. The gas sensing devices include:
pressure relief devices, pressure relays, gas-detector relays and combustible-gas relays.
The second group senses the magnitude of short-circuit current directly. The short-circuit current sensing devices include:
fuses, overcurrent relays and differential relays.

6.1.3.1 GAS-SENSING DEVICES

a) Pressure Relief Devices: The major function of the pressure relief device is to prevent rupture or damage to the transformer tank due to internal fault conditions. When the internal pressure exceeds the tripping pressure the device releases the excess gas or fluid and at the same time actuates the alarm.

b) Pressure Relays: This type of relay is very sensitive to the rate of rise in internal pressure. Normally they are provided with a pressure-equalizing opening to prevent operation of the relay on gradual rises in internal pressure due to changes in loading or ambient conditions.

The major function of this relay is to initiate isolation of the transformer from the electric system. They are normally used with transformers of 5000 kVA and above.[10]

c) Gas Detection Relays: Those are special devices that detect and indicate an accumulation of gas generated inside the transformer by winding faults or hot-spots in the core. When an accumulation of gas reaches a predetermined level an alarm will be actuated. The gas can then be withdrawn for analysis and recording. This type of relay can only be used with conservator-tank design.

d) Combustible Gas Relay: This is a special device used to periodically detect and indicate the presence of combustible gas formed by decomposition of insulating materials within the transformer. This device can be used on transformers with positive-pressure inert gas-oil preservation systems.(10) However, they are not used on substation transformers due to the expense involved.

6.1.3.2 CURRENT-SENSING DEVICES

a) Primary fuses: Fuses are relatively simple and inexpensive one-time devices that can provide short-circuit protection for a transformer primary. However, they have to meet several criteria, and their features are lacking when compared to relay protected systems. The most important criteria and limitations are:

1) They must be able to withstand the transformer magnetizing inrush current of ten to twelve times full load for 0.1 second (6 cycles) without melting or damaging the fusible element.(10) But by doing so they are less sensitive to low-magnitude fault conditions.

2) Fuses must be capable of interrupting the maximum available fault current at the application location.

3) Fuses do not provide protection against single phase operation.

4) Selective co-ordination is difficult due to limited characteristics of available fuses.

5) Normally they are applied in conjunction with a magnetizing current break switch which is interlocked with the secondary circuit breaker to prevent the switch from operating under load conditions.

b) Primary Overcurrent Relays: Primary overcurrent relays afford about the same degree of protection as do fuses, but the relays allow higher loading capabilities than fuses because of the fixed inherent time-current characteristics of fuses vs. the variable time-current relationship of an overcurrent relay. There are at least two disadvantages to primary overcurrent relays.

1) The device must cause some other equipment to function to clear the fault. This device might be a local primary breaker or another switching device. If there is no local device, some remote equipment must operate to clear the fault. Some form of transfer tripping may be required such as a pair of wires from the relay contacts to a breaker if the distance is not too great, a tone frequency-shift scheme, a high-speed grounding switch to fault one of the primary phase leads to ground intentionally, or some other scheme that might be devised.

2. The use of primary overcurrent relays as well as primary fuses inserts another step of protection into the co-ordination scheme that forces the up-stream devices to be set with longer operating times so that time selectivity can be maintained.

c) Differential Relays: Transformer differential is a protective scheme, that provides fast, sensitive protection for faults within its zone of protection. Its zone of protection extends to the area or the equipment between the upstream and downstream current transformers. The secondary cable and circuit breaker could be included. Figure 4.15 indicates the principle involved.

Several problems are involved in the application of differential relays.

1) The differential protection scheme requires some short of primary switching device or transfer-tripping scheme to effect the circuit opening to remove the short-circuit.

2) Current transformers associated with each winding have different ratios, ratings, and characteristics when subjected to heavy loads and short-circuits. Auxiliary current transformers or relays with tapped operating and restraint coils should be used.

3) Magnetizing current inrush appears as an internal fault to the differential relays. The relays must be desensitized to the current inrush, but they should be sensitive to short-circuits within the zone during the same period. This can be accomplished by the use of harmonic restraint coils. The theory behind it is that the magnetizing current inrush has a large harmonic component which is not present in short-circuit currents. Thus the harmonic restraint relays can distinguish between faults and inrush.

4) Transformer connections often introduce a phase shift between high-and-low voltage currents. This should be compensated by proper current transformer connections. Table 9 [11] shows the recommended current-transformer connections for the various power-transformer winding connections.

Transformer connection		Current-transformer connection	
Primary	Secondary	Primary	Secondary
Delta	Delta	Wye	Wye
Wye	Delta	Delta	Wye
Wye	Delta	Wye - wye-delta aux.	Wye
Delta	Wye	Wye	Delta
Delta	Wye	Wye	Wye - wye-delta aux.
Wye*	Wye	Delta	Delta

* Assume delta tertiary winding.

The main current transformers assumed to be in the line conductors and not inside any delta-connected windings.

Table 9 - Current-transformer Connections

5) Heavy currents for faults outside the zone of protection can cause unbalance between the current transformers. Percentage differential relays operating only when the difference is greater than a definite percentage of the phase current, are designed to overcome this problem.

Differential relays are often recommended on all transformers 1000 kVA and above. Harmonic restraint percentage differential relays are recommended for transformers 2000 kVA and above. (10)

6.1.4 PROTECTION AGAINST OVERVOLTAGES

Overvoltages caused by lightning, switching surges, and faults must be considered in designing transformer protection. Lightning arresters are used to control those overvoltages. The degree of protection is determined by the amount of exposure, the size and importance of the transformer to the system, and the type and cost of the arresters. In descending order of cost and degree of protection, the arresters available are: station type, intermediate type, and distribution type.

6.2 MOTOR PROTECTION

6.2.1 GENERAL DISCUSSION

There is a wide range of motors and motor characteristics in existence, because of the numerous duties for which they are used, and all of them need protection. Fortunately, the more fundamental problems affecting the choice of protection are independent of the type of motor and the type of load to which it is connected.

There are many variables involved in choosing motor protection; motor characteristics, motor starting conditions, ambient conditions, driven equipment, power system and last but not least, motor importance.

In general the conditions for which motor protection is required, can be divided into two broad categories:

a) Imposed External Conditions, including unbalanced supply voltages, undervoltage, single-phasing and reverse phase sequence starting, and, in the case of synchronous machines only, loss of synchoronism.

b) Internal Faults, including bearing failures, internal shunt faults, which are most commonly ground faults, and overloads.

Protective devices may be installed on the motor controllers or directly on the motors. The protection is usually included as part of the controller except for very small motors, which have various types of build-in thermal protection.

Motors rated 600 V or below are generally switched by contactors and protected by fuses or low voltage circuit breakers equipped with magnetic trips. Motors rated from 600 to 4800 V are usually switched by a power circuit breaker or by a contactor (often supplemented by current-limiting fuses to accomodate higher interrupting requirements). Motors rated from 2400 to 13800 V are switched by power circuit breakers.[12]

While protective relays may be applied to a motor of any size or voltage rating, in practice they are usually applied only to the larger or higher voltage motors.

Since it is virtually impossible to cover each and every available protection relay we will only try to mention the most important, without going into much detail.

6.2.2 PROTECTIVE RELAYS USED IN MOTOR PROTECTION

6.2.2.1 UNDERVOLTAGE - DEVICE 27

The usual reasons for using undervoltage protection are:

a) To prevent possible safety hazard of motor automatic restarting when voltage returns, following an interruption.

b) To avoid excessive inrush to the total motor load on the power system, and the corresponding voltage drop, following a voltage dip, or when voltage returns following an interruption.

It should be noted that for motors extremely important to continuity of service, the undervoltage relays are used for alarm purposes only.

6.2.2.2 PHASE UNBALANCE - DEVICE 46

The purpose is to prevent motor overheating damage. Motor overheating occurs when the phase voltages are unbalanced, for two reasons:

a) Increased phase currents flow in order that the motor can continue to deliver the same horsepower as it did with balanced voltages.

b) Negative-sequence voltage appears and causes abnormal currents to flow in the rotor.

Phase unbalance protection should be provided in all applications where single phasing is a strong possibility due to the presence of fuses, or disconnect switches which may not close properly on all three phases etc.

A general recommendation is to apply phase unbalance protection to all motors 1000 HP and above.[(10)]

6.2.2.3 INSTANTANEOUS PHASE OVERCURRENT - DEVICE 50

The purpose is to detect phase short-circuit conditions with no intentional delay. Fast clearing of these faults will:

a) Limit damage at the fault.

b) Limit the duration of the voltage dip accompanying the fault.

c) Limit the possibility of fault spreading, fire, or explosion damage.

In general one relay per phase should be provided (10) and should be used with the following equipment:

a) Medium voltage (2.4 - 15 kV) circuit breaker type motor starters.

b) Medium voltage contactor-type starters which do not have power fuses.

c) Low-voltage circuit breaker type motor starters used with motors whose importance justifies the costs.

6.2.2.4 TIME DELAY PHASE OVERCURRENT - DEVICE 51

The purpose is to detect:

a) Failure to accelerate to rated speed in the normal starting interval.

b) Motor stalled condition.

c) Low magnitude phase fault conditions.

6.2.2.5 OVERLOAD (PHASE OVERCURRENT) - DEVICE 49 OR 51

The purpose is to detect sustained stator current in excess of motor continuous rating and trip prior to motor damage.

Sometimes if motors have winding temperature devices and fairly close operator supervision, this protection is used for alarm purposes.

Although in the past it has been common to provide relays in only two phases, today the code stipulates the use of one relay per phase, or a single relay responsive to individual current in each of the three phases. They are normally used with contactor-type and circuit breaker motor starters.

6.2.2.6 INSTANTANEOUS GROUND OVERCURRENT - DEVICE 50 G & 50N

The purpose is to detect ground-fault conditions with no intentional delay. This can be done by using either:

a) Zero-sequence Current transformer and Ground Relay Device 50G or

b) Residually Connected Current transformer and Ground Relay - Device 50N.

6.2.2.7 TIME DELAY GROUND OVFRCURRENT - DEVICE 51G & 51N

The purpose is to detect ground-fault conditions. Two schemes are available:

a) Zero-sequence Current transformer and Time-delay Ground Relay - Device 51G or

b) Residually Connected Current transformers and Time-delay Ground Relay - Device 51N.

It should be mentioned that although early application of ground protection used current transformers and relays, to-day both instantaneous and time-delay ground-fault protection is available with solid-state tripping systems on low-voltage (up to 600 V) circuit breakers.

6.2.2.8 PHASE CURRENT DIFFERENTIAL - DEVICE 87

The purpose is to quickly detect fault conditions:

For the application of differential protection the following recommendations (10) can be made:

a) In ungrounded systems: Use differential protection with all motors above 1000 hp.

a) In grounded systems: Use differential protection with motors above 1000 hp if ground protection is not considered adequate to protect against phase to phase faults.

6.2.2.9 STATOR WINDING OVERTEMPERATURE - DEVICE 49 OR 49S

The purpose is to detect excessive stator winding temperature prior to the occurrence of motor damage. Sometimes two temperature settings are used, the lower for alarm and the higher to actuate tripping devices.

Winding temperature is detected by using: RTD'S, Thermocouples, Thermostats & temperature bulbs, and finally Thermistors with either a Positive or Negative temperature coefficient.

This type of protection is commonly applied to all motors rated 1500 hp and above.(10)

6.2.2.10 ROTOR OVERTEMPERATURE - DEVICE 49 OR 49R

It again detects excessive rotor winding temperature and is available for brush-type synchronous motors and for temperature protection (by proximity) of Wound Rotor Induction-Motor Starting Resistors.

6.2.2.11 OTHER SPECIALIZED PROTECTION

Under this heading we can include the following:

1) Synchronous motor protection which includes:

a) Damper winding protection-Device 26; protection against high currents induced to rotor damper windings if the motor takes longer to accelerate than it has been designed for.

b) Field current failure protection; during operation field current may drop to a low value. This should be monitored because motor will probably pull out of step and stall.

c) Excitation Voltage availability; permissive voltage relay that will allow starting only if excitation voltage is present.

d) Pull-out Protection-Device 78 (also 55 and 95).

e) Incomplete starting sequence-Device 48; timer blocking tripping of field current failure protection and pull-out protection during the normal starting interval.

2) Induction Motor Incomplete Starting Sequence Protection-Device 48; timer applied to protect against failure to reach normal running conditions within the normal starting time.

3) Protection against too Frequent Starting.

4) Lightning and Surge Protection; surge arrecters and surge capacitors one per phase, connected between phase-to-ground are used to limit voltage to ground impressed upon the motor stator winding due to lignt-ning and/or switching surges.

5) Protection against Overexcitation from Shunt Capacitance. When the supply voltage is switched off, an induction motor initially continues to rotate and retain its internal voltage. If a capacitor bank is left connected to the motor, or if a long distribution line having significant shunt capacitance is left connected to the motor, the possibility of overexcitation exists. Overexcitation results when the voltage versus current curves of the shunt capacitance and the motor no-load excitation characteristic intersect at a voltage above the rated motor voltage. Damaging inrush can occur if automatic reclosing or transfer takes place on a motor which has a significant internal voltage due to overexcitation.

6) Protection against Automatic reclosing or Automatic transfer. When supply voltage is switched off, motor continues to rotate and retain internal voltage. If supply returns but is out of phase with internal voltage, high inrush will occur which can damage motor windings.

7) Protection against failure to rotate or Reverse Rotation.

8) Mechanical and other protection which includes: bearing and lubricating, Ventilation and Cooling, Vibration, Liquid detectors and finally fire Detection and Protection.

6.3 MISCELLANEOUS PROTECTION

6.3.1 CABLE PROTECTION

6.3.1.1 GENERAL DISCUSSION

The electrical code requires that conductors must be protected in accordance with their current carrying capacities.

They must be protected also for short-circuit currents which can flow either for faults within the cable or «through» faults on other equipment. For this purpose total clearing times are of course the important times.

Protection can be achieved by overcurrent relays, thermal overload, fuses, differential, direct tripping overloads and other forms usually used for other equipment protection.

Generally the subtransient current of a system is used to designate the maximum available short-circuit current in the cables protected by the instantaneous relays and medium voltage switchgear circuit breakers. For cables protected by fuses, cable limiters and protectors, or low-voltage and instantaneous trip circuit breakers, the asymmetrical current value is used. However for liberal design margins where economic considerations are not critical, the momentary and interrupting current ratings of the switchgear, circuit breakers, or fuses may be used as the basis for cable selection and protection.(10)

6.3.2 BUS AND SWITCHGEAR PROTECTION

6.3.2.1 GENERAL DISCUSSION

The substation bus and switchgear is that part of the power system that is used to direct the flow of power and to isolate apparatus and circuits from the power system. It includes the bus, circuit breakers, fuses, disconnect devices, current and potential transformers, and the structure on or in which they are mounted.

Bus protection should be fast in order to limit damage. It should be very stable, i.e. it should not have any tendency to operate for faults outside the bus zone. Reliability of operation is equally necessary because failure to clear a bus fault can result in extensive damage to equipment, danger to personnel and disruption of service.

Statistics collected in the U.K. indicate that over half the bus faults that have occurred during a certain study, were due to equipment insulation failures and flashovers due to lightning. About a third of the faults were caused by human errors and the remaining 10% by miscellaneous causes, such as falling objects, and circuit breaker failures.[13] More than half the faults were to ground.[13]

The fact that the isolation of a bus causes the disruption of all the circuits connected to it means that the bus protection must be very carefully monitored to prevent inadvertend operation of the relays protecting it.

The methods of protecting substation buses and switchgear will vary depending on voltage and the arrangement of the buses. The protection schemes utilized include: Bus overcurrent protection, differential protection, frame leakage protection, Backup protection and finally voltage surge protection.

6.3.2.2 BUS OVERCURRENT PROTECTION

If the system design and operation and the function of the process served do not require fast bus-fault clearance, overcurrent protection is used on each incoming power source circuit. On low-voltage systems circuit breaker trip devices or fuses are used but in medium and high voltage systems overcurrent relays are used.

6.3.2.3 DIFFERENTIAL PROTECTION

Differential relaying provides the best possible protection for buses and switchgear. It is high speed, sensitive, and permits complete overlapping with the other power system relaying. Differential relays make use of Kirchhoff's Law; all the currents entering and leaving the protected electrical circuit (busbar zone) must sum vectorially to zero unless there is a fault therein.

The differential protection methods generally used are, in order of the quality of protection they provide:

1) Voltage responsive (which overcomes the problem of current transformer saturation by using a voltage-responsive-high impedance - operating coil in the relay).

2) Linear Coupler (free of any direct-current or alternating-current saturation by replacing iron in conventional CT's by air core mutual inductance). Secondary may be open-circuited to facilitate switching.

3) Percentage differential (to be used only when relatively few circuits are connected to the bus). CT'S should have same ratio and identical characteristics.

4) Current Responsive (utilizing simple induction-type overcurrent relays). To be used when voltage differential or linear coupler cannot be economically justified.

5) Partial Differential Protection (a modification where one or more of the load circuits are left uncompensated in the differential system). Used as primary protection for buses with loads protected by fuses, as a back-up or local back-up to complete differential protection schemes.

6.3.2.4 FRAME LEAKAGE PROTECTION

In this form of protection the switchgear framework is insulated from ground, (building steelwork) except through the primary of a current transformer, whose secondary supplies an instantaneous overcurrent relay, with current, whenever a ground fault occurs anywhere in the bus or its associated equipment.

It is essential to have some check system with a frame leakage scheme in order to prevent a spurious current, causing unwanted operation. This usually takes the form of neutral check relays operated from current transformers connected in the neutrals of the system. As an alternative, a core-balance transformer can be fitted in the cable box or three residually connected current transformers on the incoming equipment, to supply an instantaneous overcurrent relay.

6.3.2.5 BACK-UP PROTECTION

If one or more bus breakers fails to trip in the event of a bus fault, back-up protection is provided by the relaying equipment at the far ends of the circuits that continue to feed current directly to the fault. However, this back-up protection may not be adequate because of system instability and effects on other power systems, and local back-up relaying may be necessary.

6.3.2.6 VOLTAGE SURGE PROTECTION

Protection against voltage surges due to lightning, arcing, or switching is required on all switchgear connected to exposed circuits, entering or leaving the equipment. A circuit is considered exposed to voltage surges if it is connected to any kind of open-line wires, either directly or through any kind of cable, reactor, or regulator.

The protection is provided by lightning arresters connected, without fuses or disconnecting devices, at the terminals of each exposed circuit.

The arresters shoud be of the valve type, of adequate discharge capacity, and their voltage ratings should be selected to keep the voltage surges below the insulation level of the protected equipment.

7

COORDINATION OF PROTECTIVE DEVICES

7.1 GENERAL DISCUSSION

On all but the simplest systems, there may be two or more circuit breakers, or other circuit protective devices, between a fault and the source of power. In order to localize the disturbance, as much as possible, these devices should be selective in operation so that the one nearest the fault on its power-source side will have the first chance to operate. If, for any reason, this protective device fails to function on schedule, the next device in the chain, that is, the next one on the up-stream side, must be ready to take over the job of opening the circuit. To accomplish this objective, the fault-current protective devices must have been selected, as in the case of fuses and non-adjustable direct-acting trips, etc., or be capable of adjustment, to operate on the minimum current that will permit them to distinguish between fault current and permissible load-current peaks. They must function in the minimum time possible and still be selective with others in series with them. When these two requirements are met, the damage to equipment, or the interference with production due to loss of power during a short-circuit, or both, will also be at a minimum.

In summary then we can say that the objective of a coordination study is to determine the characteristics, ratings, and settings of over-current protective devices which will ensure that the minimum unfaulted load is interrupted when the protective devices isolate a fault or overload anywhere in the system. At the same time, the devices and settings selected must provide satisfactory protection against overloads on the equipment, and interrupt short-circuits as rapidly as possible.

7.2 THE MECHANICS OF ACHIEVING COORDINATION

The achievement of coordination is a "trial and error" or "cut and try" routine in which the various time-current characteristic curves of the series array of devices are matched one against another on the graph plot. This matching recognizes, not only the limitations imposed by the protective devices on one another in the series array, but also those arising from the boundaries defined by the load current, short-circuit current, motor-starting current, thermal limits of equipment, Canadian Electrical Code requirements and so forth. The protective devices must operate within these boundaries, yet, as much as possible, should provide selective coordination with other protective devices upstream and downstream.

Except for relay and certain fuse applications, selective coordination usually will be obtained in low-voltage systems when the log-log plot of time-current characteristics displays a clear space between the characteristics of the protective devices operating in series. That is, no overlap should exist between two time-current characteristics, if selective coordination is to be secured. Nevertheless, the coordination study will often stop at a point short of complete selective coordination, when a satisfactory compromise has been effected between the opposite goals of maximum protection and maximum service continuity.

7.3 CRITERIA FOR SELECTION AND COORDINATION OF PROTECTION DEVICES

In order to obtain complete coordination of the protective equipment applied, it may be necessary to obtain some or all of the following information on short-circuit currents for each local bus.

a) Maximum and minimum 0 to 3 cycle (momentary) total rms short-circuit current. Those currents are used to determine the maximum and minimum currents to which instantaneous and direct-acting trip devices respond, and to verify the capability of the apparatus applied such as circuit breakers, fuses, switches, and reactor and bus bracings.

b) Maximum and minimum 3 to 60 cycle (interrupting duty) total rms short-circuit current. The maximum 3 to 60 cycle (interrupting) current at maximum generation will verify the ratings of circuit breakers, fuses, and cables. This is also the value of current at which the circuit protection coordination interval is established. The maximum 3 to 60 cycle (interrupting) current at minimum generation is needed to determine whether the circuit-protection sensitivity of the circuits is adequate.

c) Maximum and minimum ground-fault currents.

Furthermore complete coordination will be achieved by following a certain number of restrictions stipulated by standards [10] and government authorizing and licencing agencies. [20] The applicable rules are summarized below:

1) The protective scheme should operate in a fast, selective manner to minimize damage to faulty equipment while maintaining service to as much of the plant as possible.

2) No overcurrent device should operate before a device nearer the fault has had a chance to clear the fault.

3) A margin of 0.4 seconds should be allowed between the operation of a relay and the operation of the next upstream protective device. This margin accommodates breaker operating time, relay overtravel, manufacturing and setting tolerance; it should ensure that false tripping of a backup breaker does not occur.

4) A margin of 0.2 seconds should be allowed between the clearing time of a fuse and the operation of the next upstream protective device. This margin is selected on the same basis as the previous margin.

5) A current margin of 10% should be allowed between operation of protective devices, and an extra 16% between the secondary and primary protection on a delta-wye transformer. The 10% is for manufacturing tolerances, and the 16% accommodates high phase currents in the transformer primary for line-to-line faults on the secondary.

6) The protective scheme should not operate because of the inrush currents which may occur when a transformer is energized. An inrush current of 12 times full load for 0.1 seconds may be assumed for each transformer.

7) Relays for transformers should not have a setting exceeding 20 times full load for 2 seconds to provide physical withstand protection for the unit.

8) Transformer overcurrent relays should be set according to Canadian Electrical Code, Rule 26-046. This rule states that transformer protection should be set no higher than 250% unless there is a main secondary breaker set below 250%. Then the primary protection can be up to 600% for a 6% or less transformer, or up to 400% for a 6 to 10% transformer.

9) The protective scheme should not operate on motor inrush currents. These currents and starting times will vary with motor design, load and starting method. Conservative assumptions are 600% inrush current and 10 seconds starting time.

10) The maximum effective ground-fault protection (on the secondary) must not exceed 1200 A.

PART II

APPLICATION CONSIDERATIONS OF PROTECTION AND COORDINATION PRINCIPLES

8.0 INTRODUCTION

This section of the report deals with the protection of the auxiliary power scheme of a large hydroelectric development. Specifically it presents the preliminary studies for the protection of the auxiliary services of the LG-3 powerhouse. (LG-3 is part of the La Grande complex in James Bay, Quebec).

9.0 BRIEF DESCRIPTION OF THE POWERHOUSE

The LG-3 complex is a part of a large hydroelectric development, located some 1000 kilometers north-east of Montreal.

A reservoir created by a large 110 m high dam and some 60 dykes is located 80 m higher than the powerhouse level and covers an area of 2435 km^2. The reservoir holds 25,500,000 m^3 and can have a regulated flow of 2060 m^3/sec.

There are 12 water intake gates which through 12 penstocks conduct the water from the reservoir to the corresponding waterwheels. Each waterwheel generator is capable of producing 192 MW. This corresponds to a total power of 2304 MW.

In order to prevent dangerous rising of the water level in the reservoir, a 4-gate spillway is also provided.

The auxiliary station-service power is obtained from the generator terminals and stepped down through station-service transformers. For LG-3 the auxiliary power requires .062 percent of the capacity of the powerhouse. Drawing 1 (appendix) presents the principal single-line diagram of the LG-3 complex.

10.0 NATURE OF STATION AUXILIARY SERVICES

The loads normally supplied by the station service power system can be divided into two categories, "essential" and "non-essential".

The first group includes:

1) Unit auxiliaries, essential to the starting, running and stopping of the turbine generator units. Some of those units are:

   exciter

   voltage regulator

   governor

   governor oil pressure system

   cooling pumps

   penstock valve

   intake gate

   brakes

   miscellaneous small auxiliaries such as turbine pit pumps, bearing oil pumps, etc.

2) Station auxiliaries, not directly associated with the units but that are nonetheless essential for the operation of the plant. The essential station auxiliaries include:

spillway gates
compressor for circuit breakers and station air
station battery chargers
control and metering devices
communications equipment.

The "non-essential" group includes the power and site services that are primarily for the convenience of the construction, operation, and maintenance staffs. Such loads are:

lighting
heating, air conditioning and ventilating
elevators
cranes
workshops
miscellaneous pumps, compressors etc.
town site.

11.0 LG-3 AUXILIARY SERVICES - DESIGN CRITERIA

The criteria governing the conception of the protection scheme of the auxiliary services of LG-3 are the following:

a) To insure high reliability of the auxiliary services, since the continuity of service and the good operation of the powerhouse depends on those auxiliaries.

b) To reduce to the minimum the effects which the faults could have on the operation of the powerhouse.

c) To minimize the damage of materials.

d) To provide assurance, to the extent possible, that any fault in the auxiliary services scheme will not trip the circuit breakers of the generators.

12.0 LOCATION OF STATION SERVICE TAPS

Considering the powerhouse portions of large hydroelectric developments, there are really two widely used varieties of the main single-line diagram [14]. One is where two or more generators are effectively bussed together on the low-voltage side of each main transformer, and the other is the unit generator-transformer scheme.

For the LG-3 development, the generators are bused in pairs at generator voltage and station service transformers are connected directly to the generator main leads, as shown in Drawing 2 (appendix).

This type of connection provides reliable operation, because generators are normally the most reliable sources of power in the entire system. It also keeps equipment costs to a minimum since only relatively inexpensive low-voltage equipment is needed.

13.0 LG-3 BASIC DESIGN DATA

The maximum short-circuit current levels of the 735 kV power system, supplied by Hydro-Quebec are the following:

a) Line to ground fault; 33,000 MVA

b) three-phase fault. 27,000 MVA

Step-up transformers 13.8 - 735 kV

Delta-Wye connection (grounded neutral)

Single phase rating	260 MVA
Impedance	15%

Fault levels in the 13.8 kV bus. 250 MVA

Alternating current generators 202 MVA

Transient Reactance X'_d based on 202 MVA and 13,800 volts, at rated voltage 24%

Step-down transformers 13.8 kV-600 V

Delta-Wye connection (grounded neutral)

a) Powerhouse

Three-phase rating	2000 kVA
Impedance	12%
On load tap changers	± 10%

b) Water Intake

Three-phase rating	750 kVA
Impedance	7%
Vacuum tap changers	± 5%

c) Spillway

Three-phase rating	1000 kVA
Impedance	7%
Vacuum tap changers	± 5%

Supply Cables 13.8 kV

a) Water Intake

- Length	1000 ft
- Type	1 x 3C # 1/0 AWG
- Impedance -R	0.105 ohms
$-X_L$	0.075 ohms

b) Spillway

- Length	3000 ft
- Type	1 x 3C # 1/0 AWG
- Impedance -R	0.315 ohms
$-X_L$	0.225 ohms

c) Auxiliary transformer-powerhouse

- Length	500 ft
- Type	1 x 3C # 1/0 AWG
- Impedance -R	0.053 ohms
$-X_L$	0.038 Ohms

d) 13.8 kV Bus bars - Powerhouse

- Length		300 ft
- Type		3 x 1C # 1/0 AWG
- Impedance	$-R$	0.032 ohms
	$-X_L$	0.023 ohms

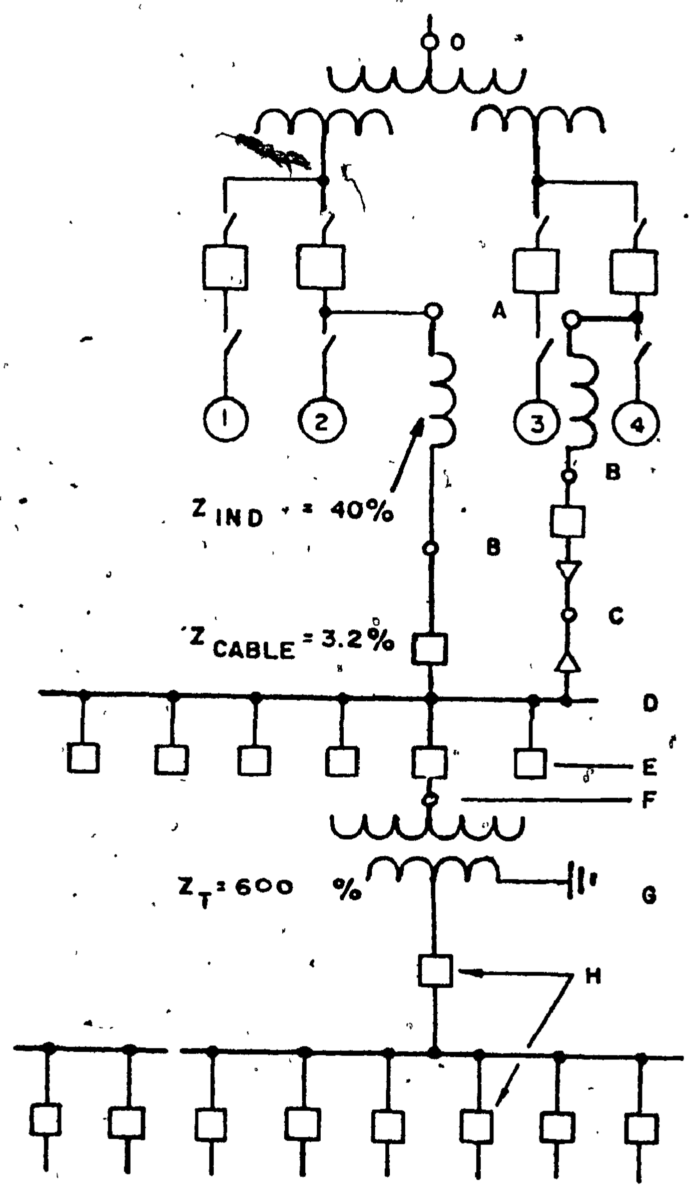
e) 600 V Bus bars - Intake

- Length		1000 ft
- Type		3 x 1C # 500 MCM
- Impedance	$-R$	0.022 ohms
	$-X_L$	0.033 ohms

14.0 SHORT-CIRCUIT CURRENT CALCULATIONS

14.1 PHASE-TO-PHASE FAULTS

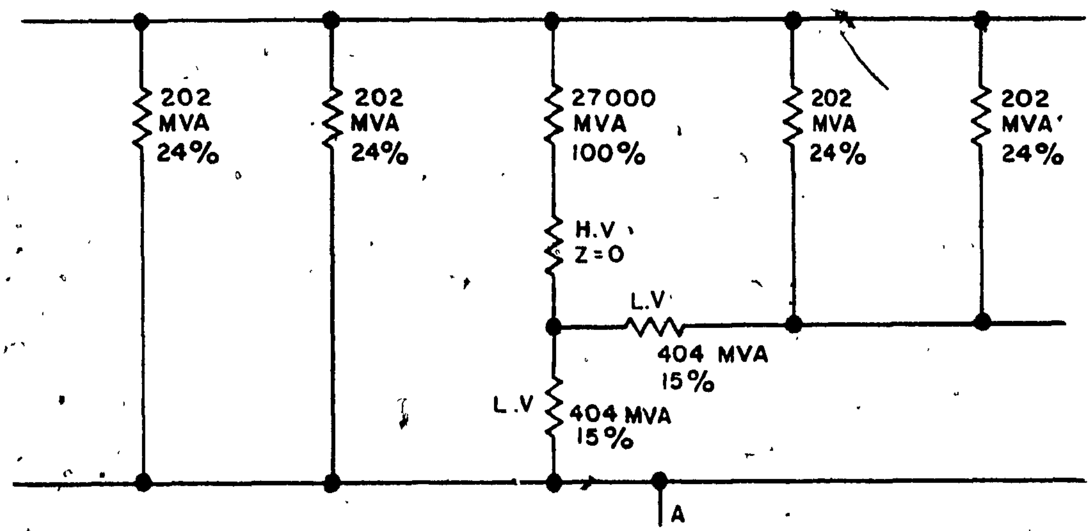
The results of the short-circuit calculations are summarized below, along with a step-by-step procedure. It should be noted that in calculating the short-circuit levels, the contribution of the motors on the load side was not considered. This does not introduce any error since they are of small capacity.



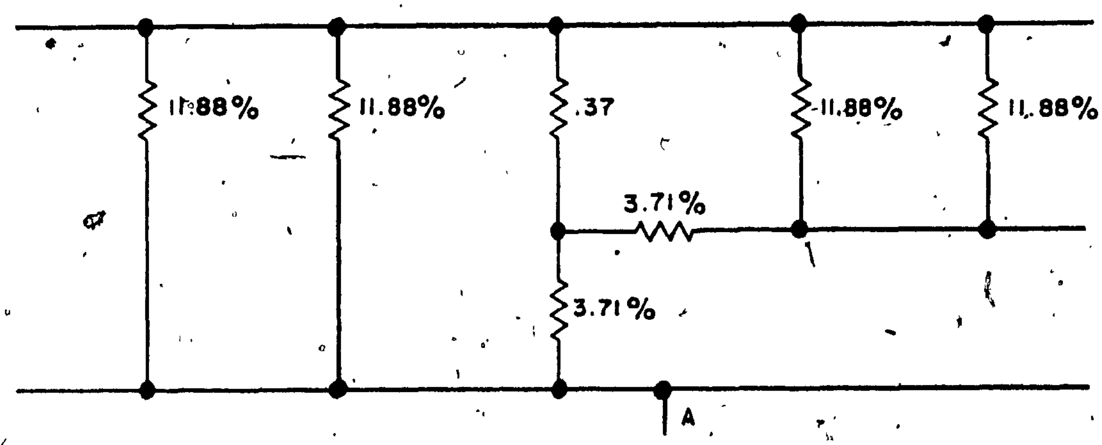
PT	MVA	AMP @ VOLTAGE
0	27,000	21,200 @ 735 kV
A	4150	173,600 13.8 kV
B	250	10,460 @ 13.8 kV
H	15.54	14,960 @ 600 V

THE VALUES FOR POINT "B" APPLY ALSO FOR POINTS C,D,E,F

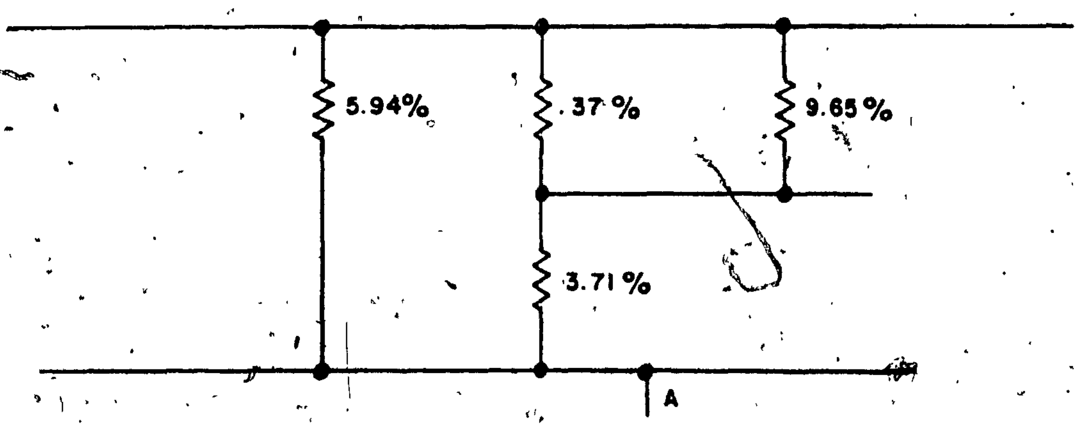
Analytical short-circuit calculations for point A are as follows. The impedance diagram is:



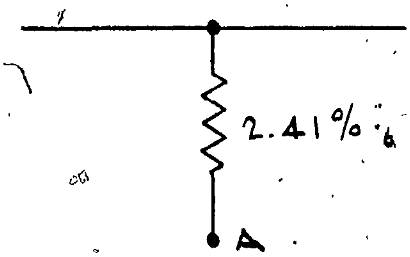
Choosing 100 MVA as base and since $X_{new\ base} = \frac{MVA_{base}}{MVA_{mach}} * X_{mach}$ the impedance diagram becomes



Combining impedances we have:



Thus Fault at A $= 100 * \frac{100}{2.41} =$ 4150 MVA



But Base Amps $= \frac{\text{Base kVA}}{\sqrt{3} * \text{Base kV}} = \frac{4150}{\sqrt{3} * 13.8} =$ 173,600 A

14.2 PHASE-TO-GROUND FAULTS

For the 13.8 kV bus the phase-to-ground voltage is

$$V_{L-N} = \frac{13.8 \text{ kV}}{\sqrt{3}} = 7967.43 \text{ V}$$

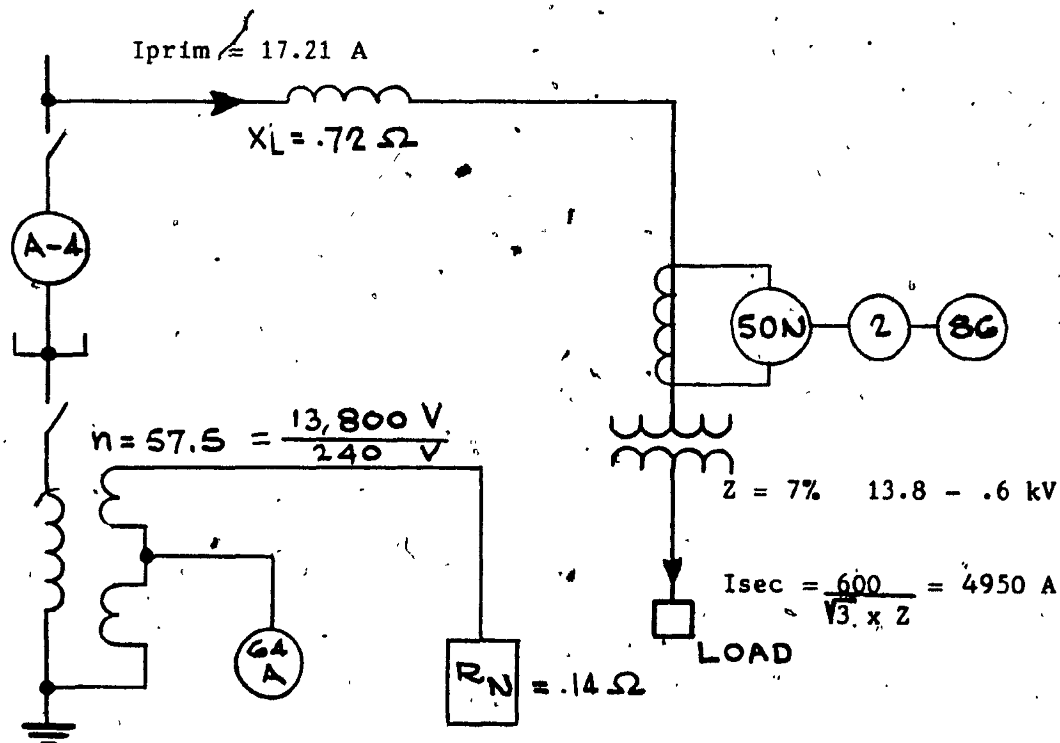


Fig. 14.1 Generator Ground Protection

By using the figure of the generator ground protection (14.1) we can calculate the maximum ground fault current on the 13.8 kV bus.

From fig. 14.1 we have that:

$$I_{primary} = \frac{V_{L-N}}{R_{primary}}$$

but $R_{primary} = R_{secondary} * n^2$

where n = turns ratio

Thus substituting we have:

Maximum primary ground fault current $I = \frac{7967.43}{.14\,(57.5)^2} = 17.21$ A

For the 600 V bus the phase-to-ground voltage is

$$V_{L-N} = \frac{600}{\sqrt{3}} = 347 \text{ v}$$

The maximum ground fault current is given by

$$I_{L-N} = \frac{V_{L-L}}{\sqrt{3} * Z} = \frac{V_{L-N}}{Z}$$

Substituting we have

$$I_{L-N} = \frac{347}{.07} = 4957 \text{ A}$$

14.3 ANALYSIS AND RECOMMENDATIONS FOR THE DIFFERENT CASES OF SHORT-CIRCUITS

Refer to Drawing 2, included in the appendix

At point A (ahead of the reactances)

For a phase-to-phase or a phase-to-ground fault, the circuit breakers of the generators and those of the auxiliary services should open. This implies the complete stop of the generators and also the minimization of the fault. This zone should be covered by the generator protection which is the responsibility of Hydro-Quebec.

At point B (after the reactances)

The same analysis and recommendation that applies for point A applies here as well. The undervoltage relays-27 - are used to initiate the change-over process. The electrical interlocking of the two main circuit breakers is achieved by using the tripping relay.

At point C (Supply to the 13.8 kV bus-bars)

For a phase-to-phase or phase-to-ground fault both main circuit breakers 12-14 and 12-15 or 12-18 and 12-19 should open. This is necessary in order to avoid the supply of power to the defective zone through an alternative path, a fact that could result in tripping of the four generators.

For phase-to-phase fault protection a simple overcurrent scheme with inverse time and short-time delay features is recommended. This will permit reasonable clearing times.

For phase-to-ground fault protection a simple overcurrent scheme is recommended having a short-time delay. This will permit coordination without the risk of false tripping from capacitive discharge of cables.

At point D (13.8 kV switchgear)

The protection described for point "C" covers equally well this zone.

At point E (13.8 kV secondary circuit breakers)

The protection provided for point "C" covers the breakers themselves for any type of internal fault.

At point F (13.8 kV feeder supply)

In the case of a phase-to-phase or a phase-to-ground fault, the feeder circuit breaker should open in order to isolate the faulted part.

For a phase-to-phase fault a simple overcurrent scheme protection is recommended.

For a phase-to-ground fault an overcurrent protection scheme is recommended having a short time delay.

At point G (13.8 kV equipment)

a). Auxiliary Transformers (Powerhouse)

Those transformers, being oil cooled present the risk of tank explosion for fault in the windings. For preventing this from happening the following protections are recommended:

- A thermal relay-49-protecting against over-temperature.
- A pressure relay-63A- utilized for alarm purposes only.
- A pressure relief relay-63D- utilized to initiate the pressure relief device mounted on the transformer tank.
- A pressure relief relay-63DC- performing the same function as-63D-above, but mounted on the on-load tap changer (LTC) compartment.

The protection of the feeder (point F) protects equally well the primary windings of the transformer.

The protection of the low voltage winding, and the 600 V bus duct, against phase-to-ground faults is effected by the use of a ground relay, installed in the neutral of the transformer secondary. This relay trips the feeder breaker.

b) <u>Auxiliary transformers</u> (Water intake and Spillway)

Those transformers, being of the dry type ANN, do not present any risk of explosion. Thus the only relay required for their protection is the thermal relay-49-which has two contacts, one for alarm purposes and the other for tripping of the 13.8 kV circuit breakers at the powerhouse. In order to protect the windings against phase-to-phase faults, a load-break fusible switch to be installed just ahead of the transformer is recommended.

The ground protection of the 13.8 kV cables protects equally well the primary windings against phase-to-ground faults.

A ground relay installed in the neutral of the transformer secondary trips the feeder breaker in case of a phase to ground fault of the transformer low voltage windings.

<u>At point H (600 V circuit breakers)</u>

For this part of the circuit it is recommended to use metal-enclosed air circuit breakers with solid-state protective relays. Those solid-state (static) relays should contain a long-time delay protection, a short-time trip, an instantaneous trip and a ground-fault protection.

14.4 COORDINATION OF PROTECTIVE DEVICES

In order to demonstrate the protection and coordination principles involved a particular, but nevertheless typical circuit (spillway circuit) will be coordinated.

A typical single line diagram is shown in fig. 14.2 where also the many different protective devices are assigned numbers from 1 (starting at the load side) to 14 (reactor). This is done in order to facilitate the presentation. At the same time those particular numbers will be used on the time-current coordination curves.

14.4.1 COORDINATION TECHNIQUE

The steps for obtaining complete coordination have been outlined in section 7.0. Here an attempt will be made to relate the theory to the actual example and elaborate whenever a clarification is deemed necessary.

The first element to be plotted in the log-log time-current coordination graph (fig. 14.3 and 14.4) is the end device represented as element 1. The load of the spillway consists of pumps, motors, and lighting. The largest single load is a 20 hp squirrel cage induction motor which at 600 V draws a full load current (FLC) of 23 A. Since actual data for this motor are not available, a typical starting time can be assumed to be 3 sec. It is also a common practice for design coordination purposes, to assume a motor locked rotor current (LRC) of 6 times the motor (FLC). Therefore LRC = 138 A.

Next, a thermal overload is chosen and plotted as element 2. For this the CGE, CR 224 overload element was chosen.

As a branch circuit breaker, element 3, a Westinghouse DS air circuit breaker is chosen. This breaker has static trip sensors which offer versatility, good response, a relatively narrow coordination band and facility for application of ground trips as compared with older oil dashpot or similar sensors. The instantaneous element is set at the usual 7 to 10 times motor FLC in order to avoid unnecessary tripping.

Now before proceeding with the coordination of element 4 which is the transformer secondary breaker, the transformer damage curve is plotted in order to establish the upper limits of settings. A typical transformer damage curve was used from reference (9) which is plotted as element 5.

The transformer full load current referred to the low side is 962 A i.e.: $\left(\frac{1000 \text{ kVA}}{\sqrt{3} * .6}\right)$.

Thus secondary breaker will be applied at 125% which corresponds to 1200 Amps. This pick-up value of 125% is the lowest commonly applied so as to provide reasonable protection but avoid nuisance tripping. A Westinghouse air circuit breaker - DS type - is again chosen. The instantaneous element is set at a nominal 7-10 times connected load to avoid false tripping on inrush following a severe voltage depression. Sufficient time delay is also provided to coordinate with downstream breakers.

The next element to be coordinated is the transformer primary fuse (element 6). It should continuously carry at least 41.8 A (962 secondary A referred to the high side i.e.: $\frac{962 * .6}{13.8}$)

To avoid blowing on inrush transient a minimum fuse value of 150% is commonly recommended. A CGE, EJ0-1, 100E power fuse was selected and applied at 200% of transformer full load current. Since the transformer is equipped with a LV protection which protects it against most faults on the 600 V system and bus this figure can be a high as 600% (Canadian Electrical Code, Rule 26-046), depending on the impedance of the transformer.

It is usual practice to show "coordination pairs" of device curves with not more than three or four curves per sheet for clarity purposes. Therefore the coordination will be carried over to a second graph. All the elements to be coordinated from now on are located in the 13.8 kV bus thus it would be advisable to use 13.8 kV as a base. This essentially means that the last three elements i.e. 4,5 and 6 would have to be reffered to 13.8 kV. This can be done quite easily by using the tranformer voltage ratio.

The next up-stream protection will be offered by element 9. This is an overcurrent relay having instantaneous (50) and time delay (51) elements. An ASEA, RXIDF-2 static relay has been chosen mainly because of its low burden. (Section 16.1 elaborates on this further). Since the tranformer is fused this relay is principally used to protect the 3000 ft of # 1/0 AWG cable and to give a tripping signal to the corresponding breaker, element 10 The cable is rated to carry a continuous current of 155 Amps. Thus since the transformer FLC is only 41.8 Amps, the relay pick-up can be set at 140 Amps and the instantaneous will be applied at about 1000 Amps so as to avoid non-selective tripping on maximum transformer low voltage fault.

($MVA_{s.c.} \approx \frac{1\ MVA}{Z} = 15\ MVA$ and

$I_{s.c.} = \frac{15\ MVA}{\sqrt{3} \times 13,800} * 1.6 = 1004.0\ A$ where 1.6 is a commonly used offset factor).

The last element to be coordinated is element 13. This is again an ASEA, RXIDF-2 overcurrent relay that simply operates on its corresponding breaker, element 12. The reactor is rated for 350 A thus at 125% the relay pick-up (minimum) should be 350 * 1.25 = 438 A. We arbitrarily set the pick-up at 480 A which corresponds to the next highest available relay tap of 4 A secondary. (CT ratio = 600/5 = 120, thus 480/120 = 4 A). It should be noted however that there must be a time delay of at least .25 s between the definite time elements of 9 and 13. This will assure us that element 9 will operate before element 13, and will allow for breaker clearing time and reset of the 13 current sensor element.

Note: Elements 8 and 11 being simple overcurrents relays (ASEA type RXIG-2) provide the phase-to-ground protection. It will be shown in section 16.2 that the current settings for the 50N relays should be approximately 1.0 A. However sufficient time delay should be provided so that proper coordination will be achieved. For example; a time delay of .1 sec for relay 8 and a time delay of .2 sec. for relay 11 will assure us of good coordination.

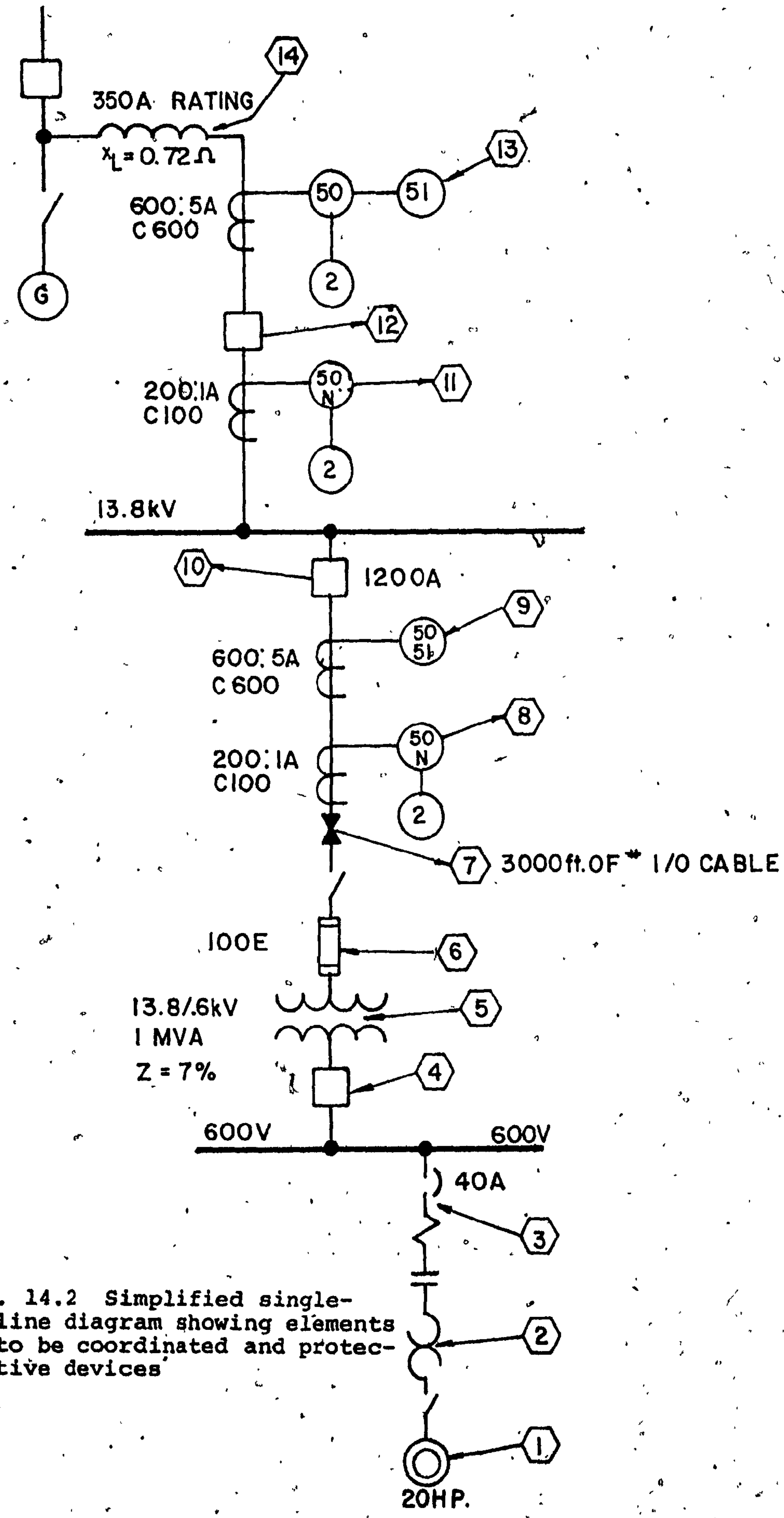


Fig. 14.2 Simplified single-line diagram showing elements to be coordinated and protective devices

LIST OF ELEMENTS SHOWN IN FIG. 14.2

1. 20 HP induction motor
2. Thermal overload, CR224C, CGE
3. Air Circuit Breaker, DS, Westinghouse
4. Transformer Secondary Breaker, DS, Westinghouse
5. Transformer damage curve
6. Transformer primary fuse EJO-1, CGE
7. Insulated cable # 1/0 AWG, Short-circuit heating limits
8. Neutral overcurrent relay RXIG-2, ASEA (Time dial of .1 s)
9. 13.8 kV bus overcurrent relay RXIDF-2, ASEA (Time dial of .7 s)
10. Circuit breaker, operated by element (9)
11. Neutral overcurrent relay RXIG-2, ASEA (Time dial of .2 s)
12. Circuit breaker, operated by element (13)
13. 13.8 kV bus overcurrent relay RXIDF-2, ASEA (Time dial of .2 s)
14. Reactor, $X_L = 0.72\ \Omega$ rated at 350 A.

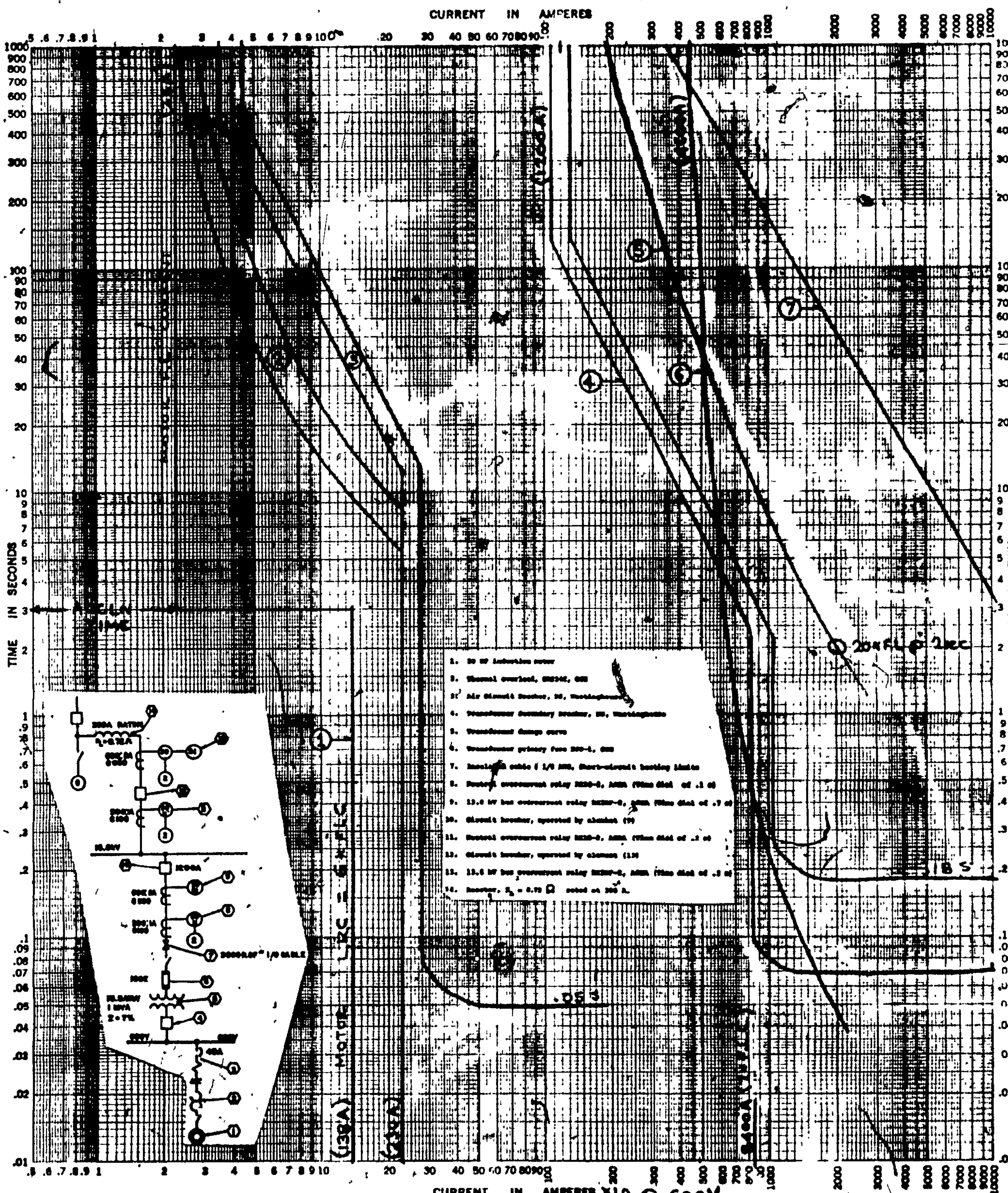


Fig 14.3 TIME-CURRENT CHARACTERISTIC CURVES

For. ______ Fuse Links. In ______

BASIS FOR DATA Standards ______ Dated ______

1. Tests made at ______ Volts a-c at ______ p-f., starting at 25C with no initial load ______

2. Curves are plotted to ______ Test points so variations should be ______

No. ______

Date ______

K+E TIME-CURRENT CHARACTERISTIC 48 5258

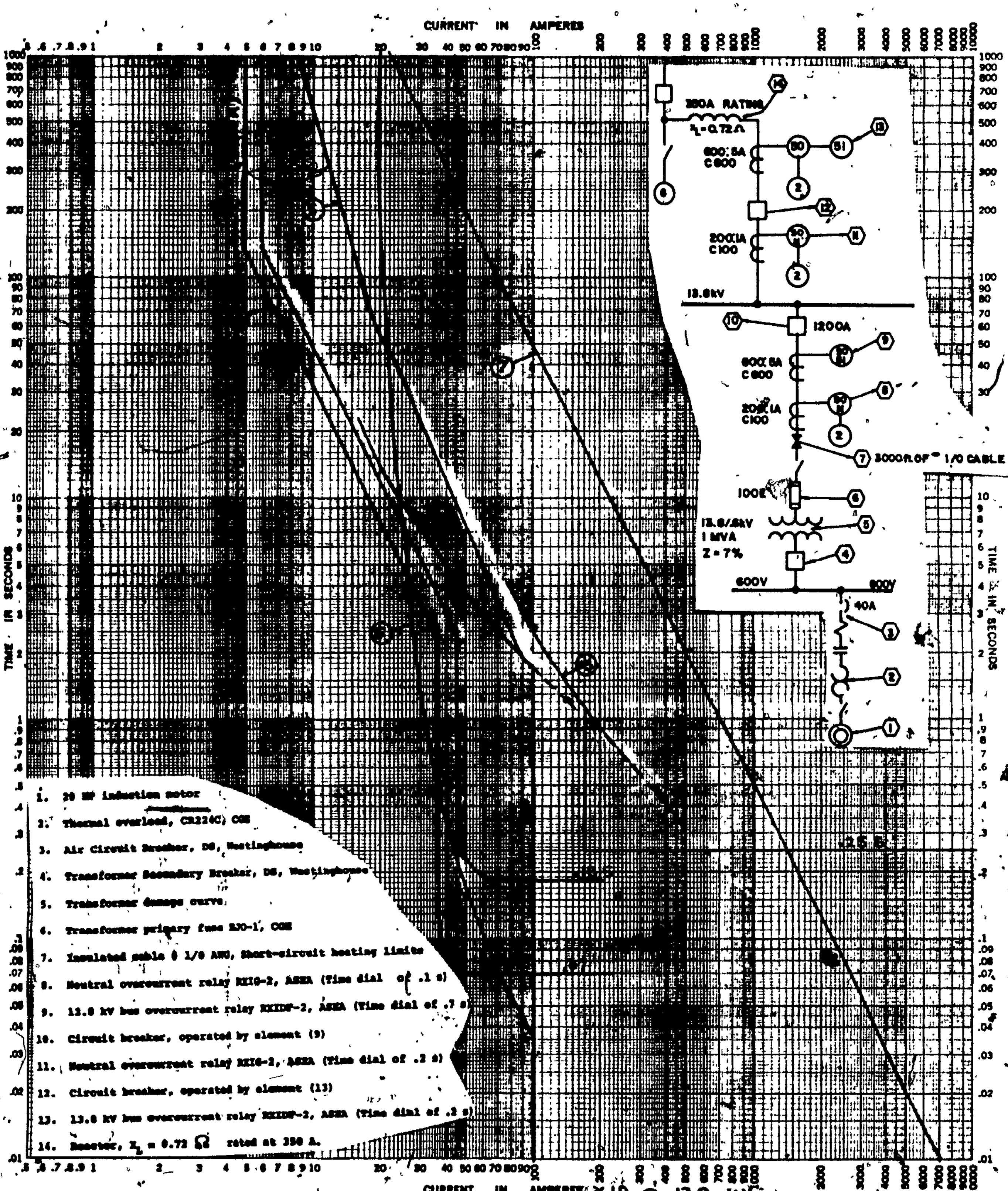


Fig 14.4 TIME-CURRENT CHARACTERISTIC CURVES

For ______ Fuse Links. In ______

BASIS FOR DATA Standards ______ Dated ______

1. Tests made at ______ Volts a-c at ______ p-f, starting at 25C with no initial load ______ No. ______

2. Curves are plotted to ______ Test points so variations should be ______ Date ______

15.0 TRANSFER AND INTERLOCKING PHILOSOPHY

Refer to Drawing 2 (appendix)

The transfer of the power supply for the two buses supplying the auxiliary loads is based on the following two principles:

- the two incoming breakers should never be operated in parallel;
- a loss of power on one of the supply paths should initiate the transfer operation between the two sources, except if this transfer is blocked due to tripping of relay 86, that is, due to a detected fault. If the above two conditions are to hold true, the circuit breakers 12-14 and 12-15 should be interlocked in such a way that one should open in order to permit the closing of the other. The same principle applies for the breakers 12-18 and 12-19. The opening of the above circuit breakers is effected by their respective locking-out relay (86), which can be triggered either by the overcurrent protections, the Hydro-Quebec protection signals or by the loss of voltage sensed by undervoltage relay 27. In the first case, a transfer to the other supply line will not be made. In the case of undervoltage detection, the transfer will be initiated by relay 27

provided that relay 86 permits such a transfer to take place. Even in the case of having a H.Q. tripping signal, the undervoltage relay should be triggered first and then the transfer will be permitted to take place.

As a consequence of this arrangement, following a fault at a location downstream of the incoming breakers, that is, in the connecting cable, in the bus, or in the feeder, a transfer will not be effected. But following a fault at a location upstream of the incoming breaker, given that this fault is not detected by the overcurrent protection, a tripping signal will be initiated by the H.Q. protection, resulting in a transfer to the unaffected power supply.

16.0 SPECIAL PROBLEMS AND SOLUTIONS

16.1 RELAYING CURRENT TRANSFORMERS

Relatively high fault levels, (250 MVA), and low feeder loads (low current transformer ratios), can cause CT saturation problems.

Two basic approaches were considered:

a) use of low burden static relays to avoid saturation, if possible.

b) use of electromagnetic elements, solving the resulting saturation problems by separation of instantaneous (50) and time (51) features, if necessary.

To avoid saturation the following equation (12) must be satisfied:

$$V_k \gg 6.28 \times I \times R \times T$$

where: V_k = voltage at the knee of the saturation curve.
I = symmetrical secondary current (Amps)
R = total secondary resistance
T = dc time constant of the primary circuit in cycles.

If it is assumed that 600/5 CT's of maximum C600 characteristic is available and that time constant of 6 cycles (.1 sec) is practical the resistance R will be

$$R \leqslant \frac{V_k}{6.28*I*T}$$

substituting values for V_k = 600 V, T = 6 cycles,

$I = \frac{10460}{120} = 87$ A we have

$$R < \frac{600}{6.28*87*6} = 0.183\ \Omega$$

This value of R is actually very low but nevertheless the new generation of static relays can satisfy it.

Static Relays

A static relay manufactured by ASEA (RXIDF-2H) can be used. The .5 A tap can be used which corresponds to a power consumption of .02 VA

Thus: Relay burden $= \frac{.02}{(.5)^2} = 0.08\ \Omega$

Lead burden of 50' of #9 Cu = $0.04\ \Omega$

Circuit burden on CT = $0.12\ \Omega$

This is less than the above mentioned maximum permissible burden (.183 Ω) required in order to avoid saturation and is a feasible solution.

Electromagnetic Relays:

Use of a typical electromagnetic relay (Canadian General Electric IAC 53) set at .6 A would impose a burden of approximately 3.5 Ohms, causing considerable saturation. Therefore one must check whether the time of saturation is enough to trip the instantaneous element (50) eg. 30 milliseconds minimum, at an assumed system time constant of 6 cycles. The applicable formula (3) is:

$$K_s = \frac{V_K * N_2}{I_1 * R} \quad \text{where}$$

V_K = Voltage at the knee of saturation curve (600 V)

N_2 = Turns ratio (120)

I_1 = Primary current (10,460 A)

K_s = CT saturation factor (10, from fig. 16.1)

R_2 = Secondary resistance.

Solving for R_2 we have:

$$R_2 < \frac{600 \times 120}{10,460 \times 10} = .69\ \Omega$$

Thus, it is seen that separate CT's must be used for the 50 and 51 elements if this approach is used.

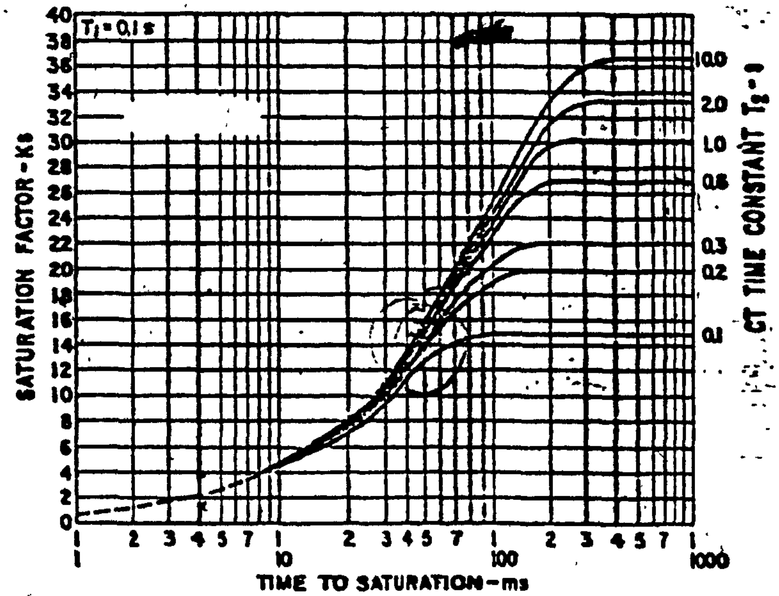


Fig. 16.1 Time to saturation curves for T = .1 sec (3)

Conclusion

Summarizing what has been said so far, it is recommended that the simple solution of using low burden static elements be used for the relaying.

16.2 CABLE GROUND FAULT PROTECTION

The cable ground fault protection must coordinate with the generator ground protection, which is represented in fig. 14.1. The common North-American relays used for generator ground protection are rated for 67 or 199 V (CV 8 of Westinghouse or IAV 51 of CGE). A minimum pick-up relay setting of 8% (corresponding to 5.4 V) is a common North-American practice.

Thus we assume a minimum setting of 5.4 V on 64 relay. This means that 10.8 V is applied to R_n. Reflected to the high side of the grounding transformer this 10.8 V is 10.8*57.5 = 621 V. But 621 V corresponds to 7.8% of the winding $\left(\frac{13,800}{\sqrt{3}} * 7.8\% \right)$ which essentially means that only 92.2% of the generator winding is protected. Since protective settings covering 90-95% of winding are common this was considered a reasonable choice.
From the above it follows that at minimum pick-up

$$I_{secondary} = \frac{10.8}{.14} = 77.14 \text{ A} \quad \text{and}$$

$$I_{primary} = \frac{77.14}{57.5} = 1.34 \text{ A}$$

Therefore the setting on the 50N relay should be about 1.0 A primary with sufficient time delay to coordinate with the 13.8 kV feeder protection ground features.

But to get a 1.0 A setting one can not use conventional residual CT connection, but must use a core balanced CT. ASEA is one of the few companies to have a matching CT-relay combination capable of satisfying this requirement. The relay is RXIG of 2.4 to 7.5 mA (.6 to 1.7 A primary) and the Current Transformer is ILKB of 200/1 ratio or IHKA of 100/1 ratio. The choice of the current transformer depends on the size of the cables.

It should also be mentioned that care should be taken to ensure that the sheaths of the cables are properly grounded, if the ground protection is to function correctly. The best way would be to ground the sheath only at the one end (switchgear) and insulate them at the generator end.

CONCLUSION

CONCLUSION

The technique for providing a safe, selectively coordinated, power system was studied and an overview of the basic principles involved was attempted.

The first and basic step is the determination of short-circuit currents. Once the short-circuit levels are determined, the designer can specify proper interrupting requirements, provide component protection and proceed to coordinate the system. Proper coordination will be accomplished when the following steps are completed: decision as to the degree of coordination necessary, cut and try process of plotting protective-device characteristic curves, and specification of the particular devices and settings required.

It should be mentioned that many variations and refinements may be instituted in a given protective scheme. However the recommended practice is to adjust protective device settings by actual field tests during installation.

Finally care should always be taken to ensure that the protective scheme is kept up to date. This essentially means that each and every change in the system - addition of capacity or load or rearrangement - must be recognized and the protective device settings readjusted accordingly.

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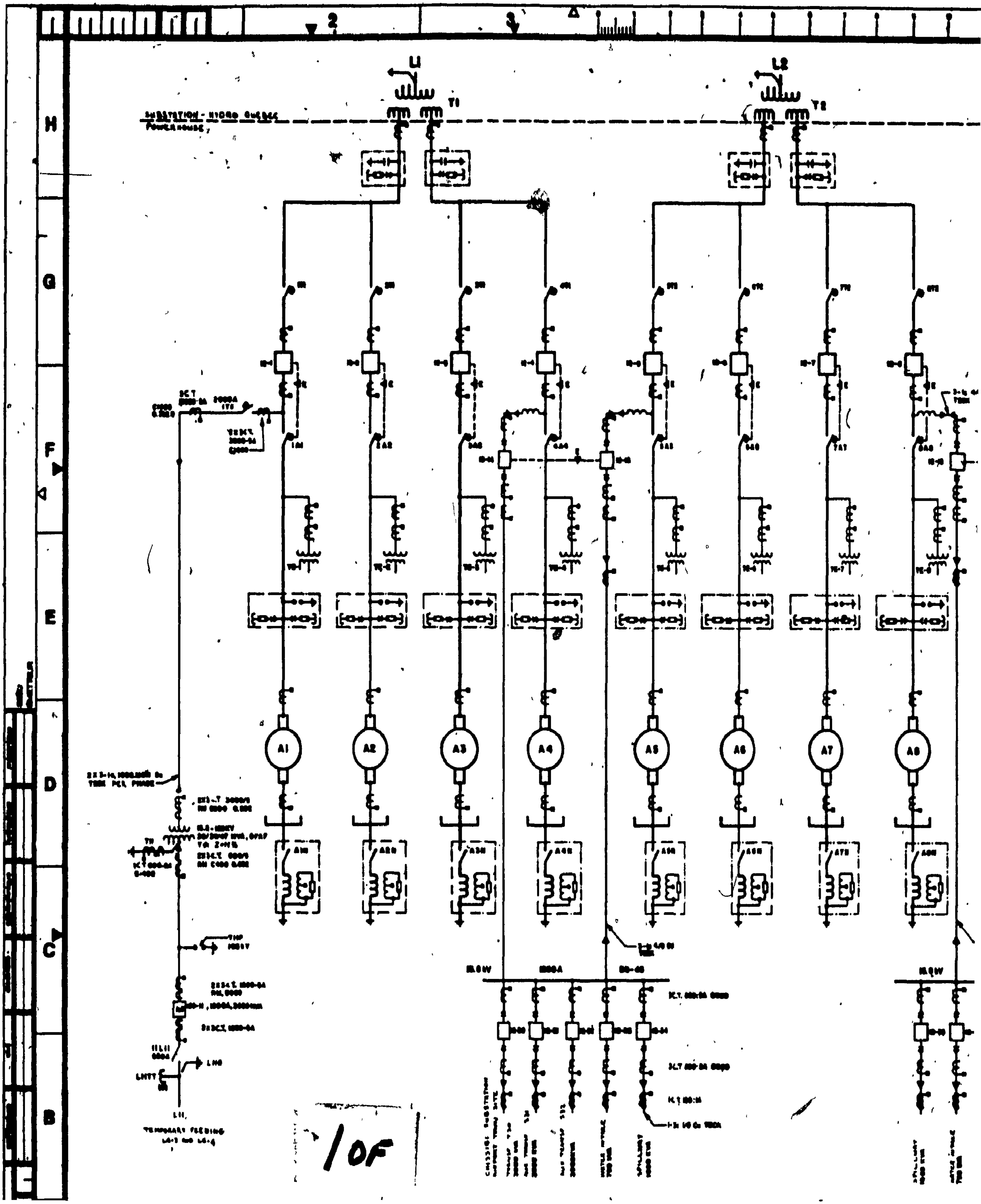
APPENDIX



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L1
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SUBSTATION - HYDRO QUEBEC
POWERHOUSE
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TEMPORARY FEEDING
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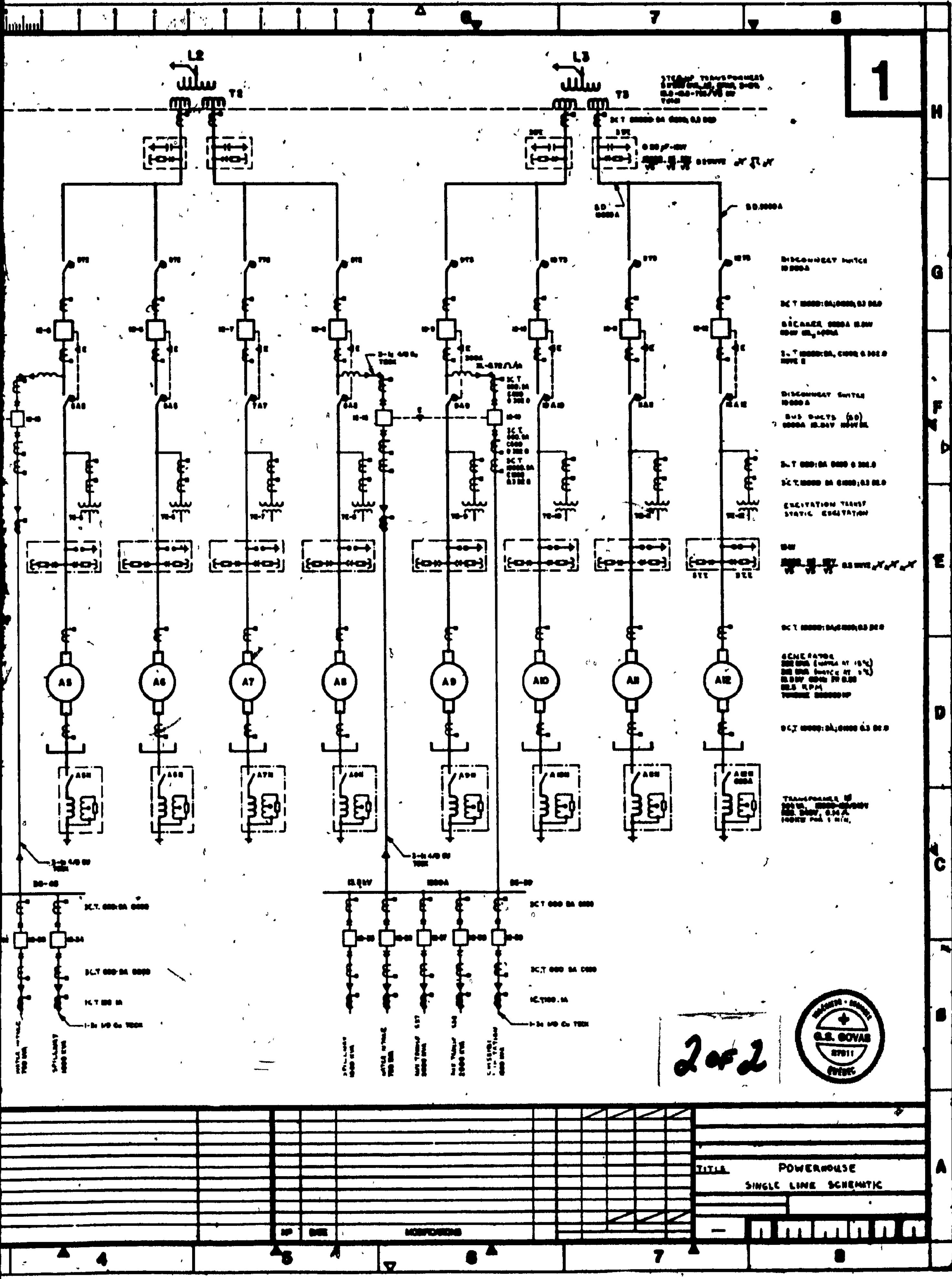
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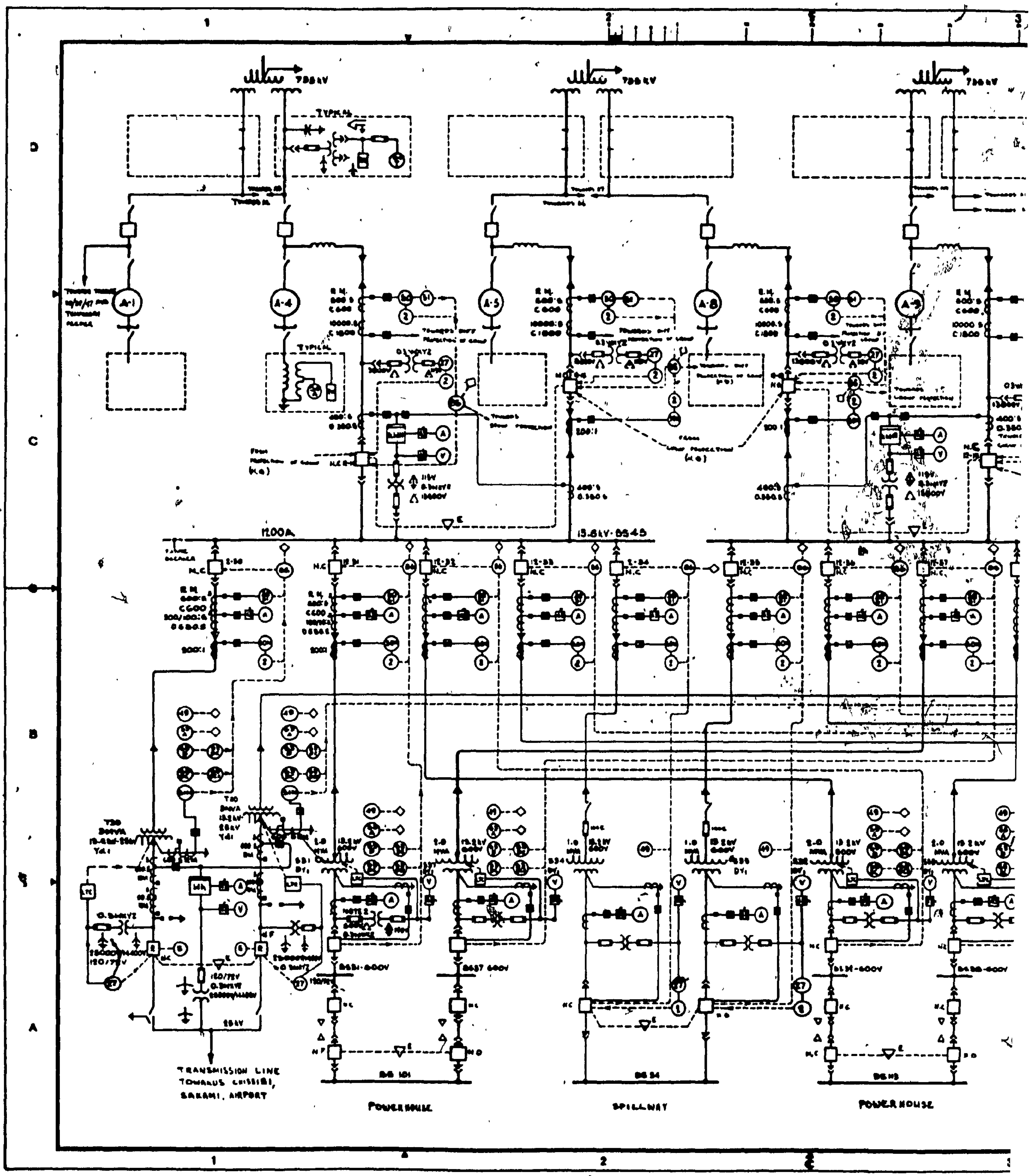
2 of 2
G.S. GOVAS
TITLE POWERHOUSE
SINGLE LINE SCHEMATIC
MODIFICATIONS

1 OF



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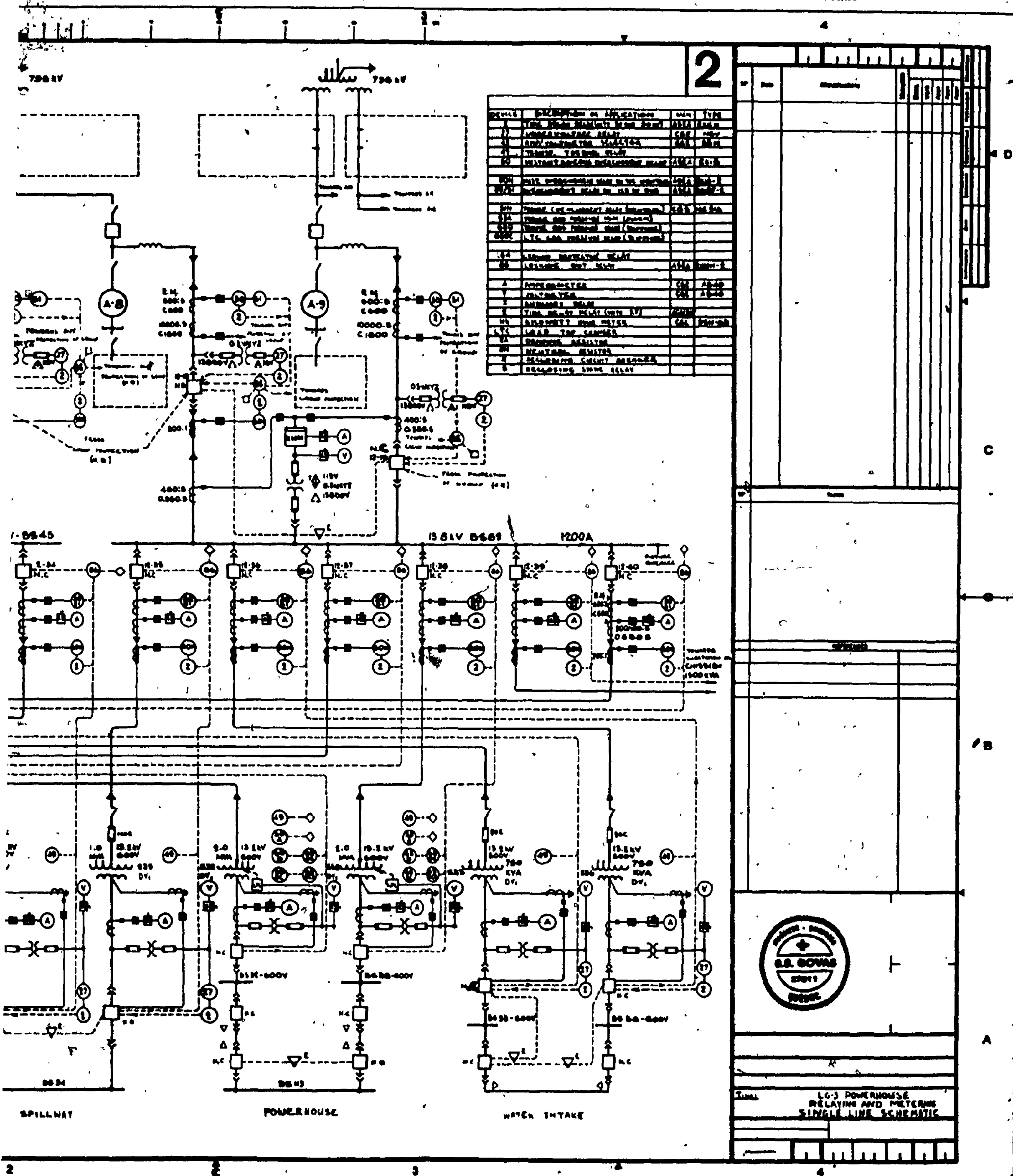
TYPICAL
1200A
TRANSMISSION LINE
POWERHOUSE
SPILLWAY
POWERHOUSE



LG-3 POWERHOUSE
RELAYING AND METERING
SINGLE LINE SCHEMATIC

Selections from ANSI C37.2-1970

IEEE Device Numbers and Functions For Switchgear Apparatus

The devices in switching equipments are referred to by numbers, with appropriate suffix letters when necessary, according to the functions they perform.

These numbers are based on a system adopted as standard for automatic switchgear by IEEE, and incorporated in American Standard C37 2-1970. This system is used in connection diagrams, in instruction books, and in specifications.

Device Number	Definition and Function
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 which 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 described later.
3	**Checking or interlocking relay** is a device which 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, 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 No. 1 or equivalent, and the required permissive and protective devices, that serve to make and break the necessary 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 one 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 disconnective device – such as a knife switch, circuit breaker or pullout fuse block, used for the purpose of 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 used for the purpose of reversing a machine field or for performing any other reversing functions.
10	**Unit sequence switch** 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 over-speed.
13	**Synchronous-speed device**, such as a centrifugal-speed switch, a slip-frequency relay, a voltage relay, an undercurrent relay or any type of device, operates at approximately synchronous speed of a machine.
14	**Under-speed device** functions when the speed of a machine falls below a predetermined value.
15	**Speed or frequency, matching device** functions to match and hold the speed or the frequency of a machine or of a system equal to, or approximately equal to, that of another machine, source or system.
16	Reserved for future application.
17	**Shunting or discharge switch** 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 which 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 73 function which serves for the switching of resistors.
18	**Accelerating or decelerating device** is used to close or to cause the closing of circuits which are used to increase or to decrease the speed of a machine.
19	**Starting-to-running transition contactor** is a device which 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 in a fluid line. Note: The function of the valve may be indicated by the use of the suffixes, see Page 5

Device Number	Definition and Function
21	**Distance relay** is a device which functions when the circuit admittance, impedance or reactance increases or decreases beyond predetermined limits.
22	**Equalizer circuit breaker** is a breaker which 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** functions to raise or to 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 which switches on a space heater in a switchgear assembly when the temperature falls to a desired value as distinguished from a device which is used to provide automatic temperature regulation between close limits and would be designated as 90T
24	Reserved for future application.
25	**Synchronizing or synchronism-check device** 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** functions when the temperature of the shunt field or the armortisseur 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 device which 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 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** connects a circuit such as the shunt field of a synchronous converter, to a source of separate excitation during the starting sequence; or one which energizes the excitation and ignition circuits of a power rectifier.
32	**Directional power relay** is one which 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** 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 used 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** operates or permits the operation of another device on a predetermined polarity only or verifies the presence of a polarizing voltage in an equipment.
37	**Undercurrent or underpower relay** functions when the current or power flow decreases below a predetermined value.
38	**Bearing protective device** functions on excessive bearing temperature, or on other abnormal mechanical conditions, such as undue wear, which may eventually result in excessive bearing temperature.
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** 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 which functions to apply, or to 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** transfers the control circuits so as to modify the plan of operation of the switching equipment or of some of the devices
44	**Unit sequence starting relay** is a device which functions to start the next available unit in a multiple-unit equipment on the failure or on the non-availability 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 which 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** functions upon a predetermined value of polyphase voltage in the desired phase sequence.

Device Number	Definition and Function
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 of 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 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.

Device Number	Definition and Function
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.
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 which 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 or secondary neutral 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.

Device Number	Definition and Function
66	**Notching or jogging device** 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 also 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 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 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.

Device Number	Definition and Function
74	**Alarm relay** is a device other than an annunciator, as covered under device No. 30, which 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.
78	**Phase angle measuring, or out-of-step protective relay** is a relay that functions at a predetermined phase angle between two voltages or between two currents or between voltage and current.
79	**Ac reclosing relay** is a relay that controls the automatic reclosing and locking out of an ac circuit interrupter.
80	**Flow Switch** is a switch which operates on given values, or on a given rate of change, of flow.
81	**Frequency relay** is a relay that functions on a predetermined value of frequency – either under or over or on normal system frequency – or rate of change of frequency.
82	**Dc reclosing relay** is a relay that controls the automatic closing and reclosing of a dc circuit interrupter, generally in response to load circuit conditions.

Device Number	Definition and Function
83	**Automatic selective control or transfer relay** is a relay that operates to select automatically between certain sources or conditions in an equipment, or performs a transfer operation automatically.
84	**Operating mechanism** is the complete electrical mechanism or servo-mechanism, including the operating motor, solenoids, position switches, etc., for a tap changer, induction regulator or any similar piece of apparatus which has no device function number.
85	**Carrier or pilot-wire receiver relay** is a relay that is operated or restrained by a signal used in connection with carrier-current or dc pilot-wire fault directional relaying.
86	**Locking-out relay** is an electrically operated hand, or electrically, reset relay that functions to shut down and hold an equipment out of service on the occurrence of abnormal conditions.
87	**Differential protective relay** is a protective relay that functions on a percentage or phase angle or other quantitative difference of two currents or of some other electrical quantities.
88	**Auxiliary motor or motor generator** is one used for operating auxiliary equipment such as pumps, blowers, exciters, rotating magnetic amplifiers, etc.
89	**Line switch** is used as a disconnecting load-interrupter, or isolating switch in an ac or dc power circuit, when this device is electrically operated or has electrical accessories, such as an auxiliary switch, magnetic lock, etc.
90	**Regulating device** functions to regulate a quantity, or quantities, such as voltage, current, power, speed, frequency, temperature, and load, at a certain value or between certain (generally close) limits for machines, tie lines or other apparatus.

Device Number	Definition and Function
91	**Voltage directional relay** is a relay that operates when the voltage across an open circuit breaker or contactor exceeds a given value in a given direction
92	**Voltage and power directional relay** is a relay that permits or causes the connection of two circuits when the voltage difference between them exceeds a given value in a predetermined direction and causes these two circuits to be disconnected from each other when the power flowing between them exceeds a given value in the opposite direction.
93	**Field changing contactor** functions to increase or decrease in one step the value of field excitation on a machine.
94	**Tripping or trip-free relay** functions to trip a circuit breaker, contactor, or equipment, or to permit immediate tripping by other devices; or to prevent immediate reclosure of a circuit interrupter, in case it should open automatically even though its closing circuit is maintained closed.
95 96 97 98 99	Used only for specific applications on individual installations where none of the assigned numbered functions from 1 to 94 is suitable.

Supervisory Control and Indication. A similar series of numbers, prefixed by the letters RE (for "remote") shall be used for the interposing relays performing functions that are controlled directly from the supervisory system. Typical examples of such device functions are: RE1, RE5, and RE94.

Note The use of the "RE" prefix for the purpose in place of the former 200 series of numbers now makes it possible to obtain increased flexibility of the device function numbering system For example, in pipeline pump stations, the numbers 1 through 99 are applied to device functions that are associated with the over-all station operation A similar series of numbers, starting with 101 instead of 1, are used for those device functions that are associated with unit 1; a similar series starting with 201 for device functions that are associated with unit 2; and so on, for each unit in these installations.