ABSTRACT

COORDINATION OF DISTRIBUTION SYSTEM PROTECTION

Anastassios Vassiliou Psychogios

The effects of short-circuit and normal operation conditions on a power system network are included in a general review of various problems associated with the determination of the electrical characteristics of all substation components. A general overview of a possible interconnection between them to permit the substation to function as a unit with reliability, safety of personnel, switching flexibilities and readiness, and, in general, to be utilized with the most practical way.

The time coordination problem is described and its effects on the choice of substation equipment considered. The design of a typical substation involving the use of a digital computer is included as an example.

TABLE OF CONTENTS

TABLE OF CONTENTS

CHAPTER II - SHORT CIRCUIT CALCULATIONS IN THREE-PHASE SYSTEMS

CHAPTER III - FUSES

CHAPTER IV - CIRCUIT BREAKERS

CHAPTER V - RELAYS

CHAPTER VI - TRANSFORMERS

CHAPTER VII - CAPACITORS

CHAPTER VIII - COORDINATION OF OVERCURRENT DEVICES

PAGE

CHAPTER IX - MECHANICAL AND THERMAL STRESSES DUE TO SHORT-CIRCUIT CURRENT

CHAPTER X - GROUNDING

CHAPTER XI - SUBSTATIONS

APPENDIX A - PROCEDURE EXAMPLE

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LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES

CHAPTER I

INTRODUCTION

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INTRODUCTION

The modern substation is a complex structure since it requires numerous items of equipment and allied services before it can serve its purpose. Both civil and electrical work are involved in a substation. The work on a substation starts from the civil and electrical survey of the area to choose the site. The electrical design of a substation mainly deals with the selection of proper equipment, their location in the yard, and an organized time-current study of them in series from the utilization device to the source to accomplish selectivity, continuity, and safety. This time-current study of these devices is known as "Time Coordination".

For reliable operation of a power system network, a study of all conditions under normal and short-circuit operation of the power system network is very important. It is, also, important to examine all substation components as far as their electrical duties, ratings, and choice are concerned. Equally of importance, the mechanical and thermal stresses on conductors, and the grounding problem should be considered to avoid conductor failure or melting and personnel danger.

This report will examine and study the criteria under which the selection of equipment and time coordination problems can be handled properly for the system to be selective and safe.

CHAPTER II

SHORT-CIRCUIT CALCULATIONS IN THREE-PHASE SYSTEMS

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SHORT-CIRCUIT CALCULATIONS IN THREE-PHASE SYSTEMS

2.0 INTRODUCTION

The nature of the short-circuit currents in three-phase systems will be examined here and hence the determination of the transient capabilities of the systems' components can be possible. The analysis of power systems by symmetrical components has made possible the accurate calculation of fault currents and voltages for asymmetrical faults directly from system constants. Generally, the three-phase fault gives maximum fault current, but line-to-ground may give maximum difficulty of detection since currents may not be all that large, depending on location and nature of ground connections.

Instead of giving a rigorous analysis of the subject, the discussion will be limited to the three-phase short-circuit calculations applied to low-voltage systems.

2.1 NORMALIZATION USING PER UNIT OR PERCENTAGE QUANTITIES

This is essentially the choice of a new set of units based on two arbitrarily chosen quantities. The quantities normally used are volt-amperes and voltage, the values being termed base quantities. From these all other units or base quantities are defined. And since data is usually given as total three-phase kilovoltamperes (kVA) or megavoltamperes (MVA) and line-to-line kilovolts (kV) then the following formulas relate the various quantities [5]:

Base current,

$$I_b = \frac{VA_{base}\text{(3-phase or total voltampères)}}{\sqrt{3} * V_{LLbase}\text{(line-to-line voltage)}} \text{ in amperes} \tag{2.1}$$

Base impedance,

$$Z_b = \frac{V^2_{LLbase}}{VA_{base}\text{(total)voltamperes}} \text{ in ohms} \tag{2.2}$$

Hence, the per-unit quantities are:

$$Z_{pu} = \frac{Z_a\text{(actual impedance),ohms}}{Z_b\text{,ohms}} \tag{2.3}$$

$$I_{pu} = \frac{I_a\text{(actual current),A}}{I_b\text{,A}} \tag{2.4}$$

$$V_{pu} = \frac{V_{LLa}\text{(actual L-to-L voltage),V}}{V_{LLb}\text{,V}} \tag{2.5}$$

$$VA_{pu} = \frac{VA_a\text{(actual total VA),VA}}{VA_{base}\text{ (total),VA}} \tag{2.6}$$

Per-unit values may be changed from one voltampere and voltage base to another as follows:

Let the letter n denote the new base and the letter o the old base. Then

$$I_{bo} = \frac{VA_{bo}}{\sqrt{3}\, V_{LLbo}}, \quad I_{bn} = \frac{VA_{bn}}{\sqrt{3}\, V_{LLbn}} = I_{bo} \frac{VA_{bn}}{VA_{bo}} * \frac{V_{LLbo}}{V_{LLbn}}$$

But $I_{puo} = \frac{I_a}{I_{bo}}$ and $I_{pun} = \frac{I_a}{I_{bn}}$

Thus
$$I_{pun} = I_{puo} * \frac{VA_{bo}}{VA_{bn}} * \frac{V_{LLbn}}{V_{LLbo}} \qquad (2.7)$$

Similarly, it can be shown that

$$(Z,\ R,\ X)_{pun} = (Z,\ R,\ X)_{puo} * \frac{VA_{bn}}{VA_{bo}} * \frac{V^2_{LLbo}}{V^2_{LLbn}} \qquad (2.8)$$

$$(VA,\ P,\ Q)_{pun} = (VA,\ P,\ Q)_{puo} * \frac{VA_{bo}}{VA_{bn}} \qquad (2.9)$$

What is usually chosen is a base VA (VA_b) equal to the largest VA in the system under consideration, whereas the base voltage is chosen as the nominal voltage of each voltage level of the system. As a result, the normalized impedances are automatically referred to all parts of the system. [1] , [5]

2.2 ASYMMETRY DUE TO THE dc COMPONENT

Basically, there are two components of current at the time a fault occurs:

(1) An ac component of short-circuit current flows as determined by the ac voltage and impedance of the system. This is

referred to as the symmetrical short-circuit current. The short-circuit currents for the combination of line and transformer are [7]:

Three-phase fault $= \dfrac{V_{LL}}{\sqrt{3}\,(Z_1 + Z_t)}$ amperes in each phase (2.10)

Line-to-neutral fault $= \dfrac{V_{LL}}{\sqrt{3}\,(2Z_1 + Z_t)}$ amperes (2.11)

Line-to-line fault $= \dfrac{V_{LL}}{2\,(Z_1 + Z_t)}$ amperes (2.12)

where: Z_1 = line-to-neutral impedance in ohms, or the impedance of one conductor to the point of fault.

Z_t = transformer impedance in ohms, or

$$Z_t = \frac{Z_{t\%} * 10kV^2_{LL}}{kVA} \qquad (2.13)$$

$Z_{t\%}$ = transformer impedance in percent

kVA = rating of the three-phase transformer bank

(2) The dc component flows to satisfy the inductance effect; that is, the current cannot change instantaneously. This dc component is initially equal in magnitude and of opposite instantaneously polarity to the ac component of fault current. Note that the addition of the ac and dc components at time equal zero gives zero current provided $i(0^-) = 0$. The dc component

decays to zero. The rate at which it decays is a function of the ratio of the system reactance to resistance (X/R) up to the point of fault.

The resultant short-circuit current may be offset due to the dc component and, hence, is referred to as the asymmetrical short-circuit current. The rms value of this current is given by:

$$I_{asym} = \sqrt{(I_{sym}^2) + (I_{dc}^2)} \qquad (2.14)$$

where

I_{sym} = rms value of the symmetrical ac component current

I_{dc} = value of the dc component

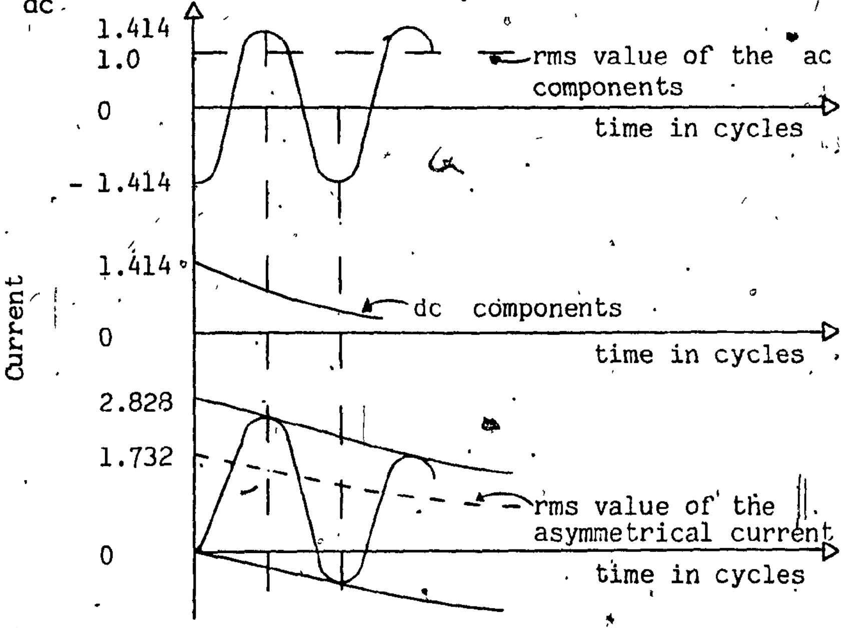


FIG. 2.1 Typical Curves of ac and dc Components Resulting in a Fully Asymmetrical Short-Circuit Current for One Phase of a 3-Phase System; Zero Current Prior to Fault.

As can be seen from Fig. 2.1, the maximum rms value of asymmetrical current can be as high as 1.73 times the symmetrical current (rms) at the instant the fault accurs. Sometimes the rms value of the asymmetrical current for the phase that has maximum asymmetry may actually exceed even 1.73 times the symmetrical component depending on load conditions prior to the fault in the particular circuit under consideration. But, since circuit breakers are capable of beginning current interruption only between 0.5 to 1 cycle after the fault occurs and due to the rapid decay of the dc component, an asymmetry factor 1.73 is large enough to determine the rms value of the asymmetrical current. This asymmetry factor (1.73) is also enough to include the effects of synchronous and asynchronous motors.[9]

2.3 GENERAL PROCEDURE FOR FAULT CALCULATIONS

It is usually permissible to simplify the calculation of fault currents by omitting all static loads, all resistances, the magnetizing current of each transformer, and the capacitance of the transmission line. Under the assumptions

(a) time-variation of synchronous generator parameters is negligible

(b) no significant synchronous or induction motor loading

(c) no current before fault

the step-by-step analysis is as follows:

(1) A common value of base kVA is chosen for all parts or voltage levels in the system; often the rating of the largest unit is chosen. The base voltage is the nominal voltage at each part of the system.

(2) The system is represented by an equivalent circuit containing only inductive reactances and sources. (See Chapter VI, reference [5] .)

(3) The symmetrical short-circuit current (I_{sym}) is calculated using standard steady-state analytical techniques.

(4) The symmetrical short-circuit current is multiplied by 1.73 to obtain the rms value of the maximum possible asymmetrical current.

CHAPTER III

FUSES

CHAPTER III

FUSES

3.0 INTRODUCTION

A method of protecting circuits against the damages of overloads and short circuits is through the use of fuses. A fuse is defined by NEMA as:

> "A devise which protects a circuit by fusing open its current-responsible element when an overcurrent or short circuit passes through." [8] .

Fuses are available having interrupting capacity ratings up to 200 000 A [8] symmetrical, rms and the current limiting ability to provide maximum protection for all circuit components.

3.1 LOW-VOLTAGE FUSE RATINGS

Low voltage fuses have current, voltage, interrupting, and kVA ratings which should not be exceeded in application. Some fuses are rated, also according to their current-limiting capability which is established in accordance with the maximum peak let-through current (I_p) and the maximum let-through energy ($R\int I^2_{asym}\,dt$) by the fuse when clearing a fault.

where: R = fuse resistance

(1) The current rating of a fuse is the maximum direct or rms alternating current, in amperes, at rated frequency which it will carry without exceeding specified limits of temperature

rise. The range of ratings is from a few milliamperes to 6 000 A.

(2) The voltage rating is the maximum alternating or direct-current voltage at which the fuse is designed to operate. The standard ratings are 600, 300, 250, or 125 V alternating or direct current or both.

(3) The interrupting rating is the assigned maximum short-circuit current (usually alternating current) at rated voltage which the fuse will safely interrupt. Their interrupting ratings are 10 000, 50 000, 100 000 or 200 000 A.

(4) The kVA rating or breaking capacity at a fuse is the product of the rms value of the ac component of that current which would flow under fault conditions and the system voltage. The fault current normally has a very large first loop, but since it generates sufficient energy, the fuse melts well before the peak of this loop is reached. Since the cut-off current (see Fig. 3.1) is largely determined by the amount of energy needed to melt the element, its value will vary according to that current which would flow under fault conditions. The cut-off current is always less than the peak value of the fault current. Thus, a fuse almost never actually passes a current equivalent to its rupturing or breaking capacity. It is however assigned that value because it prevents the development of this current by its cut-off action.

3.2 TYPES OF FUSES

Only two types will be mentioned.

(1) Plug fuses: They may be used in circuits up to 30 A. Their use is limited to circuits rated at 125 volts or less, except that they may be used in installations having a grounded neutral with a maximum of 150 volts to ground. They are not used in main power flow of substations.

(2) Cartridge fuses: They are classified in ratings of up to 600 A and from 601 to 6 000 A. Fuses classified up to 600 A are rated "not over 250 volts", "not over 300 volts", and "not over 600 volts". Fuses classified 601 to 6 000 A are rated at 600 volts or less only. Some cartridge fuses have a dual element (time delay) which combines a thermally controlled element that functions in the case of an overload and a fusible element that operates under short circuit. Its design permits matching of fuse characteristics with the load so that superior protection is provided.

3.3 SELECTIVITY OF FUSES

Since the electrical distribution system is the heart of most industrial, commercial, and institutional type installations, it is imperative that any unnecessary shutdowns of electrical power be prevented. Unnecessary blackouts can be avoided by the proper selection of overcurrent protective devices. Selectivity or coordination may be defined as the complete isolation of a faulted circuit to the point of fault without disturbing any of the other protective devices in the system and therefore unfaulted parts of system. In practical terms, (see Fig. 3.1), for selectivity the total clearing energy of fuse B must be less than the melting energy of fuse A when they are operating in series and fuse A feeds fuse B.

3.4 CHARACTERISTICS OF FUSES

There are two types of fuse characteristics: melting time-current characteristics and total clearing time-current characteristics. Typical characteristics are shown in Fig. 3.2 and Fig. 3.3. For selectivity the total clearing curve of fuse B should be placed to the left of the melting curve of fuse A on the time-current characteristics of the whole system. Details are given in Section A.4 of the Appendix.

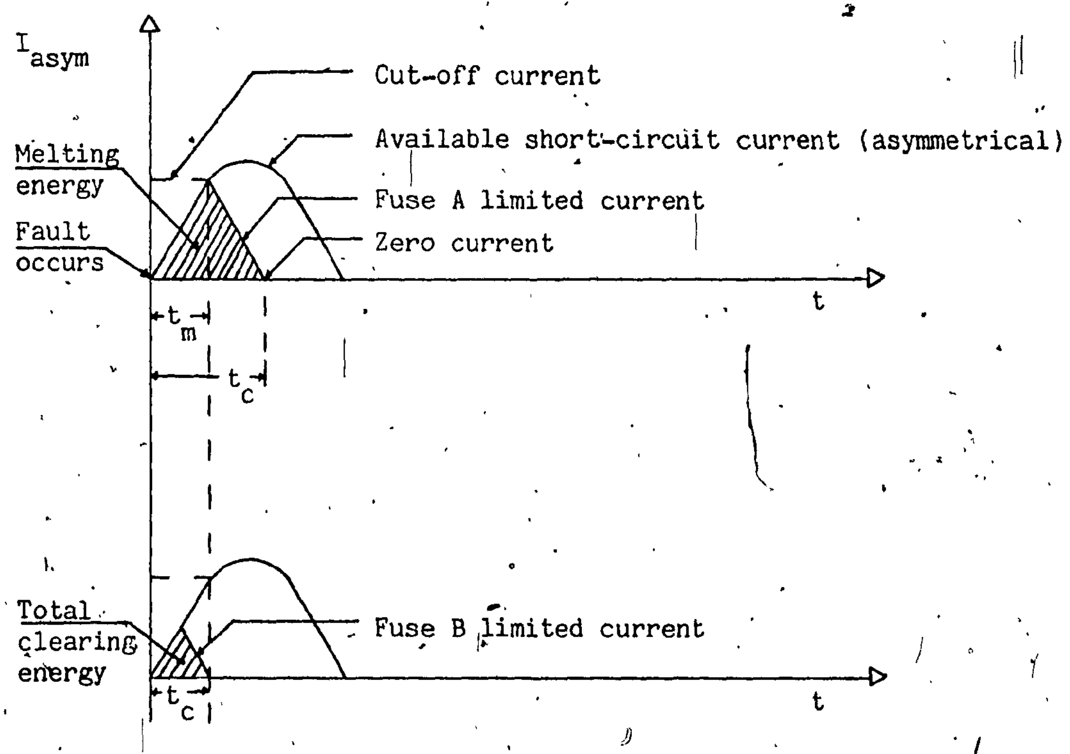
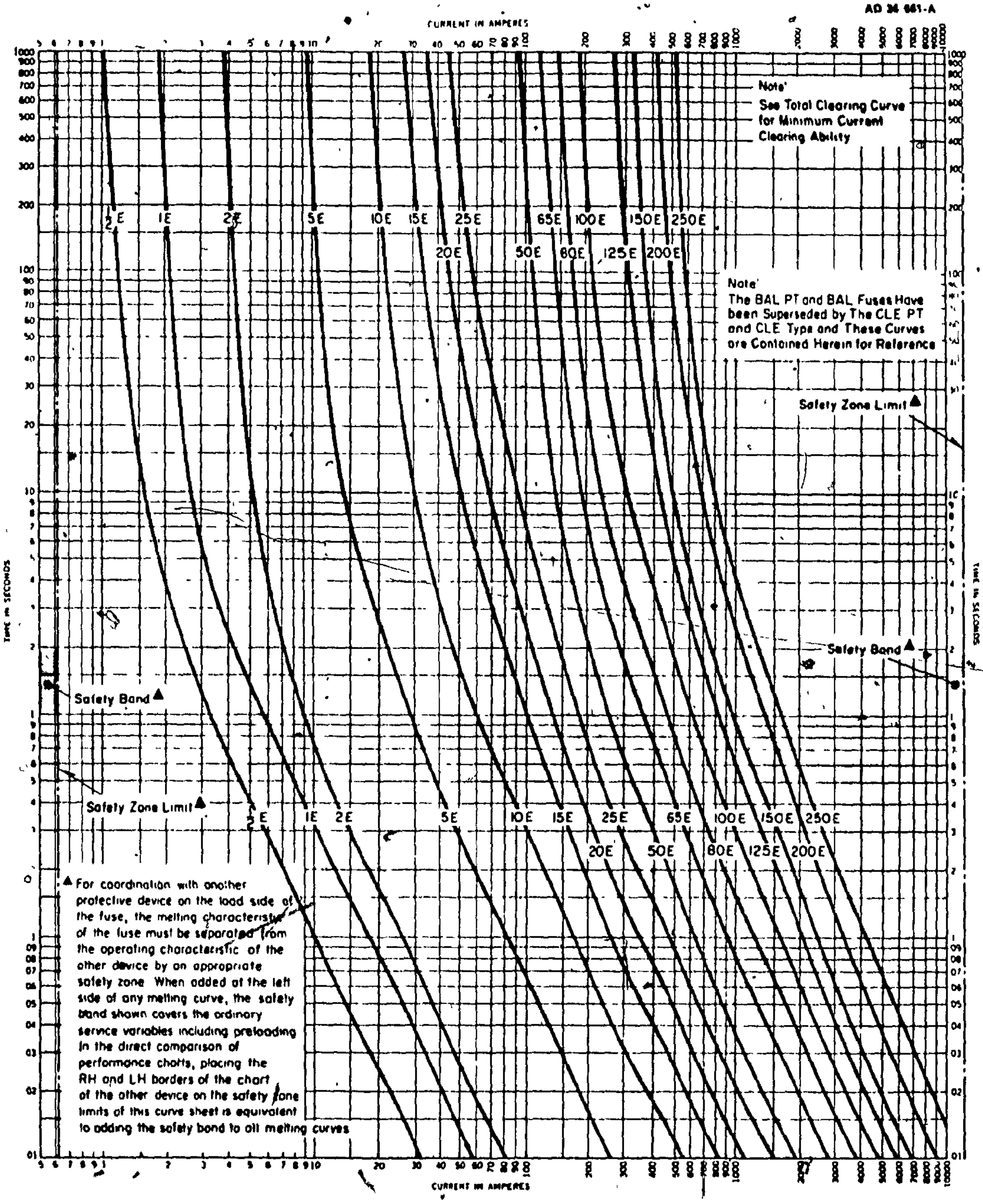


FIG. 3.1 Typical Clearing and Melting Energy at a Short Circuit
t_m = melting time, t_c = clearing time



Note: See Total Clearing Curve for Minimum Current Clearing Ability

Note: The BAL PT and BAL Fuses Have been Superseded by The CLE PT and CLE Type and These Curves are Contained Herein for Reference

▲ For coordination with another protective device on the load side of the fuse, the melting characteristic of the fuse must be separated from the operating characteristic of the other device by an appropriate safety zone. When added at the left side of any melting curve, the safety band shown covers the ordinary service variables including preloading. In the direct comparison of performance charts, placing the RH and LH borders of the chart of the other device on the safety zone limits of this curve sheet is equivalent to adding the safety band to all melting curves

Type BAL-PT, -10, -25, -200 and -300 Current Limiting Power Fuses

Melting time-current characteristics, 2 4 to 34 5 Kv

Curves are based on tests starting with fuse units at an ambient temperature of 25 C and without initial load. Curves are plotted to minimum test points so variations should be positive

Westinghouse Electric Corporation
Switchgear Division Power Switching Equipment, East Pittsburgh Pa
Printed in U.S.A.

Curve No 18

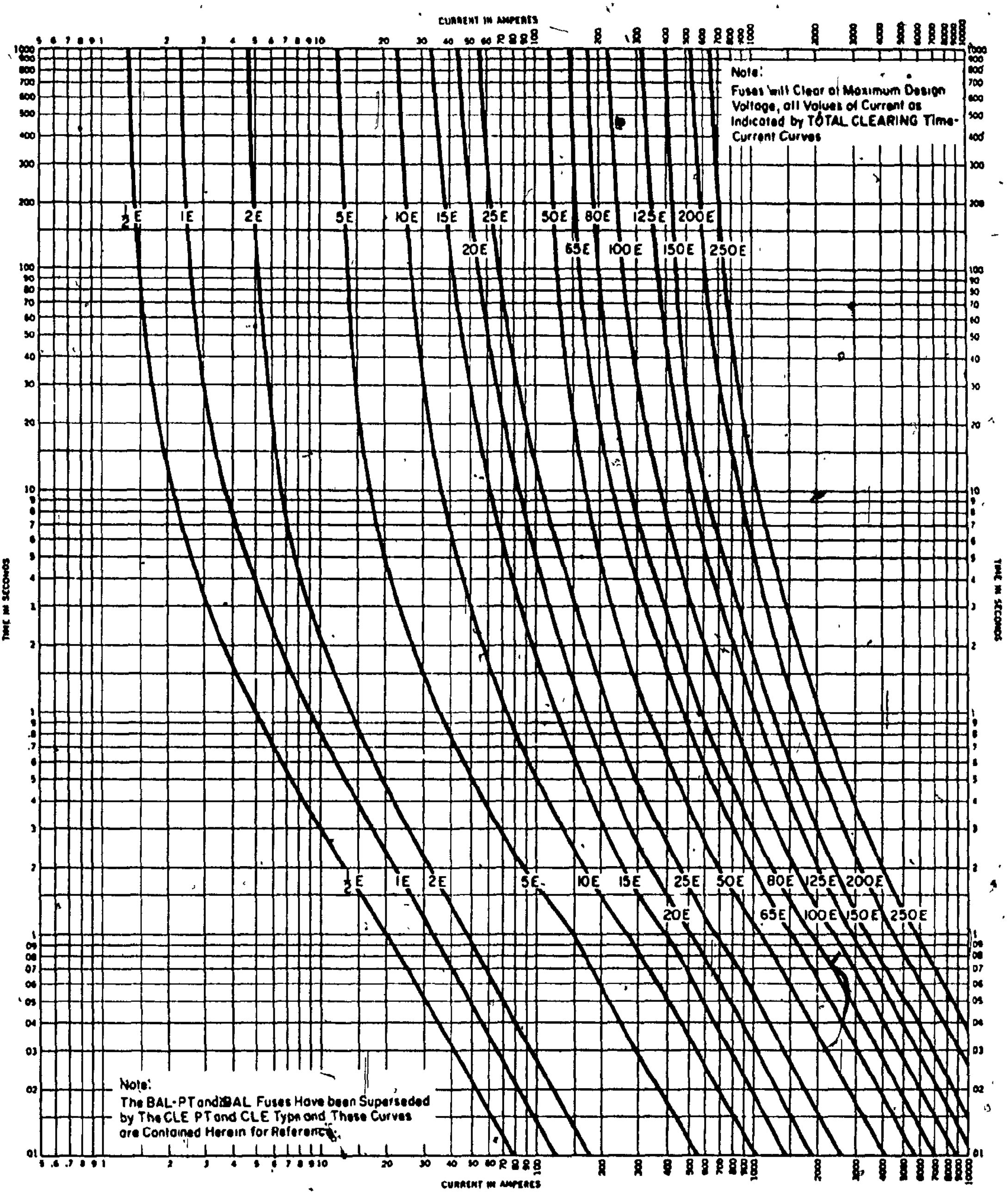
Supersedes Curve No 15, dated January 1961

Reference No 459344

May 19[illegible]

FIG. 3.2

AD 36-661-A



Note:
Fuses will Clear at Maximum Design Voltage, all Values of Current as Indicated by TOTAL CLEARING Time-Current Curves

Note:
The BAL-PT and BAL Fuses Have been Superseded by The CLE PT and CLE Type and These Curves are Contained Herein for Reference.

Type BAL-PT, -10, -25, -200 and -300 Current Limiting Power Fuses

Total clearing time-current characteristics, 2.4 to 34.5 Kv

Curves are based on tests starting with fuse units at an ambient temperature of 25°C and without initial load. Curves are plotted to maximum test points so variations should be negative.

Westinghouse Electric Corporation
Switchgear Division, Power Switching Equipment, East Pittsburgh, Pa.
Printed in USA

Curve No. 19

Supersedes Curve No. 19, dated January, 1961
Reference No. 458292
May, 1965

FIG. 3.3

3.5 ADVANTAGES AND DISADVANTAGES OF A FUSE

Some merits and disadvantages are stated below to give a better feeling of where and why a fuse should be chosen.

3.5.1 Advantages

(1) Capital cost is considerably less than any other type of protection.

(2) It provides a current limiting effect under short-circuit conditions due to cut-off.

(3) The minimum time of operation can be made much smaller than that with circuit breakers.

(4) It requires no maintenance.

(5) It interrupts enormous short-circuit currents without the noise associated with circuit breakers.

3.5.2 Disadvantages

(1) On heavy short-circuits, discrimination between fuses in series cannot be obtained unless there is considerable difference in the relative sizes of the fuses concerned.

(2) Time is lost in replacing fuses after operation.

(3) Cost of replacement.

(4) It is extremely difficult to coordinate fuses in a radial distribution system and thus provide secondary protection.

CHAPTER IV

CIRCUIT BREAKERS

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CIRCUIT BREAKERS

4.0 INTRODUCTION

There are two basic classifications of low-voltage (11 kV common or below) circuit breakers, (1) molded-case circuit breakers and (2) low-voltage power circuit breakers (air type). Oil breakers are usually used on high-voltage circuits. Since they require maintenance, the oil is easily inflammable and may form an explosive mixture with air, they are seldom used in enclosed spaces and on low-voltage circuits.

(1) A molded-case circuit breaker is one which is assembled as an integral unit in a supporting and enclosing housing of insulating material.

(2) A low-voltage power circuit breaker is one for use on circuits rated up to 15 kV alternating current and below, but not including molded-case circuit breakers.

Basic ratings are:

(i) Rated voltage
(ii) Rated frequency
(iii) Rated continuous current
(iv) Rated interrupting current
(v) Rated short-time current (low-voltage power circuit breakers only).

A knowledge of the currents resulting from various types of fault at a location in a distribution system is essential for the effective operation of what is known as system-protection. When a short circuit occurs, enormous energy may be fed into the fault with considerable damage and interruption of service. The aims of protective devices are to achieve (1) discrimination, (2) speed of operation, (3) reliability, (4) stability, and (5) back-up protection.

Discrimination is its effectiveness in isolating only the faulty part of the system. Speed of operation is required in order that no damage may be done to the power system by the short-circuit currents. Reliability is required, as the protective device is added because it is intended to improve the reliability of the whole system. Stability is the property of remaining inoperative with faults occuring outside the protected zone (called external faults). Back-up protection is a completely separate arrangement which operates to remove the faulty part if the main protection fails to operate. The back-up system should be as independent of the main protection as possible possessing its own current transformers and relays.

Here, it is not intended to give an account of circuit breakers, but their ratings and tripping devices will be briefly discussed.

4.1 RATINGS

(1) Rated Voltage: Nominal voltage is the system voltage for which the breaker is intended and it is stated in terms of three-phase line-to-line voltage. Maximum voltage is the maximum voltage at which the breaker can operate without insulation damage. It is advisable to avoid operation there. Its significance is to

meet the insulation requirement of that transient overvoltage.

(2) Rated Frequency: This is the frequency (or range of frequencies) for which the other ratings are applicable.

(3) Rated Continuous Current: This is the maximum current the breaker can stand with continuous operation; it is not to be confused with the direct current.

(4) Rated Interrupting Current: The interrupting rating of a breaker is expressed as the maximum current that the breaker can interrupt at a specified voltage.

(a) In a 3-phase circuit, this current is the asymmetrical current which is defined as the average of the rms values of asymmetrical currents in the three phases measured at the instant half a cycle after the fault occurs. [1], [6]

(b) In dc circuits, it is the maximum value of the current flowing during the fault transient.

The standard interrupting duty cycle of a circuit breaker with instantaneous tripping for fault currents consists of an opening operation, followed after a 15-second interval by a close-open operation. The standard interrupting duty cycle of circuit breaker with delayed tripping for fault currents is defined as previously, the tripping being delayed by the associated tripping devices.

(5) Rated Short-Time Current: This is the value of fault current that the breaker can successfully carry for a short-time interval, based on the following duty cycle. [9]

The standard short-time duty cycle consists of maintaining rated short-time current for two periods of one-half second each, with a 15-second interval of zero current between the one-half second periods. The short-time current is defined in the same manner as the interrupting current.

4.2 SERIES OVERCURRENT TRIPPING DEVICES

Before proceeding to the actual tripping devices, some comments on the term "pickup" are required.

This term has acquired several meanings. For many devices, pickup is defined as that minimum current which starts an action. For instance, the pickup current of an overcurrent protective relay is the minimum value of current which will cause the relay to close its contacts. A trip device with a long-time delay, short-time delay, and an instantaneous characteristic will have three pickup values.

There are, therefore, three basic over-current tripping characteristics used on low-voltage breakers:

(I) Long-Delay: This characteristic is furnished by a magnetic element which gives a delayed tripping in the order of seconds or even minutes for values of overcurrent only a few multiples of the trip coil rating. Both the pickup current and the time-delay unit are adjustable and therefore two settings are required to define completely the long-delay characteristic. Its usual function is to furnish overload protection for conductors or apparatus or both.

(2) Short-Delay: This characteristic is also furnished by a magnetic element that gives a time delay in the order of cycles for currents having the approximate magnitude of fault current. Two settings are required to define completely the short-delay characteristic, namely, a pickup setting and a time-delay setting. Its usual function is to provide a short-time delay for fault currents in order to give selectivity with other circuit breakers.

(3) Instantaneous Trips: This characteristic is furnished by a magnetic instantaneous device with no intentional time delay. Only pickup setting is required to define the instantaneous characteristic. Its usual function is to give short-circuit protection to load circuits. Typical tripping characteristic curves are shown in Fig. 4.1, 4.2.

4.3 REVERSE-CURRENT TRIPPING DEVICES

Reverse-current tripping devices of the instantaneous type are available for applications on dc systems. Such devices will trip for reverse-current down to 5 percent of the current rating.

4.4 SHUNT TRIPPING DEVICES

Shunt trip attachments are solenoid mechanisms that trip the breaker when energized through a control switch contact or relay contacts. Shunt trip attachments are required on all electrically operated breakers and on breakers that are tripped by relays.

Other tripping devices are: undervoltage tripping attachments, closing devices, control relays, alarm switches, auxiliary switches, and interlocks utilized in order to obtain better and safer performance.

4.5 CIRCUIT BREAKER CHARACTERISTICS

The two main types of circuit breakers have different characteristics. A low-voltage power circuit or an air circuit breaker has characteristics as shown in Fig. 4.1. It can be seen these breakers have a great number of combinations of settings for long-delay pickups and times, short-delay pickups and times, and instantaneous pickups as well. There is also, a short-delay pickup and ground time for ground protection. The method for choosing these settings is described in detail in the appendix. A molded-case circuit breaker has typical characteristics as shown in Fig. 4.2. The curves represent current tripping limits for the breaker. For a given current, at rated ambient temperature, a breaker will clear the circuit automatically at some total time within the two extreme values defined by "maximum" and "minimum" curves. The upper left portions of these curves show the inverse time delay tripping of the breakers due to thermal action.*

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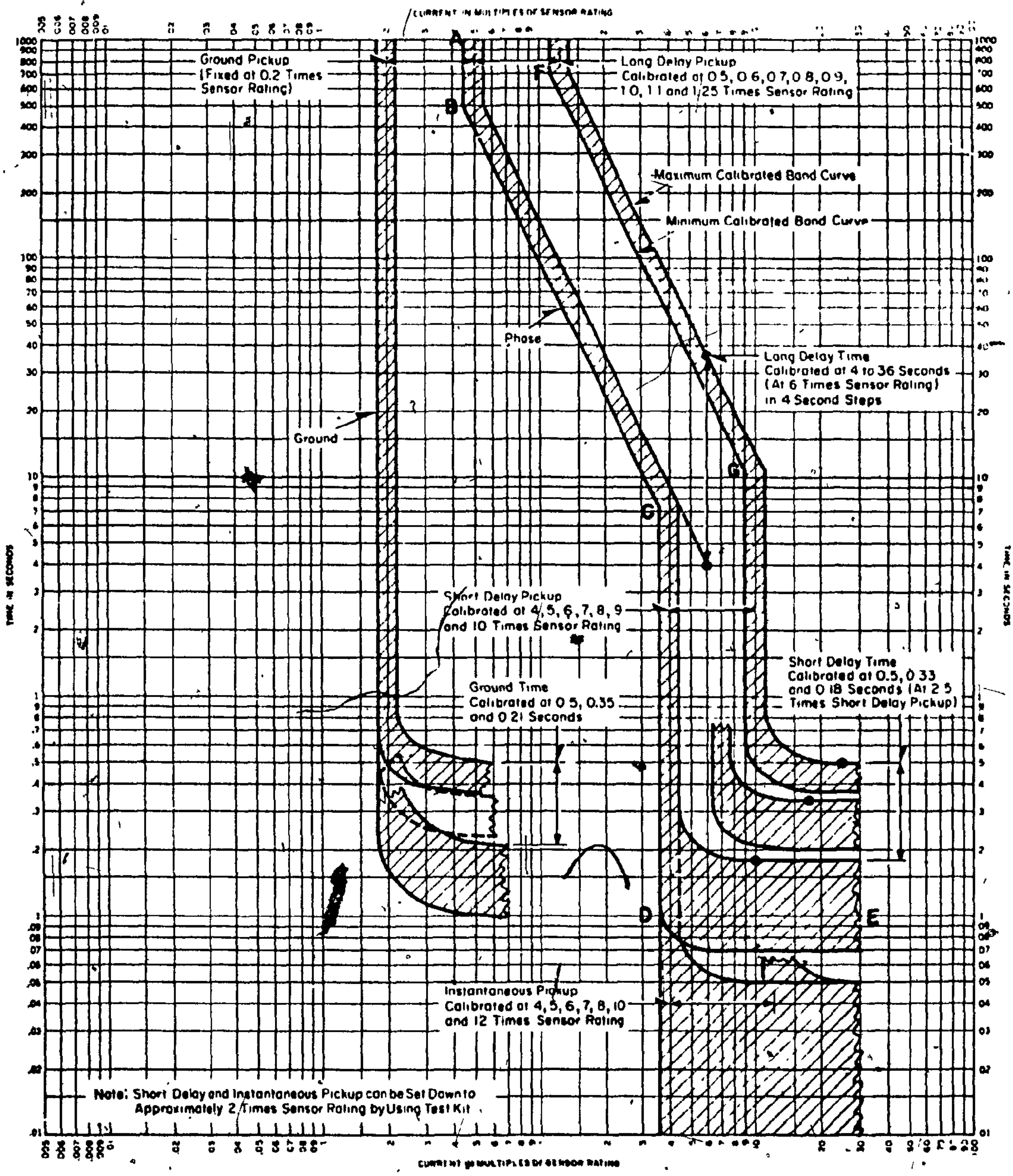
* Thermal magnetic breakers are usually equipped with a thermal-front adjustable magnetic trip unit. In the trip unit, thermal trip elements indirectly heated by a transformer, provide inverse time delay characteristics for overload conditions. Being transformer heated, the thermal elements do not respond to direct current and therefore must be used on alternating current circuits only.



Type DB Air Circuit Breakers with Amptector
For Application up to 600 Volts Ac
Time Current Characteristics

Curve No. 1

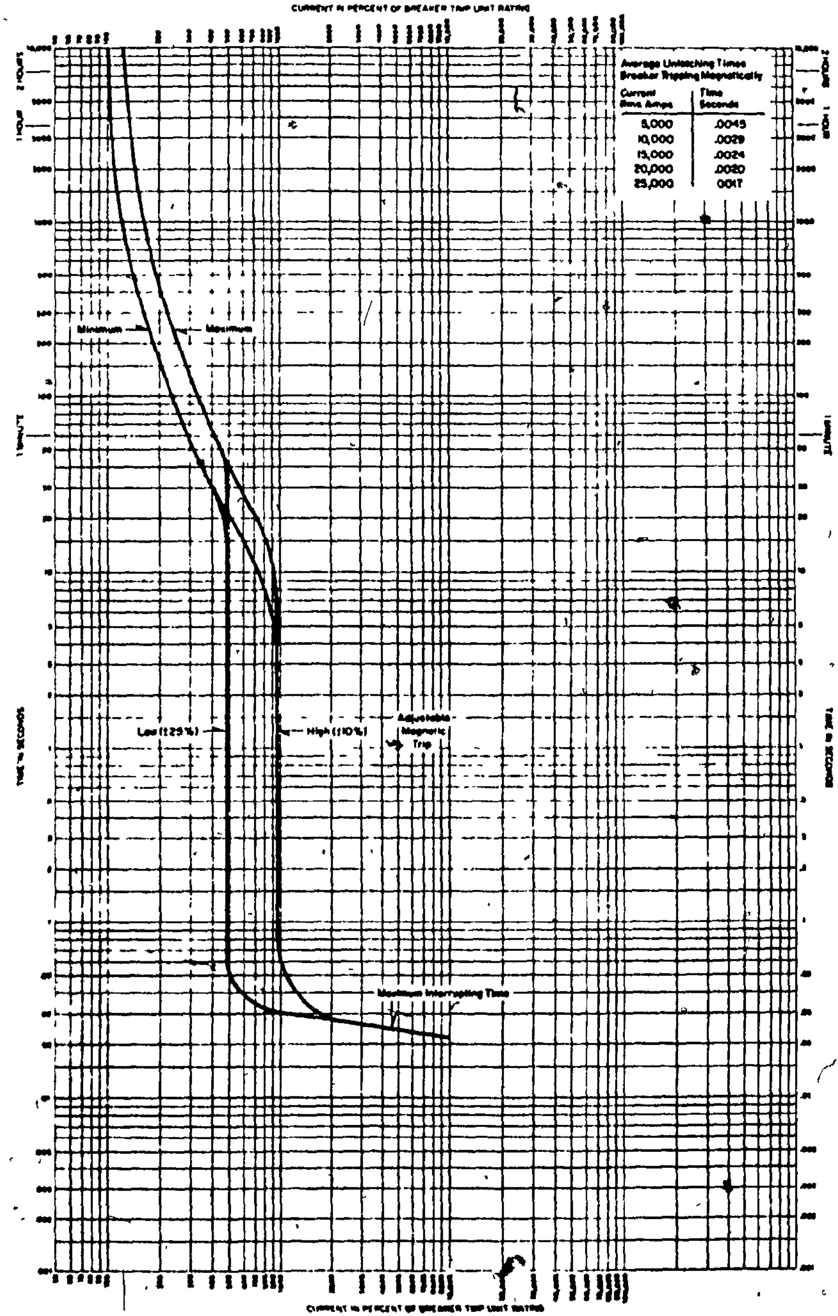
New Information
Reference No. 620660-B
March, 1972

Westinghouse Canada Limited
Industrial Products Division, Hamilton, Canada
Printed in Canada

FIG. 4.1

Maximum and Minimum Characteristics Curves (40°C Ambient • Cold Start)

For Type JA70 to 225 Amperes, 600 Volts Ac; 250 Volts Dc, 2 and 3 Pole



Average Unlatching Times Breaker Tripping Magnetically

Current Rms Amps	Time Seconds
5,000	.0045
10,000	.0029
15,000	.0024
20,000	.0020
25,000	.0017

Maximum and Minimum Characteristic Curves
40°C Ambient, Cold Start • Thermal Magnetic

Curve No. SC-343-70

Interrupting Capacity (Symmetrical Amperes)

Breaker	240 Volts	480 Volts	600 Volts
JA, KA	[illegible]	[illegible]	[illegible]
HKA	[illegible]	[illegible]	[illegible]

FIG. 4.2

The lower right segments of these curves portray the magnetic tripping action of the breakers. In the case of the front adjustable thermal-magnetic breakers, the magnetic tripping elements may be adjusted to trip at values within a specific current range. Currents equal to or greater than these magnetic settings will cause instant tripping. Typical breaker unlatching times are tabulated for high current values; on respective breaker curves these are the time-current values actually required for the breaker trip element to trigger the release mechanisms. In application, the curves can be moved parallel to themselves along the current axis by varying different settings.

CHAPTER V

RELAYS

CHAPTER V

RELAYS

5.0 INTRODUCTION

A protective relay is a device whose function is to detect defective lines or apparatus or other power system conditions of an abnormal or dangerous nature and to initiate appropriate control circuit action. Usually, they trip circuit breakers.

Protective relays constantly monitor the power system to assure maximum continuity of electrical service with minimum damage to life and property. Protective relays are a form of active insurance. By their application in the power system, abnormalities are quickly recognized and action initiated to isolate the faulted equipment. Like insurance, one can have as much or as little protection as desired, depending on the individuality of the power system and its engineers and operators. Since continuity of service and maximum equipment protection are incompatible goals, compromises become necessary and must be evaluated on the basis of comparative risks.

5.1 RELAY TYPES, CHARACTERISTICS AND RATINGS

All relays, except the thermal type, operate on:

(1) Electromagnetic attraction

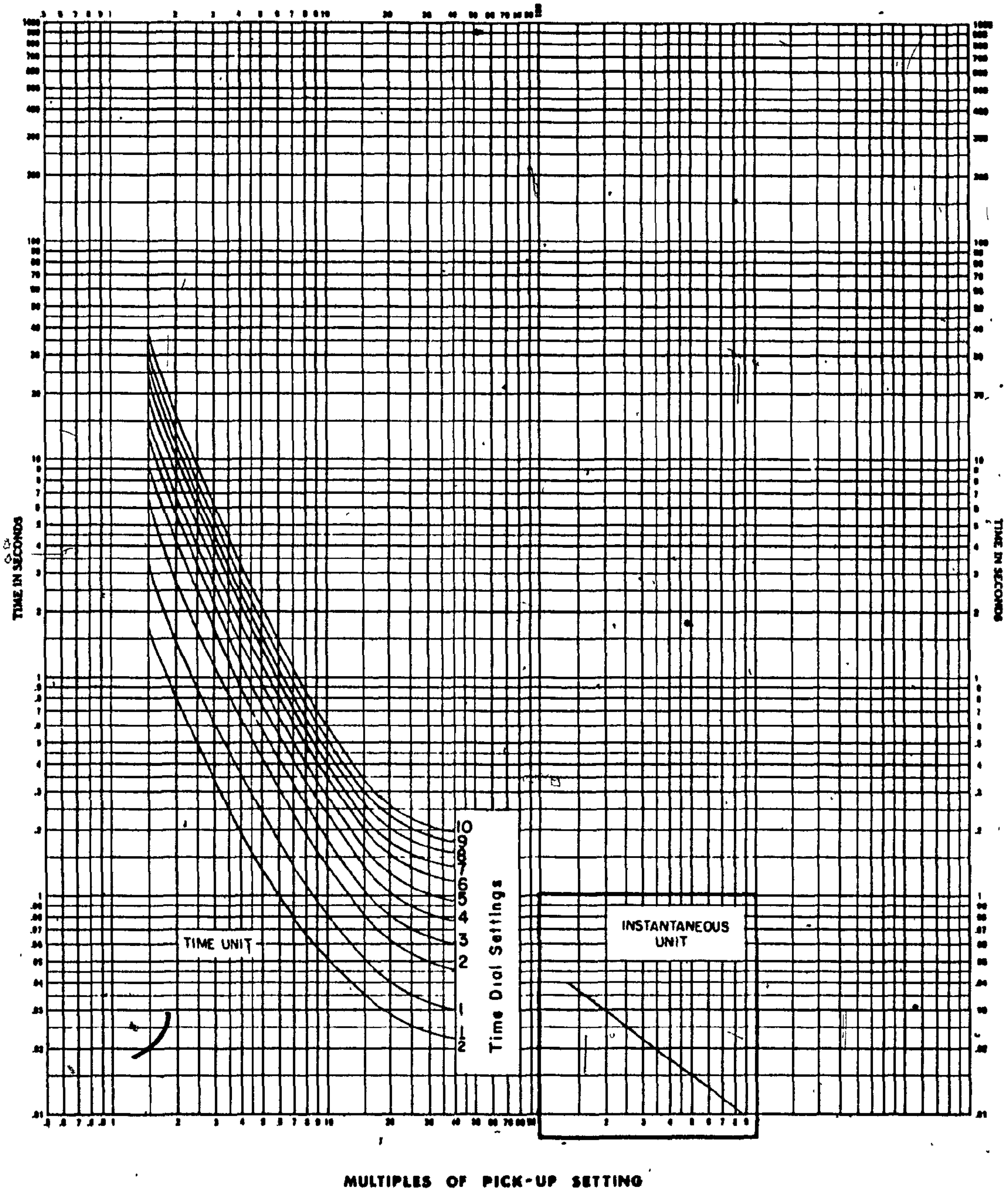
(2) Electromagnetic induction

The electromagnetic induction relays consist of an induction unit or an induction unit with an instantaneous unit which permits instantaneous tripping for extremely high currents, or an induction unit with an ac tripping unit for use where dc power is unavailable or ac tripping is preferred.

The induction unit may have one or two circuit-closing contacts which close as the current increases to the pickup value as set on the tap block. The time delay for closing the contacts is determined by the setting of the time dial. Typical time-current characteristics are shown in Fig. 5.1.

As can be seen on the curve, with a slight overcurrent, say the value obtained with the 1.5 multiple of pickup setting (tap), the relay contacts will close in 1.7 to 36 seconds, depending on the time dial setting. If, however, the overcurrent is the 20 tap, the relay would operate in .029 to 0.26 seconds. In other words Fig. 5.1 indicates the time required for the contacts to close with a particular time-dial setting when the current is a prescribed number of times the current tap setting.

The induction element is usually designed to use any one of three operating coils, each having a different combination of taps; for instance, Fig. 5.1 gives these different combination of taps, i.e. 0.5, 0.6, 0.8, 1, 1.2, 1.5, 2 amperes; 1.5, 2, 2.5, 3, 4, 5, 6 amperes; 4, 5, 6, 8, 10, 12, and 16 amperes.



GENERAL ELECTRIC

TIME OVERCURRENT RELAY
IAC 77 RELAY

GES-7005

EXTREMELY INVERSE STANDARD TIME
TIME-CURRENT CURVES

OTHER RELAYS WITH DUPLICATE
TIME DELAY CHARACTERISTICS

IAC90, IBC77-78, IBCG77-78, IBCV77-78,
JBC77-78, JBCG77-78, JBCV77-78

RATINGS (AMPERES)

TIME UNIT	INSTANTANEOUS UNIT
0.5-2	2-8
1.5-6	4-16
4.0-16	10-40
	20-80
	40-160

SETTINGS

TIME UNIT (TAPS)	INST UNIT
0.5, 0.6, 0.8, 1.0, 1.2, 1.5, 2.0 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0 4.0, 5.0, 6.0, 8.0, 10.0, 12.0, 16.0	CONTINUOUSLY ADJUSTABLE

LOW VOLTAGE SWITCHGEAR DEPT., PHILADELPHIA, PA.

FIG. 5.1

It is worth stating here the device function numbers for use with all external diagrams:

50	-	Instantaneous Unit
51	-	Overcurrent Relay
51N	-	Ground Overcurrent Relay
52	-	Power Circuit Breaker
TC	-	Trip Coil
A	-	Auxiliary Contact, closed when breaker closes

5.2 TAP SELECTION AND SETTINGS

To illustrate the process of selecting taps and settings, the following example uses values typical of many distribution systems. Suppose that a primary relay has to be coordinated with the main secondary protection circuit breaker. The transformer is of 1 000 kVA, 3-phase, 13 800/480-V rating, $X = 5.75\%$. Any current at the secondary greater than 2083 A (1 000 kVA/480 V) will normally overload the transformer. Thus, the maximum selected current of the breaker during which circuit interruption is expected is 2083 A. If we choose as $V_b = 480$ V, $S_b = 1\,000$ kVA, then $I_b = 1 * 10^6/(\sqrt{3} * 480) = 1\,200$ A and $I_{pu} = 1/0.0575 = 17.39$. Therefore, a short after the main secondary circuit breaker will produce a symmetrical short-circuit current equal to 20 869 A. ($I_{sym} = I_{pu} * I_b$) (Everything is referred to the low-voltage side). Then, the procedure is as follows:

(1) The continuous current at the primary (I_p) is

$$I_p = \frac{VA}{\sqrt{3} * V_{LL}} = \frac{1 * 10^6}{\sqrt{3} * 13\,800} = 42 \text{ A} \qquad (5.1)$$

Since the current transformer should be about 150-250 percent of the I_p a 100/5 ratio current transformer can be assumed.

(2) To obtain the current rating for the relay overload unit, it is expected that the maximum selected current of the breaker be the minimum pick-up current of the relay. This is because for selectivity, any current deviation above its normal value at the secondary has to be interrupted by the main secondary circuit breaker first and in case of its failure to do so, then the primary relay undertakes this duty.

Thus

$$I_{\text{relay overload}}(I_{ro}) = \frac{\text{minimum pick-up current}}{\text{current transformer ratio}} * \frac{1}{\frac{\text{primary voltage}}{\text{secondary voltage}}} \qquad (5.2)$$

(This is done when all the characteristics are referred to the secondary voltage).

$$I_{ro} = \frac{2\,083}{\frac{100}{5} * \frac{13\,800}{480}} = 3.6 \text{ A}$$

Therefore a tap setting of 3.6 A can be chosen if it exists or the next higher tap setting. If the next higher tap setting is 4 A, this is chosen.

(3) The actual relay pick-up for the chosen tap setting (I_{rp}) then is

$$I_{rp} = \text{tap setting} * \text{current-transformer ratio} * \frac{\text{primary voltage}}{\text{secondary voltage}} \qquad (5.3)$$

or

$$I_{rp} = 4 * \frac{100}{5} * \frac{13\ 800}{480} = 2\ 300 \text{ A}$$

(4) The current rating for the instantaneous unit is given by

$$I_{\text{relay instantaneous}}(I_{ri}) = \frac{\text{max. asymmetrical short-circuit current}}{\text{current-transformer ratio}} * \frac{1}{\frac{\text{primary voltage}}{\text{secondary voltage}}} \qquad (5.4)$$

or

$$I_{ri} = \frac{20\ 869 * 1.73}{\frac{100}{5} * \frac{13\ 800}{480}} = 63 \text{ A}$$

Hence the instantaneous setting should be at 63 A which is between the rating range 40 - 160 A of the relay (Fig. 5.1).

Note that I_{rp} and I_{asym} are referred to low-voltage side of the transformer whereas the I_{ro} and I_{ri} are referred to the primary and are the actual currents being monitored by the relay.

CHAPTER VI

TRANSFORMERS

CHAPTER VI

TRANSFORMERS

6.0 INTRODUCTION

Transformers can be grouped into two categories:

(a) power transformers

(b) instrument transformers

Power transformers are used to provide the power needed by the substation and instrument transformers are used to feed the protective devices of the substation.

6.1 POWER TRANSFORMERS

They can be classified in accordance with the forms of construction, type of cooling, number of phases, power capacity, type of insulation, type of primary and secondary windings connection (Y, Δ) etc.

There are many factors to be considered in the choice of a power transformer. Basically, the rated kVA output of a transformer, the voltage transformation, the windings connection (Y, Δ), the short-circuit impedance, the number of phases (single, two or three-phase transformer), and the limited duration of a short-circuit in seconds should be considered.

For the limited duration of a short-circuit, the following time periods or intermediate values by interpolation can be used [2] :

Symmetrical Current in any Winding	Time Period in Seconds
25 times base current	2
20 times base current	3
16.6 times base current	4
14.3, or less, times base current	5

TABLE 6.1 Limited Duration Time Periods for Power Transformers

This time period is very important for the selection of the rated short-time current for tripping of switchgear. The tripping time of a circuit breaker should be less than the time given in Table 6.1 of an adjacent transformer. It is this table which is used to construct the time-current characteristic of a transformer (see Fig. A.6, Characteristic no. 5).

The rated kVA output of a power transformer is that output which the transformer can deliver continuously at rated secondary voltage without exceeding a given temperature rise measured under prescribed test conditions. The choice of the rating of a power transformer depends on the maximum load demands.

For more detailed consideration, refs [1], [2], [7], and [8] are suggested.

6. INSTRUMENT TRANSFORMERS

There are potential or voltage and current instrument transformers. Voltage transformers are very well known so that their duty will be omitted [1]. Current transformers and their duty will be explained briefly. They are used to obtain currents which are proportional to the system (primary) currents and which can be used in measurement and control circuits. Often the primary conductor itself, e.g. an overhead line, forms a single primary turn (bar primary). Whereas instrument current transformers have to remain accurate only up to slight overcurrents, protection current transformers must remain proportional up to, say, twenty times normal full load [4].

A major problem exists when two current transformers are used which should have identical characteristics up to the highest fault current, e.g. in pilot wire schemes. Because of saturation in the silicon steel used and the possible existence of a direct component in the fault current the exact matching of such current transformers is difficult. A pilot wire scheme is a system protection method which requires that a relay shall operate when the currents at two points of the system are unequal. At the occurence of a fault, although the currents in the primaries of the current transformers are equal, they may produce currents in the secondaries which vary by more than the permissible difference if the current transformers are not identical (see ref. [2], Chapter IX). The nominal secondary current rating of current transformers is now usually 1 A but 5 A has been used in the past [9].

CHAPTER VII

CAPACITORS

CHAPTER VII

CAPACITORS

7.0 INTRODUCTION

In distribution systems capacitors are often used to improve the power factor by compensating at least partially the reactive component of load current (shunt capacitors). The main advantages of advancing the phase to as near unity power factor as possible are:

(a) the load power output of a given plant is increased for the same apparent power and with it the earning capacity

(b) line losses are reduced to a minimum

(c) voltage regulation is considerably reduced, and

(d) there is a beneficial effect upon the stability of the system.

Usually, the average values of power factor for different kinds of loads are the following [9]:

Lighting	0.95
Lighting and power demanded, mainly the former	0.8 - 0.85
Lighting and power demanded, mainly the latter	0.75
Power demanded	0.65 - 0.70
Single-phase power demanded	0.5

In all cases the power factor is lagging. There are many methods of advancing the power factor, but only one will be examined, using static shunt capacitors.

7.1 STATIC SHUNT CAPACITORS

To find the value of a capacitor connected in parallel with a load required to raise the power factor PF_1 of a three-phase load to a value PF_2, all that has to be done is:

Usually, V_{LL}, PF_1, PF_2, and total power P_{L3} at load are given.

Then

(a) The reactive power (Q_1) per phase before the addition of any reactance is

$$Q_1 = \frac{P_{L3}}{3} \tan \left[\cos^{-1} (PF_1)\right] \quad \text{kVAR} \qquad (7.1)$$

(b) The reactive power (Q_2) per phase that should exist after the addition of capacitance, i.e., with the PF_2 power factor is

$$Q_2 = \frac{P_{L3}}{3} \tan \left[\cos^{-1} (PF_2)\right] \quad \text{kVAR} \qquad (7.2)$$

(c) The difference is the required reactive power per phase to be added

$$Q = Q_2 - Q_1 \qquad (7.3)$$

(d) The reactive current (I_2) for the required reactive power (Q) for the star bank connection is

$$I_2 = \frac{\sqrt{3}Q}{V_{LL}} \qquad (7.4)$$

(e) Since the reactance X_c for the star bank connection is

$$X_c = \frac{V_{LL}}{\sqrt{3} * I_2} = \frac{1}{\omega C_s}$$

then

$$C_s = \frac{\sqrt{3}\, I_2}{\omega\, V_{LL}} \qquad (7.5)$$

(C_s = required capacitance in the star bank)

(f) Since $Z_Y = Z_\Delta / 3$, then the required capacitance in the delta bank is

$$C_\Delta = \frac{I_2}{\sqrt{3}\,\omega V_{LL}} \qquad (7.6)$$

(g) Finally, the rating (kVAR) for both cases is

$$kVAR = \sqrt{3}\, I_a\, V_{LL} \qquad (7.7)$$

[I_a is defined in the appendix (A.2)]

CHAPTER VIII

COORDINATION OF OVERCURRENT DEVICES

CHAPTER VIII

COORDINATION OF OVERCURRENT DEVICES

8.0 INTRODUCTION

Coordination is a study of an electric power system consisting of an organized time-current study of all devices in series from the utilization device to the source. This study is a comparison of the time it takes the individual devices to operate when certain levels of normal or abnormal current pass through the protective devices. In most power distribution systems the tripping elements are arranged in a coordination scheme so that only the breaker closest to the fault should operate to clear the fault and leave the rest of the system operating normally.

To ensure that a system has been coordinated, the time-current characteristics of all the devices in series must be plotted in such a manner so that no overlap of these characteristics occurs within the values of short-circuit current applicable. Consideration must also be given to primary protective devices, and their trip characteristics should be plotted and converted to the same voltage base as the secondary devices.

8.1 CHARACTERISTIC CURVES

A basic understanding of time-current characteristics is essential to any study. On an ordinary coordination curve, time zero is considered as the time at which the fault occurs, and all times shown on the curve are the elapsed times from that point. The curves that are drawn are response times and all the devices between the fault and the source experience the same current until one of them interrupts the circuit.

A coordination curve is arranged so that the region below and to the left of the curve represents an area of no operation. The curves, in current and time coordinates, represent in pairs the family of loci which indicate how long a period of time is required for device operation at a selected value of current. Protective relay curves are usually represented by a single line only. Circuit breaker tripping curves which include the circuit breaker operating time as well as the trip device time are represented as bands. The bands represent the limits of maximum and minimum times at selected currents during which circuit interruption is expected. The region above and to the right of the curve or band represents an area of operation.

Fig. 8.1 shows a time-current curve represented as a band. Time t_2 is the maximum time from the initiation of the current flow I within which operation of the device and circuit breaker is assumed. Time t_1 is the time from initiation of the current flow I within which the current must be normalized to prevent the device under consideration from operating due to the impulse characteristic at the trip device.

The characteristics of an air circuit breaker can move in a parallel way. To be more specific, and referring to Fig. 4.1 line AB moves parallel to the time axis, line BC parallel to itself or to line FG, line CD parallel to the time axis again and line DE parallel to the current axis.

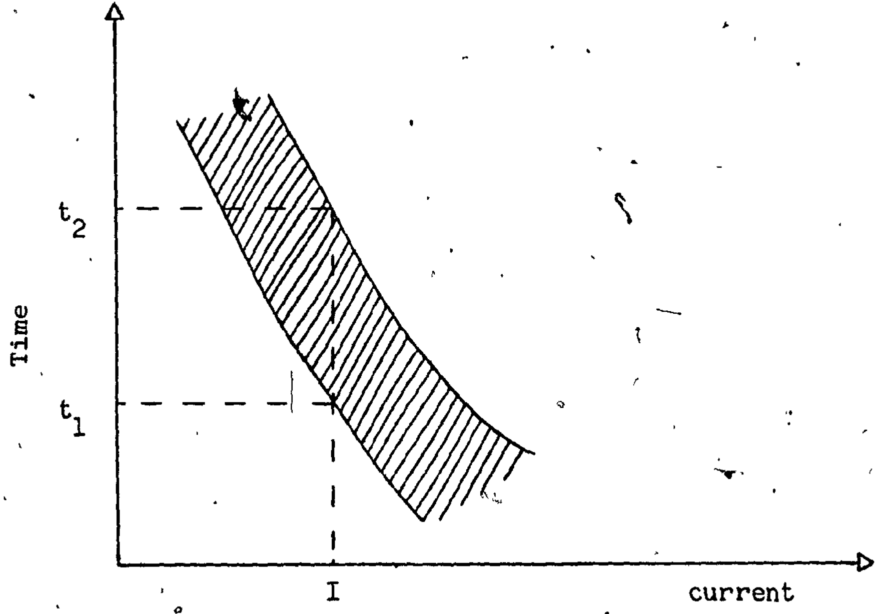


FIG. 8.1 Time-Current Curve of Tripping Devices.

For molded-case circuit breakers the time-current characteristics move to the right or left of their original position without any change of their slope.

8.2 COORDINATION TIME INTERVALS

When plotting coordination curves, certain time intervals must be maintained between the operating times of various protective devices in order to ensure correct sequential operation of the devices. These intervals are required because relays have over-travel, fuses have damage characteristics, and circuit breakers have certain speeds of operation. Sometimes these intervals are called margins.

Since these intervals cannot, in general, be specified, only a slight separation is planned between the different characteristic curves. This lack of a specified time margin is explained by the incorporation of all the variables plus the circuit breaker operating times for these devices within the band of the device characteristic curve.

Some general rules concerning the continuous-current ratings of fuses, breakers and relays are:

A fuse is selected such that its rating should be 200 percent of the transformer rated current to override the transformer magnetizing inrush current and provide adequate fault protection.

The transformer main secondary breaker should be of the selective type with series overcurrent tripping devices having long and short-delay characteristics and a 25-33 percent continuous current greater than the transformer rated current.

The primary ratings of the current transformers on the high voltage side should be about 150-250 percent of the power transformer rated current.

A general rule can also be observed that a maximum of four low-voltage air circuit breakers can be operated selectively in series, one of these being a feeder breaker with instantaneous overcurrent tripping. (A feeder breaker usually is the one following the main secondary breaker).

8.3 DATA REQUIRED FOR A COORDINATION STUDY

(1) One-line diagram of the system or portion of the system involved in the study.

(2) Apparent power and voltage ratings as well as the impedance and connections of all transformers.

(3) A complete short-circuit study as described in Chapter II.

(4) The time-current characteristics of all the devices under consideration.

(5) Conductor sizes, types and configurations, or the expected maximum loading on any circuit considered.

(6) Current transformer ratios.

All these items can be shown on the one-line diagram to facilitate the process. The procedure is better presented by the aid of the example given in Sections A.2 and A.3 of the Appendix.

CHAPTER IX

MECHANICAL AND THERMAL STRESSES DUE TO SHORT-CIRCUIT CURRENT

CHAPTER IX

MECHANICAL AND THERMAL STRESSES DUE TO SHORT-CIRCUIT CURRENT

9.0 INTRODUCTION

On a current-carrying conductor two types of stresses are noticed: thermal and mechanical.

When the current direction is the same on parallel conductors, attractive forces (F_C) are produced as a result of the magnetic field and repellent forces are produced when the current direction is opposite. These forces produce mechanical stresses in both conductors and insulators.

On the other hand, thermal stresses are produced on a current-carrying conductor depending on the duration and magnitude of the short-circuit current. The excess temperature then produced can damage the conductor.

9.1 MECHANICAL STRESSES

Since the mechanical stresses depend largely on the particular construction of each conductor and it is not possible for a rigorous analysis to be presented, single cross-section rigid conductors will be examined. Details are given in [11]

9.1.1 Conductor stresses are produced by the action of the force (F_C) between conductors within a supporting distance. The magnitude of this force is given by the following equation:

$$F_c = 0.2 * I_{ip}^2 * \frac{L}{a} \qquad \text{N} \qquad (9.1)$$

and the main conductor stress is given by equation

$$\sigma_c = u \frac{F_c L}{1.2W} \qquad \text{kPa} \qquad (9.2)$$

and from (9.1) and (9.2)

$$\sigma_c = u \frac{I_{ip}^2 * L^2}{6 * a * W} \qquad \text{kPa} \qquad (9.3)$$

or

$$L = \sqrt{\frac{6 * \sigma_c * a * W}{u * I_{ip}^2}} \qquad \text{cm} \qquad (9.4)$$

where:

a = conductor spacing in cm

I_{ip} = impulse current (peak value) in kA ($I_{ip} = I_p * \sqrt{\frac{2\sigma_2}{\sigma_1}}$)

I_p = maximum asymmetrical short-circuit current (peak value) in kA ($I_p \simeq 1.9\sqrt{2}\, I_{sym}$)

I_{sym} = symmetrical short-circuit current in kA

L = distance between supports in cm

u = frequency factor for conductor stress

W = resistance moment (section modulus) of conductor in cm^3

σ_c = maximum conductor stress in kPa

σ_1 = minimum yield point stress of conductor in kPa

σ_2 = maximum yield point stress of conductor in kPa

It is recommended that σ_c does not exceed twice the minimum yield point stress σ_1 of the conductor [11].

The frequency factor (u) with dc current is taken equal to two, u = 2, and with an ac and three-phase circuits $u \leq 1$ But the value of u = 1 can always be used instead of $u \leq 1$ for more safety.

To assure safety, L should be considerably less than the one found from equation (9.4).

The value of a determines the most critical distance from an insulation point of view, because when the magnitude of the electric field intensity (kV/m) exceeds the dielectric strength of a substance, the insulation breaks down and arcing (conduction) occurs between conductors. It is also necessary to compensate for surges (lightning, switching, etc.) and field non-uniformity. Thus, considering that the dielectric strength of air is 3 000 kV/m, the distance a for bare conductors in such a medium should be

$$a \geq 40 * \frac{\text{rated voltage (kV)}}{3\,000} * 100 \quad \text{cm} \tag{9.5}$$

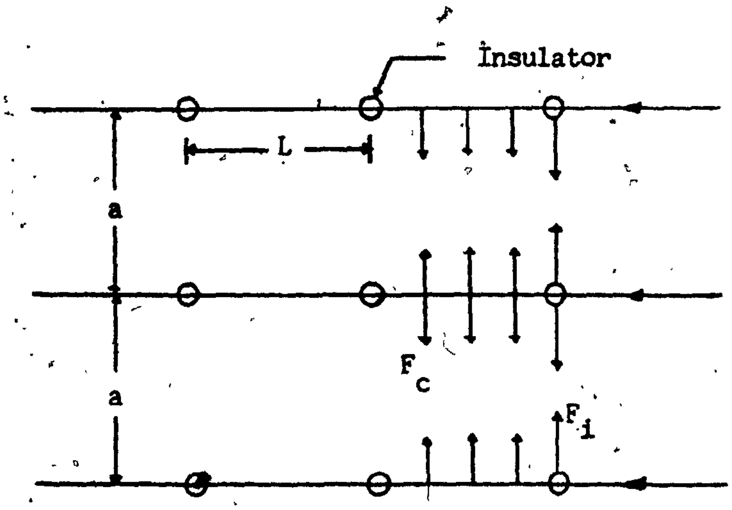


FIG. 9.1 Typical Three-Phase Conductor Arrangement Showing L, a, F_c, F_i

9.1.2 Insulator stresses are produced in the insulators (see Fig. 9.1) by the load (force) F_i.

Where

$$F_i = u_i F_c = u_i * 0.2 * I_{ip}^2 * \frac{L}{a} \quad N \qquad (9.6)$$

and

u_i = Frequency factor for reaction of support: it can take the value of u

However, in order to obtain a high margin of safety, load F_i should not be greater than 80% of the nominal maximum load (F_n) of a chosen type of insulator.

That is

$$F_i \leq 0.8 F_n \qquad (9.7)$$

Equation (9.7) should be satisfied and if not, then either L is reduced or a is increased or even the choice of another insulator with greater F_n is recommended. L and a should also satisfy equations (9.4) and (9.5) respectively. [10] , [11] .

9.2 THERMAL STRESSES

Thermal stresses are produced on a current-carrying conductor and depend on the duration and magnitude of the short-circuit current. What is examined in thermal stresses is the minimum cross-section q of a current-carrying conductor required to carry its maximum current without melting. Usually, since all conductors are made from copper or aluminum, the following equation is valid for these two conductors [1] :

$$q = knI_{sym}\sqrt{t} \qquad mm^2 \qquad (9.8)$$

where:

I_{sym} = in kA

t = fault duration time in s (see Chapter X, section 10.1)

n it takes many different values depending on the operating system voltage, minimum and maximum temperature and type of insulation used for the specific conductor.

For bare copper lines: $n = 7$ with $50^{\circ}C \leq T \leq 200^{\circ}C$

For bare aluminum lines: $n = 11.2$ with $50^{\circ}C \leq T \leq 180^{\circ}C$ and all operating voltages.

k = asymmetry coefficient depending on the ratio R/X of the short-circuit path. Its value varies from $k = 0$ for large ratios to $k = 1.73$ for small ratios.

For a complete analysis and details, reference [11] is suggested.

CHAPTER X

GROUNDING

CHAPTER X

GROUNDING

10.0 INTRODUCTION

To ensure safety of personnel and provide a predetermined path for ground-fault currents, all metal parts of electrical apparatus, other than the conductors, are bonded together electrically and connected to a low-resistance earth electrode. The current paths must have a current-carrying capacity sufficient to deal with the maximum fault currents (I_{asym}), and a resistance low enough to prevent dangerous voltages appearing between any points which a person could reach simultaneously. In addition to personnel protection, protection systems have been developed and employed that react quickly to currents taking wrong paths (paths to ground), thus protecting the system from ground faults.

Here, solutions to these problems will be examined.

10.1 SUBSTATION GROUNDING

A grid or a mat is usually the most practical way to do the grounding at substation yards. Ground rods or pipes are usually made of copper driven vertically at the surface and are interconnected by ground conductor (copper) buried horizontally to form a mesh, so that if one rod is accidentally disconnected it will not interrupt the path to the ground. For the same reason, major plant and the ground rods of switchboards should be connected to the station system at no fewer than two points. The spacing between rods should be between

5 m and 20 m [14], [15]. Depending upon the soil resistivity a depth (h) of about 0.5 m to 1.5 m is usually chosen for the ground conductor. Typical rod size is 3 m length * 1.9 cm diameter.

The cross-section of the ground conductors is proportional to the current which they may have to carry so that the maximum allowable copper temperature of 300°C will not be exceeded with a fault duration of 0.5 seconds [14]. This cross-section can be calculated using the following equation with $t = 0.5$ seconds and $n = 7$ (for bare copper conductor), (Chapter IX, Equation 9.8).

$$q = knI_{sym} \sqrt{t} \quad mm^2 \tag{9.8}$$

Furthermore, where ground conductors are run on walls or steelwork, stand-off saddles should be used to minimize the risk of corrosion particularly in boiler houses, where sulphurous moisture may be present.

From a design point of view the ground resistance (R_g) is given by Laurent's formula [14] as

$$R_g = \frac{\rho}{4r} + \frac{\rho}{L} \tag{10.1}$$

where:

ρ = the average resistivity of the ground in ohm-meters
L = the total length of buried (ground) conductor in meters
r = radius of equivalent circle whose area is equal to that of grid in meters ($r = \sqrt{A/\pi}$)
A = substation area

The minimum length (L) of buried conductor required for safety of personnel is obtained [13] by

$$L = \frac{1.5\,\rho I_{sym}\sqrt{t}}{165 + 0.25\,\rho_s} \qquad (10.2)$$

where

t = maximum duration of shock is seconds (usually 0.5 s)

I_{sym} = in amperes

ρ_s = resistivity of ground immediately beneath the feet, in ohm-meters

Another requirement which has to be satisfied is:

$$R'_g = \frac{E_r}{I_{sym}} \qquad (10.3)$$

where

R'_g = ground resistance

E_r = rise potential in volts

Thus

R_g should be less or equal to R'_g

Hence, a step-by-step approach has as follows:

(1) ρ and ρ_s can be measured [16]. The available substation area (A) can be measured as well, and values for t, E_r, and h can be chosen. Usually,

$3\,000 \le \rho_s \le 5\,000$ ohm-meters

$0.5 \le h \le 1.5$ m

$t = 0.5$ seconds

$5\,000 \le E_r \le 12\,000$ V

The value of ρ varies in accordance with the type of ground as follows:

Type of Ground	Resistivity in ohm-meters
Wet organic soil	10
Moist soil	100
Dry soil	1 000
Bed rock	10 000

(2) From equation (9.8) the minimum grid conductor diameter can be calculated for bare copper wire baring in mind the CSA recommendations, i.e.

Fault Current (A)	Conductor Size
≤ 5 000	No. 2/0 AWG
5 001 - 10 000	250 MCM
10 001 - 25 000	500 MCM
25 001 ≤	1 000 MCM

(3) The required $\underline{L}$ and $\underline{R'_g}$ can be evaluated using equations (10.2) and (10.3) respectively: (finally, greater or equal $\underline{L}$ should be used). The value of $\underline{R'_g}$ varies in accordance with the station capacity. CSA recommendations are:

Ground Resistance (ohms)	Station Capacity (kVA)
15	1 500
10	1 501 - 10 000
2	10 001 and above

(4) The length and width of the available substation area are divided into little squares to form a mesh starting with a side length of each square of 20 m (spacing among buried conductors). The total length (TL) of the buried conductor of the (so constructed) grid is evaluated and a comparison is needed with the one calculated by equation (10.2). If $TL < L$, then the spacing among buried conductors is reduced gradually up to 5 m until $TL \geq L$. If even now $TL < L$, then the possibility of increasing the available substation area is examined. But if $TL \geq L$ is achieved for a spacing (M), $5 \leq M \leq 20$ meters, then $\underline{R}_g$ is calculated from equation (10.1) and is compared to that either obtained by equation (10.3) or read from CSA recommendations. Once more, if $\underline{R}_g > \underline{R}'_g$, then the possibilities of increasing $\underline{L}$ further or $\underline{A}$ or even reducing ρ are examined. The criterion is economical and depends also on the region morphology.

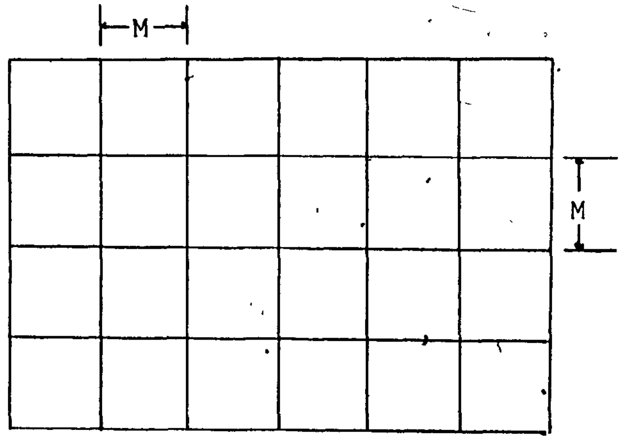


FIG. 10.1 A Grounding Grid

(5) The resistance of a single ground rod follows Sunde's equation [12], i.e.

$$R_r = \frac{\rho}{\pi L_1} \ln \frac{1.27 L_1}{\sqrt{dh}} \qquad (10.4)$$

where:

R_r = resistance of ground rod in ohms

L_1 = length of ground rod in meters

d = diameter of the rod in meters

ρ = soil resistivity in ohm-meters

h = buried depth in meters

Since it is difficult to give a generalized formula for the total number of rods required, the following empirical formula can be used applied only to ground rod having the typical rod size (3 m * 1.9 cm)

For Utility Applications	For Industrial Applications
$1.5\ R_r \leq n \geq 0.75\ R_r$	$0.75\ R_r \leq n \geq 0.25\ R_r$

where:

n = number of total rods required.

10.2 TRANSMISSION LINE GROUNDING

Transmission lines usually are grounded with one or more grounding rods driven vertically at the surface. The grounding resistance, in ohms of one rod is given by equation (10.4). It is evident that when the ground fault current is very high, even a grounding rod having low grounding resistance may produce potential gradient on the ground which may be dangerous to human and animal life.

For proper safety and when the earth resistivity is high, either we increase the number of buried grounding rods or one of the following grounding arrangements is used.

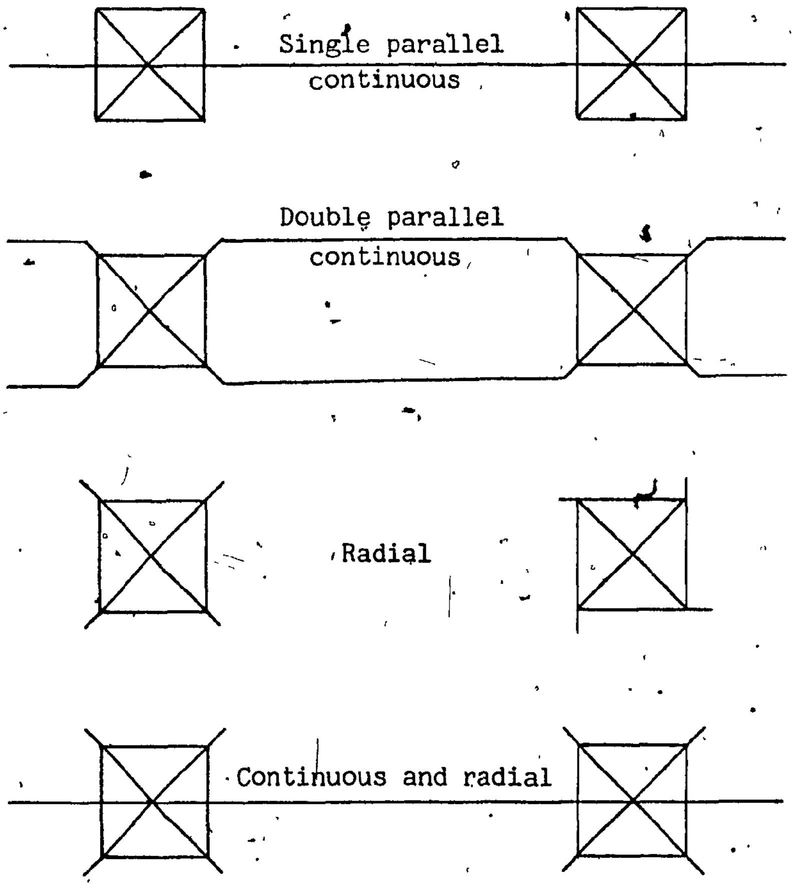


FIG. 10.2 Grounding Arrangements of Transmission Lines

Equation (10.4) is still valid for the above arrangements introducing only a small error due to non-uniformity of the ground current flow from different parts of the ground wire.

10.3 GROUND FAULT PROTECTION

A protective system has to react, not only to the magnitude and duration of the current, but also to know the path which the current is taking; and if the path in wrong to react quickly, no matter what the magnitude of the current is, since undoubtedly any current following a wrong path is likely to create damage.

On a grounded system the wrong path usually is from a live conductor to ground (excluding, of course, return currents in a neutral conductor). Such a path to ground usually involves arcing. During the first few cycles the fault current will be of relatively low magnitude due to the high impedance of arc resistance, but with formation of ionized gases, vaporized metal arc resistance decreases and the current rises.

An ungrounded system is, in effect, grounded through the capacitance of the system and if a ground does occur on any one phase, capacitive current will flow through to ground. The magnitude of such currents will vary appreciably with the capacitance of the system. Published figures indicate that capacitive currents may vary from 200 mA to 2 amperes per 1 000 kVA [17]. Ungrounded systems can operate without interruption of service where one phase is grounded, but voltage build-ups appear on the ungrounded phases, particularly if the ground fault is of an arcing nature. Such voltage build-ups (up to 7 times line voltage) can cause extensive outages and insulation damages.

Since, generally speaking, grounded systems are considered safer than those which are ungrounded, an examination of ground fault protection to these systems will be presented [17] .

A standard overcurrent protective system reacts only to the magnitude and duration of the fault currents (overload and high magnitude currents). When it is used by itself, there are two opposing requirements which must be fulfilled in coordination:

(a) Pickups and time delays must be set as low as possible so as to make protection as effective as possible at low values of fault current.

(b) Pickups and time delays have to be set high enough so as both not to overlap with the characteristics of the devices "down stream", and to withstand normal overloads and current inrushes in a particular circuit.

Therefore, such coordination is only a compromise solution.

A ground protective system reacts to the wrong path which the current is following (low value ground fault currents). It is a multiple component electrical device designed to protect distribution systems and their equipment from the dangers of low voltage ground faults. It consists of a current monitor or zero sequence current transformer, a ground fault sensor or relay, and a circuit breaker with a magnetic shunt trip. The "window" type of current monitor is common, its magnitude core surrounding all conductors including the neutral if present. It comes with circular or rectangular openings, with rectangular split core designs and a variety of sizes to accommodate all standard bus and cable arrangements. The sensor is available in two different units: standard and interlocking. The standard unit observes the time delay setting before signaling the shunt to trip the breaker. The interlocking unit, on the other hand, overrides its time delay, and signals its shunt to trip immediately. At the same time, it also signals other sensor units to delay tripping, or block tripping completely.

As long as there are no grounds, the circuit is balanced and the current monitor output will be zero. The magnitude of the currents (eigher load or short circuit) in the conductors cancel each other through the zero sequence current transformer. However, when a ground occurs, the current monitor output will not be zero and a current flows from the current monitor to the sensor. When the current reaches the pre-selected detection point, the sensor goes into operation. Standard or interlocking circuity in the sensor determines the action.

The combination of the standard overcurrent protective system and the ground protective system introduces the so called "total protection" scheme. This scheme eliminates entirely the necessity to keep overload protection settings low for the purpose of reacting quickly to low fault values. More margin for spacing between the curves can be made to allow for the tolerances and the inaccuracies of the devices. Therefore, immediately, the job of coordination becomes easier and more reliable. In its simplest form the addition of a single sensor operated by a current monitor over the grounding strap (equipment ground) and an automatic switching device for the main incoming service is necessary. The main disadvantage of such a scheme is that the whole system is tripped out by the main service protector (circuit breaker) regardless of the location of the ground fault anywhere on the system. In some instances, on the other hand, the economics of an electrical installation are such that a complete "total protection" scheme can be justified (a complete "total protection" scheme is one where a ground protective device is used in each section of the system fully coordinated with the "upstream" or "downstream" devices in addition to the standard overcurrent protective scheme).

CHAPTER XI

SUBSTATIONS

CHAPTER XI

SUBSTATIONS

11.0 INTRODUCTION

In between the power house and ultimate consumer a number of transformation and switching stations have to be created. These are generally known as substations. The electrical design of a substation mainly deals with the selection of proper equipment and its location or placement in the yard in a proper way which would presuppose a fair knowledge and understanding of the principles, operations of working and the types of the various equipment.

As in any other design, the substation should be flexible and economical but not at the cost of continuity of supply, simple and easy in maintenance. A flexible system would present alternative arrangements in the event of an outage on any piece of equipment. Such a system would also present no difficulty in expansion or augmentation of the system.

11.1 ELECTRICAL - PLANT LAYOUT

There are many types of substations depending on the purpose and on the constructional features of the substation (step-up, secondary, distribution substations, outdoor, indoor type, etc...). But the electrical work involved for all of then comprises:

(1) Choice of busbar arrangement.

(2) Selection of isolators, instrument transformers, power transformers, circuit breakers, protective relays, lightning arresters, voltage regulating equipment, grounding, etc.

(3) Provision of facilities such as illumination, fire protection, cabling, grounding, communication facilities, ac auxiliary supply, dc auxiliary supply, interlocks etc.

There are numerous variations of busbar arrangements, the choice of which depends on various factors such as system voltage, flexibility, reliability of supply and cost, position of the substation in the system, etc.

A typical and most common busbar arrangement is shown in Fig. 11.1, the so called "single bus with sectionalizing scheme".

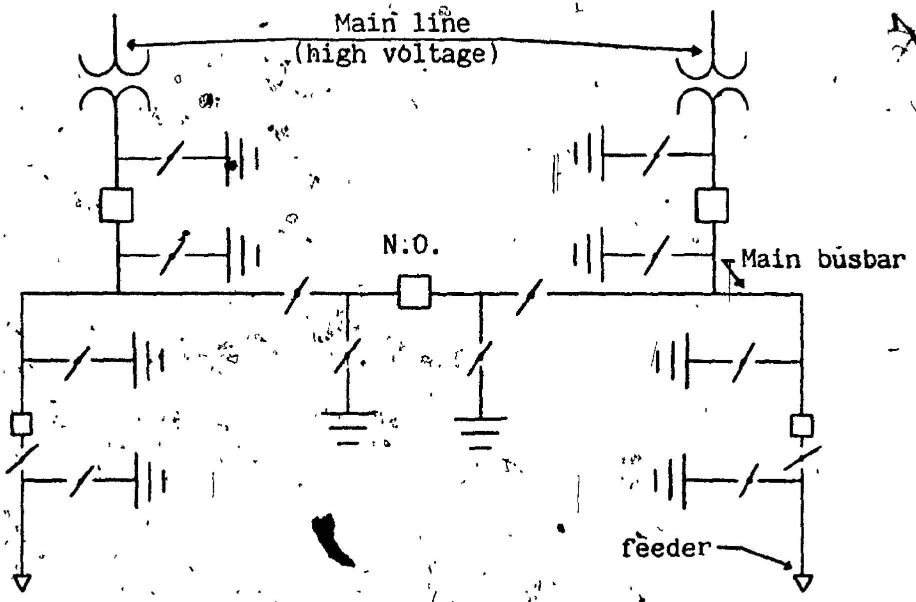


FIG. 11.1 Single Bus with Sectionalizing Scheme

⊡ = circuit breaker

||–/– = ground switch

= transformer

–/– = isolator

N.O. = normally opened

The bus circuit breaker (tie breaker) and the two incoming breakers are so interlocked that only two breakers can be closed at a time. Normally, each section continues to cater to its load. If the incoming circuit on any section has to be taken out the tie breaker can be closed and supply restored to the outgoing circuits of this section.

11.2 LIGHTNING ARRESTERS

Lightning arresters should have their own earth electrodes. They should not be connected in any way to the station earthing system because, owing to the extremely steep wave fronts of the discharge, dangerous voltages may appear over quite short lengths of conductors. A lightning arrester is usually placed on the main line between the circuit breaker and the high-voltage side of the feeding transformer before the entrance to the building, one needed on each feeder.

11.3 CHOICE OF OPERATING VOLTAGE

An appropriate study for the choice of the operating voltage of a system must be made before the electrical layout of the substation can be settled. The criterion is the cost estimation. The analysis of cost takes into account the switchgear, cables and motors. The operating voltage chosen is that which will result in minimum total cost using equipment having standard ratings [8].

CHAPTER XII

CONCLUSION

CHAPTER XII

CONCLUSION

It can be concluded, that the basis for carrying out the analysis and synthesis of a substation is the determination of the short-circuit currents. The accuracy of the calculated values is not critical and a variation of 5 to 10 percent can be tolerated. This comes as a result of the fact that the final choice of the equipment of a substation is usually slightly greater than the calculated rated values to compensate for unpredictable overcurrents. In addition to that, the known methods for determining those currents are not very advanced and exact as shown in Chapter II.

Knowing these short-circuit currents it is possible to calculate the mechanical and thermal stresses applied to the conductors, and thus, to choose conductors of appropriate size. Under the short-circuit conditions, the switchgear capacities and the ground electrode required are also determined for the safety of a substation.

The determination of the ratings of the transformers and capacitors used can be accomplished from calculations under normal conditions. The transformers should not only withstand the load requirements but also be ready to face possible future substation expansions. For economical utilization of the substation, static capacitors should be added to improve the power factor.

The coordination problem is very delicate but is necessary to provide selectivity for better performance of the system. (Chapter VIII gives somes details on how this problem can be approached with the appropriate placement of the time-current characteristics).

Some general principles and recommendations about substations for a safer, more economical, more flexible in utiliaztion and reliable way of operation are stated in Chapter XI.

In the Appendix, a collective example is presented in an attempt to try to combine all the material and give more understanding of the design routine leading to the choice of equipment.

Finally, a computer program is attached which renders easier and faster the way to determine currents, voltages, and powers for N loads connected to the same feeder via a busbar.

To integrate, [illegible] was presented is just a hint that could be very helpful in determining the electrical behavior of substations; however, the [illegible]ct of the problem was not studied [8]. This is very imp[illegible] well, for it gives the criterion upon [illegible] operation of the system is chosen.

APPENDIX A

APPENDIX A

PROCEDURE EXAMPLE

A.0 INTRODUCTION

Up to now some necessities and possible factors have been considered which affect the design of a station (or substation). In addition to that an effort has been made to explain the most important components of a station (or substation), as they relate to the electrical layout. Hereafter, the Montreal METRO substation is presented as an example to employ the previous Chapters' analysis.

A.1 BRIEF DESCRIPTION OF THE LAYOUT

Fig. A.1 is a high-voltage one line diagram of the METRO substation. Fig. A.2 shows more details about each PSD (Poste Secondaire de Distribution) secondary substation. The METRO substation (lighting load) consists of 20 such PSD secondary substations each having a capacity of 450 kVA, that is a total of 9 000 kVA. There are seven rectifier secondary stations of 2 500 kW each, i.e. a total of 17 500 kW. Two garages also exist from 1 500 kVA each or 3 000 kVA total. Since the power factor (PF) for those seven rectifier stations is very close to that of the lighting load above, kW and kVA can be added algebraically to end up with a total of 29 500 kVA. Here, the demand factor is assumed to be 50% so that the demanded kVA is 14 750.

There are also two emergency power supplies. These power supplies consist of a combination of a diesel engine with a power generator of 400 kW each. This is the power demanded by the lighting system, telecommunication, signaling, ventilation plus station water pumps.

The whole system works as follows [Fig. A.1]:

(1) Normal operation: Normally the tie breaker T-1 is opened and T-2, T-3 are closed. Line #1 and line #2 share the required power between PSD-1 or PSD-2 and the rectifier stations. Either PSD-1 or PSD-2 can be considered as "stand by" and their operation is controlled by the automatic transfer unit (TA). They never work both at the same time.

The rectifier stations work with 750 V dc and are connected to the main bus in such a way as to reduce the possibility of failure to a minimum.

(2) Abnormal operation: Much care has been taken to increase the reliability of this substation, for it is a means of transportation.

If line #1 is out of order, T-1 is switched on, breaker A opens automatically and line #2 undertakes line 1's duties leaving the rest of the system untouched. The same will happen if line #2 is out of order, i.e. T-1 is switched on, breaker B opens automatically and line #1 undertakes line 2's duties.

If PSD-1 is out of order then the TA unit switches PDS-2 in automatically and vice-versa. The same could have happened if all PSD-1's failed.

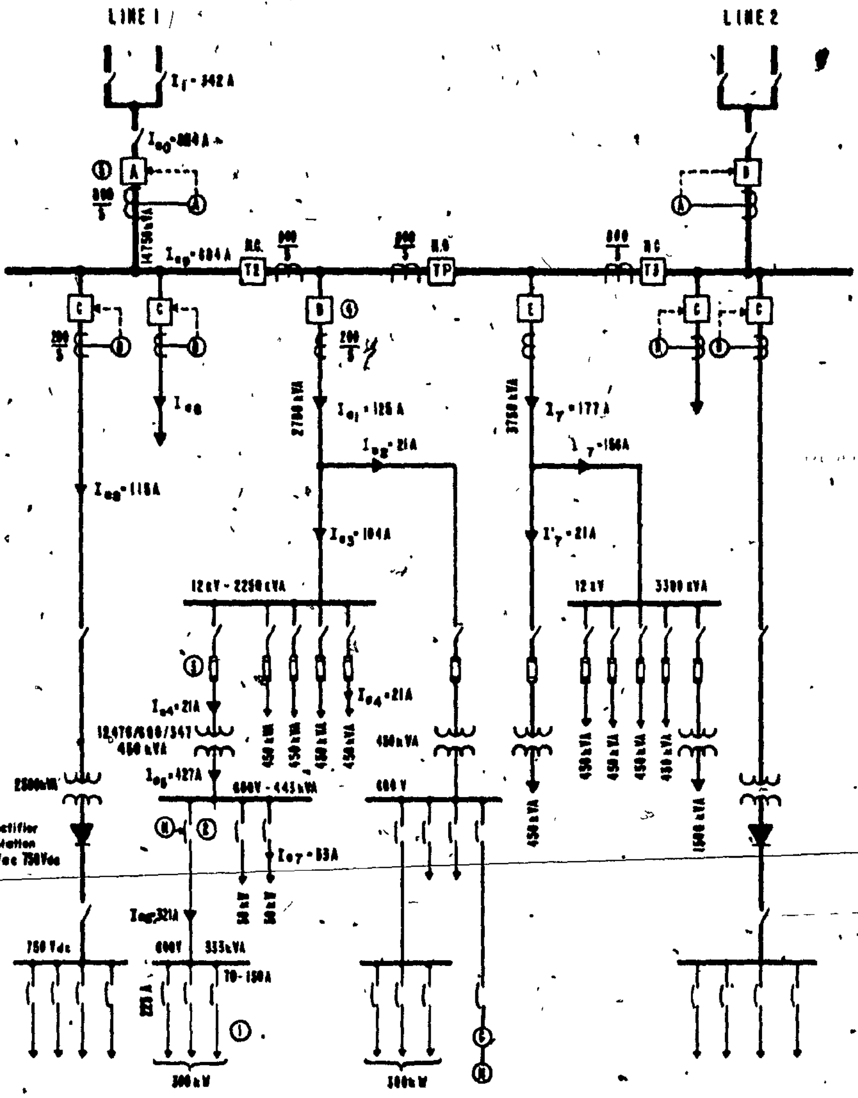


FIG. A. 4. One - Line Diagram Shown The Load Contribution.

A.3 SHORT-CIRCUIT CALCULATIONS

Given: (From the Hydro-Quebec incoming line)

Incoming voltage $V_i = 12\,470$ V $= V_{LL}$.

Short-circuit kVA available at the input $S_i = 500\,000$ kVA

In the lighting section of the system a transformer of 450 kVA/3-phase, 12 470/600/347 V, X = 5.75% is available.

The value of 14 750 kVA is chosen as the base kVA since this corresponds to the demand power stated in page 63. As a base voltage, the values of 12 470 V and 600 V are chosen for the high-voltage level and low-voltage level respectively.

(a) Point #5 (Fig. A.4) : A short at point #5 can produce a symmetrical short-circuit current of

$$I_{sym} = \frac{500 * 10^6}{\sqrt{3} * 12\,470} = 23\,150 \text{ A and}$$

$$I_{asym} = 23\,150 * 1.73 = 40\,050 \text{ A}$$

Since

$$S_i = 500\,000 \text{ kVA and } S_{base} = 14\,750 \text{ kVA.}$$

Then

$$I_{pu} = \frac{500\,000}{14\,750} = 33.89 \text{ (for high-voltage level).}$$

where:

I_{pu} = per unit current

For a short at point #5 the reactance per unit (X_{pu}) is:

$$X_{pu} = \frac{V_{pu}}{I_{pu}} = \frac{1}{33.89} = 0.0295 \quad (V_{pu} = \text{voltage per unit})$$

(b) Point #4: A short at point #4 will produce a symmetrical short-circuit current almost equal to that at point #5, for the distance from point #5 to point #4 is approximately 10 m and the conductor reactance can be considered as negligible.

(c) Point #3: A cable for three phase system, single conductor #2/0 AWG copper, cross-linked polyethylene insulated, shielded PVC jacket, 15 kV grounded (100% insulation level) is used. The inductive reactance of this cable is 0.108 ohms/km at 60 Hz. The maximum estimated distance from point #4 to point #3 is 3.44 km. Thus, the total reactance of the cable is 0.108 * 3.44 = 0.3715 ohms, and the reactance per unit is:

$$X_{pu} = 0.3715 \frac{14\,750 * 1\,000}{(12\,470)^2} = 0.0352$$

Hence, a short at point #3 produces a current of [see Fig. A.5]

$$I_{pu} = \frac{1}{0.0295 + 0.0352} = 15.456$$

Since the base current for the 12 470 V side is:

$$I_b = \frac{14\ 750\ 000}{\sqrt{3} * 12\ 470} = 683 \text{ A}$$

then the

$$I_{sym} = 15.456 * 683 = 10\ 556 \text{ A}$$

and

$$I_{asym} = 10\ 556 * 1.73 = 18\ 262 \text{ A}$$

(d) Point #2: The per-unit reactance of the transformer is:

$$X_{pu} = 0.0\ 575 * \frac{14\ 750}{450} = 1.884$$

Thus, the equivalent reactance circuit is:

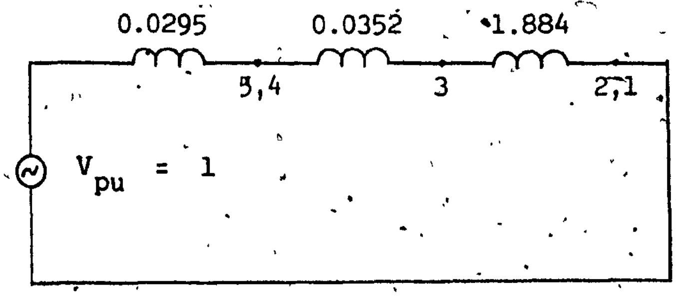


FIG. A.5 Equivalent Reactance Circuit.

A short at point #2, then, will produce a current of

$$I_{pu} = 1/(0.0295 + 0.0352 + 1.884) = 0.513 .$$ Since I_b for the 600 V side is

$$I_b = \frac{14\ 750\ 000}{\sqrt{3} * 600} = 14\ 193 \text{ A}$$

then the

$$I_{sym} = 0.513 * 14\ 193 = 7\ 281 \text{ A}$$

and

$$I_{asym} = 7\ 281 * 1.73 = 12\ 596 \text{ A.}$$

(e) Point #1: Since the distance from point #2 to point #1 is approximately 15 m, the conductor reactance can be considered as negligible, and it can be assumed that the asymmetrical short-circuit current has that value calculated for point #2 ($I_{asym} = 12\ 596$ A).

A.4 COORDINATION

Everything is referred to 600 volts and the lighting and rectifier loads are best considered separately. The equipment is chosen on the basis of its suitability to the coordination problem. (It should be noted that the equipment identification numbers and the respective currents handled when identical it is only as a coincidence and for a particular manufacturer).

A.4.1 Lighting

(1) Continuous Current Ratings

(a) Breakers at point #1 [Fig. A.4] : The loads at point #1 are such that breakers rated at 70, 150 and 225 amperes are the most suitable. The actual breakers are molded-case types HFB-70A, HFB-150A, and HKA-225A.

(b) Breaker at point #2: The current flowing through this branch (I_{a6}) is 321 A. Of the standard ratings available, the smallest rating above 321 A is 400 A, which is type DB-50 air-circuit breaker of this one particular manifacturer.

(c) Fuse at point #3: The 450 kVA transformer rated current on the primary side is 21 A (I_{a4}). And since the rated current of the fuse should be approximately 200% of the transformer rated current a BAL-PT-50E would normally be supplied.

(d) Relay at point #4: The current (I_{a1}) is 125 A. And since the current rating at the primary of the current transformer should be about 150-250 percent of I_{a1} a 200/5 ratio current transformer can be assumed. (For tap setting see below). A CO-7 relay is chosen, for the characteristics coordinate best with those of the other breakers, relays, and fuses.

(2) Interrupting and Short-Time Current Requirements

(a) Point #1: Since the short-circuit current on the 333 kVA bus is 12 506 A (I_{asym}) and the interrupting capacities of HFB-70 A, HFB-150 A and HKA-225 A are 14 000, 14 000 and

25 000 A symmetrical respectively (as shown on their characteristics), these breakers may be safety used.

(b) Point #2: Again, the interrupting capacity of the DB-50 air-circuit breaker is 42 000 A symmetrical, a value more than adequate for the 7 281 A symmetrical-short-circuit current of that point.

(c) Point #3: The type 50E fuse has an interrupting rating of 84 000 amperes at 12 470 volts and hence it is adequate.

(d) Point #4: Based on the given short-circuit kVA of 500 000, the type 150DHP500 breakers are adequate.

(3) Tripping Characteristics

(a) Point #1: The characteristics of the HFB-70 A and HFB-150 A have been placed on Fig. A.6 with long-delay pickup at 70 and 150 amperes respectively. Next the characteristics of the HKA-225 A breaker have been placed with a long-delay pickup at 225 A and instantaneous tripping at 1 125 A. (Note that the HKA-225 A breaker has an adjustable magnetic trip with a continuous range of 1 125 to 2 250 amperes.) The other two breakers can trip instantaneously at a non-adjustable value at about 10 times the long-delay pickup. The overlapping of these three breakers on the time-current characteristics does not really matter, for they do not have to be selective among themselves, but they have to do so with the breakers that are in series with them. Their curves were plotted just to be compared with the other breakers in series.

(b) Point #2: The DB ~~air~~-circuit breaker characteristics can be placed on the same figure A.6 as follows:

The main objective is to avoid overlapping. Thus, from Fig. A.6 the values of the critical current and times for possible overlapping can be read. These are at the elbow or at the intersection of the 16-second line with the 2 100 A line. Now, from the time-current characteristics of the DB breaker a setting for the long-delay time and the short-delay pickup can be chosen such that, at 16 seconds or so, the line CD of Fig. 4.1 can be placed to the right of the 2 100 A to avoid overlapping. If a long-delay time setting of 16 seconds and a short-delay pickup setting #6 are chosen, the intersection of those two lines (the 16-second line and the 6 * 400 = 2 400 A line) gives the starting point. In other words, it is now possible to draw two more lines, one parallel to the BC line and one parallel to CD line or the 2 400 A line. Two more settings, namely the long-delay pickup and the short-delay time will define where to stop the lines previously drawn. Keeping in mind that overlapping should be avoided and that the characteristics should be placed as much to the left as possible for a good protection, a setting of 1.25 * 400 A and an 0.18 second setting for the long-delay pickup and the short-delay time respectively are adequate to avoid overlapping and furnish good protection. Thus, those two lines can be stopped at the 500 A line and at the 0.18 second line. Note that these lines are the median of the breaker band. Finally, the time-current characteristic of the breaker is drawn keeping the same band width along those lines.

(c) Point #3: Again, the fuse characteristic should be placed to the right of the DB air-circuit breaker characteristics. The critical point again is the elbow at 16 seconds and now at 2 600 A. Thus, the melting time-current characteristic of the 50E fuse should meet these requirements. From the melting time-current characteristics of this fuse, 16 seconds correspond to 130 amperes. Referring this current to the 600 volts base we have (12 470/600) * 130 = 2 701 A. Thus, this fuse can be kept and what is needed is a transfer of the melting and total clearing time-current characteristics from the 12 470 V base to the 600 V base. Table (A.1) shows the time-current correspondance according to the following rule:

$$I_{600} = kI_{12\,470} \quad \left(k = \frac{12\,470}{600} = 20.78\right) \text{ for the same time.}$$

(d) Point #4: The characteristics of the relay should be placed to the right of that of the breakers and fuse. The minimum long-delay pickup is the current I_{al} = 125 A times the voltage transformation ratio (12 470/600), or 2 598 A (referred to the low-voltage side). Since this current is larger than the total-clearing current of the fuse (2 000 A) it can be used. Thus, the relay overload current referred to the high-voltage side is:

$$I_{ro} = \frac{2\ 598}{\frac{200}{5} * \frac{12\ 470}{600}} = 3.1\ A$$

Hence, the 2 - 6 A range is chosen for the CO-7 relay. The 4-ampere tap setting is chosen. The relay overload pickup referred to the low-voltage side for the chosen tap setting is:

$$I_{rp} = 4 * \frac{200}{5} * \frac{12\ 470}{600} = 3\ 325\ A$$

To set the instantaneous unit, the symmetrical short-circuit current is used. At branch #5, the I_{sym} was found to be 7 281 A. And the I_{asym} is 7 281 * 1.73 = 12 596 A. To override this low-voltage fault the minimum instantaneous setting allowable should be calculated using this I_{asym} = 12 596 A. But since this current does not give too much chance to the fuse to interrupt a possible fault the instantaneous setting should be moved to the right a little bit more. In this case a value of 33 000 A is assumed. Thus

$$I_{ri} = \frac{33\ 000}{\frac{200}{5} * \frac{12\ 470}{600}} = 39.7\ A$$ (referred to the high-voltage side).

In the range of 10-40 A, the 40 A setting is chosen.

There is a time dial setting to be chosen as well. This can be done by keeping in mind that no overlapping is allowed. A #5 time dial setting is the most suitable, for at 6 seconds and at 4 987 A, it is placed to the right of the total-clearing curve of the fuse curve. A #4 setting is too close together and a #6 is too far apart. Thus,

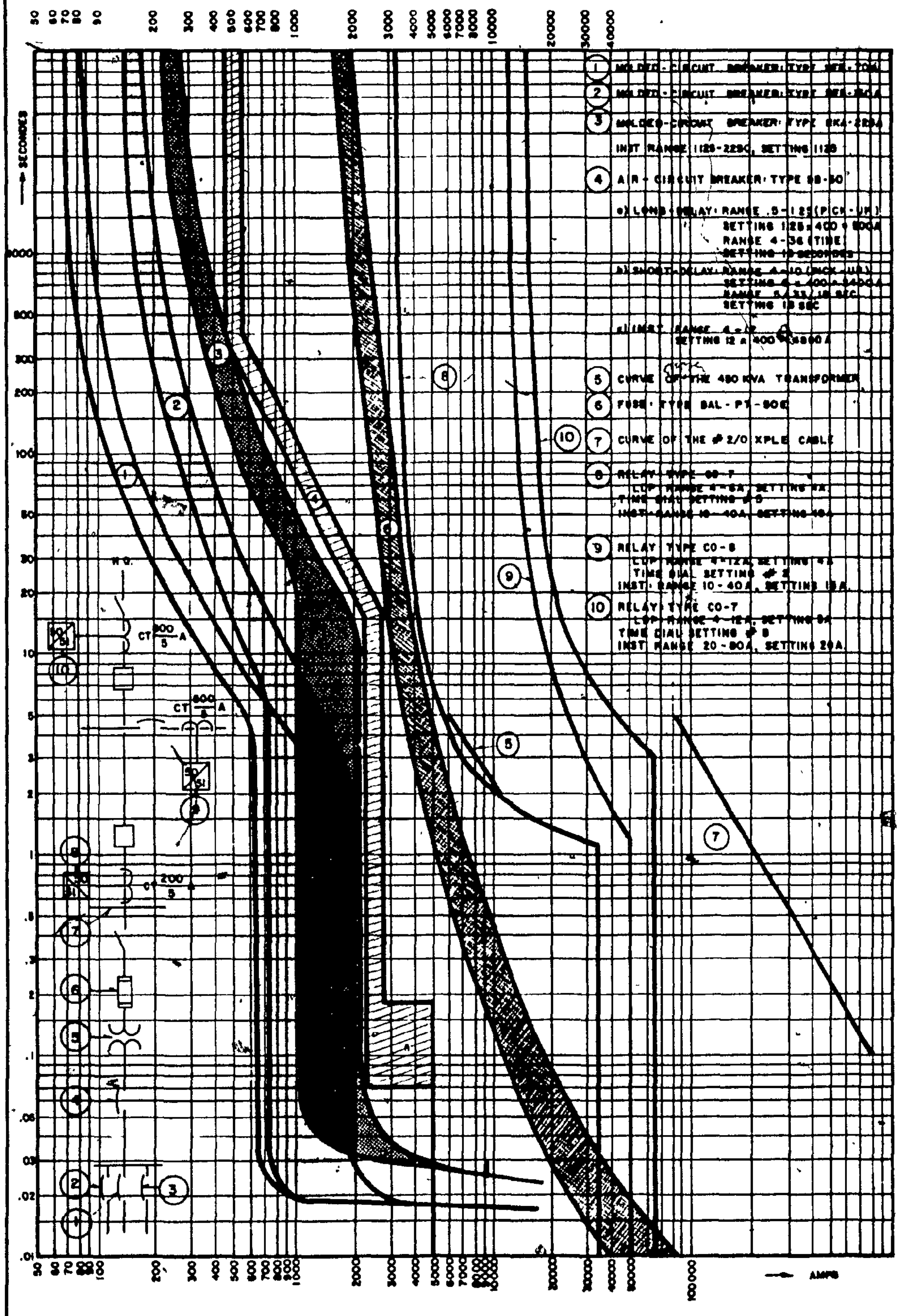


FIG.A.6 – Coordination Time Current Charcteristics of all the Protective Devices

MELTING CURVE			TOTAL CLEARING CURVE		
Time	Fuse Amperes at 12 470 V	Fuse Amperes at 600 V	Time	Fuse Amperes at 12 470 A	Fuse Amperes at 600 V
1000	93	1 932	1000	120	2 493
500	97	2 015	500	125	2 597
100	110	2 285	100	130	2 701
50	120	2 493	50	138	2 867
10	144	3 000	10	165	3 425
5	160	3 324	5	200	4 156
1	252	5 236	1	315	6 545
.5	320	6 649	.5	435	9 039
.2	457	9 496	.2	700	14 546
.1	620	12 883	.1	1 100	22 858
.05	870	18 078	.05	1 299	27 000
.01	1 900	39 489	.01	4 010	83 327

TABLE (A.1). Transformation of BAL-PT-50E Fuse Characteristics from 12 470 to 600 V.

Multiples of Tap Value Current	Relay Current (A)	Time (s)
1.5	1.5 * 3 325 = 4 987	6
2	2 * 3 325 = 6 650	3.55
3	9 975	2.3
4	13 300	1.9
5	16 625	1.65
6	19 950	1.5
7	23 275	1.38
8	26 600	1.3
9	29 925	1.22
10	33 250	1.15

TABLE (A.2). Transformation of CO-7 Relay Characteristics from 12 470 to 600 V.

another table has to be constructed to transfer the CO-7 relay characteristics to Fig. A.6 . [See table (A.2)] .

To finish with the lighting coordination two more points should be checked out, the transformer and cable characteristics. The time-current characteristics are placed on Fig. A.6 . Since the transformer characteristic is on the right of the fuse curves and the cable one is on the right of the CO-7 relay curve, then protection is assumed.

A.4.2 Rectifier Station

Since the current $I_{a8} = 115 \simeq 125 = I_{a1}$ then the same type of current transformer (200/5) can be used and the same type of relay (CO-7) with the same settings. Thus, seven such relays must be used because there are seven rectifier stations.

A.4.3 Combination of Lighting and Rectifier Stations

At branch #0 the current $I_{a0} = 684$ A. Hence, an 800/5 current-transformer ratio can be used with the same type of relay (CO-7). What changes here are the relay settings.

It is a common practice to have the tie breakers on a main bus the same as the feeder breaker. That is, the tie breakers are the same as the A one. Again, what changes is the relay settings. For the tie breakers the CO-8 type relay is used.

Since the current at branch #9 is 509 A (684 * .75) or 10 578 A referred to the low-voltage side and long-delay pickup of the relay at point #4 is less (3 325 A), the 10 578 A value has to be chosen to calculate I_{ro} :

$$I_{ro} = \frac{10\ 578}{\frac{800}{5} * \frac{12\ 470}{600}} = 3.18 \text{ A} \quad \text{(relay range 2 - 6 A)}$$

The setting #4 is adequate and thus

$$I_{rp} = 4 * \frac{800}{5} * \frac{12\ 470}{600} = 13\ 300 \text{ A.}$$

The instantaneous setting for the relay at branch #4 was 33 000 A. If a value of 33 000 * 1.5 $\simeq$ 50 000 A is chosen to calculate I_{ri}, then

$$I_{ri} = \frac{50\ 000}{\frac{800}{5} * \frac{12\ 470}{600}} = 15 \text{ A (relay range 10 - 40 A)}$$

A CO-8 relay with time dial setting at #2 can be used with the tie breakers.

A CO-7 relay is chosen for the A and B breakers with

$$I_{ro} = \frac{14\ 215}{\frac{800}{5} * \frac{12\ 470}{600}} = 4.97 \text{ A} \quad (684 * \frac{12\ 470}{600} = 14\ 215)$$

A 5 A setting can be used (relay range 4-12 A)

and

$$I_{rp} = 5 * \frac{800}{5} * \frac{12\ 470}{600} = 16\ 627 \text{ A}$$

The instantaneous setting is

$$I_{ri} = \frac{50\ 000 * 130\%}{\frac{800}{5} * \frac{12\ 470}{600}} = 19.5$$

A 20 A setting can be used (relay range 20-80 A).

This time-dial setting for the A breakers should be set in such a way that sufficient time is provided between the relay on T or C breakers (Fig. A.4) and the A and B breakers for instantaneous-tripping selectivity. Between T's and C's it does not really matter, for these relays are operating in parallel.

A.5 GRID CALCULATIONS

Assumptions:

$$\rho = 250 \text{ ohm-m} \quad h = 0.5 \text{ m} \quad A = 130 * 130 \text{ m}^2$$

$$\rho_s = 4000 \text{ ohm-m} \quad t = 0.5 \text{ seconds}$$

From the CSA recommendations and for 23 150 A symmetrical short-circuit current, a 500 MCM conductor can be used, ($d_c = 0.813 * 0.0254 = 0.02$ m).

Also:

$$L \geq \frac{1.5 * 250 * 23\,150 * \sqrt{0.5}}{165 + 0.25 * 4\,000} = 5\,269 \text{ m}$$

$$R_g = \frac{250}{4 * 65} + \frac{250}{5\,269} = 1 \text{ ohms} \quad \left(r = \sqrt{\frac{(115)^2}{3.14}} = 65 \text{ m}\right)$$

$$R'_g = 2 \text{ ohms} \quad \text{(from CSA recommendations)}$$

$$TL = 2 * 115 * \left[\frac{115}{5} + 1\right] = 5\,520 \text{ m} \quad (M = 5 \text{ m})$$

$$R_r = \frac{250}{3.14 * 3} \ln \frac{1.27 * 3}{\sqrt{0.019 * 0.5}} = 97 \text{ ohms}$$

and

$$n = 0.75 * 97 = 73 \text{ rods}$$

Since $R_g < R'_g$ and $TL > L$ the following configuration can be used:

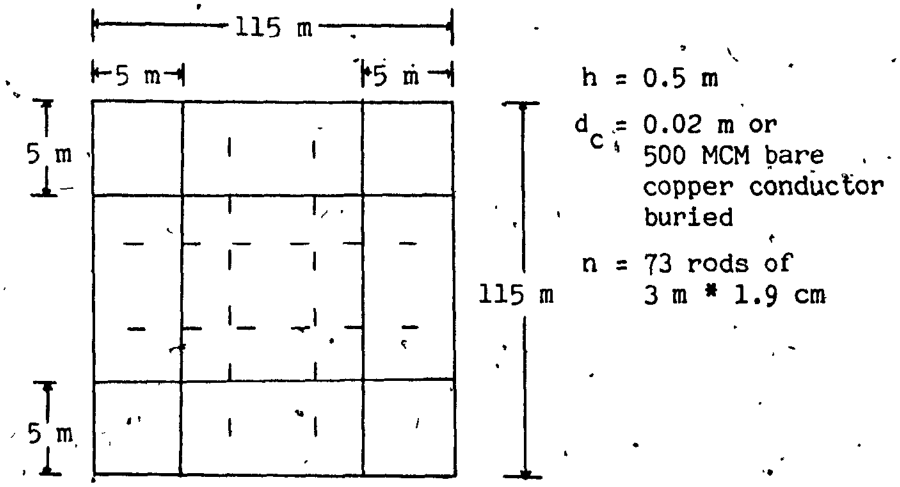


FIG. A.7 Grid Configuration

A.6 COMPUTER CALCULATIONS

What follows is a computer program in FORTRAN which calculates the voltage, in-phase and reactive current, real and reactive power, and the load impedance per phase of the configuration shown in Fig. A.8, as well as the total reactive and apparent power of each load. It, also, determines the total load current. These quantities can be obtained for the feeder feeding N branches (loads) as well, given V_{LL}, P_{L3} and the power factor (PF) of each load. (P_{L3} = load real power for three phases).

The sequence of computations is as follows:

Given the configuration of Fig. A.8, V_{LL}, P_{L3} and PF for each load, determine the voltages, currents, and power per phase per load and for the main feeder under normal condition.

First, a number is given to each branch starting with LN1, LN2, ..., LNN (for N loads).

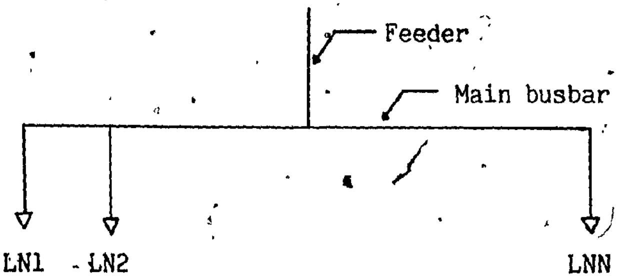


FIG. A.8 Connection of N Loads to a Main Busbar Feeding by a Main Feeder

Then we feed to the computer as many cards as there are branches (loads), plus one more to inform the computer about the number of loads following. Hence, for 5 loads, 6 cards are needed. The first contains the number 5 and what follows is 5 more cards with V_{LL}, P_{L3} and PF each given in volts, watts respectively. The computer output is given as shown in the computer program. Voltages are given in volts, currents in amperes, powers in watts, and impedances in ohms.

It is worth noting that the total calculated reactive power per load can be considered as the reactive power required per load for static capacitors to bring the power factor to unity.

```
      PROGRAM TASSOS (INPUT,OUTPUT)
C V1=LINE-TO-NEUTRAL VOLTAGE
C I1=IN-PHASE CURRENT PER PHASE
C I2=REACTIVE CURRENT PER PHASE
C I=APPARENT CURRENT PER PHASE
C P1=REAL POWER PER PHASE
C Q1=REACTIVE POWER PER PHASE
C R1=LOAD RESISTANCE PER PHASE
C X1=LOAD REACTANCE PER PHASE
C QT=TOTAL REACTIVE POWER
C SAT=TOTAL APPARENT POWER
C PT=TOTAL REAL POWER
C THE LETTER B IN FRONT OF THE ABAVE NOTATIONS DENOTES BUSBAR CONDITIONS
      COMPLEX A7,ZL
      BI1=0.
      BI2=0.
      BQT=0.
      BPT=0.
      BSAT=0.
      PRINT 10
   10 FORMAT (*1*)
      READ,N
      DO 1 K=1,N
      READ,VLL,PL3,PF
      A1=SQRT(3.)
      V1=VLL/A1
      P1=PL3/3.
      AI1=P1/V1
      A2=ACOS(PF)
      A3=TAN(A2)
      Q1=P1*A3
      AI2=Q1/V1
      A4=AI1**2+AI2*[illegible]
      AI=SQRT(A4)
      QT=3.*AI2*V1
      A5=P1**2+Q1**2
      A6=SQRT(A5)
      SAT=3.*A6
      A7=CMPLX(AI1,-AI2)
      ZL=V1/A7
      R1=REAL(ZL)
      X1=AIMAG(ZL)
      BI1=BI1+AI1
      BI2=BI2+AI2
      BPT=BPT+PL3
      BQT=BQT+QT
      BSAT=BSAT+SAT
      PRINT 2,K
    2 FORMAT (2X,*LOAD NUMBER*,2X,I3,/)
      PRINT 3
    3 FORMAT (14X,*V1*,21X,*I1*,17X,*I2*,16X,*I*,15X,*P1*)
      PRINT 4,V1,AI1,AI2,AI,P1
    4 FORMAT (5F20.2,/)
      PRINT 5
    5 FORMAT (14X,*Q1*,21X,*R1*,17X,*X1*,16X,*QT*,15X,*SAT*)
```

```
      PRINT 6,Q1,R1,X1,QT,SAT
    6 FORMAT (5F20.2,/)
    1 CONTINUE
      BA8=BI1**2+BI2**2
      BI=SQRT(BA8)
      PRINT 7
    7 FORMAT (2X,*MAIN BUSBAR CONDITIONS*,/)
      PRINT 8
    8 FORMAT (14X,*BI1*,17X,*BI2*,17X,*BPT*,16X,*BQT*,15X,*BSAT*,
     +20X,*BI*)
      PRINT 9,BI1,BI2,BPT,BQT,BSAT,BI
    9 FORMAT (6F20.2)
      STOP
      END
```

```
LOAD NUMBER     1
            V1                  I1                  I2                  I                   P1
            346.41              288.68              139.81              320.75              100000.00
            Q1                  R1                  X1                  QT                  SAT
          48432.21                 .97                 .47           145296.63              333333.33
LOAD NUMBER     2
            V1                  I1                  I2                  I                   P1
            346.41               48.11               23.30               53.46               16666.67
            Q1                  R1                  X1                  QT                  SAT
           8072.04                5.83                2.82            24216.11               55555.56
LOAD NUMBER     3
            V1                  I1                  I2                  I                   P1
            346.41               48.11               23.30               53.46               16666.67
            Q1                  R1                  X1                  QT                  SAT
           8072.04                5.83                2.82            24216.11               55555.56
MAIN BUSBAR CONDITIONS
            BI1                 BI2                 BPT                 BQT                 BSAT
            384.90              186.42           400000.00           193728.84              444444.44
```

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REFERENCES

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