To the Graduate Council:

I am submitting herewith a thesis written by Yet-Chow Frederick Hui entitled "A Digital Computer Program for Achieving Coordination of Protective Devices in Power Distribution Systems." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science with a major in Electrical Engineering.

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A DIGITAL COMPUTER PROGRAM FOR ACHIEVING COORDINATION OF PROTECTIVE DEVICES IN POWER DISTRIBUTION SYSTEMS

A Thesis

Presented for the

Master of Science

Degree

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Yet-Chow Frederick Hui

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ABSTRACT

This thesis describes a digital computer program which can be used for coordinating protective devices in power distribution systems. The program automatically selects time and current settings for each adjustable device and produces computer plotted curves of the total system design. Use of the program is illustrated by two coordination examples.

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CHAPTER I

INTRODUCTION AND BACKGROUND

Introduction

Fault protection is essential in power system planning and design. The necessity for protection becomes evident when one considers the structure of a distribution system. For economical reasons, electrical energy is transmitted from the generating station over high tension lines to substations where the level of the voltage is reduced for local distribution. In the local distribution system, parallel feeder lines are connected to the bus voltage from the substation in order to provide service for a given geographical area. Each feeder line will have additional parallel connected lines at reduced voltage levels. Ultimately, individual load elements will be serviced by the system.

The distribution network must be so designed to insure that faults will neither disrupt unnecessarily the service of the system nor damage transformers and transmission lines. A major portion of the design problem must be devoted to selecting and coordinating the protective devices within the system.

For flexibility in design application, many of the protective devices are manufactured so that the user can adjust the operating characteristics. Viewing the protective devices as cascade elements in the system, one recognizes that the individual adjustments cannot be made arbitrarily if the total system is to be coordinated.

Normally, the coordination problem is solved by trial and error procedures. Such techniques require hand plotting the characteristic curves which is a tedious and time consuming task. This thesis presents the development of a digital computer program which eliminates the need for the designer to carry out the trial and error graphical design.

Background

Background material on the problem of system protection and device selectivity is described in the following from a historical point of view.

In the late nineteenth century, ac distribution systems were gaining in popularity. Increased employment of ac systems meant increased interconnected transformer networks. For these complicated interconnected distribution networks, an insulation failure in the primary circuits usually caused secondary circuits to encounter disturbances and widespread fire risks. Protective devices were used for the protection of apparatus and transmission lines in the secondary circuits[1]. The demand of applicable devices led to the investigation of time-current characteristics of relays, standardization of enclosed fuses and design of high capacity fuses.

During 1930-1940 further studies on system protection and characteristics of protective devices were conducted. These studies pointed out the desirable characteristics of a protected system, and these system characteristics were summarized into three main points in the following.

1. The system should possess high speed fault clearing capability to minimize system damage and fire risk.

2. The system should be able to maintain maximum continuity of power distribution by proper isolation of faulted portions from the system.

3. The system should be able to provide apparatus and circuits in the system with maximum protection[2].

The problem of device selectivity was investigated in the 1930's, but most papers on this subject were published in the 1940's. In 1948, the American Institute of Electrical Engineers published a paper on recommended practices on the installation of distribution systems on shipboard[3]. This paper prompted J. R. Cole to design and test a distribution system on shipboard with selective tripping arrangements[4]. The desirability of selective tripping placed demand on protective devices that have various time delays so that the desired tripping effect could be produced. An air delay circuit breaker with long time delay, short time delay, and instantaneous trip units was introduced by B. G. Tremblay and M. E. Horn in 1950[5].

Fuses and protective relays were used in coordination of systems in industrial plants during 1950-1960. In 1954, Fusetron duel-element fuses and high capacity fuses were introduced by J. C. Lebens to coordinate systems[6]. Protective relaying on industrial power systems was studied by C. M. Lathrop and C. E. Schleckser[7]. The coordination and maintenance of relays were investigated by T. L. Bourbonnais II[8]. Related problems of voltage dips under fault conditions, short-circuit current carrying capacity of conductors, momentary duty of devices, and

interrupting capacity of fuses and breakers were also considered by Bourbonnais. Two papers were found on the settings of protective devices, and F. P. Brightman was the author of both papers[9,10].

The criteria for protective design presented in this thesis essentially follows the procedure adapted by Brightman. However, the major emphasis is given to developing a computer program for achieving the design objectives rather than new procedures for setting the system protective devices.

Chapter II presents background material which is essential to the coordination study of protective devices. The material in Chapter III illustrates the organization and main functions of the computer program. Two design examples are given in Chapter IV. In each case a comparison is made between the results achieved by customary hand design and those obtained from the computer program. Chapter V gives a brief summary of the thesis and recommends future work for improving computerized protective coordination.

CHAPTER II

FUNDAMENTALS OF COORDINATING PROTECTIVE DEVICES

This chapter describes background material which is essential to the coordination study of protective devices. A coordinated system is defined with the aid of an example. Characteristics of circuit breakers, relays, and fuses are illustrated so that device selection for power system protection can better be understood.

The Basic Problem

Figure II.1 shows a portion of an uncoordinated power distribution system with fuses as protective devices. The following events may occur if the system is uncoordinated. First, whenever a fault occurs at position P, fuse B is blown before fuse A begins to melt. Thus, feeder line X is isolated from the system so that power cannot be distributed to any of the loads. Second, whenever a fault occurs at position Q, fuse C begins to melt and is damaged before fuse B completely clears the fault.

The above system is uncoordinated because inappropriate current ratings are selected for fuses A, B, and C. If appropriate current ratings are observed, faults at positions P and Q will be localized, as soon as they occur, by fuses A and B, respectively, so that power distribution can be maintained in the rest of the system. Localization of the two faults also facilitates the fault detection process so that a minimum of time is required for fault correction. Due to the desirability of a coordinated system, it can be concluded that an uncoordinated system is only designed accidentally.

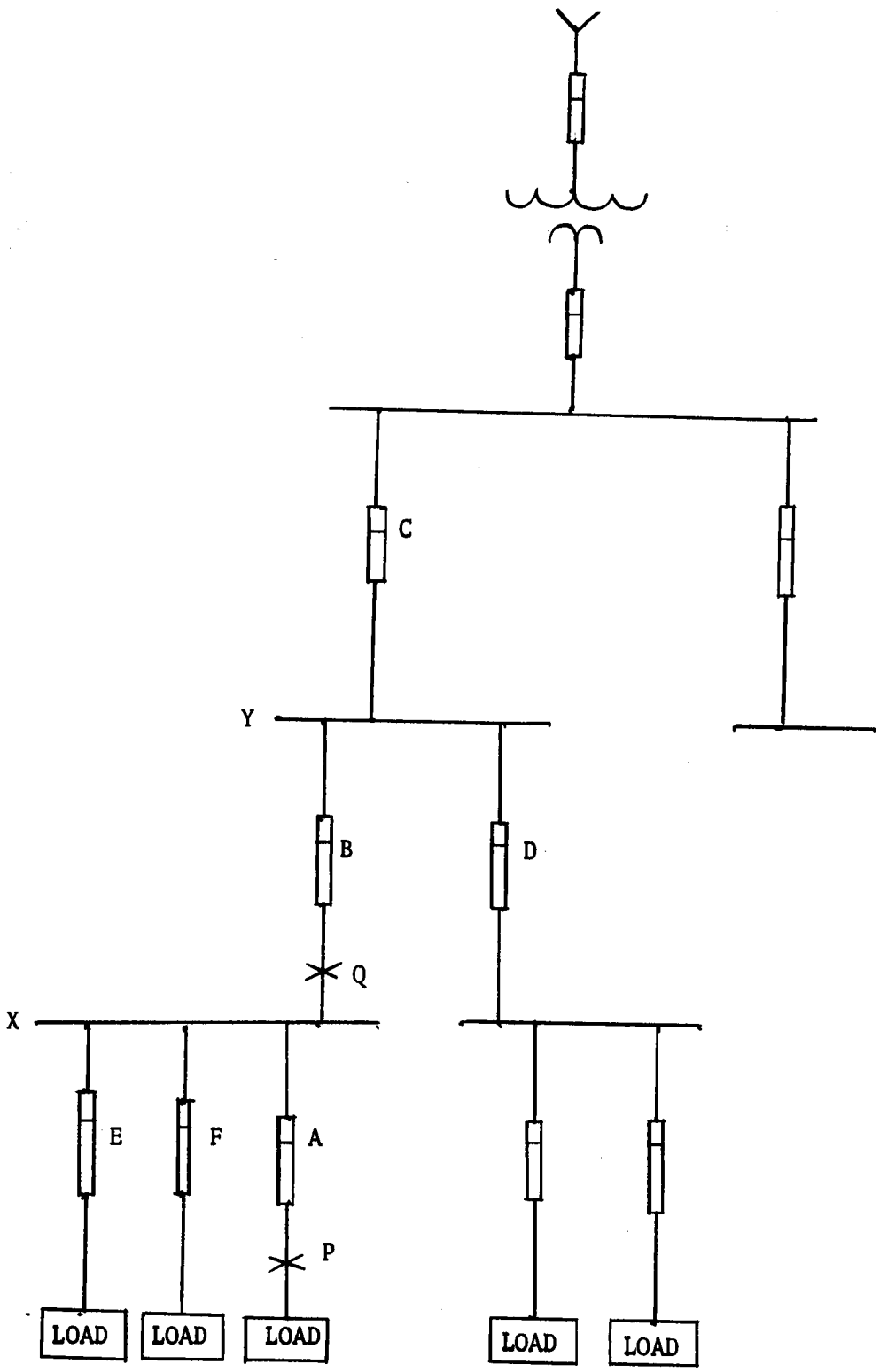


Figure II.1. Illustration of a portion of a power distribution system.

From the above example, it is observed that if all protective devices are coordinated, then the resulting system is coordinated. Operating mechanisms and characteristics of basic protective devices are explained in the following section. This knowledge is essential to the understanding of achieving device coordination.

Basic Protective Devices

Due to the fact that systems exist with various characteristics, different types of protective devices are manufactured for applications to various cases. However, considerations are restricted to basic overcurrent protective devices operating under four overcurrent effects; namely, the electromagnetic attraction, electromagnetic induction, thermal-bending, and thermal melting effect[17]. The three basic overcurrent protective devices are circuit breakers, overcurrent relays, and current-limiting fuses, and the study of these devices is conducted in that order.

The fault clearing characteristics of circuit breakers depend solely on breaker trip units. These trip units consist of trip coils which, under fault conditions, activate trip levers to unlatch the breakers. These breaker characteristics are represented by unlatching time-current curves and total fault clearing time-current curves similar to those shown in Figure II.2.

Circuit breakers may be equipped with three trip units; namely, long time delay, short time delay, and instantaneous trip. The characteristic curves of each of these units are isolated from Figure II.2 and illustrated in Figure II.3. In Figure II.3(a), I1 is the pickup current value of the time time delay unit, and current I2, when existing for a

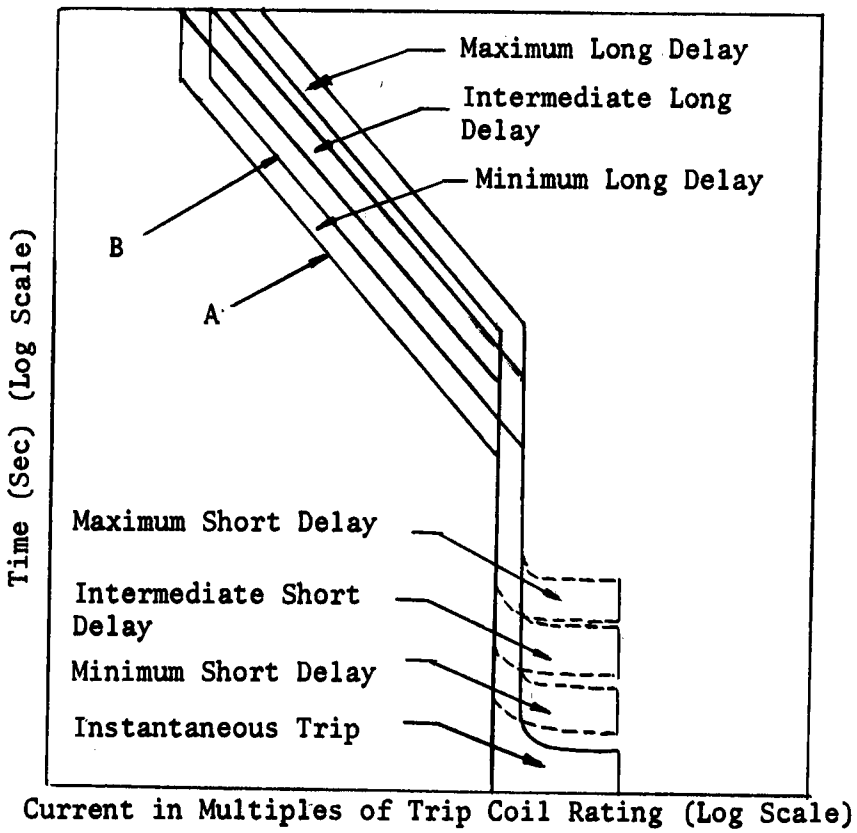
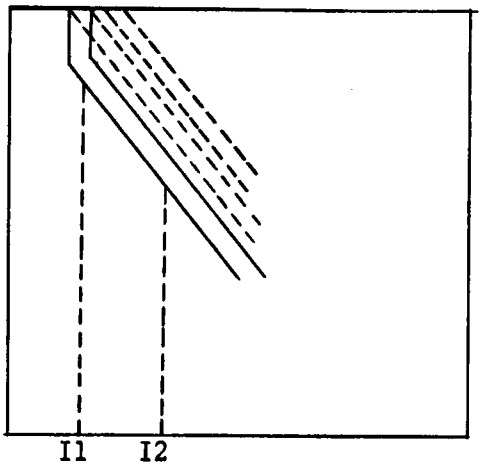


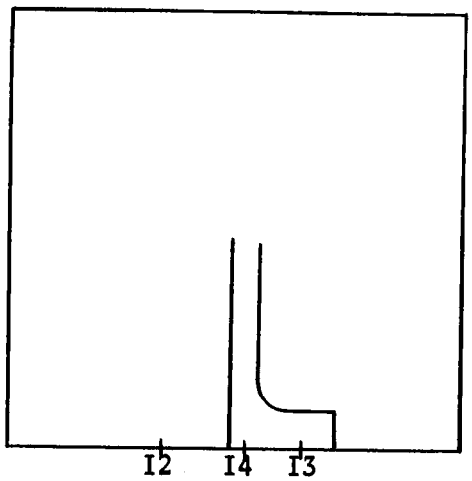
Figure II.2. Typical characteristic curves of a circuit breaker.

Diagram Notes:

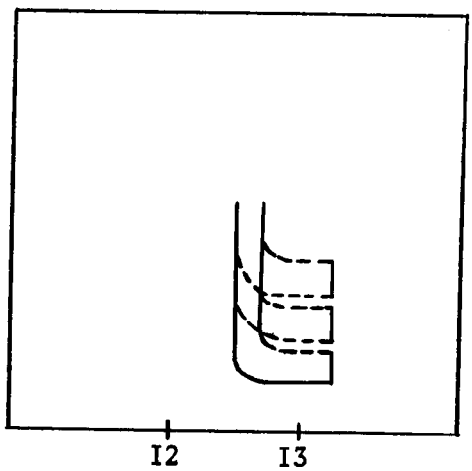
1. Curve A describes the minimum time for the breaker to unlatch.
2. Curve B describes the total clearing time of the breaker.
3. In the regions between curves A and B, the breaker may or may not have cleared the fault completely.



(a) Long Time Delay



(b) Instantaneous Trip



(c) Short Time Delay

Figure II.3. Operating regions of a circuit breaker.

long time period, generates a sufficiently large electromagnetic effect which causes the tripping circuit to be closed. In Figure 11.3(b), the pickup current value is set at I4 which is a multiple of the instantaneous trip coil rating. Current I2 is allowed to exist by this trip unit, but current I3 generates an electromagnetic effect which trips the breaker instantaneously. Similarly, in Figure II.3(c) fault current I3 causes the short time delay unit to trip.

As a conclusion to the explanation of the characteristics of circuit breakers, the special feature of a molded case circuit breaker is considered. The long time delay units of the molded case circuit breakers are preset and sealed in by manufacturers. If a different delay characteristic is desired, the whole delay unit must be changed. Instantaneous trip units may be set for several pickup current values only in larger frame sizes. Furthermore, the maximum settings are ten times the trip coil ratings for molded case circuit breakers.

The basic duty of overcurrent relays is simply opening and closing contacts according to the magnitude of overcurrents. Figure II.4 shows two contacts "a" and "b"; "a" is normally opened and "b" normally closed. The pickup current value is the minimum value of current required to either close contact "a" or to open contact "b", and the reset value is the maximum current required to either open "a" or close "b"[12]. These two values are depicted in Figure II.5.

In general, relays have inverse, very inverse, or extremely inverse time-current characteristics, each of which can further be varied within a spectrum by adjusting time dials mounted on relays. Figure II.6 shows typical relay characteristic curves which are plotted as multiples of tap

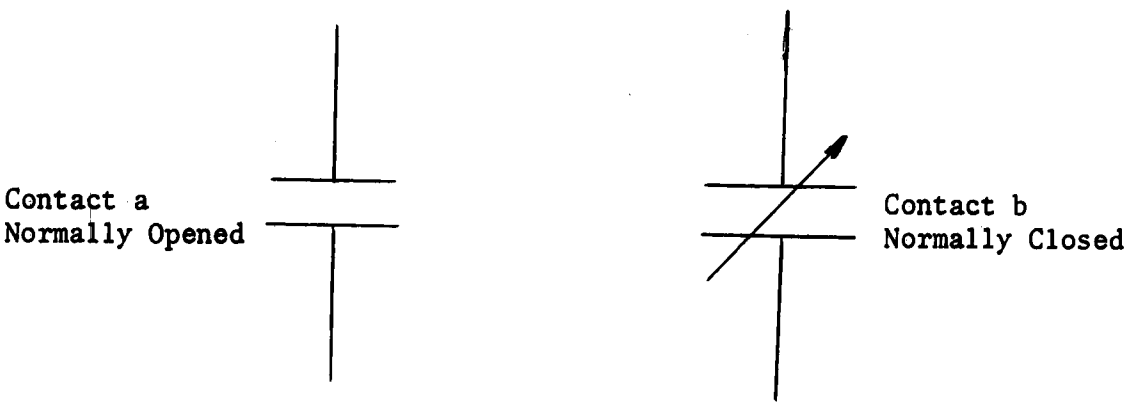


Figure II.4. Symbols used for normally opened and normally closed relay contacts.

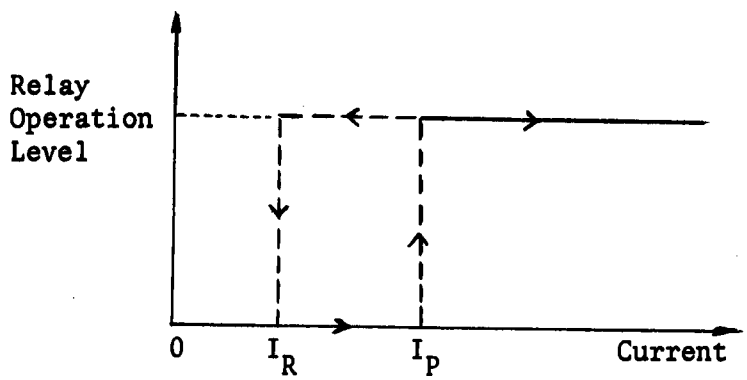


Figure II.5. Current operating characteristics of a typical relay.

Note: I_P = Relay Pickup Current.

I_R = Relay Reset Current.

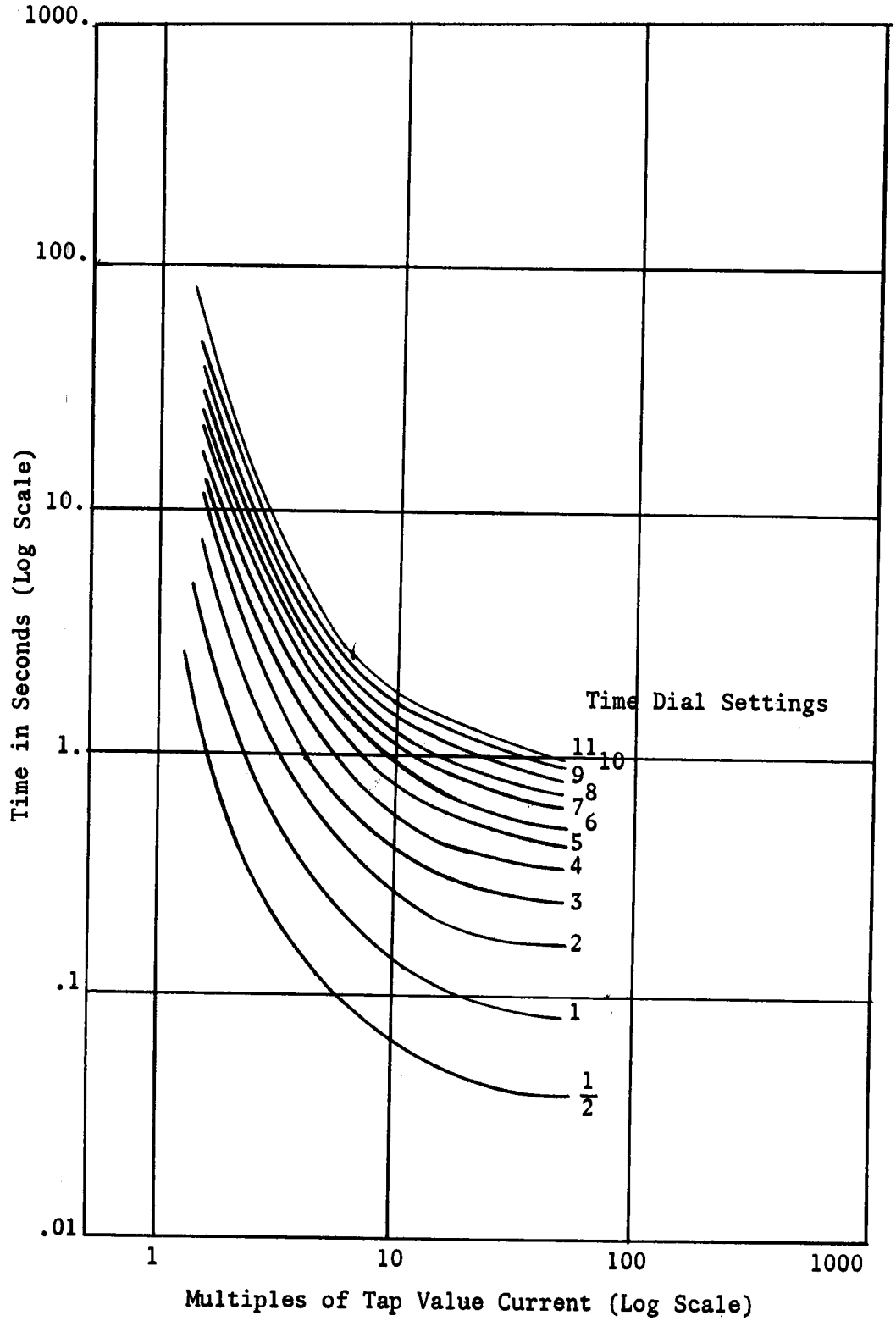
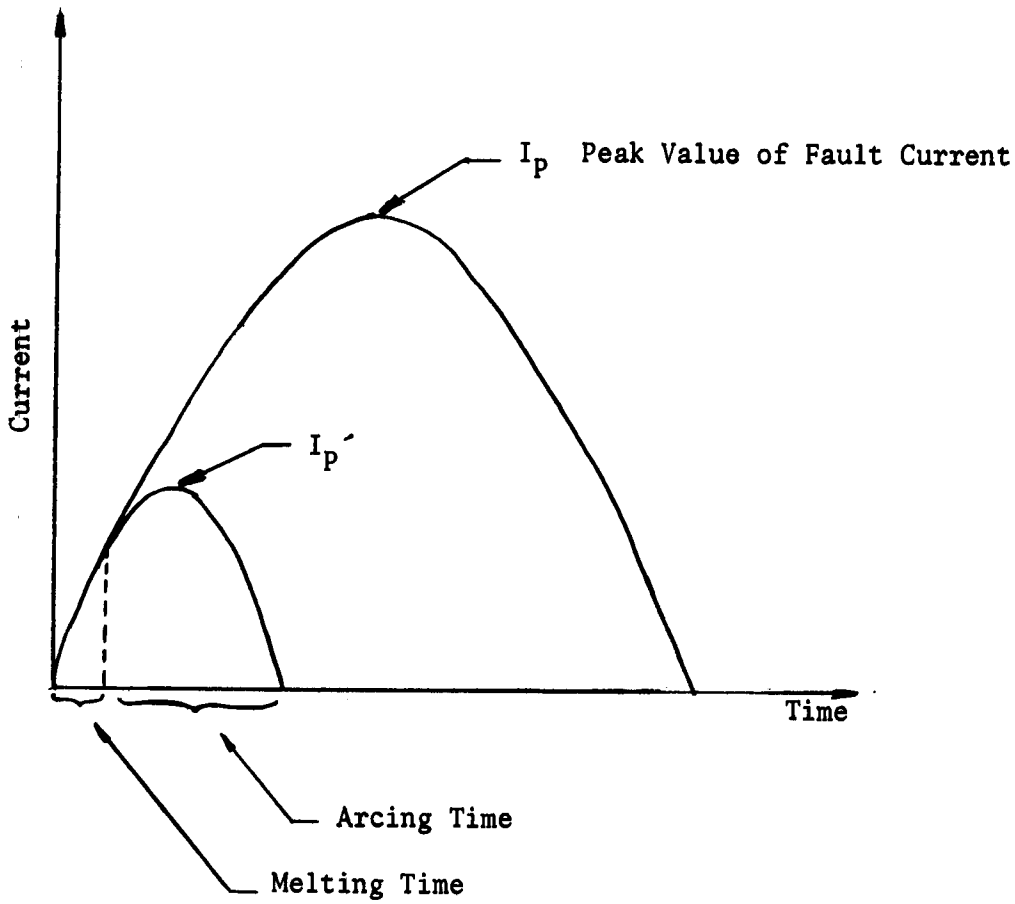


Figure II.6. Illustration of relay very inverse characteristic curves.

values of current transformers. Occasionally, characteristic curves may begin from 1.5 times the transformer tap values to allow for relay pickup delays due to inertia.

The last type of devices considered is current limiting fuses which are rated according to their normal current carrying capacity. These fuses will melt and later blow when overcurrents persist, thus limiting the overcurrents from reaching their maximum values. The fault clearing process is illustrated in Figure II.7 which also shows the melting time of the fuse, arcing time of the overcurrent, and the total fault clearing time. These characteristics of fuses, with no exception, are described by time-current curves; namely, melting time curves, short time curves, and total clearing time curves.

General observations on the characteristics of the basic devices serve as a conclusion to the description in this section. First, fuses do not clear faults as fast as relays and circuit breakers at low overcurrents, but they are blown faster by high fault currents. Ample types of fuses are available to provide flexibility in coordination with other devices. Proper ratings of fuses must be selected so that surges of overcurrents, which will not cause damage to the system, will not damage the fuses accidentally. Second, relays are more accurate devices than fuses and circuit breakers. The inverse characteristics of relays can be adjusted by time dials. Third, circuit breakers are equipped with adjustable time delay or instantaneous trip units although instantaneous trip units are only used to protect load elements due to coordination difficulties. Circuit breakers can interrupt large fault currents; but



Total Clearing Time

= Arcing Time + Melting Time

Figure II.7. Illustration of current limiting effect of fuse.

at very high values of fault currents, fuses are blown by the thermal effect of the fault currents before breakers are unlatched to clear the faults by the electromagnetic effect of the fault currents.

Device Selection

After the characteristics and operating mechanisms of the basic devices are described, the next step in coordinating a system is to select devices to protect the total system. General recommendations of power system protection are available since engineers first started to work in this field as early as the beginning of the twentieth century. However, voltage, current and frequency ratings of devices are selected according to the operation specifications of the system obtained under normal and short circuit conditions by performing system analysis.

The maximum and minimum fault currents are calculated by knowing the impedance and power sources of the system. Asymmetrical currents, being equal to the sum of symmetrical ac currents and their dc components, are maximum currents encountered under short circuit conditions. Although the dc components decay rapidly, they are significant within the first few cycles of fault currents[16]. Thus, asymmetrical currents, rather than symmetrical currents, are used for determining the momentary duty of protective devices.

The device selection process can be summarized by two general guidelines. First, sufficient interrupting capacity of a device is essential in preventing damage to both the device and the protected load element. Second, devices must be adjustable so that flexibility to coordinate with other devices is provided[17].

Device Setting Selection

After devices are selected with appropriate ratings, the last step in the coordination procedure is adjusting device pickup current and time delay settings of circuit breakers and relays. Setting devices for achieving coordination of systems may be complicated due to the many possible combinations of devices as illustrated in Figure II.8[17].

The settings of these devices are usually obtained by hand plotting device characteristic curves. The following example describes the procedure for arriving at a final coordination plot of a system. The system under consideration, shown in Figure II.9, consists of four protective devices; a primary fuse, A, two circuit breakers, B and C, and a molded case circuit breaker, D. Coordination plotting begins by tracing the preselected curve of D on a master sheet of log-log scale paper. Breaker C is equipped with a long and a short time delay unit, and one pickup current setting is selected for each delay. The resulting characteristic curve of the breaker is sketched on the master sheet closest to the curve of D but without overlapping it. Similarly, the characteristic curve of breaker B, which is also equipped with a long and a short time delay unit, is sketched on the master sheet closest to the curve of breaker C but without overlapping it. Finally, the primary fuse curve is sketched in and the plot is completed with pickup current settings of all devices found. The actual hand plot is shown in Figure II.10.

The principal criterion used in the coordination plotting is that coordinated devices do not overlap each other. Figure II.11 shows the effect of two curves, a fuse curve and a breaker curve, crossing each

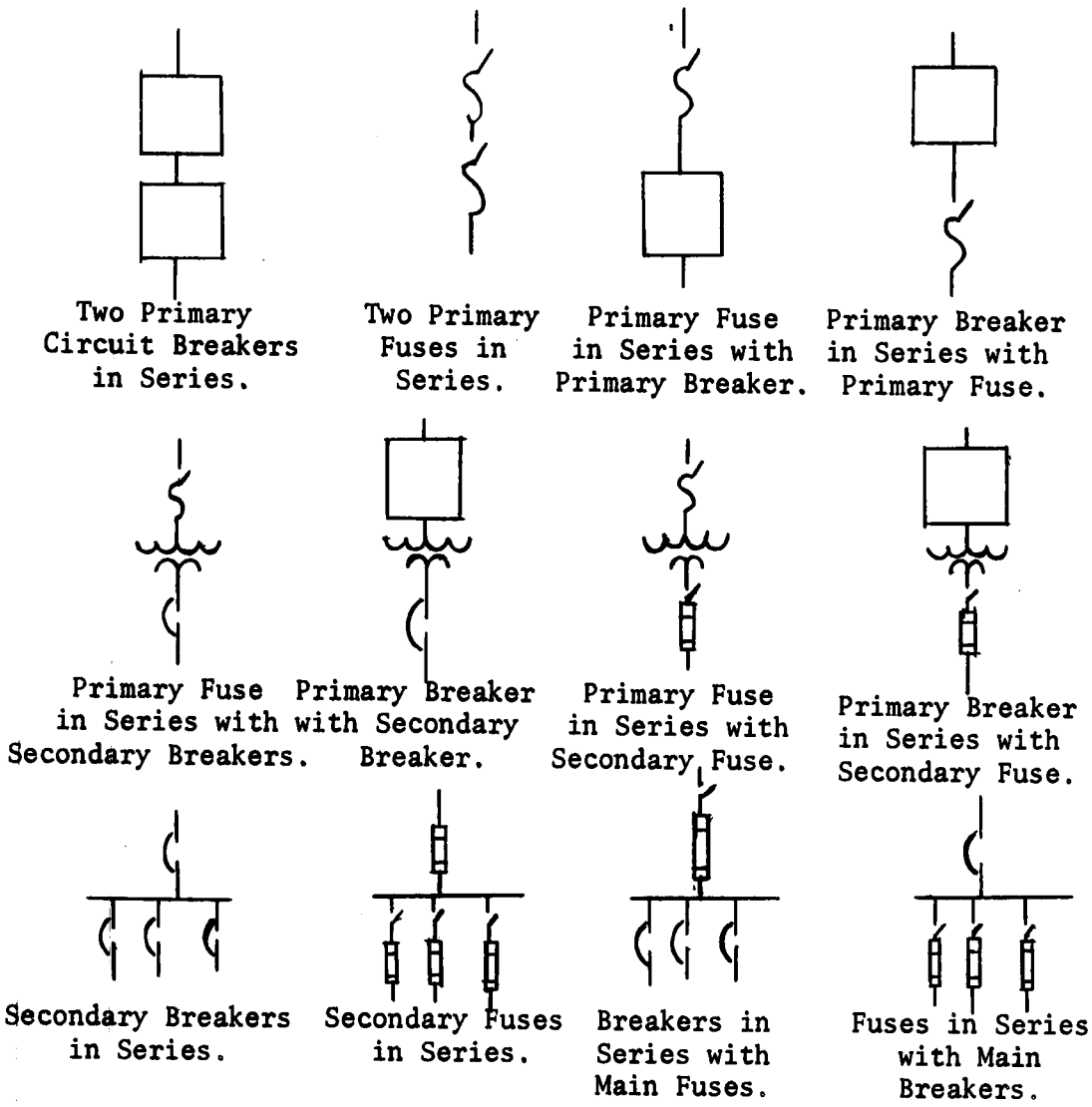


Figure II.8. Illustrations of protective devices and their application.

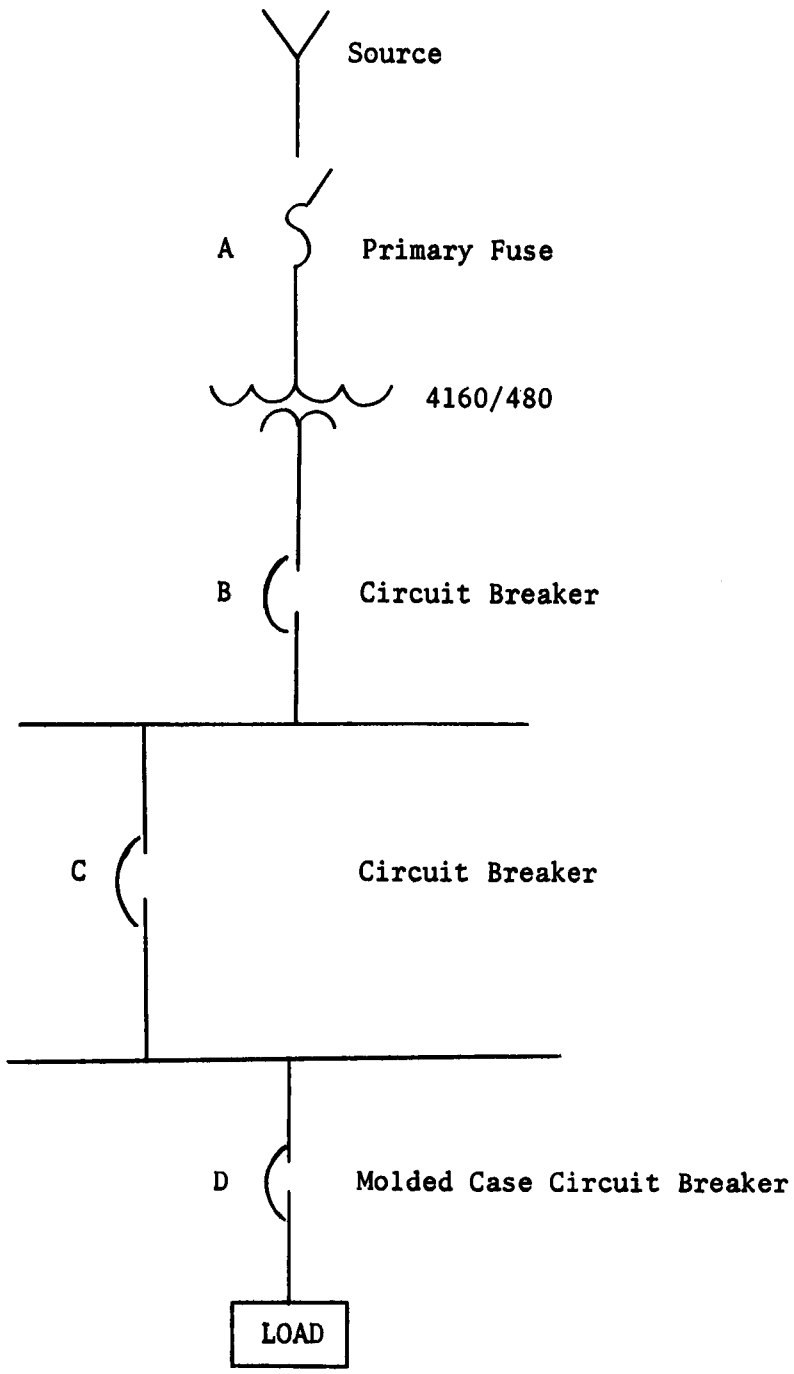


Figure II.9. One-line diagram of a power distribution system.

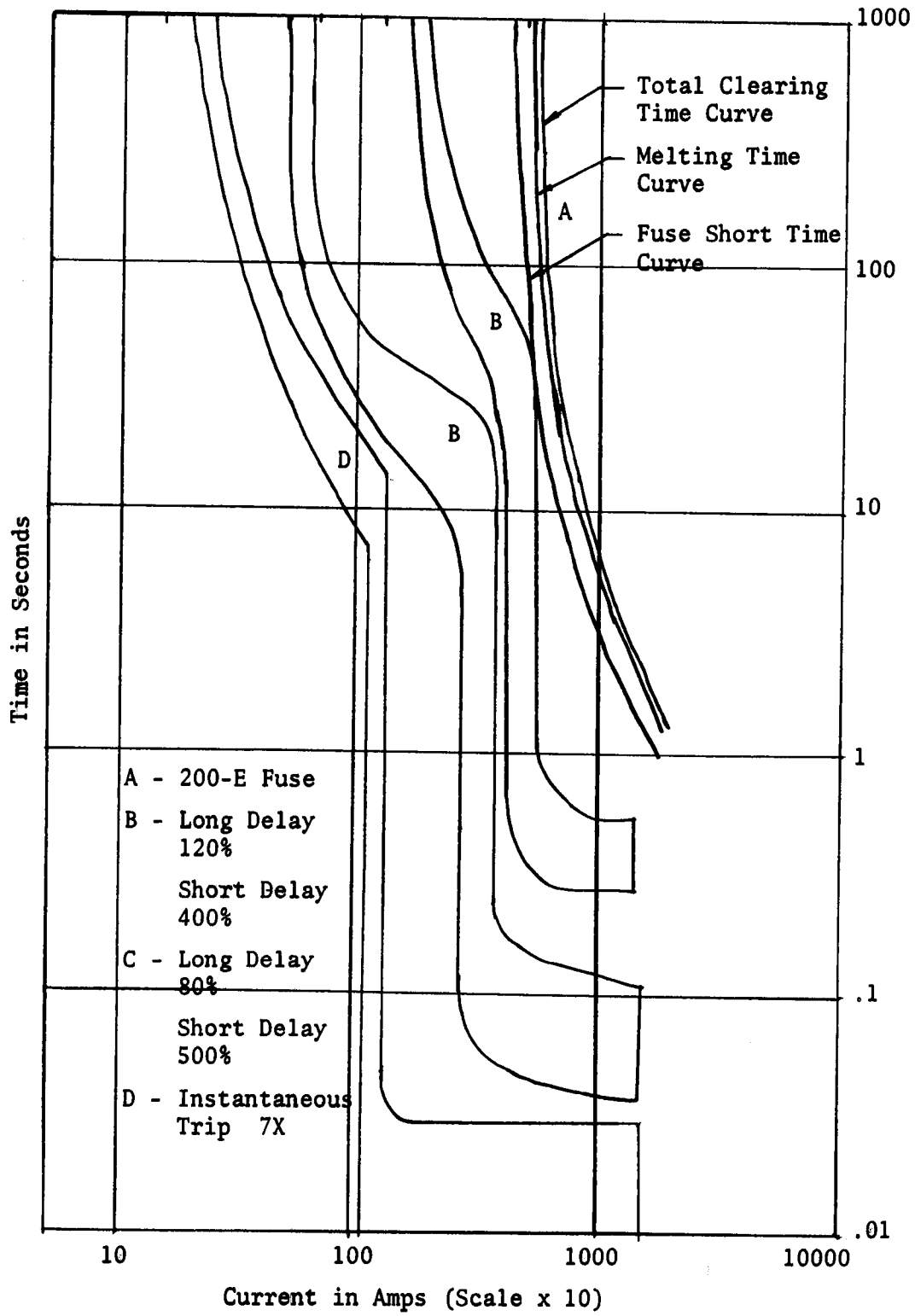


Figure II.10. Hand plotting result of example.

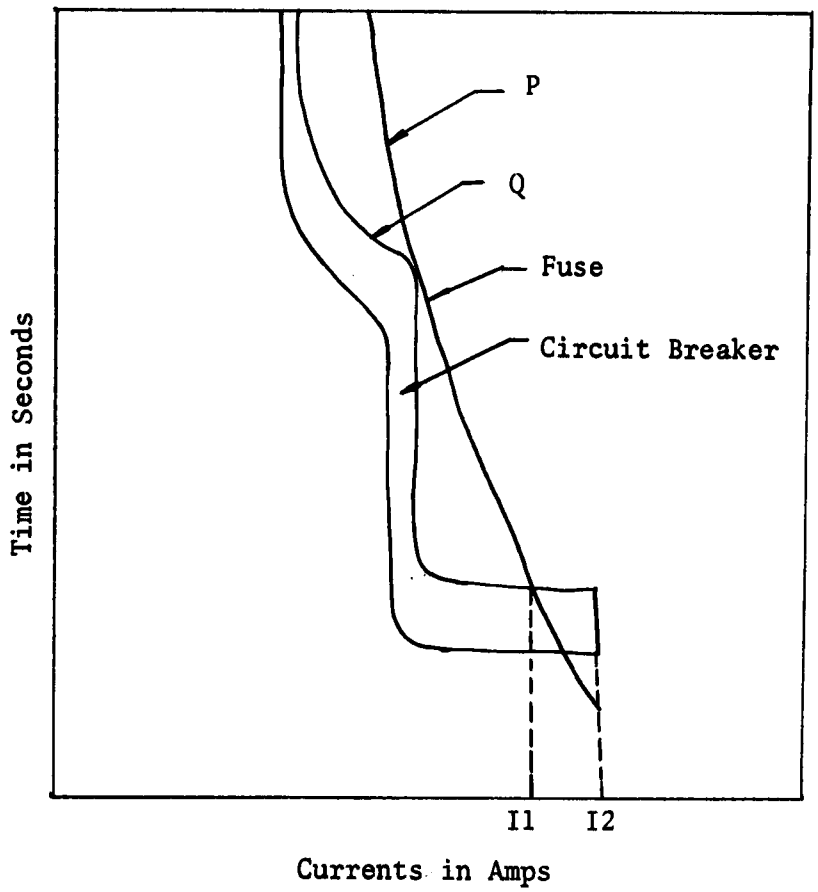


Figure II.11. Diagram illustrating improper coordination between a circuit breaker and fuse.

other at I1. I2 is the maximum fault current. At current values lower than I1, the breaker clears the fault, but at currents between I1 and I2, the fuse is blown before the breaker clears the fault completely. Thus, the two devices are not coordinated. This coordination principle is utilized by a digital computer program designed to perform device setting selections. This program is described in the next chapter.

CHAPTER III

A DIGITAL COMPUTER PROGRAM FOR ACHIEVING COORDINATION OF PROTECTIVE DEVICES

The FORTRAN program written for computer solution of the coordination problem is presented in this chapter. The four main elements of the program are data acquisition, curve generation, curve selection, and computer plotting the final design with a CALCOMP plotter. A flowchart is presented to facilitate explanation of how the overall program operates.

Organization of Program

A block diagram of the program is shown in Figure III.1. The program is divided into seven parts which are represented by D1 to D7. These seven parts cover characteristic curves of circuit breakers with solid state trip devices, circuit breakers with series overcurrent trip devices, molded case circuit breakers, relays, and fuses. All seven parts are directly controlled by the main program which acts as a seven-way switch. Subroutine CALCOM is called by the main program for plotting the curves stored in memory.

Multiple designs (stacked jobs) can be processed by inserting appropriate data cards at a specified location.

Basic Functions of Program

The program has four main functions. It reads in data of a curve corresponding to one setting of a device. The curves corresponding to other settings of the device are generated using incremental offsets in

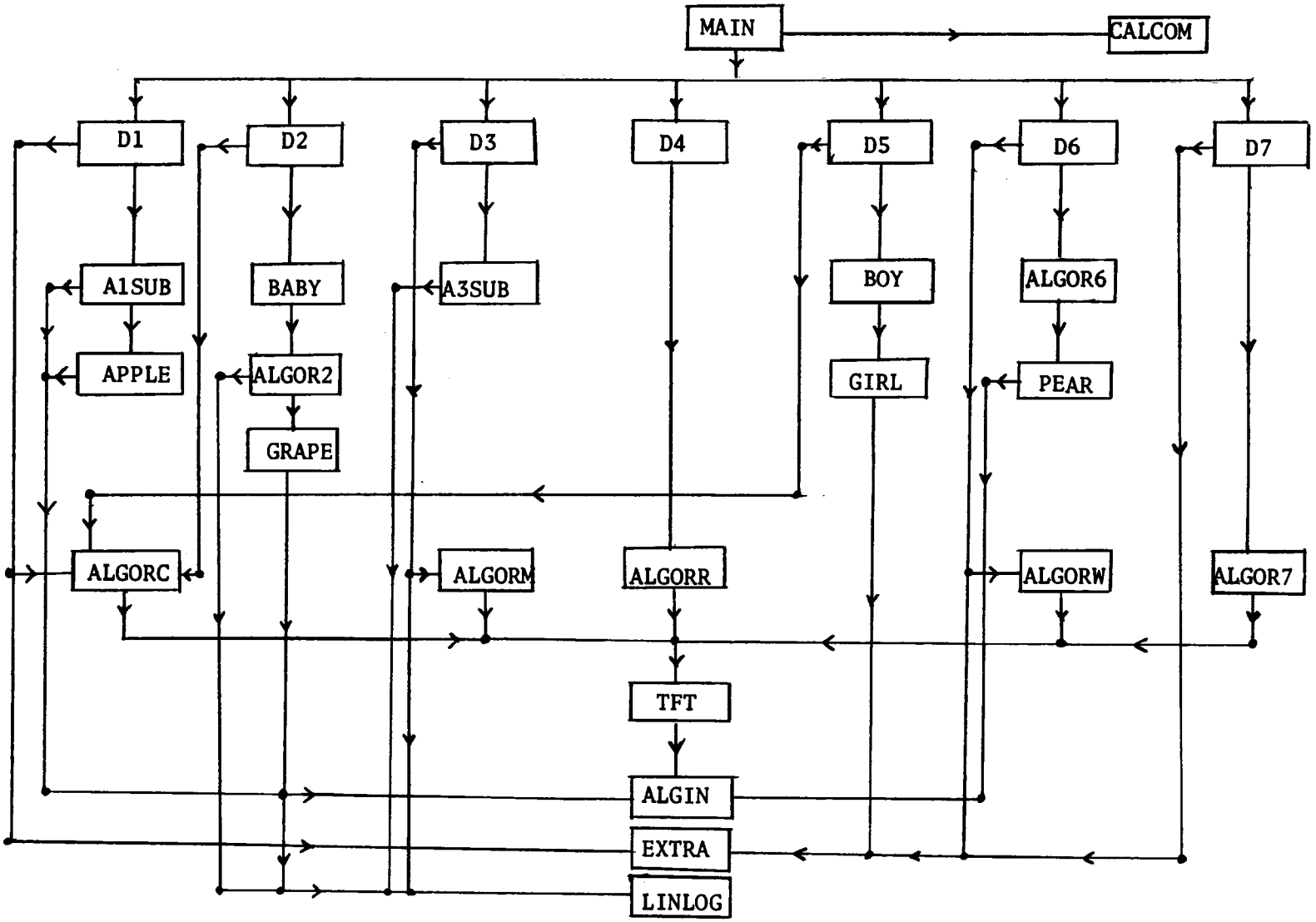


Figure III.1. Block diagram illustrating the organization of the digital computer program.

time and current. After these characteristic curves are stored, subroutines are called to logically select appropriate curves to meet design requirements. The selected curves are stored and later used for preparing the CALCOMP rendition of the total design.

Data acquisition. The optimum number of data points needed for representing a device characteristic curve is decided by the program user. For example, curves of circuit breakers with solid state trip devices mainly consist of straight line portions so that only ten data points are assigned to represent each curve. On the other hand, each of the curves of circuit breakers with series trip devices are approximated by eighteen points. Increasing the number of data points for describing each curve will yield a better curve definition. However, memory requirement for storage will increase and therefore the user must make a compromise between curve definition and storage requirements.

Curve generation. Fuse and relay curves cannot be suitably generated and are consequently read in for each separate characteristic. Therefore, the main concern in this section is curve generation for circuit breakers.

Curves of different circuit breaker trip units are generated in separate subroutines. For the different settings, these curves are more or less parallel to each other. If one of the curves is taken as a reference, curves of other settings can be generated by shifting this reference curve. Data points of the reference curve are read and stored, and a constant added to each point so as to shift the reference either

vertically or horizontally. If the reference is taken from logarithmic scales, each point must be multiplied by a factor in order to produce the same effect.

Two typical examples are used to illustrate the curve generation function of the program. In each case, detailed explanations are given as to the significance of the device characteristic curves and the techniques of generating these curves.

Example 1. This example illustrates the curve generation process by using a General Electric circuit breaker which is equipped with solid state overcurrent trip devices. The characteristic curves for the breaker are shown in Figure III.2.

From the figure, it is observed that long time delay curves can be selected from the minimum, intermediate, or maximum time delay bands. The value of the pickup current may be set in the range from 80 percent to 130 percent by the continuous current rating of the trip coil.

Similarly, short time delay curves can be selected from the minimum, intermediate, or maximum bands. The pickup current can be set at 4X, 5X, 6X, 8X, 10X, or 12X the trip coil rating or in the range from 2X to 5X of the rating.

Although there are different time delay settings and options, these curves can be generated by reading in curves of the minimum band of the long delay set at 80 percent of the coil rating, and the minimum band of the short delay set at 10X the coil rating. Ten data points are taken from each curve.

The pair of curves read in are shown in Figure III.3 and the positions of the ten points on each curve are labelled. The intermediate

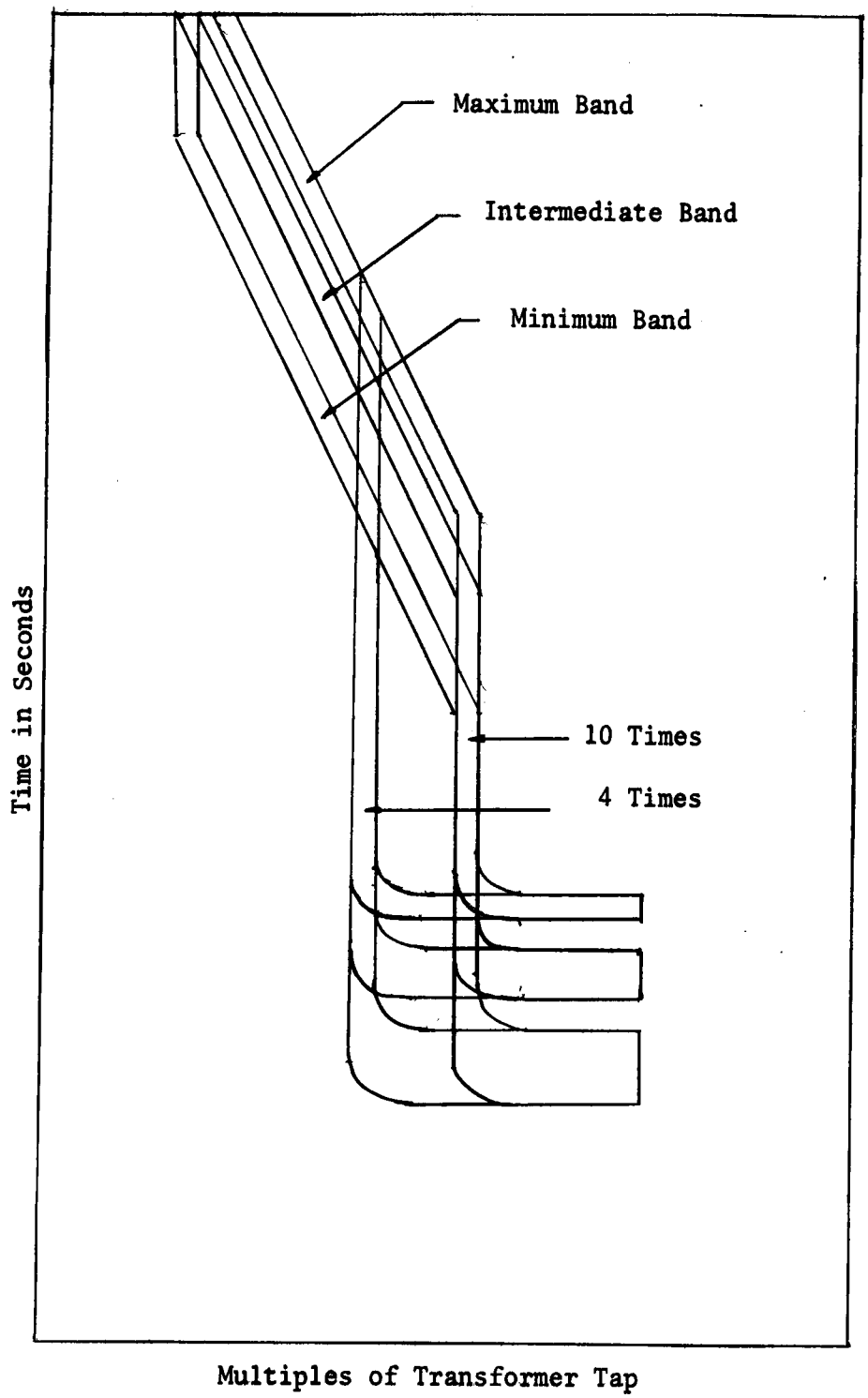


Figure III.2. Characteristic curves of a General Electric circuit breaker equipped with long and short time delay units.

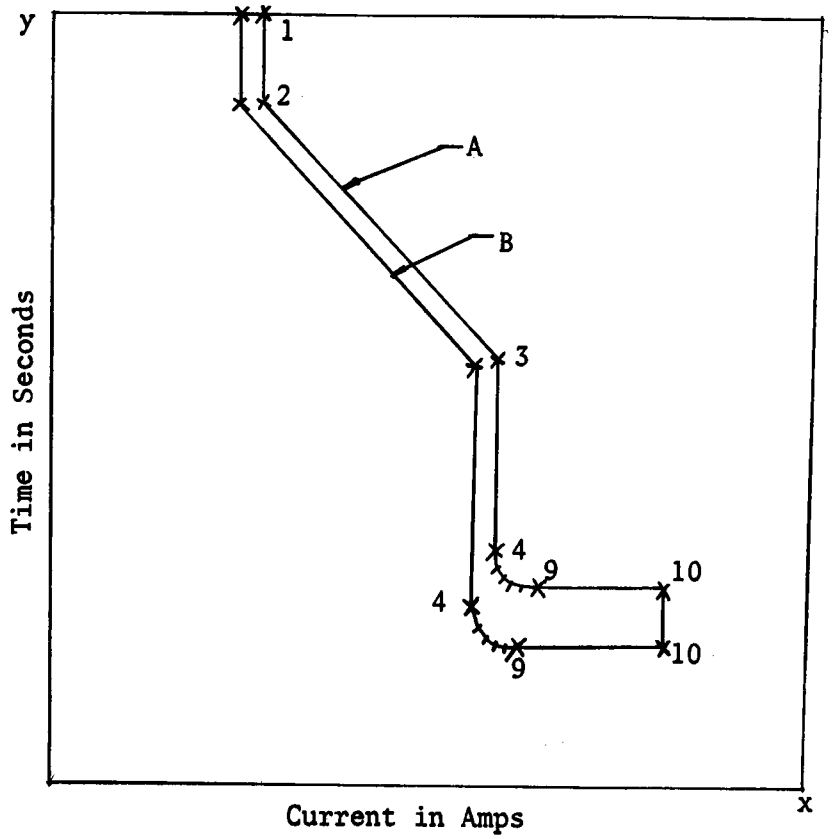


Figure III.3. Illustration of positions of the ten points taken from each breaker curve.

and maximum bands can be generated by applying a multiplying factor to each of the y values of the first three points on each curve. The long time delay settings are generated by moving the first two points to the right of the 80 percent curve. For example, points 1 and 2 of the 80 percent curve are shifted to the new positions 1' and 2', as shown in Figure III.4, to generate the 160 percent setting. The x values of 2' and Q are the same, but the y value of point Q is interpolated between points 2 and 3, so that Q can replace point 2'.

Similarly, the intermediate and maximum bands of the short time delay can be generated by multiplying a factor to each of the points from 3 to 10. For example, points from 3 to 10 of the 10X curve are shifted left, as shown in Figure III.5, to generate the 4X setting. The x values of points 3' and R are the same, but the y value of R must be interpolated between points 2 and 3 so that R can replace 3'.

Example 2. This example illustrates the curve generation process by using a Westinghouse air circuit breaker type DB which is equipped with a long time and a short time delay unit. The characteristic curves for this breaker are shown in Figure III.6.

The long time delay setting of the breaker can either be 30 seconds or 20 seconds. The long delay pickup current can be 80 percent, 90 percent, 100 percent, 110 percent, 130 percent, and 160 percent of the trip coil rating. The 100 percent curve is drawn in solid lines, the 80 percent and 160 percent curves are drawn in dotted lines, curves of other settings are to be inserted.

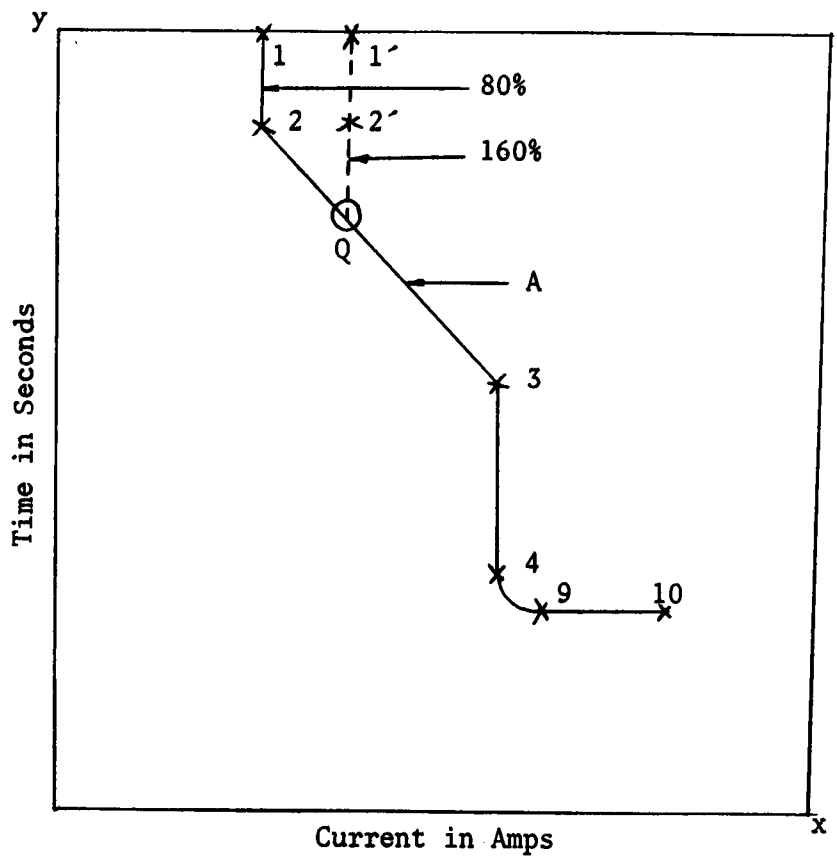


Figure III.4. Curve shifting for generating long time delay settings illustrated by curve A of Figure III.3 for Example 1.

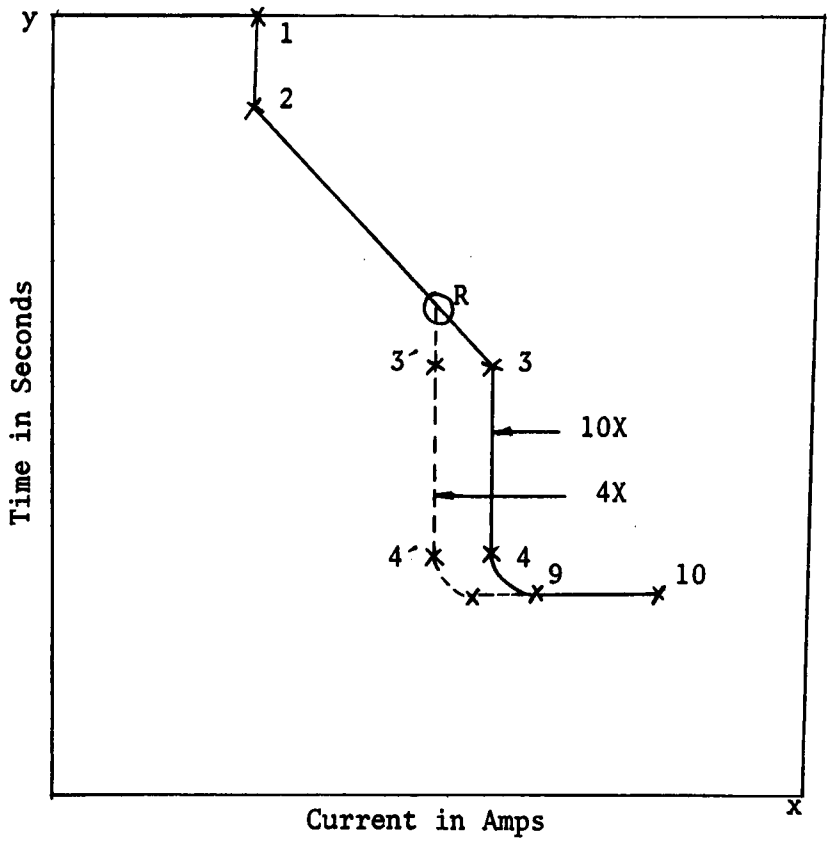


Figure III.5. Illustration of curve shifting for short time delay settings in Example 1.

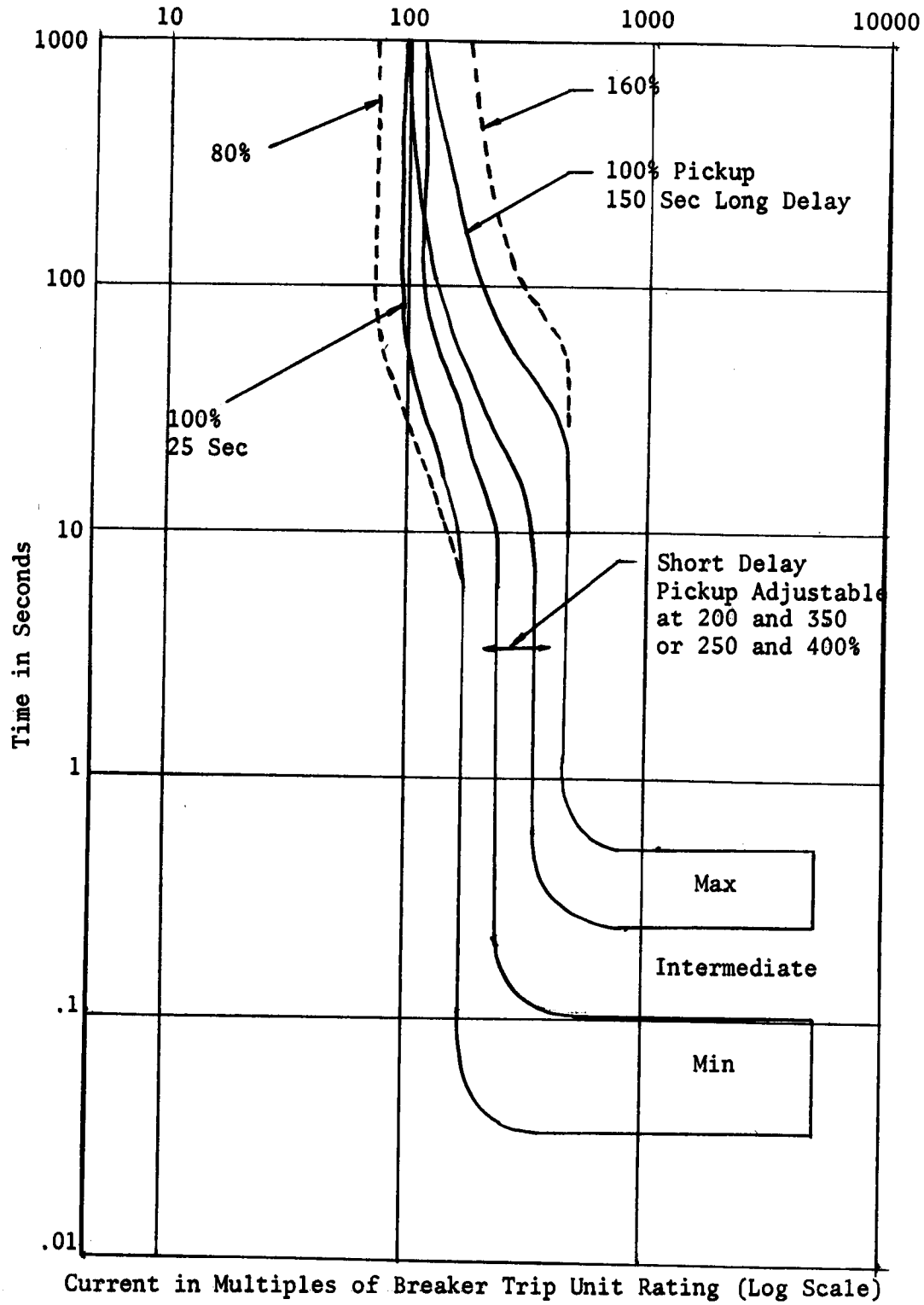


Figure III.6. Illustration of the characteristic curves of a Westinghouse circuit breaker.

The short time delay can be selected from three time bands, maximum, intermediate, and minimum. The short delay pickup current can either be set at 200 and 350 or 250 and 400 percent of trip unit rating.

Each curve in this example is represented by eighteen points, and the positions of these points appearing on the 100 percent long delay and 400 percent short delay curves are shown in Figure III.7. These curves are read in as reference curves. No long delay options will be generated, but the short delay options are generated by adding constant multiples to each of the y values of points 13 to 18.

Figure III.8 shows that the 100 percent long delay curve is shifted to generate the 160 percent curve. Each of the twelve points moves a different distance to the right.

Figure III.9 shows that the short delay curve is shifted from the 400 percent to the 250 percent setting. The y values of points 12 and 12' are the same. If the x value of 12' is less than that of point 10 but larger than that of 9, the new curve will move down from 9 to 12'.

Curve selection. When curves corresponding to all settings of the trip units are generated and stored, a bank of curves is developed for that device. When this device is called upon to coordinate with a previous device, curves from the bank are called, one by one, to be tested for coordination with curves of the previous device. If the desired curve from the bank is found, it is stored for plotting.

In the selection process, the single criteria followed by the computer is that the correct curve of the next device must not overlap

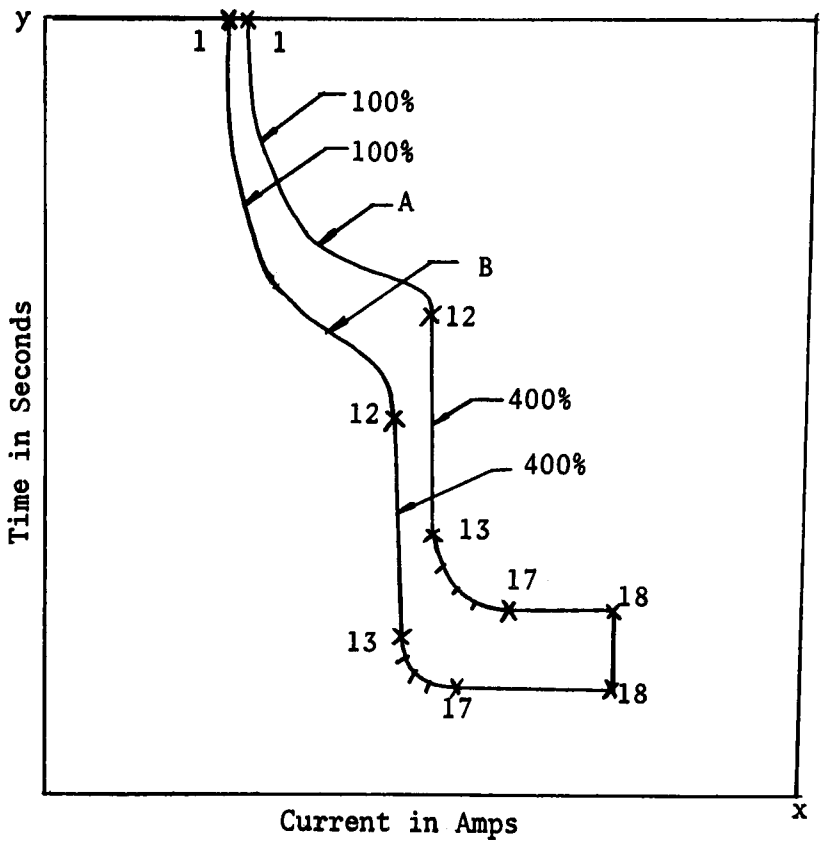


Figure III.7. Illustration of the positions of the data points on the reference curves of Example 2.

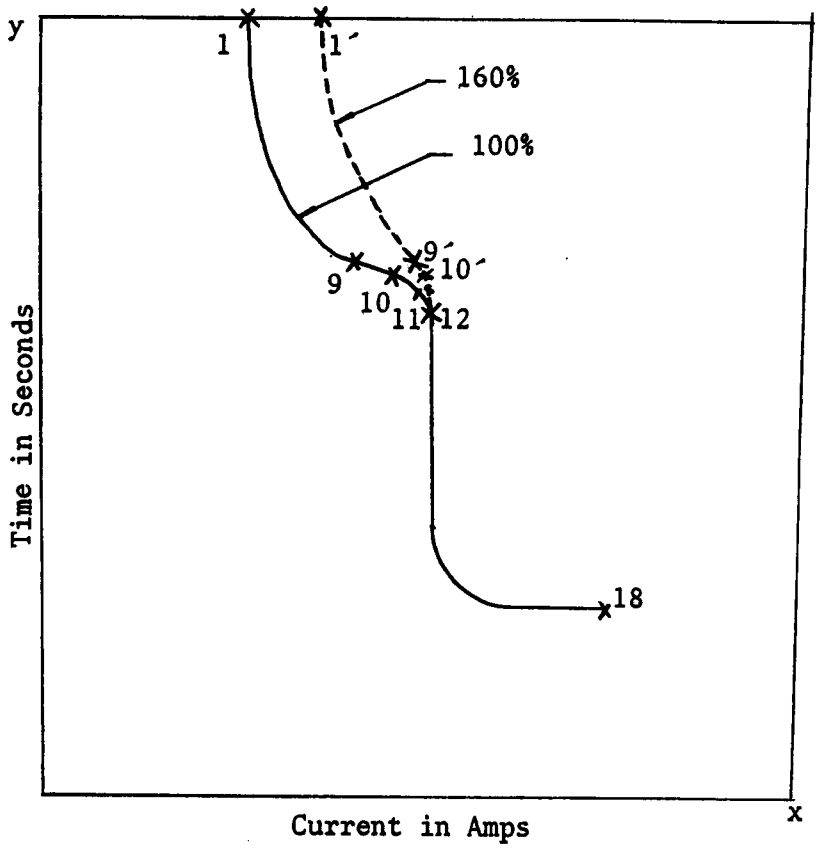


Figure III.8. Illustration of the 100 percent to 160 percent shift of the long delay by using curve A of Figure III.7.

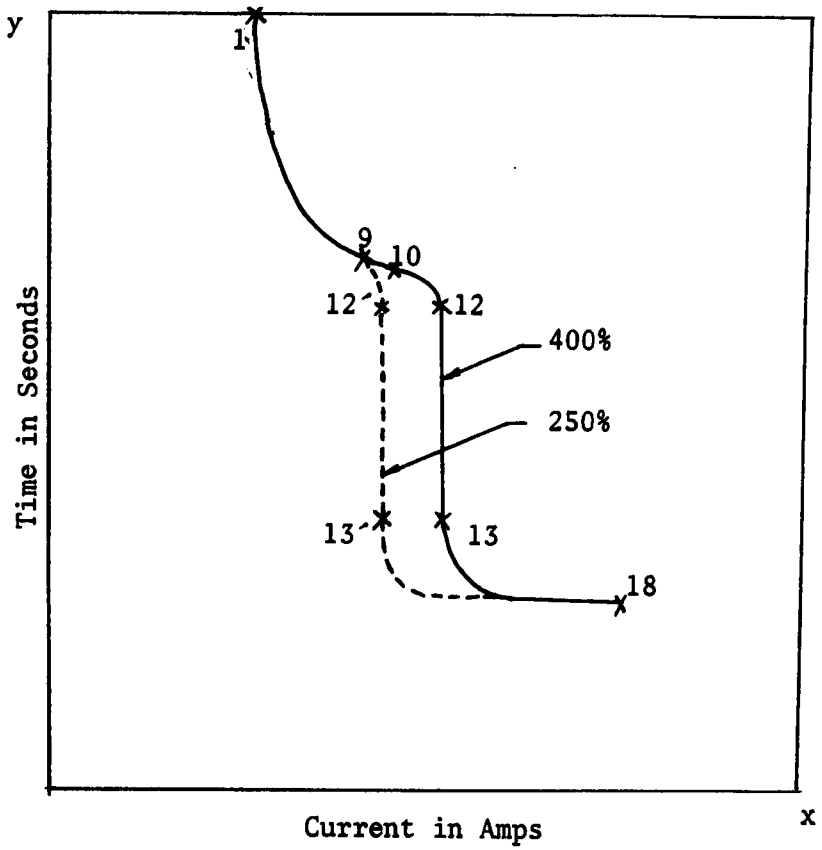


Figure III.9. Illustration of the 400 percent to 250 percent shift of the short delay.

the curve of the previous device. This criteria is specified in subroutine TFT, and curves of the previous device are stored in subroutine EXTRA.

Two pairs of breaker curves, A and B, C and D, are shown in Figure III.10. Curves A and B are preselected by the program user and stored in EXTRA; curves C and D are to be chosen from a bank of generated curves. An attempt is made to coordinate the two breakers, wherein curve A from EXTRA is tested for overlapping with curve C. When the desired curve C is found, the corresponding curve D is also known. Both C and D are stored in EXTRA and A and B are replaced. Curve D will be used to coordinate with curves of the next device.

In every curve selection subroutine, TFT is called to test for overlapping. The operation of subroutine TFT is simply to compare the y values of the two curves under investigation with regard to common x values for the two curves. Figure III.11 shows curves P and Q which are to be tested for coordination. At values x1 and x2, y1 and y2 of Q are detected by TFT to be higher than that of P, but y3 of Q is detected to be less than y3 of P. A signal is set up by TFT for indicating that overlapping occurs between the two curves.

Interpolation is employed by TFT for appropriate applications, and this interpolation is performed by subroutine ALGIN. The function of ALGIN is illustrated by a simple example shown in Figure III.12. The x and y axes are assumed to have linear scales. Point R falls between points 1 and 2, x1 is given and y1 is desired. A calculated amount is added to the y value of point 2 to yield y1. For interpolation on

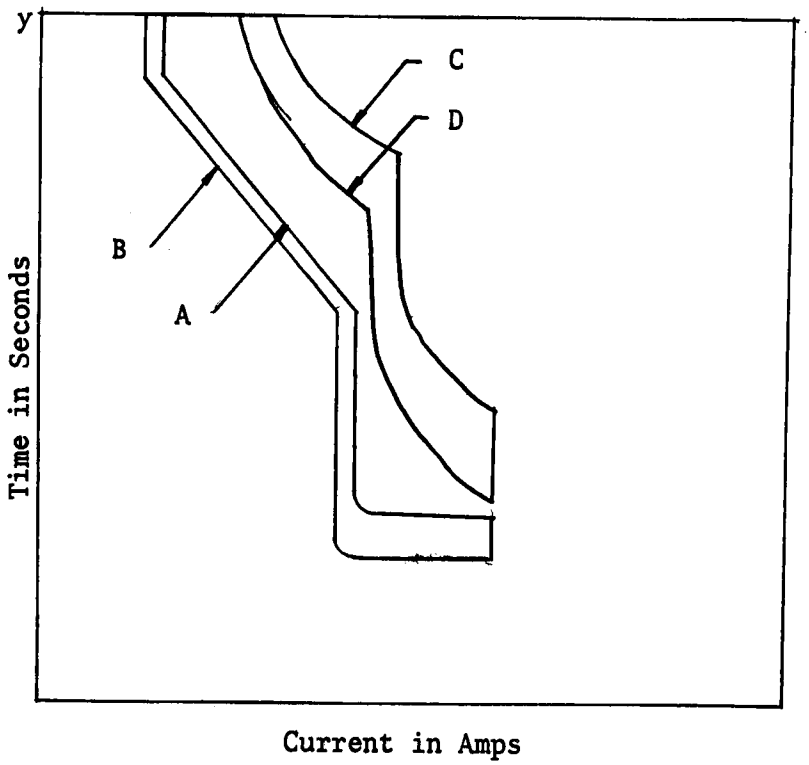


Figure III.10. Illustration of the operation of subroutine EXTRA.

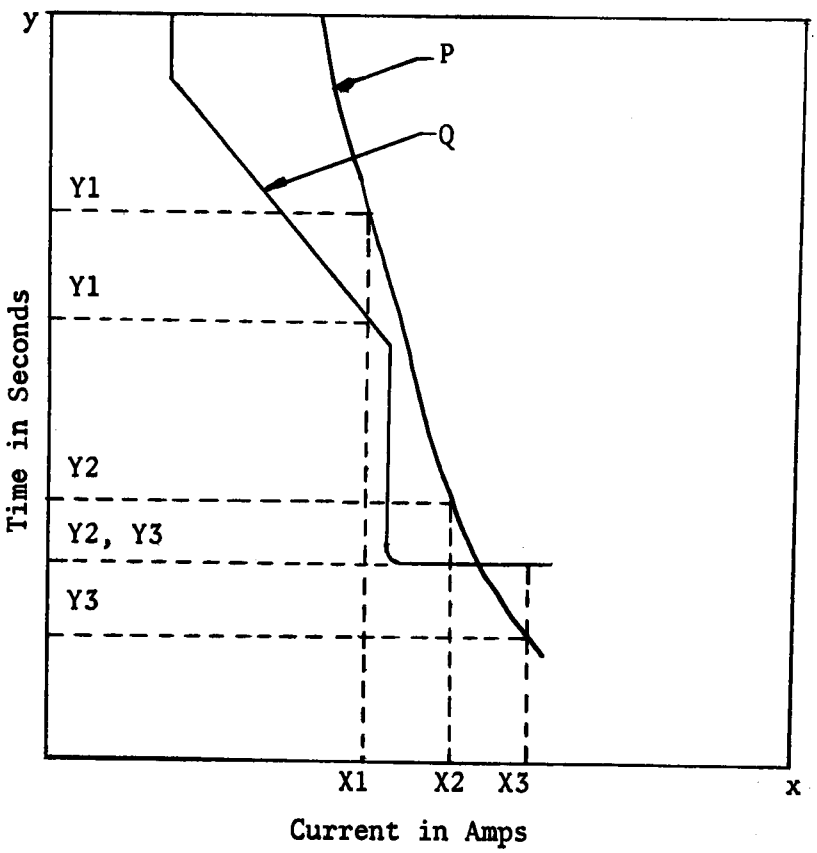


Figure III.11. Illustration of the operation of subroutine TFT.

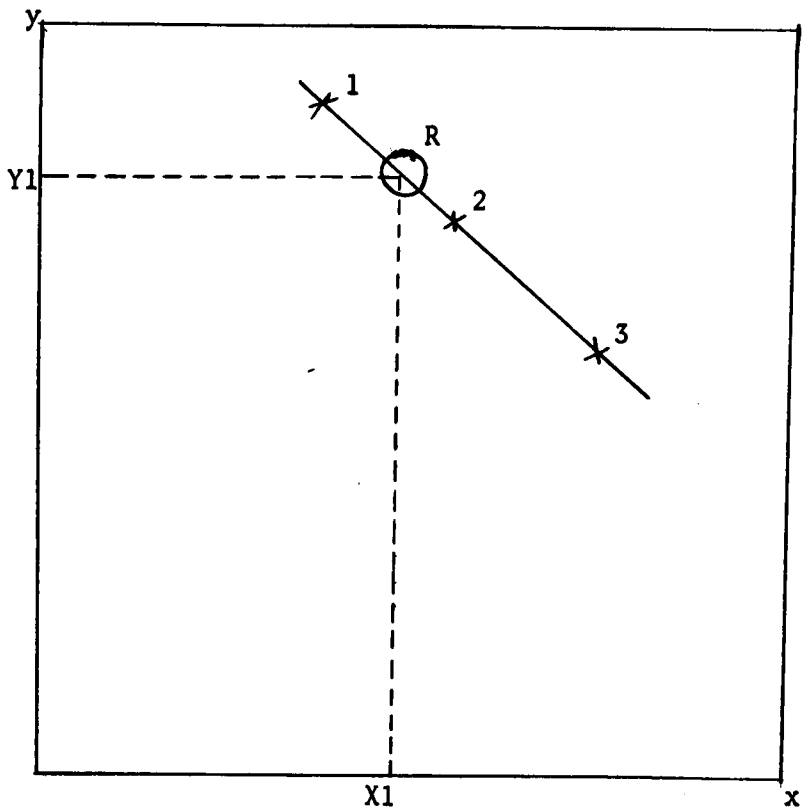


Figure III.12. Illustration of operation of subroutine ALGIN.

logarithmic scales, ALGIN takes logarithms of appropriate data sets before the interpolation is performed.

In concluding this section, the importance of systematically eliminating curve settings in the selection process is illustrated using two examples. The purpose of a proper order in eliminating undesired curves is twofold. The first is to insure that each device setting is tested. The second purpose is to reduce the time required for testing settings that are not applicable.

Example 3. In this example, the settings of a circuit breaker are tested for coordination with a previous device. The breaker is equipped with a long and short delay unit which has three pickup current settings for each unit. The three long delay settings are denoted by J1, J2, J3 and the three short delay settings denoted by K1, K2, K3 as shown in Figure III.13. The flow diagram for the order of curve elimination is presented in Figure III.14.

Example 4. In this example the time-current curves of a relay are tested for coordination with a previous device. The twelve inverse time curves are shown in Figure III.15. If curve 1 is tested and eliminated, curve 12 will be tested next. If curve 12 is also eliminated, none of the others will be applicable. If curve 12 is not eliminated, a desired curve is selected among curves 2 to 11.

Curve plotting. When the devices in a system are coordinated, the selected curves of the devices are stored for plotting. Subroutine

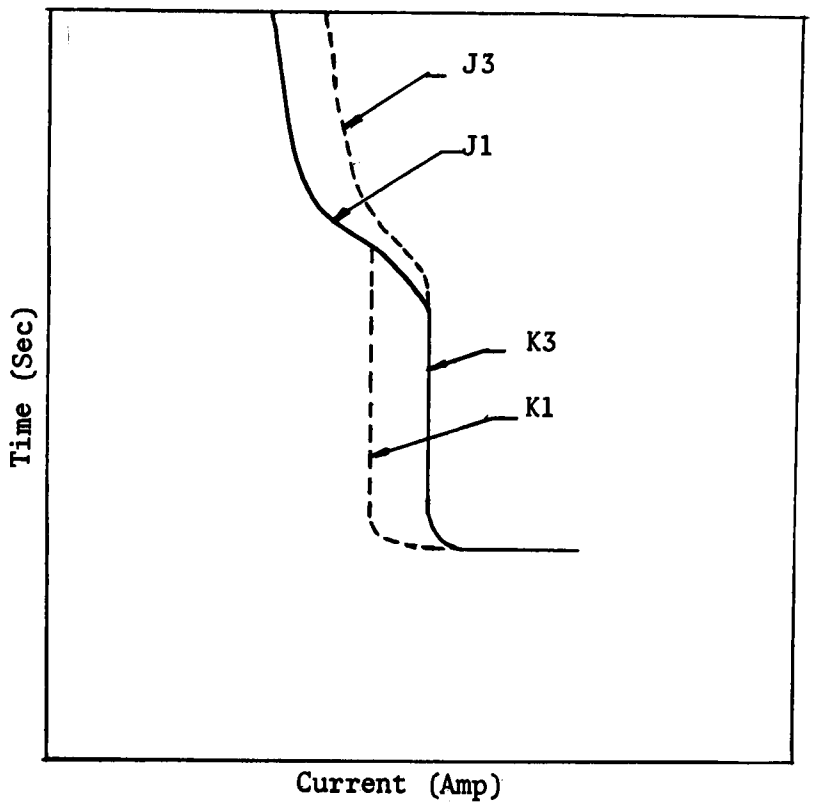


Figure III.13. Illustration of the labels used in Example 3.

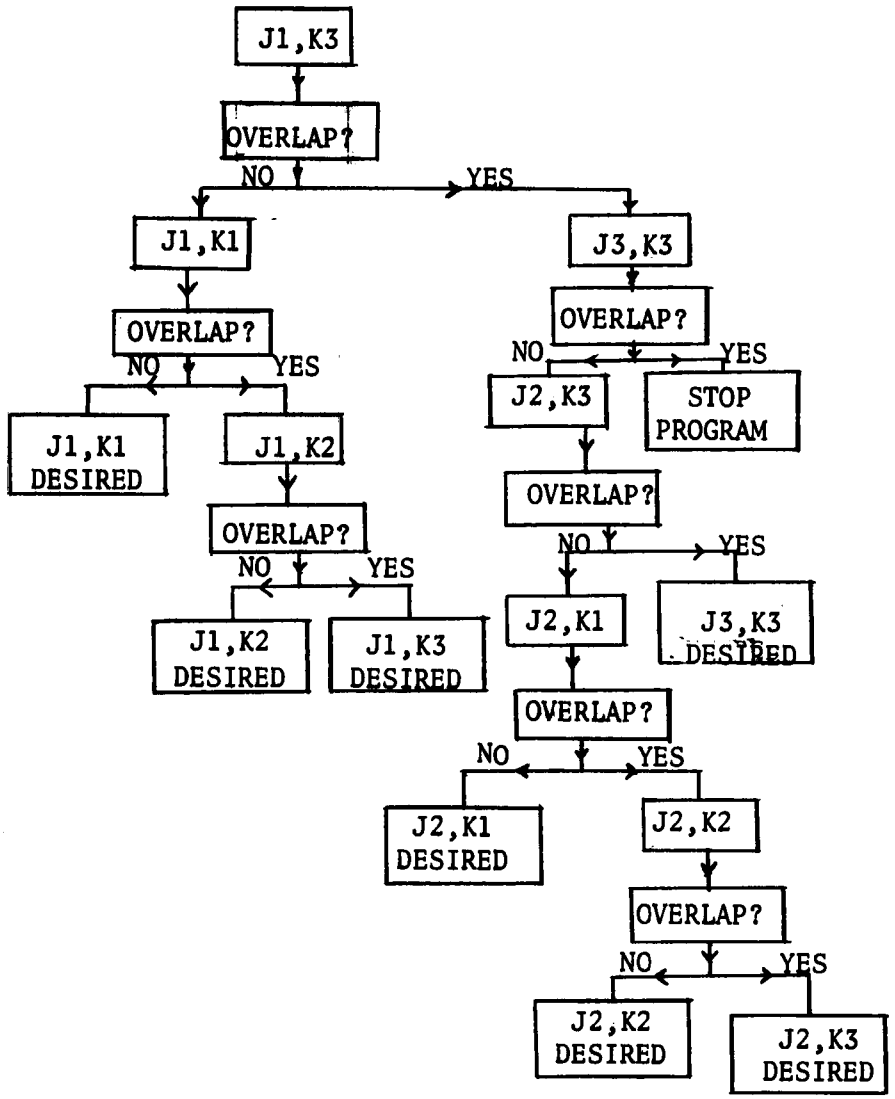


Figure III.14. Flow diagram illustrating the order of curve elimination in Example 3.

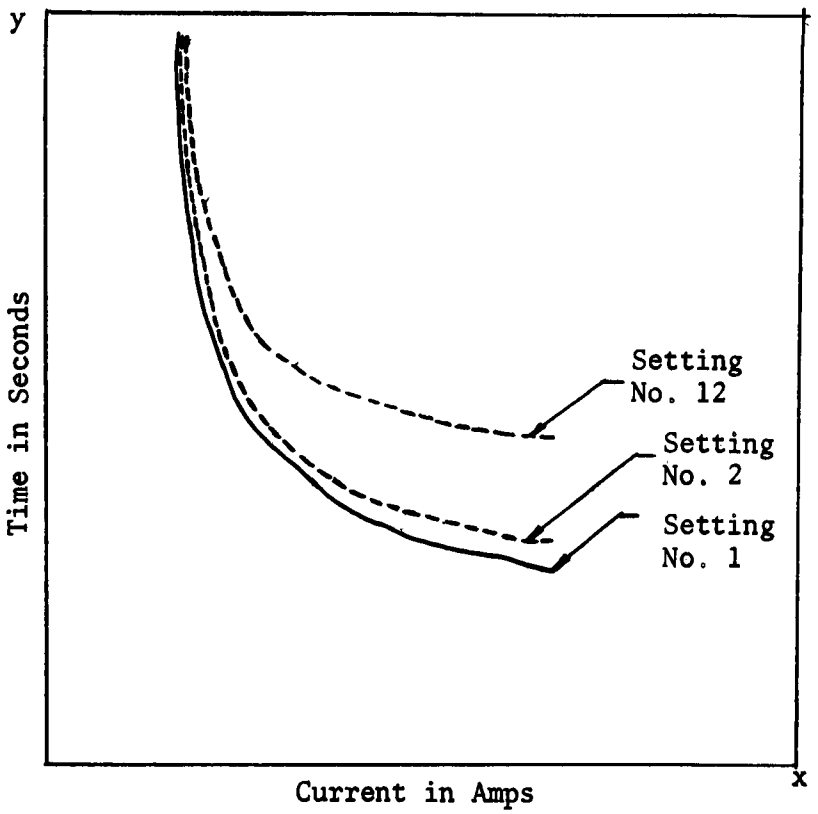


Figure III.15. Illustration of the order of curve elimination for Example 4.

CALCOM is called by the main program to initiate the CALCOMP plotter, to draw and label logarithmic axes and grid lines, and to plot the stored curves.

Summary

This chapter presents the organization and functions of the program. Block diagrams, figures and examples, when applicable, are inserted to clarify the presentation. The program is used in two comprehensive examples described in the next chapter.

CHAPTER IV

EXAMPLES FOR ILLUSTRATING THE USE OF THE DIGITAL COMPUTER PROGRAM

In this chapter two examples are utilized for illustrating the use of the digital computer program. The first example is an illustration of coordinating three protective devices in a system, and the second example is similar to a design problem given in Reference 1. The system setup in both examples is briefly described and the required data for specifying each protective device are introduced.

Computer plots and hand plots of both systems are presented so that comparisons of the two methods of coordination can be made.

Example for Coordinating Three Protective Devices of a System

This example illustrates the coordination of three protective devices in a system. The operation voltage for this system is 480 volts ac, the operation frequency is 60 cycles, and the three devices A, B, C and shown in Figure IV.1. These devices are selected according to their applicability to the specifications obtained by normal and fault system analysis. Device A is a Westinghouse type CO-9 overcurrent relay with a very inverse time-current characteristic and a pickup current setting of 8 amps. Device B is a General Electric type AK-25 low voltage power circuit breaker with solid state overcurrent trip devices. The trip units are long delay and short delay units and the current rating of the breaker

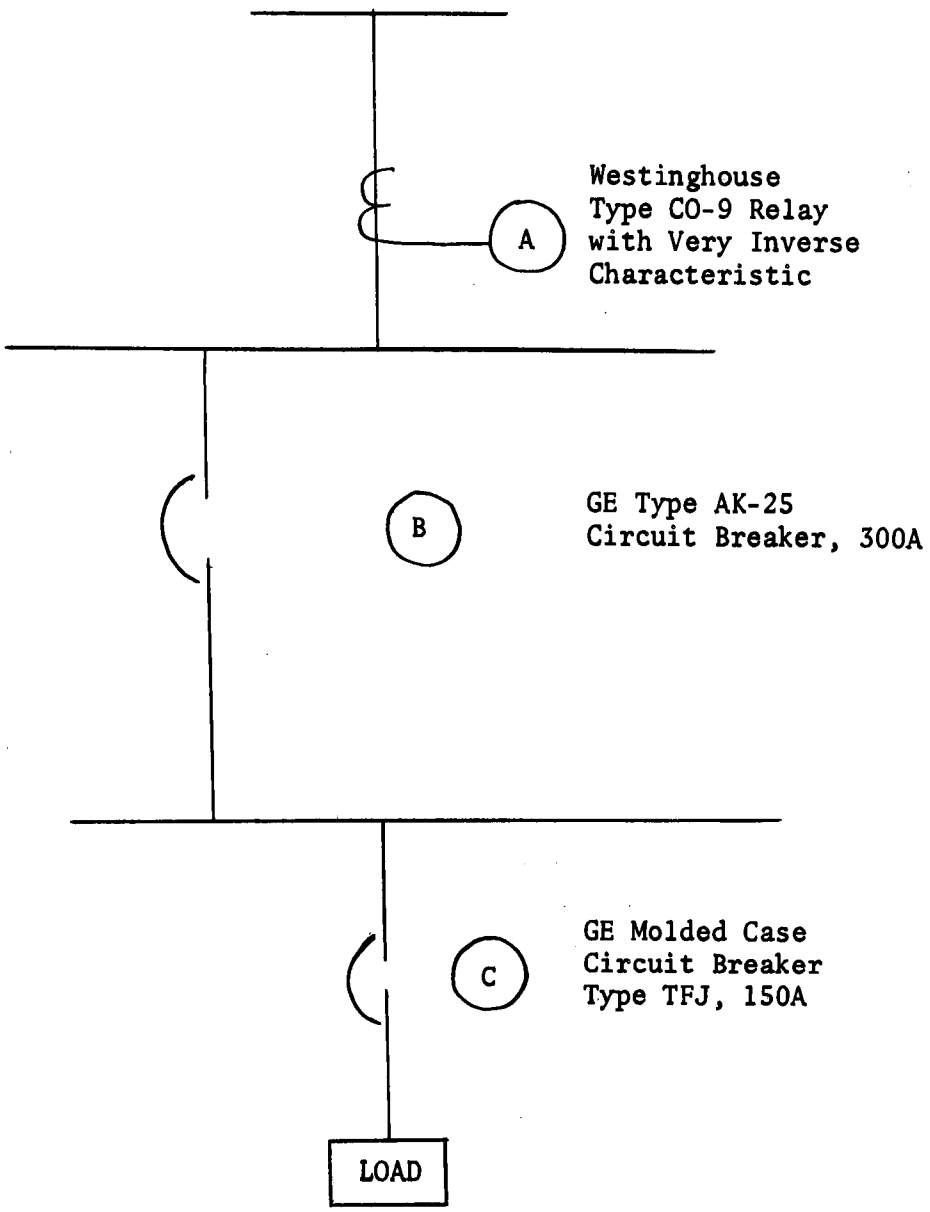


Figure IV.1. One-line diagram for Example 1.

is 300 amps ac. Device C is a General Electric molded case circuit breaker type TFJ with a current rating of 150 amps ac. General information for application of the computer program to this example is described in the following.

The number of devices to be coordinated, the names of the devices, and the order of coordination of the devices are specified in the data set for the main program. The number of instantaneous settings provided by the molded case circuit breaker is five, and the five settings are shown in Figure IV.2. The instantaneous setting is preselected to be setting number four. The current rating of this breaker is specified as 150 amps, the number of data points for defining each breaker curve is eighteen, and the eighteen points for each of curves P and Q are punched on cards.

The minimum bands of both long and short delays are selected to be the reference curves. The number of data points for defining each reference curve is ten, and the two data sets for the two reference curves are punched on cards. The number of both long and short delay current settings is six, and the number of long and short time delay options is three. Multiplying factors for the generation of the current settings and time options are specified.

All twelve curves corresponding to the twelve time-dial settings of the relay are read in, and each curve is approximated by eleven points.

Five curves are plotted on the CALCOMP plotter for this example. For each curve, the value of the starting point and the number of logarithmic cycles per inch are specified for each of the two axes. A

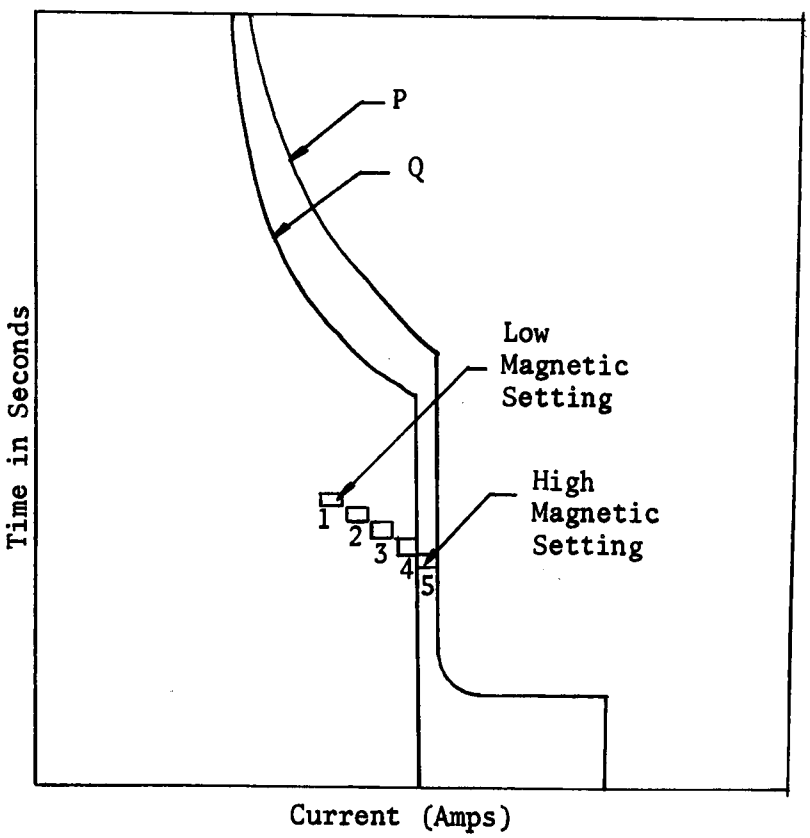


Figure IV.2. Illustration for the settings of the instantaneous trip unit of the molded case circuit breaker.

hand plot for the design is shown in Figure IV.3 while a computer plot for the same design is shown in Figure IV.4. The long and short delay settings of device B, and the time dial setting of device C obtained from both plots are compared and found to be identical.

Example for Coordinating Four Protective Devices of a System

This example illustrates the coordination of four protective devices in a system. The four devices A, B, C, D are shown in Figure IV.5. These devices are selected according to their applicability to the specifications obtained by normal and fault system analysis. The normal current flowing in the primary of the transformer is 104 amps, and the normal current in the secondary is 900 amps. The maximum fault current existing in the main bus is 18,000 amps and that existing in the control center bus is 14,000 amps. Both fault currents are expressed in symmetrical rms values.

The primary side of the transformer is protected by device D, a type 200-E fuse. Device C is a secondary circuit breaker of Westinghouse type DB-50 with a current rating of 1200 amps. Device B is a feeder circuit breaker of Westinghouse type DB-25 with a current rating of 600 amps. Both devices B and C are equipped with long and short delay units. Protecting the load is device A, a molded case circuit breaker of General Electric type TFJ with a current rating of 150 amps.

General information for application of the computer program to this example is described in the following.

As in the previous example, the number of devices to be coordinated, the names of the devices, and the order of coordination of the devices

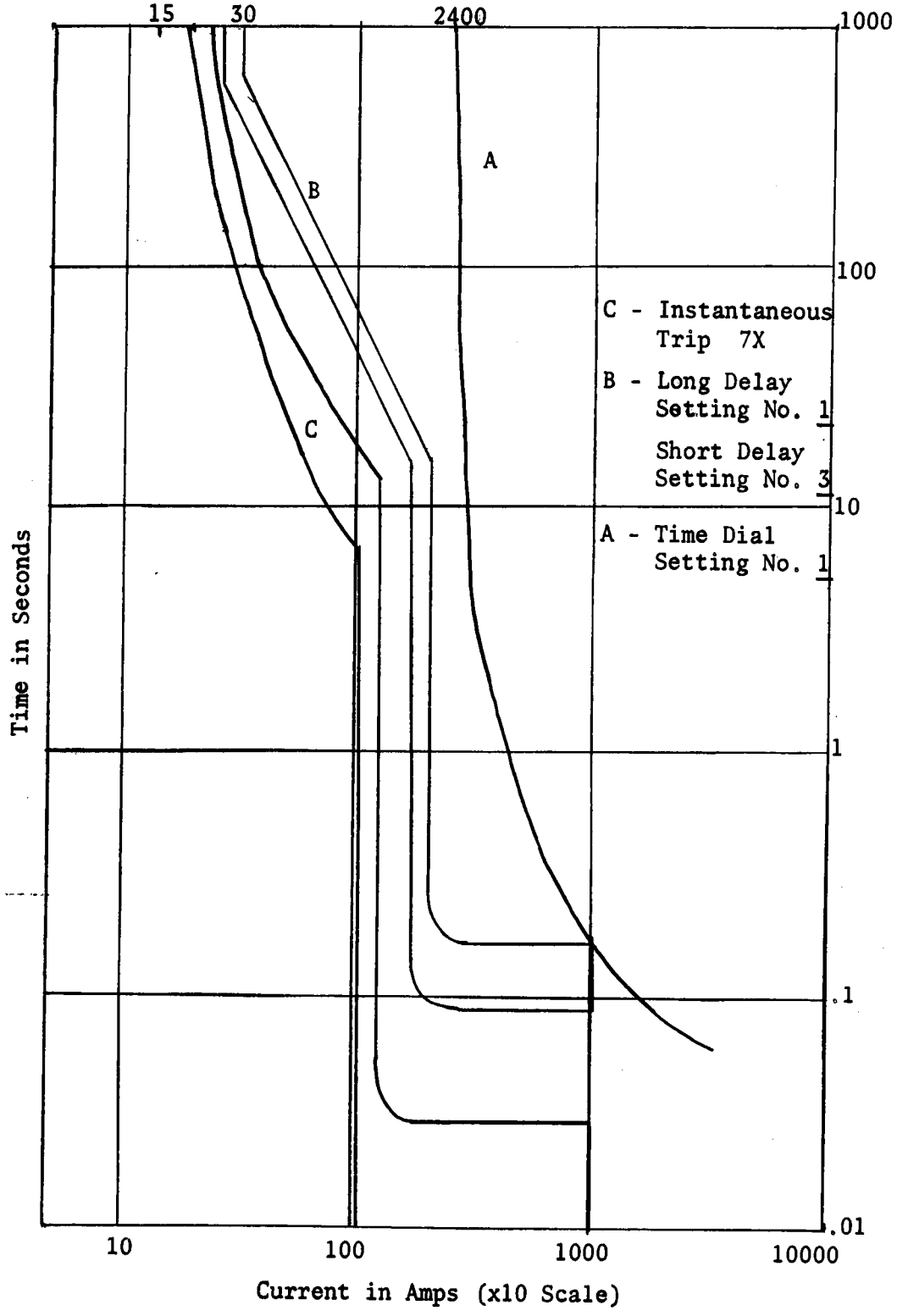


Figure IV.3. Hand plot of Example 1.

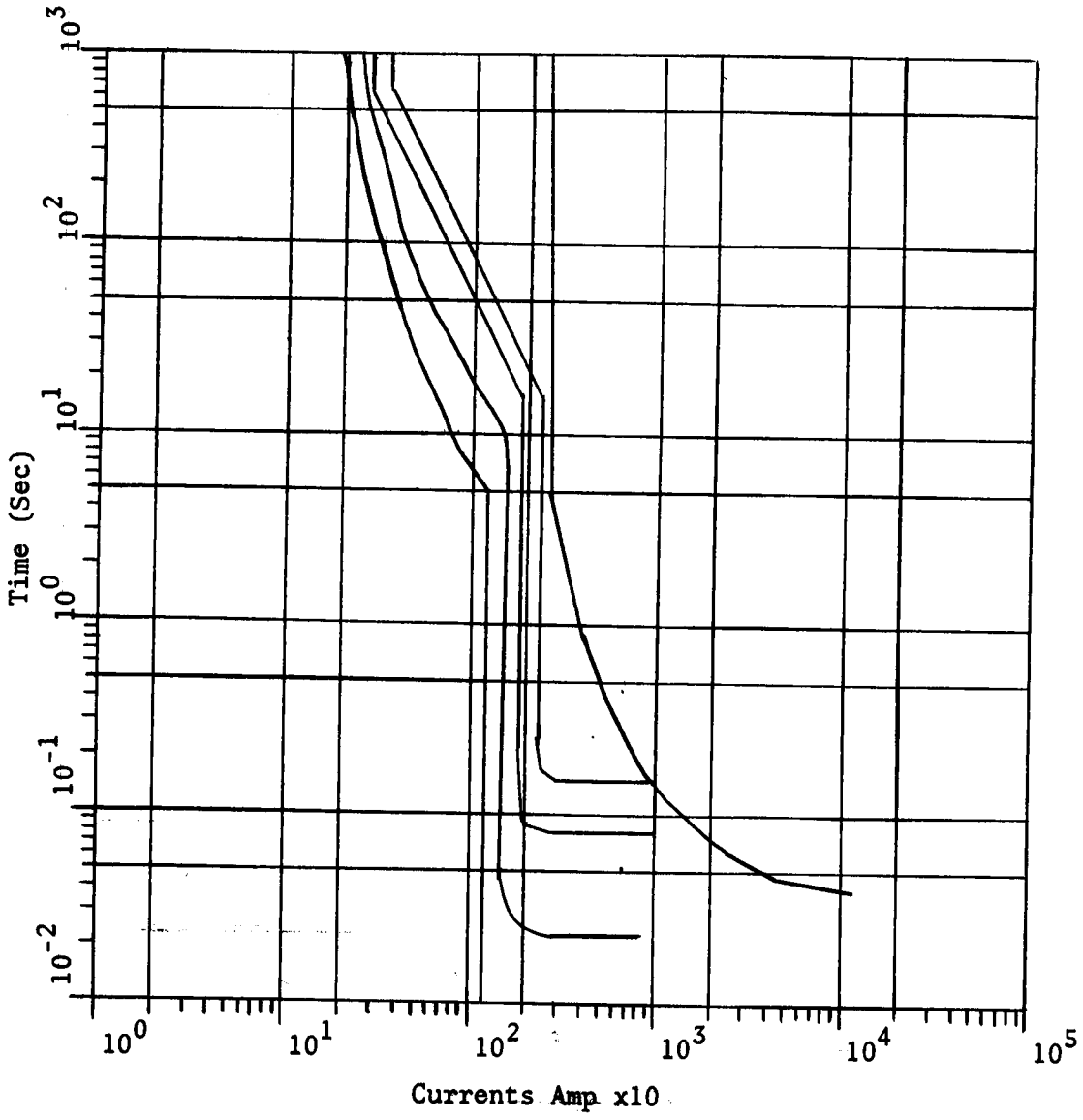


Figure IV.4. Computer plot for Example 1.

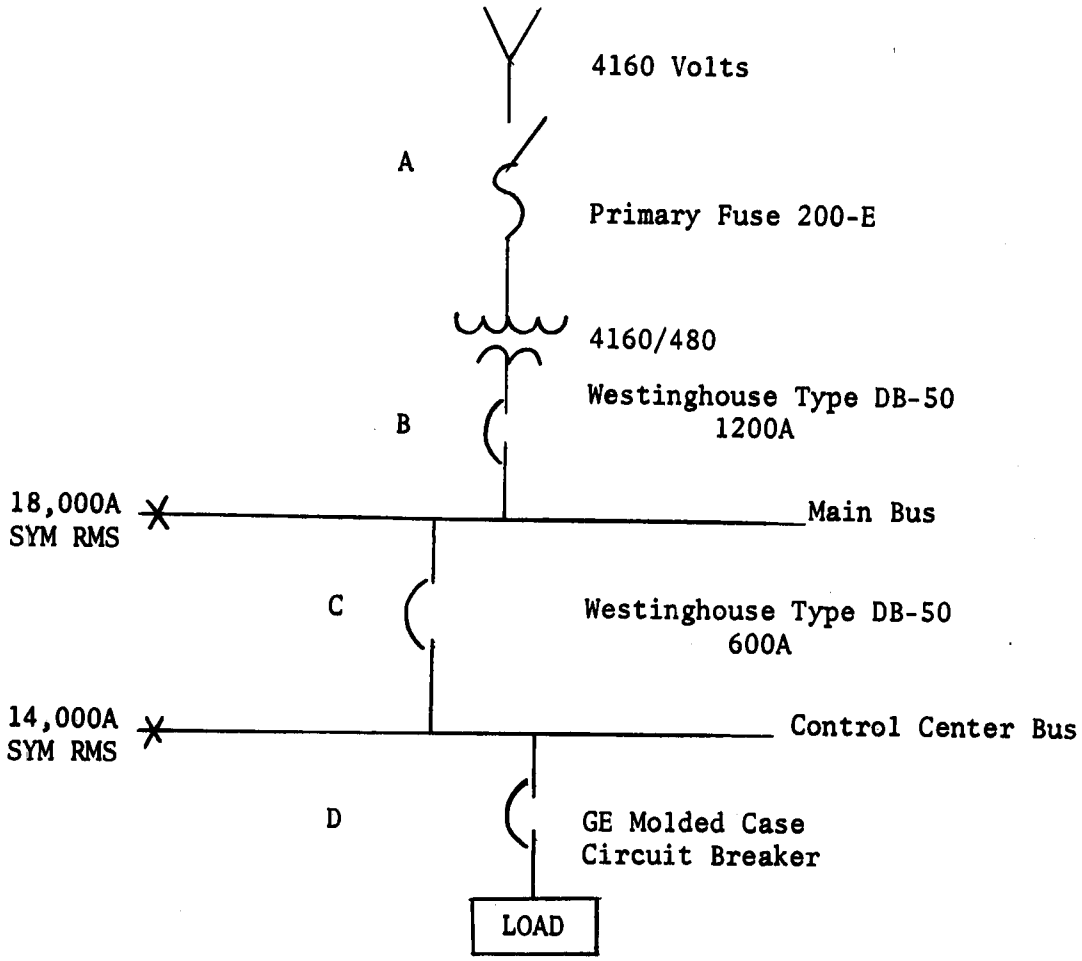


Figure IV.5. One-line power distribution system.

are specified for the main program. Items required to be specified for the molded case circuit breaker A and breakers B and C are the same as those specified in the previous example. The differences between the specifications of the two examples are the number of points used to define each reference curve, the number of long and short delay current settings, the number of time band options, the current ratings, the multiplying factors, and the data sets for the reference curves.

It is assumed that a choice among the three fuses, 150-E, 200-E, 250-E, is desired. The melting time, short time and total clearing time curves for these fuses are read in.

The hand plot and computer plot of this example are shown in Figure II.10, page 20, and Figure IV.6, respectively. The instantaneous trip of device D is preset at 700 percent of the trip coil rating, and the long delay and short delay settings for devices B and C are found to be identical in both plots.

Summary

The above two examples specify in general the kind of data sets required for the operation of the computer program. The next chapter points out the shortcomings of the program and improvements that can be made for the feasibility of the program.

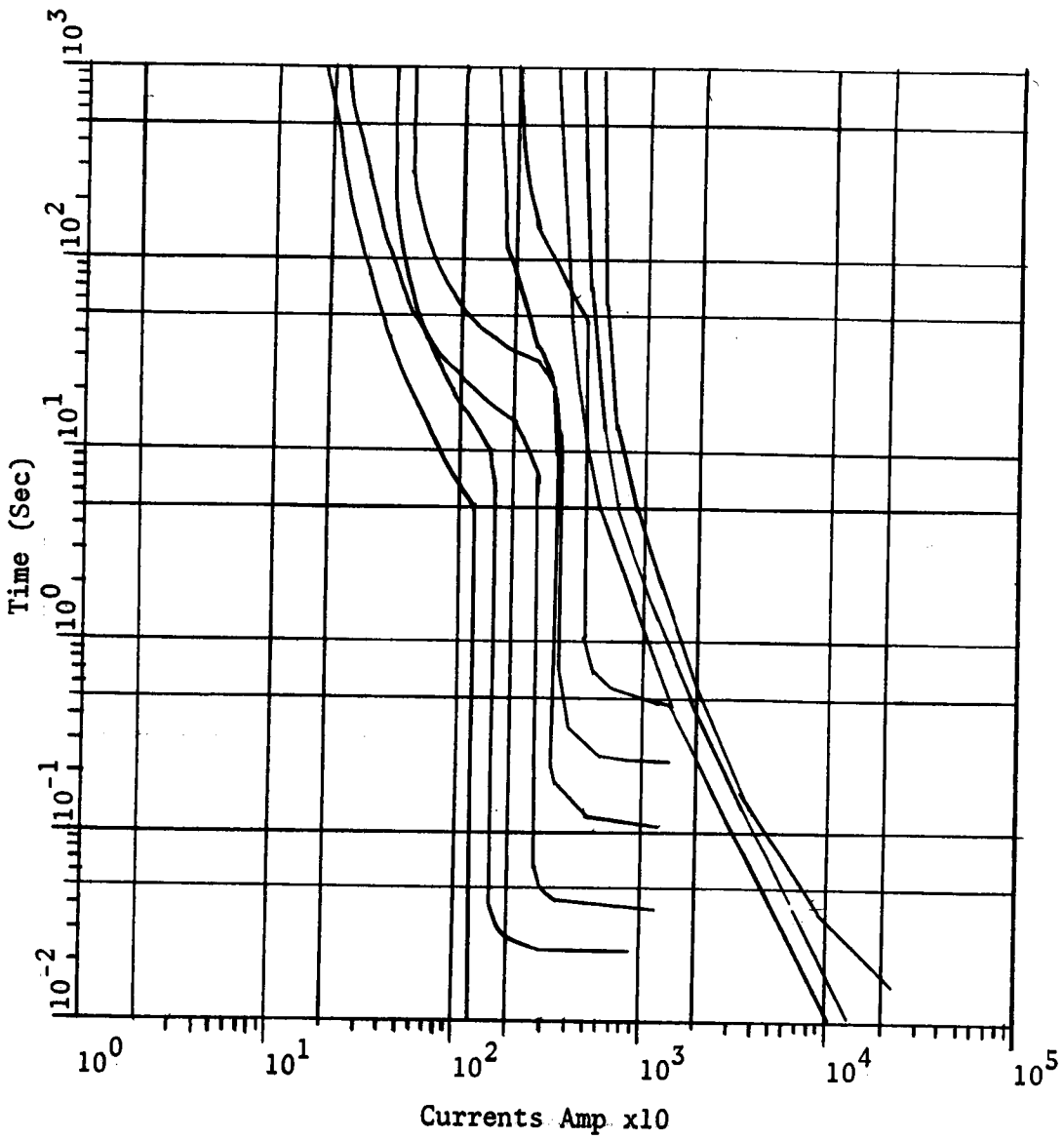


Figure IV.6. CALCOMP output plot.

CHAPTER V

CONCLUSION

A digital computer program for curve selection to achieve device coordination is presented in this thesis. Reading in data points for approximating characteristic curves of circuit breakers, relays and fuses is the first of four main functions of the program. The second function is to generate, by data transfer, curves corresponding to various time and current settings of circuit breakers and relays. Curve selection using appropriate algorithms is the third function, and plotting selected curves on a CALCOMP plotter being the last function.

The use of the program is illustrated by two examples in which the results of computer plots and hand plots of coordinated device curves are compared. Although the program can coordinate more than four protective devices, such coordination is usually not required.

This program is most effective in dealing with curves of circuit breakers with solid state series overcurrent trip devices and curves of molded case circuit breakers because these curves are readily represented by linear approximation. The most difficult curves to handle are those which cannot be effectively represented by straight line segments. In such cases, a large number of data points is consumed before good approximation of the curves can be achieved.

Data acquisition is the most time-consuming aspect of the computer solution to coordinated design. Data sets, when prepared, should be stored on magnetic tapes. The utilization of a magnetic pen will

facilitate this data acquisiton process. The x and y coordinates of data points selected to represent a curve are sensed by the magnetic pen and recorded automatically on magnetic tapes. Consequently, if this technique is followed, the time required for taking data points would be greatly decreased. In addition, this process would provide superior accuracy of data points and thus yield better computer output plots.

Memory storage employed by the program should be reduced so that the program can be extended to coordinate devices with curves other than those considered in this paper.

Finally, the work in this thesis demonstrates that the digital computer can be effectively employed in coordinated protective design of power systems, and the program relieves the engineer of the time-consuming task of preparing hand plots for the trial and error design steps.

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REFERENCES

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APPENDIX

APPENDIX

The purpose of this appendix is to give detailed instructions for users of the digital computer program for achieving coordination of protective devices in power distribution systems. The appendix is divided into three parts. The capabilities and limitations of the subprograms and the interpretations of the computer printouts are presented in Part I. Individual instructions for supplying input data to the main program and each of the subprograms are provided in Part II. Listed in Part III are the input and output data for the two coordination problems in Chapter IV.

Part I. General Guideline to the Use of the Digital Computer Program

Capabilities and Limitations of the Subprograms

The computer program is divided into a main program and seven subprograms, D1 to D7. Each of these subprograms is used to handle one type of characteristic curves. The general type of curves handled by the subprograms and typical samples of the curves are given in the following:

Subprogram	General Type of Characteristic Curves	Typical Samples
D1	Curves of circuit breakers with solid state overcurrent trip devices	General Electric Curve No. GES-6020
D2	Curves of circuit breakers with overcurrent trip devices	General Electric Curve No. GES-6000
D3	Curves of molded case circuit breakers	General Electric Curve No. GES-6013
D4	Curves of overcurrent relays	Westinghouse Curve No. 418266
D5	Curves of circuit breakers with overcurrent trip devices	General Electric Curve No. GES-6012
D6	Curves of circuit breakers with overcurrent trip devices	Westinghouse Curve No. 388630
D7	Curves of fuses	E type curves

Each subprogram may be viewed as an algorithm, so that other types of curves other than those listed may also be handled successfully if the application of this algorithm is appropriate.

The calling of the subprograms are subjected to the following limitations. The program will handle a maximum of four devices in one coordination problem so that the subprograms will only be called four times. Some of the subprograms can be called three times consecutively, but some can only be called once. Specifically, D1, D6 and D7 can be called once, twice or three consecutive times within the first three calls, but D3 and D5 are limited to the first call, and D2 is limited to the second or third call. There is no limit imposed on the calling of D4.

Computer Output

The computer output of each coordination problem consists of a CALCOMP plot and a printout of output data. Examples of computer plots are given in Chapter IV, but interpretations of the printout are given below. Data of the selected curves of each device are printed out, and the identification of this selected curve is given above the set of output data. Usually, the output specification of one device is followed by that of the next device. However, if no curve is selected from the next device, the reject signal "I AM IN FRONT OF STOP" will be printed out. Sometimes, although a curve is found by a last effort, the reject signal is still printed out and should be ignored.

The printout of a sample of the identifications given above the set of output data looks like the following:

D6, K6, J6, KC, JC 4 5 1 1.

This sample shows that the selected curves are from D6 and that

K6=4
J6=5
KC=1
JC=1.

K6 and J6 indicate the settings for this device, and KC and JC indicate the settings of the previous device. The numeral 4 indicates that the selected instantaneous or short time setting is setting No. 2. If this numeral is 8, for example, the selected instantaneous or short time setting will be setting No. 4. If there are four settings 4X, 6X, 9X and 12X, setting No. 2 refers to 6X and setting No. 4 refers to 12X. The numeral 5 for J6 means that the selected long delay setting is setting No. 5. The identification statement of the selected curves from D4 is different from the rest and a sample is shown below:

D4, AFTER ALGORR, J4 = 3.

The numeral 3 indicates that the time dial is set at the second setting.

Part II. Instructions for Using the Main Program and Subprograms

Input data are supplied to the main program and all the subprograms. One set of input data is provided for each device. If a subprogram is called three consecutive times, one set of data is supplied each time the subprogram is called by the main program.

In preparing the following instructions, the number of long delay, short delay, and instantaneous settings, and the number of data points per reference curve are fixed for the sake of convenience. Changes in these items can be accomplished with minor changes in the reading formats.

1. Instructions for Using the Main Program

Description. Three data cards are specified for initiating the main program. The first card specifies the number of devices used in the coordination problem and the settings preselected for the first device being called. The instantaneous or short delay setting is denoted by Kn and the long delay setting is denoted by Jn. n specifies the type of device. For example, the settings of the device in D1 are denoted by K1 and J1. Figure A.1 illustrates the number system used to specify K1 and J1. This number system applies to Kn and Jn in general. Curve P is always specified by odd values of K1, and curve Q is always specified by even values. If the number of short delay settings is 5, the values of K1 range from 1 to 10. If the fourth setting is selected, curves P and Q will be denoted by 7 and 8, respectively. Only the

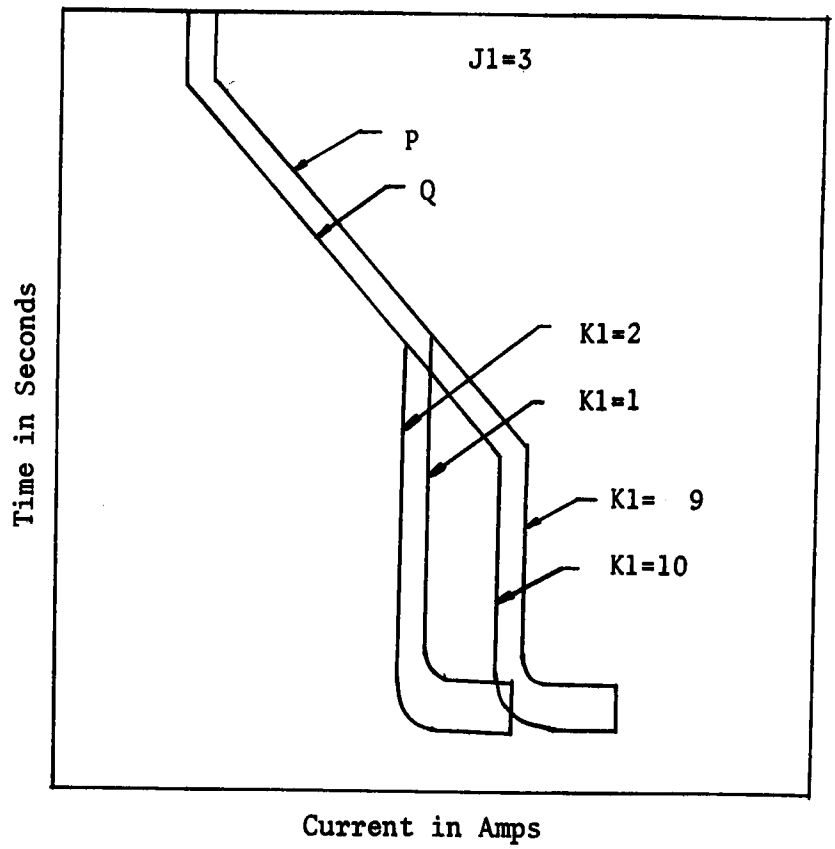


Figure A.1. Diagram illustrating the specifications of J1 and K1.

number 7 will be punched in card No. 1. The specification of J1 is simple. If the number of long delay setting is 6, the values of J1 range from the lowest setting value, 1, to the highest setting value, 6. If the third setting is selected, J1 will be 3.

The second card specifies the type of device and the order of the devices being called. Although all five devices should be specified, the number of devices in the coordination problem is fixed by card No. 1. The fourth card specifies the number of data points per reference curve for each of devices No. 1 to No. 7.

User Supplied Input Format.

Card Number	Program Variable Name	Description	Data Card Columns	Format
1	NM5	Number of devices used	1-5	I
	Kn	Instantaneous or short delay setting preselected	5-10	
	Jn	Long delay setting preselected	11-15	
2	I(1)	First device being called (1 for D1, 2 for D2, 3 for D3, 4 for D4, 5 for D5, 6 for D6, 7 for D7)	1-5	I
	I(2)	Second device being called	6-10	
	I(3)	Third device being called	11-15	
	I(4)	Fourth device being called	16-20	
	I(5)	Fifth device being called	21-25	
3	DOT	.	1	A

Card Number	Program Variable Name	Description	Data Card Columns	Format
4*	ME1	Number of data points per reference curve for device number 1	1-5	I
	ME2	Number of data points per reference curve for device number 2	6-10	
	ME3	Number of data points per reference curve for device number 3	11-15	
	ME4	Number of data points per reference curve for device number 4	16-20	
	ME5	Number of data points per reference curve for device number 5	21-25	
	ME6	Number of data points per reference curve for device number 6	26-30	
	ME7	Number of data points per reference curve for device number 7	31-35	

2. Instructions for Using Subprogram D1

Description. Fifteen data cards are supplied to this subprogram. Data card No. 1 is used to trigger long delay and short delay options. Multiplying factors for generating the short delay and long delay options are specified on card No. 2. These multiplying factors are labeled and shown in Figure A.2. The number of long delay settings (6),

*This card is placed at the beginning of the input data deck for the subprogram CALCOM.

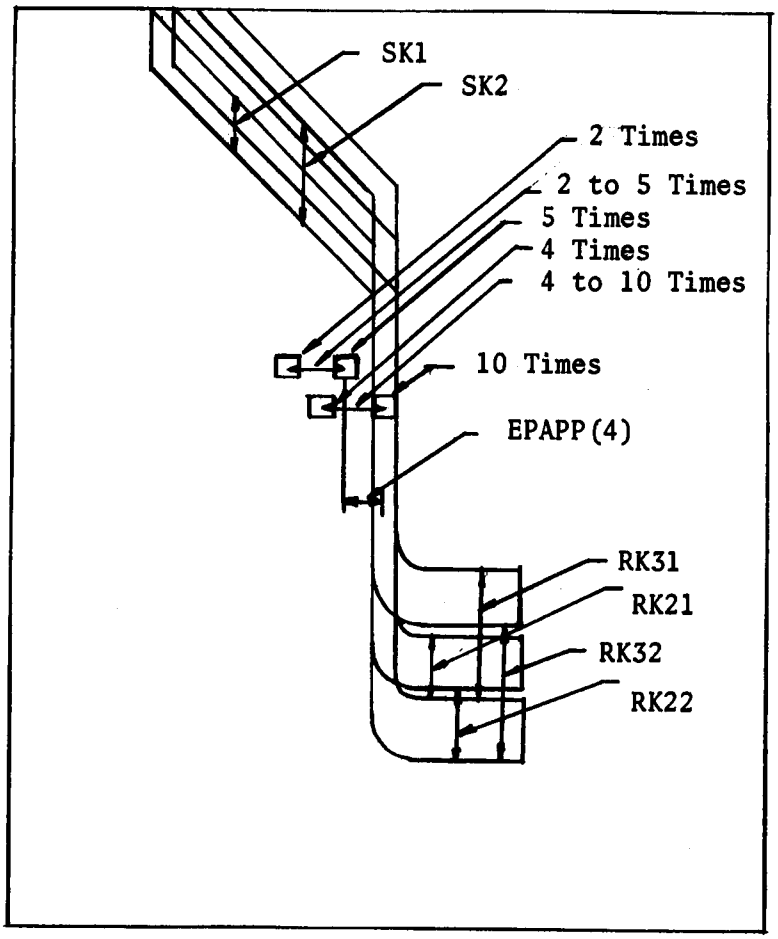


Figure A.2. Diagram illustrating the positions of RK21, RK22, RK31, RK32, SK1, SK2, and EPAPP(4).

the number of short delay or instantaneous settings (6), and the number of data points used to represent each characteristic curve (10) are specified on card No. 3.

Different ranges of instantaneous or short delay settings occur in different devices, and these differences in the ranges of settings are accounted for by specifying, on data card No. 4, the distances shifted by the reference curves. One of the shifted distances, EPAPP(4), is labeled and shown in Figure A.2.

The current ratings of three devices are specified on card No. 5 for the case when D1 is called consecutively to coordinate the three devices. In other cases, arbitrary numbers may be assigned to needless specifications. The distance shifted from the reference curves for generating a new short delay or long delay setting is specified on card No. 6 and 7, respectively. Typical distances shifted are labeled and shown in Figure A.3.

The input data for the reference curves are specified on cards No. 8 to 15. The reference curves are the curves for the 80 percent long delay setting of the minimum long delay band, and maximum short delay setting of the minimum short delay band or maximum setting of the instantaneous trip.

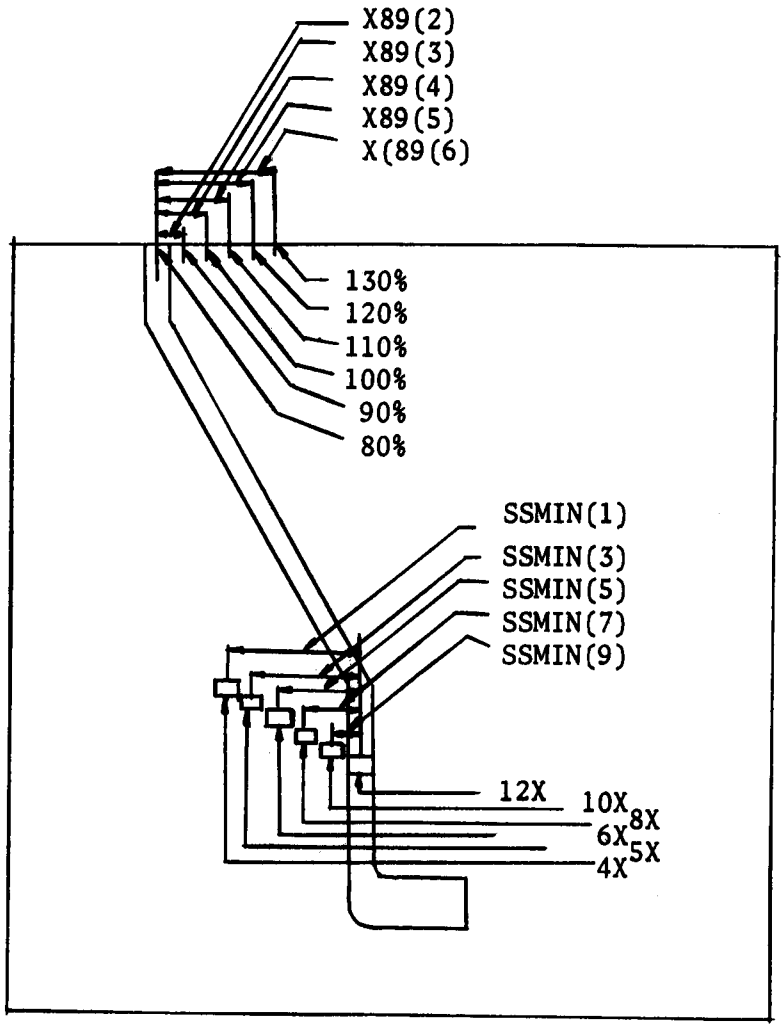


Figure A.3. Diagram illustrating the positions of X89(2) to X89(6) and SSMIN(1) to SSMIN(9).

User Supplied Input Format.

Card Number	Program Variable Name	Description	Data Card Columns	Format
1	NBA	Short delay options (1 for instantaneous settings and minimum short delay, 2 for intermediate short delay, 3 for maximum short delay)	1-5	I
	MBA	Long delay options 1-minimum 2-intermediate 3-maximum	6-10	
2	RK21 RK22 RK31 RK32	Multiplying factors for generating the short delay options (see Figure A.2, page 70)	1-10 11-20 21-30 31-40	F
	SK1 SK2	Multiplying factors for generating the long delay options (see Figure A.1)	41-50 51-60	
3	MJ1	Number of long delay settings	1-5	I
	N1	Number of short delay or instantaneous settings	6-10	
	M1	Number of data points for each reference curve	11-15	
4	EPAPP(4)	Distance shifted by the reference curves for generating curves taken from a device with a range of four instantaneous settings	1-10	F
	EPAPP(5)	Distance shifted by the reference curves for generating curves taken from a device with a range of four instantaneous settings	11-20	

Card Number	Program Variable Name	Description	Data Card Columns	Format
	EPAPP(6)	Distance shifted by the reference curves for generating curves taken from a device with a range of six instantaneous settings	21-30	
	EPAPP(7)	Has the value 1.0 (reference curves are taken from a device with a range of seven instantaneous settings)	31-40	
5	RV11	Current rating of the first device being called	1-10	F
	RV12	Current rating of the second device being called	11-20	
	RV13	Current rating of the third device being called	21-30	
6	SSMIN(J) J=1,12,2	Distances shifted for generating new instantaneous or short delay settings	1-10 11-20 . .	F (Six data per card)
7	X89(J) J=2,6	Distances shifted for generating new long delay settings	1-10 11-20 . . . 41-50	F
8-9	X(11,1,I1) I1=1,10	Input data for curve A (see Figure III.3, page 28)	1-10 11-20 . . .	F (Six data per card)
10-11	Y(11,1,I1) I1=1,10			
12-13	X(12,1,I1) I1=1,10	Input data for curve B (see Figure III.3)	1-10 11-20 . . .	F (Six data per card)
14-15	Y(12,1,I1) I1=1,10			

3. Instructions for Using Subprogram D2

Description. Twenty-five cards are supplied to this subprogram. The current rating of the device is specified on card No. 1. The number of long delay settings (6), the number of short delay settings (7), and the number of data points for representing each reference curve (18) are specified on card No. 2.

The distances shifted by the reference curves for generating the short delay settings are specified on cards No. 3 and 4, and those shifted distances are labeled and shown in Figure A.4. The distances shifted by the reference curves for generating curves taken from a device with a different number of short delay settings are specified on card No. 5.

The reference curves A and B are the curves of the 100 percent long delay setting and maximum short delay setting. The input data for curve A of Figure A.4 are specified on cards No. 6 through 11. The distances shifted by reference curve A for generating long delay settings are specified on cards No. 12 through 15. These shifted distances are labeled and shown in Figure A.5. The input data for curve B of Figure A.6 are specified on cards No. 16 through 21, and the distances shifted by reference curve B for generating the short delay settings are specified on cards No. 22 through 25.

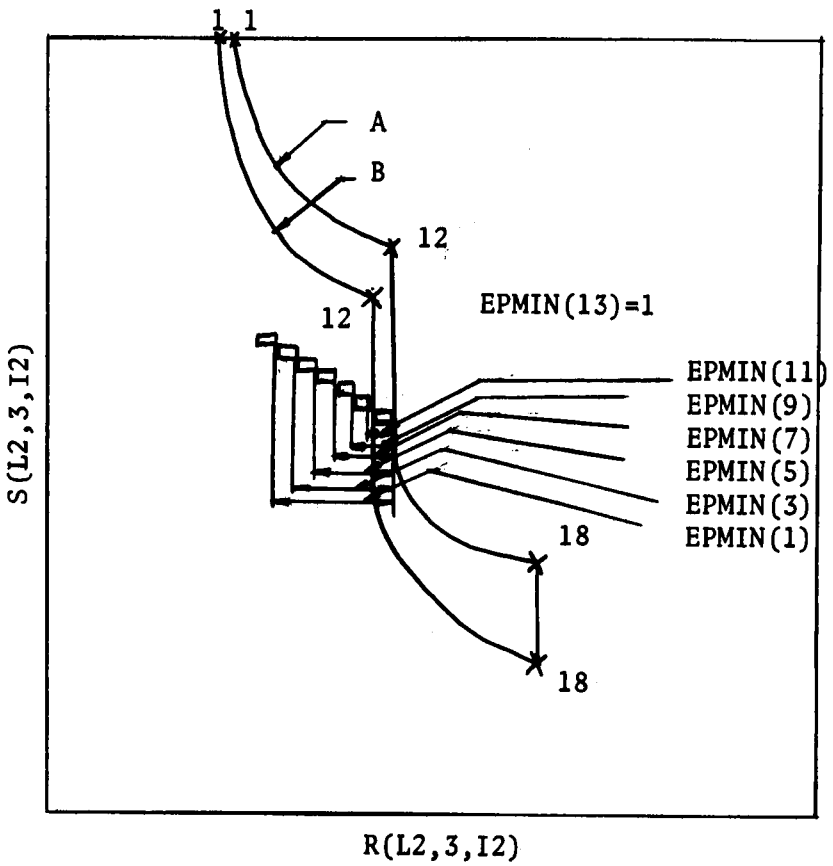


Figure A.4. Diagram illustrating the input data of the reference curves and EPMIN(1) to EPMIN(13).

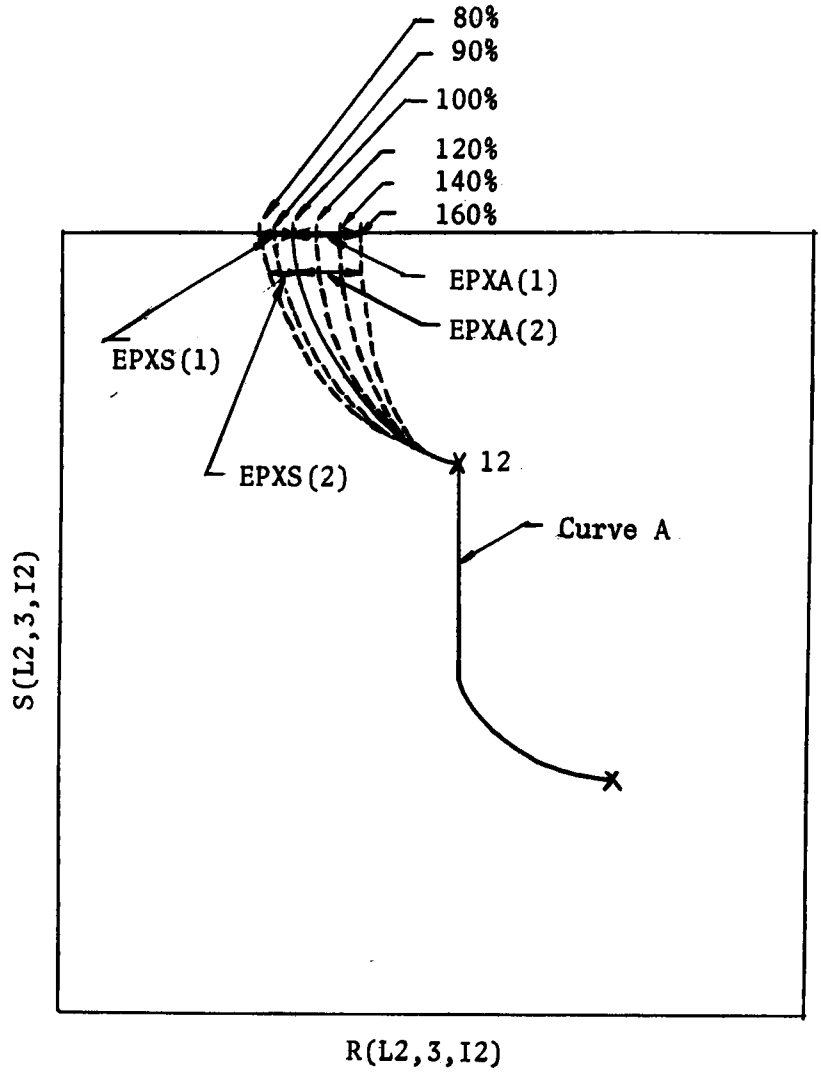


Figure A.5. Diagram illustrating EPXS(1), EPXS(2), EPXA(1) and EPXA(2) of curve A.

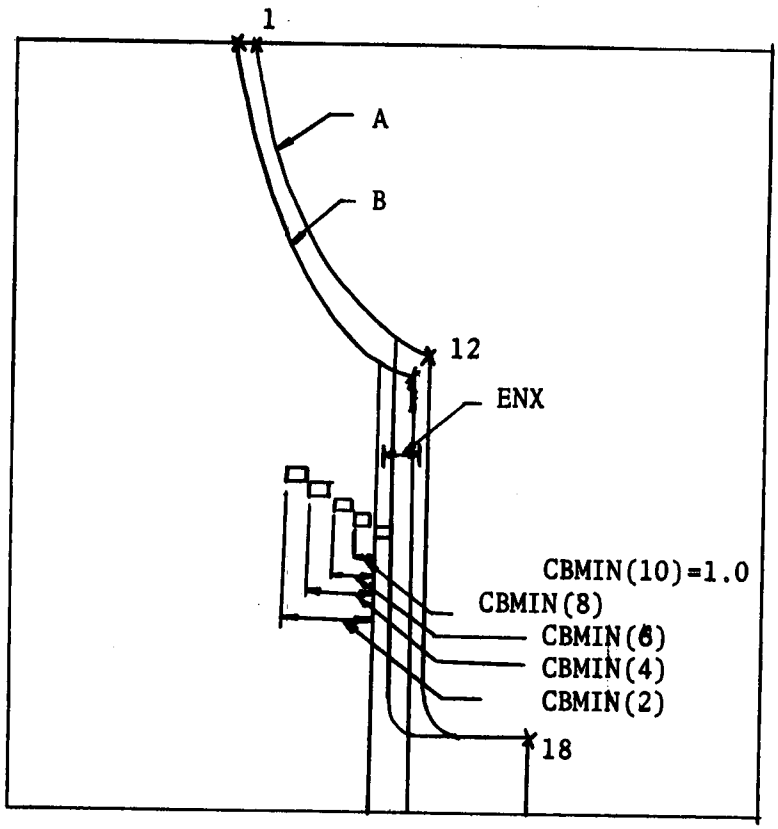


Figure A.6. Diagram illustrating the input data of curves A and B, and positions of CBMIN(K3) and ENX.

Card Number	Program Variable Name	Description	Data Card Columns	Format
1	RV2	Current Rating of the device	1-10	F
2	MJ2	Number of long delay settings	1-5	I
	N2	Number of short delay settings	6-10	
	M2	Number of data points for representing each reference curve	11-15	
3-4	EPMIN(I) I=1,14,2	Distances shifted by the reference curves for generating short delay settings (see Figure A.4)	1-10 11-20 . . .	F (Six data per card)
5	EPAP(4)	Distance shifted by the reference curves for generating curves taken from a device with four short delay settings	1-10	F
	EPAP(5)	Distance shifted by the reference curves for generating curves taken from a device with five short delay settings	11-20	
	EPAP(6)	Distance shifted by the reference curves for generating curves taken from a device with six short delay settings	21-30	
6-8	R(13,3,I2) I2=1,18	Input data for Curve A (see Figure A.4)	1-10 11-20 . . .	F (Six data per card)
9-11	S(13,3,I2) I2=1,18			

Card Number	Program Variable Name	Description	Data Card Columns	Format
12-13 14-15	EPXS(I2) I2=1,12 EPXA(I2) I2=1,12	Distances shifted by reference curve A for generating long delay settings (see Figure A.5)	1-10 11-20 . . .	F (Six data per card)
16-18 19-21	R(14,3,I2) I2=1,18 S(14,3,I2) I2=1,18	Input data for curve B (see Figure A.4)	1-10 11-20 . . .	F (Six data per card)
22-23	EPXS(I2) I2=1,12 EPXA(I2) I2=1,12	Distance shifted by reference curve B for generating long delay settings (see Figure A.5)	1-10 11-20 . . .	F (Six data per card)

4. Instructions for Using Subprogram D3

Description. Sixteen data cards are supplied to this subprogram. Distances shifted for generating the instantaneous settings are specified on data cards No. 1 and 2. Figure A.6 shows these shifted distances with appropriate labels. The number of instantaneous settings (5), the number of data points for representing each reference curve (18) and the variable MM3 are specified on data card No. 3. Variable MM3 is set equal to ten for the sake of convenience. The current rating of the device and the variable ENX are specified on card No. 4. ENX is labeled in Figure A.6. The input data for the reference curves are specified on data cards No. 5 through 16. The reference curves are the curves with the maximum instantaneous setting.

User Supplied Input Format.

Card Number	Program Variable Name	Description	Data Card Columns	Format
1-2	CBMIN(K3) K3=1,10	Distances shifted for generating the instantaneous settings	1-10 11-20 . . .	F (Six data per card)
3	NCR	Number of instantaneous settings	1-5	I
	M3	Number of data points for representing each reference curve	6-10	
	MM3	MM3=10	11-15	
4	RV3	Current rating of device	1-10	F
	ENX	Distance shifted by the reference curves for generating curves taken from a device with a different current rating	11-20	
5-7 8-10	A(9,1,I3) I3=1,18 B(9,1,I3) I3=1,18	Input data for curve A (see Figure A.6)	1-10 11-20 . . .	F (Six data per card)
11-13 14-16	A(10,1,I3) I3=1,18 B(10,1,I3) I3=1,18	Input data for curve B (see Figure A.6)	1-10 11-20 . . .	F (Six data per card)

5. Instructions for Using Subprogram D4

Description. Twenty-nine cards are supplied to this subprogram. The option on the number of relays contained in the coordination problem is triggered by data card No. 1. The values of the pickup currents for

the relays are specified on cards No. 2 and 3. When the coordination problem contains only one relay, the value of the pickup current is specified on card No. 3. In this case, although card No. 2 is unnecessary, it must also be filled with arbitrary values. Cards No. 5 through 29 contain input data for representing characteristic curves of the relays. The way these data are read in is shown in Figure A.7.

User Supplied Input Format.

Card Number	Program Variable Name	Description	Data Card Columns	Format
1	NANCY	0--if there is only one relay in the coordination problem; 1--if there is more than one relay in the coordination problem	1-5	I
2	RV41	Value of pickup current for relay No. 1	1-10	F
	RV42	Value of pickup current for relay No. 2	11-20	
	RV43	Value of pickup current for relay No. 3	21-30	
	RV44	Value of pickup current for relay No. 4	31-40	
3	RV4	Value of pickup current for the relay	1-10	F
4	M4	Number of points taken from each characteristic curve	1-5	I
	N4	Number of time dial settings	6-10	

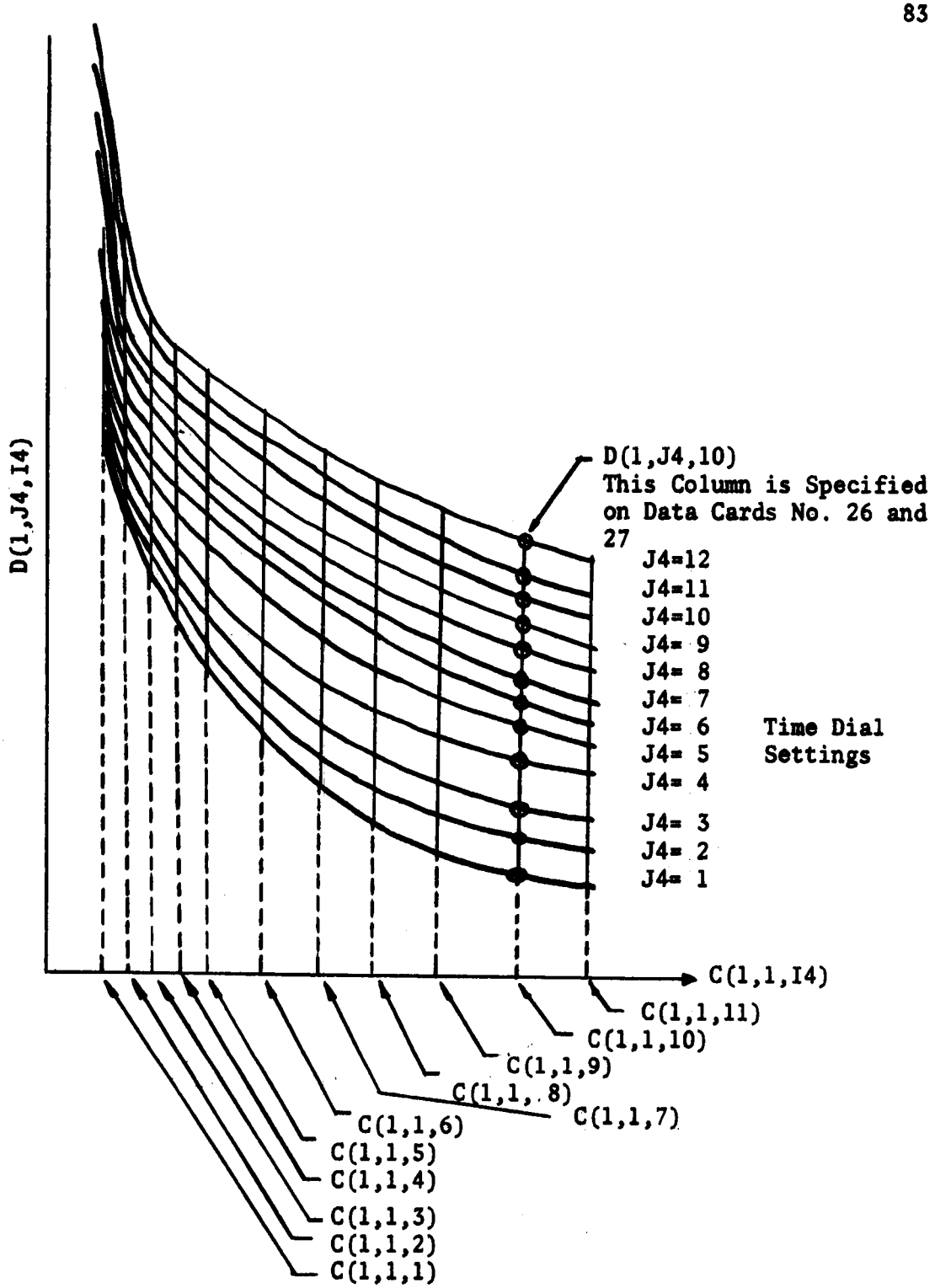


Figure A.7. Diagram illustrating the input data for curves of relays.

Card Number	Program Variable Name	Description	Data Card Columns	Format
5-6	C(1,1,I4) I4=1,11	Input data (see Figure A.5)	1-10 11-20 . . .	F (Six data per card)
7-29	D(1,J4,I4) J4=1,12 I4=1,11			

6. Instructions for Using Subprogram D5

Description. Fifty-nine cards are supplied to this subprogram. The reason for the large number of data cards is that reference curves are renewed for every instantaneous setting. The current rating of the device is specified on card No. 1. The distances shifted by the reference curves for generating instantaneous settings are specified on card No. 2 and defined in Figure A.8. The number of instantaneous settings (4), and the number of data points for representing each reference curve (18) are specified on card No. 3. Input data for each of the reference curves and the distances shifted by the first twelve points of each of the reference curves for generating the long delay settings are specified on the rest of the cards. All the reference curves are curves with 100 percent long delay settings.

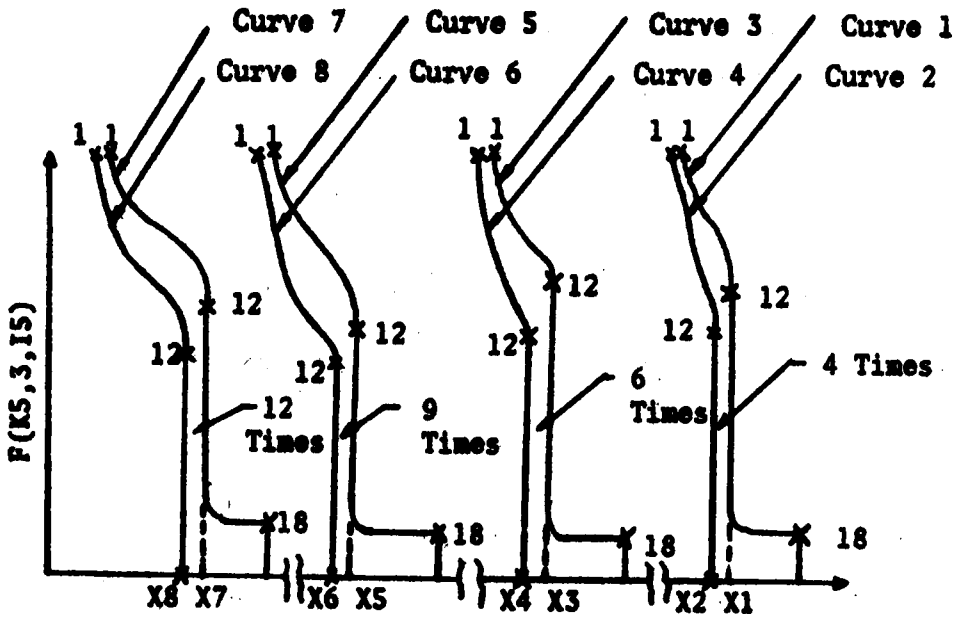


Figure A.8. Diagram illustrating the input data for the reference curves 1 to 7.

Diagram Note: $PMIN(1) = \frac{X7}{X1}$ $PMIN(5) = \frac{X7}{X5}$

$PMIN(2) = \frac{X8}{X2}$ $PMIN(6) = \frac{X8}{X6}$

$PMIN(3) = \frac{X7}{X3}$

$PMIN(4) = \frac{X8}{X4}$

User Supplied Input Format.

Card Number	Program Variable Name	Description	Data Card Columns	Format
1	RV5	Current rating of the device	1-5	I
2	PMIN(K5) K5=1,6	Distances shifted by the reference curves for generating instantaneous settings	1-10 11-20 . . . 51-60	F
3	N5	Number of instantaneous settings	1-5	I
	M5	Number of data points for representing each reference curve	6-10	
4-6 7-9	E(K5,3,I5) I5=1,18 F(K5,3,I5) I5=1,18	Input data for curve 7 (see Figure A.8) Block D	1-10 11-20 . . .	F (Six data per card)
10-11 12-13	PXS(I5) I5=1,12 PXA(I5) I5=1,12	Block E Distances shifted by the first twelve points of reference curve 7 for generating long delay settings (see Figure A.9)	1-10 11-20 . . .	F (Six data per card)
14-16 17-19		Same as block D (Data are for curve 8)		
20-21 22-23		Same as Block E (Data are for curve 8)		
24-25	E(K5,3,I5) I5=1,12	Input data for curve 1 (see Figure A.8) Block F	1-10 11-20 . . .	F (Six data per card)

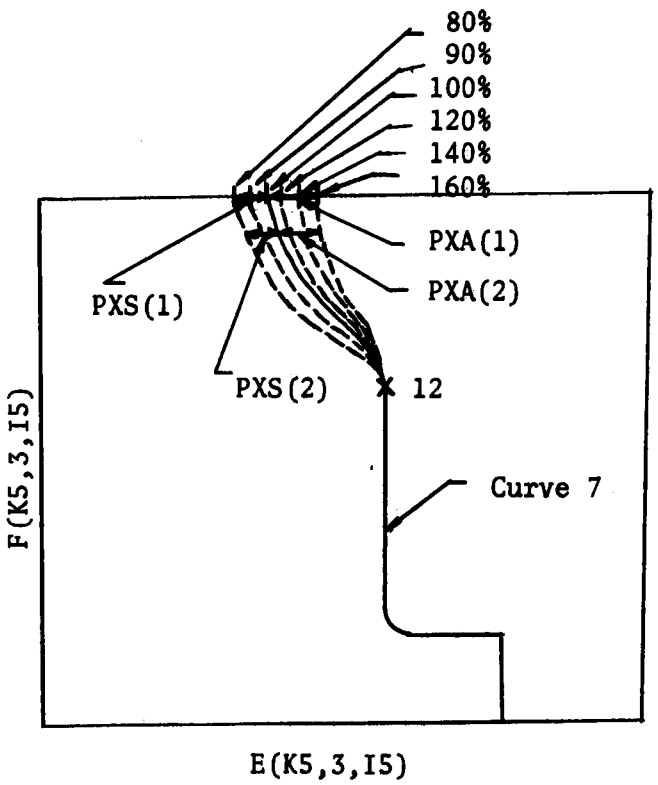


Figure A.9. Diagram illustrating the positions of PXS(1), PXS(2), PXA(1) and PXA(2).

Card Number	Program Variable Name	Description	Data Card Columns	Format
26-27 28-29		Same as block E (Data are for curve 1)		
30-31		Same as block F (Data are for curve 2)		
32-33 34-35		Same as block E (Data are for curve 2)		
36-37		Same as block F (Data are for curve 3)		
38-39 40-41		Same as block E (Data are for curve 3)		
42-43		Same as block F (Data are for curve 4)		
44-45 46-47		Same as block E (Data are for curve 4)		
48-49		Same as block F (Data are for curve 5)		
50-51 52-53		Same as block E (Data are for curve 5)		
54-55		Same as block F (Data are for curve 6)		
56-57 58-59		Same as block E (Data are for curve 6)		

7. Instructions for Using Subprogram D6

Description. Twenty-five cards are supplied to this subprogram. Data card No. 1 is used to trigger short delay options, and the multiplying factors for generating the short delay options are specified on card No. 2. These multiplying factors are labeled and shown in

Figure A.10. The number of instantaneous or short delay settings (3), the long delay setting that is used as reference (3rd), the number of long delay settings (6), and the number of data points per reference curve (18) are specified on card No. 3. The current ratings of each of the circuit breakers are specified on card No. 4. An arbitrary number is assigned to the current rating of each circuit breaker not used. The distance shifted by the reference curves for generating instantaneous and short delay settings are specified on card No. 5. These shifted distances are labeled and shown in Figure A.10. Input data for each of the reference curves and the distances shifted by each of the reference curves for generating the long delay settings are specified on the rest of the cards. The reference curves are the curves with 100 percent long delay setting and maximum short delay or instantaneous setting.

User Supplied Input Format.

Card Number	Program Variable Name	Description	Data Card Columns	Format
1	NCAA	Time band option 1--minimum short time delay or instantaneous trip 2--intermediate short time delay 3--maximum short time delay	1-5	I
2	RY11 RY20 RY12E RY13O RY13E	Multiplying factors for generating the short delay options (see Figure A.10)	1-10 11-20 21-30 31-40 41-50	F
3	N6	Number of instantaneous or short delay settings	1-5	I

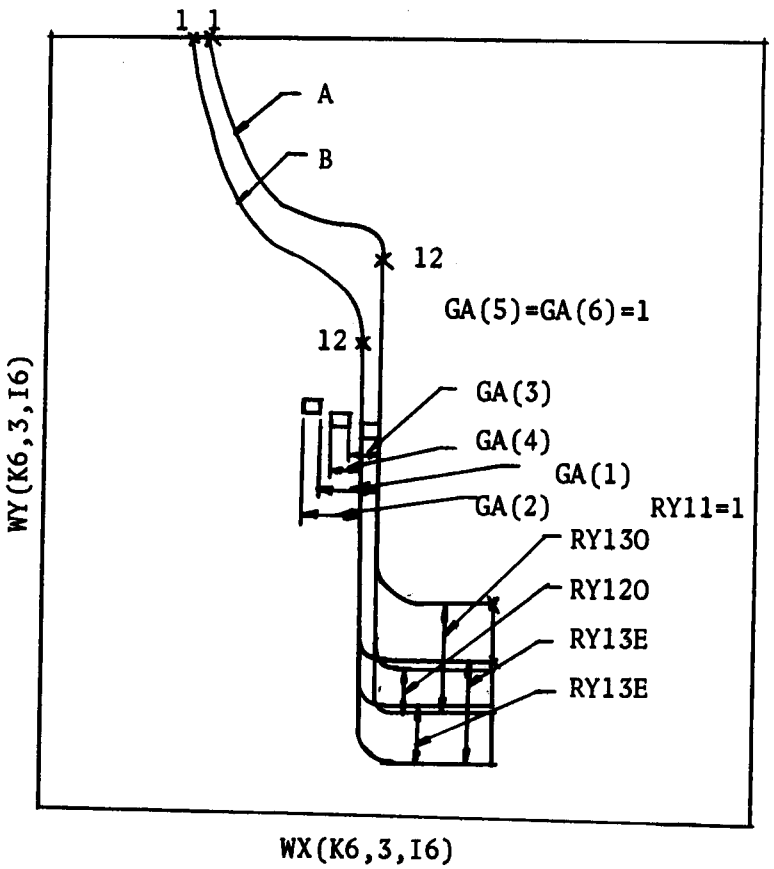


Figure A.10. Diagram illustrating the positions of GA(1) to GA(6), RY11, RY13O, RY13E, RY12O, RY12E and the input data of curves A and B.

Card Number	Program Variable Name	Description	Data Card Columns	Format
	MJJ	the long delay setting that is used as reference	6-10	
	MJ6	Number of long delay settings	11-15	
	M6	Number of data point per reference curve	16-20	
4	RV61	Current rating of device No. 1	1-10	F
	RV62	Current rating of device No. 2	11-20	
	RV63	Current rating of device No. 3	21-30	
5	GA(MI) MI=1,6	Distances shifted by the reference curves for generating instantaneous or short delay settings	1-10 . . . 51-60	F
6-8	WX(5,3,I6) I6=1,18	Input data for curve A (see Figure A.10)	1-10 11-20 . . .	F (Six data per card)
9-11	WY(5,3,I6) I6=1,18			
12-13	EXS(I6) I6=1,12	Distance shifted by reference curve A for generating long delay settings (see Figure A.11)	1-10 11-20 . . .	F (Six data per card)
14-15	EXA(I6) I6=1,12			
16-18	WX(6,3,I6) I6=1,18	Input data for curve B (see Figure A.10)	1-10 11-20 . . .	F (Six data Per card)
19-21	WY(6,3,I6) I6=1,18			
22-23	EXS(I6) I6=1,12	Distance shifted by reference curve B for generating long delay settings (see Figure A.11)	1-10 11-20 . . .	F (Six data per card)
24-25	EXA(I6) I6=1,12			

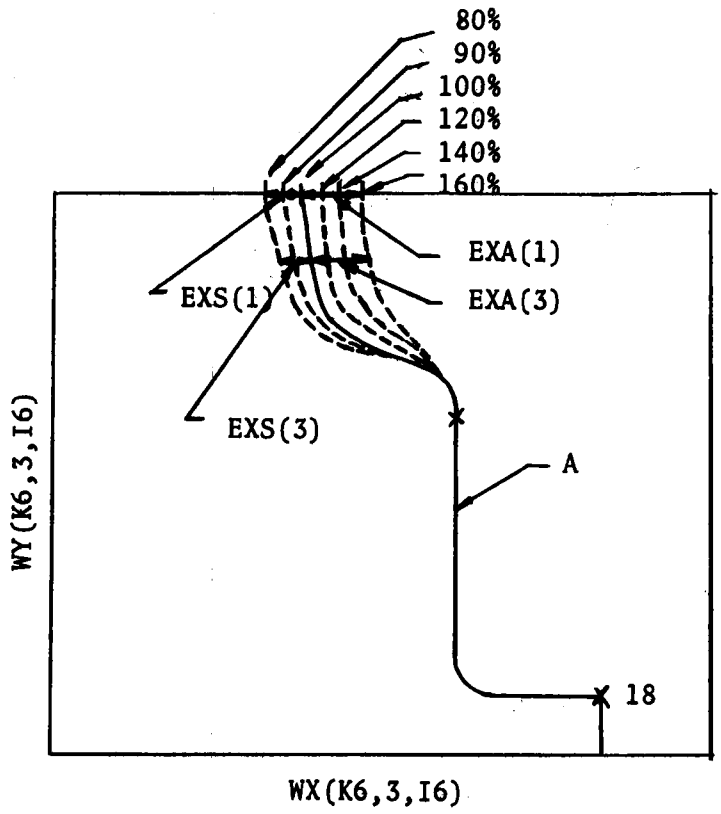


Figure A.11. Curve A is isolated from Figure A.10 for illustrating the positions of EXS(1), EXS(3), EXA(1) and EXA(3).

8. Instructions for Using Subprogram D7

Description. The number of data per reference curve (8) and the number of types of fuses (3) are specified on card No. 1. The three types of fuses used as examples are 150-E, 200-E, and 250-E. Three curves, short time, melting time and total clearing time curves, are specified for each type of fuses. Only the short time curves of the three fuses are shown in Figure A.12. In Figure A.12, FX and FY are the x and y inputs, K7 is the type of curve, J7 is the type of fuse, and I7 is the data number.

User Supplied Input Format.

Card Number	Program Variable Name	Description	Data Card Columns	Format
1	M7	Number of data points per reference curve	1-5	I
	N7	Number of types of fuses	6-10	
2-9	FX(1,J7,I7) J7=1,3 I7=1,8	Input data of the short time curves of the three fuses (see Figure A.12)	1-10 11-20 . . .	F (Three data per card)
10-17	FX(2,J7,I7) J7=1,3 I7=1,8	Input data of the melting time curves of the three fuses		
18-25	FX(3,J7,I7) J7=1,3 I7=1,8	Input data of the total clearing time curves of the three fuses		
26-27	FY(1,1,I7) I7=1,8	Input data of the short time curve (see Figure A.12)	1-10 11-20 . . .	F (Four data per card)

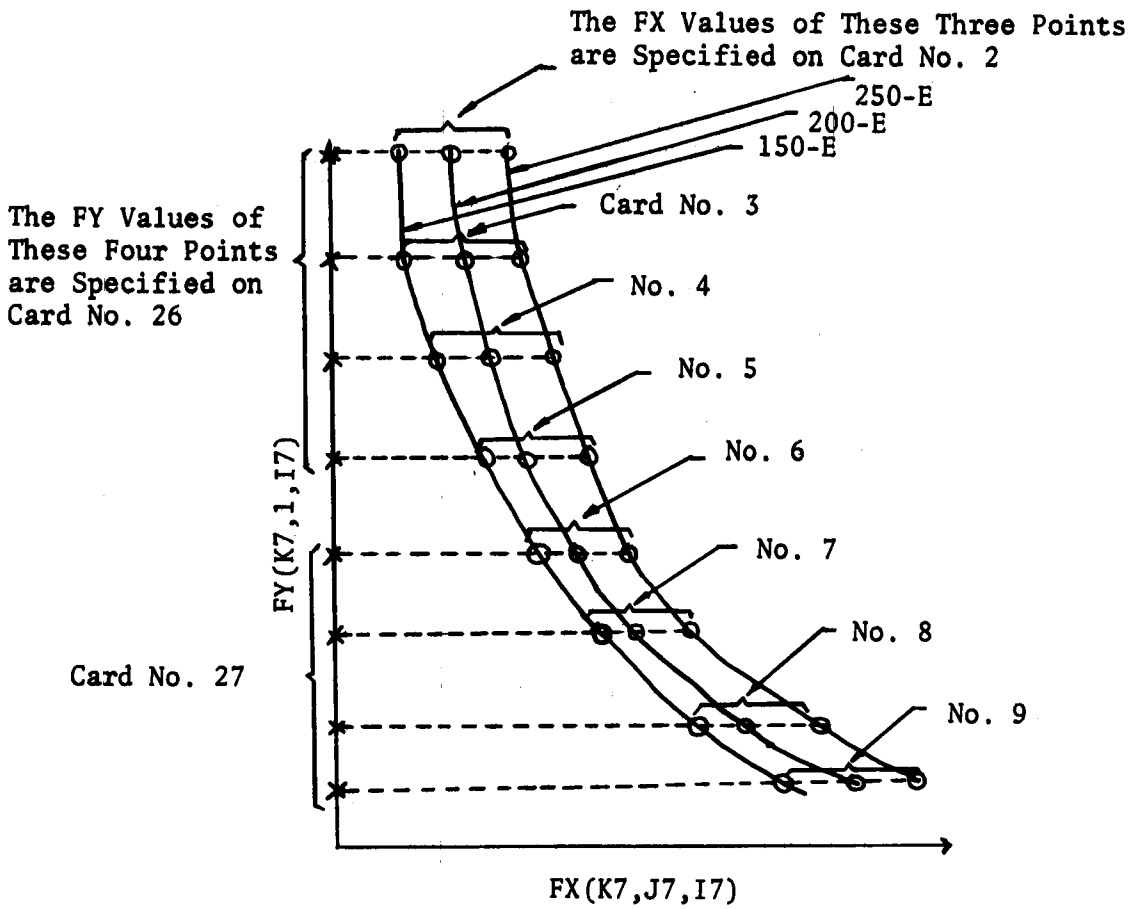


Figure A.12. Diagram illustrating input data of the short time curves of the three fuses.

Card Number	Program Variable Name	Description	Data Card Columns	Format
28-29	FY(2,1,I7) I7=1,8	Input data of the melting time curve		
30-31	FY(3,1,I7) I7=1,8	Input data of the total clearing time curve		

Instructions for Using Subprogram CALCOM

User Supplied Input Format.

Card Number	Program Variable Name	Description	Data Card Columns	Format
1-21		Starting point of the x array	1-10	F
		Number of cycles per inch on the x axis	11-20	F
		Starting point of the y array	21-30	F
		Number of cycles per inch on the y axis	31-40	F

Part III. Input and Output Data for Examples IV.1 and IV.2

Listings of the input and output data for the two coordination problems in Chapter IV are given below:

(A) A Listing of the Input Data for Example IV.1

```
    3        7    1
    3        1    4        4    1
*
1.475          1.54          1.27          1.39          1.12          1.26
1.075          1.14          1.            1.
    5       18    10
15.            1.27
1.55           1.7           2.            2.35          2.5           3.
3.5            4.3           5.            6.            9.5           14.
14.            15.5          17.           18.5          25.           80.
1000.          550.          300.          170.          130.          77.
55.            38.           28.           20.           10.           6.2
.04            .03           .027          .025          .023          .023
1.2            1.4           1.5           1.55          2.            2.5
3.1            4.4           5.            6.5           8.            12.
12.            12.           12.           12.           12.           12.
1000.          400.          290.          250.          96.           47.
27.            14.           10.           6.5           4.7           2.8
.04            .01           .01           .01           .01           .01
    1        2
2.             2.5           3.333         5.            3.            5.4
    6        6    10
2.47           1.            1.            1.
15.            30.           50.
3.             2.4           2.            1.5           1.2           1.
1.14           1.28          1.41          1.55          1.75
.9             .9            11.5          11.5          11.8          12.2
13.5           15.           17.5          49.
1000.          350.          2.4           .24           .21           .17
.16            .15           .15           .15
.7             .7            9.            9.            9.5           10.
11.            12.5          14.           49.
1000.          350.          2.4           .24           .1            .09
.085           .082          .08           .08
    0
1.             1.2           5.            30.
240.
    11       12
1.             1.1           1.3           1.6           2.            2.75
3.6            6.            10.           20.           50.
```

1000.	1000.	1000.	1000.	1000.	1000.
1000.	1000.	1000.	1000.	1000.	1000.
4.7	9.	20.	28.	34.	44.
58.	62.	70.	100.	160.	300.
2.5	5.	13.	18.	26.	30.
40.	45.	53.	60.	70.	80.
1.	2.5	5.5	8.5	12.	15.
18.	21.	24.	27.	31.	36.
.55	1.	2.8	4.2	6.	7.5
9.	11.	12.	14.	16.	18.
.27	.67	1.4	1.9	2.6	3.4
4.2	4.9	5.8	6.5	7.5	8.5
.17	.4	.7	1.2	1.6	2.
2.5	3.	3.5	4.	4.5	5.
.1	.24	.44	.65	.9	1.2
1.4	1.7	1.9	2.2	2.5	2.9
.065	.14	.25	.4	.55	.72
.85	1.	1.2	1.35	1.5	1.75
.046	.1	.19	.29	.41	.55
.62	.78	.89	1.	1.2	1.3
.04	.086	.17	.25	.34	.45
.5	.6	.7	.8	.9	1.

10	18	18	11	18	18	8
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	
1.	1.		.01		1.	

(B) A Listing of the Output Data for Example IV.1

```
D3,K3,J3,KC,JC          8     1     0        0
X31,Y31,X32,Y32
        18.0000            1000.0000            23.2500            1000.0000
        21.0000             400.0000            25.5000             550.0000
        22.5000             290.0000            30.0000             300.0000
        23.2500             250.0000            35.2500             170.0000
        30.0000              96.0000            37.5000             130.0000
        37.5000              47.0000            45.0000              77.0000
        46.5000              27.0000            52.5000              55.0000
        66.0000              14.0000            64.5000              38.0000
        75.0000              10.0000            75.0000              28.0000
        97.5000               6.5000            90.0000              20.0000
       120.0000               4.7000           142.5000              10.0000
       123.6549               2.7998           152.9500               6.1992
       124.3267               0.0400           153.8181               0.0400
       124.3267               0.0100           170.2986               0.0300
       124.3267               0.0100           186.7791               0.0270
       124.3267               0.0100           203.2596               0.0250
       124.3267               0.0100           274.6750               0.0230
       124.3267               0.0100           878.9602               0.0230
EXTRA KC,JC,I(JJ-1)=3            8     1

D1,K1,J1,KC,JC          6     1     8        1
X11,Y11,X12,Y12
        34.5600            1000.0000            26.8800            1000.0000
        34.5600             647.7588            26.8800             648.5171
       230.0000              15.9087           180.0000              15.8782
       230.0000               0.2400           180.0000               0.2400
       235.9998               0.2100           190.0000               0.1000
       243.9998               0.1700           200.0000               0.0900
       270.0000               0.1600           220.0000               0.0850
       300.0000               0.1500           250.0000               0.0820
       350.0000               0.1500           280.0000               0.0800
       980.0000               0.1500           980.0000               0.0800
EXTRA KC,JC,I(JJ-1)=1            7     3
I AM IN FRONT OF STOP

D4,AFTER ALGORR,J4=              1
X4,Y4
       240.0000            1000.0000
       263.9998               4.7000
       311.9998               2.5000
       383.9998               1.0000
       480.0000               0.5500
       660.0000               0.2700
```

863.9998	0.1700
1440.0000	0.1000
2400.0000	0.0650
4800.0000	0.0460
12000.0000	0.0400

(C) A Listing of the Input Data for Example IV.2

```
    4       7    1
    3       6    6        7    1
*
1.475        1.54          1.27          1.39          1.12          1.26
1.075        1.14          1.            1.
    5      18    10
15.          1.27
1.55         1.7           2.            2.35          2.5           3.
3.5          4.3           5.            6.            9.5           14.
14.          15.5          17.           18.5          25.           80.
1000.        550.          300.          170.          130.          77.
55.          38.           28.           20.           10.           6.2
.04          .03           .027          .025          .023          .023
1.2          1.4           1.5           1.55          2.            2.5
3.1          4.4           5.            6.5           8.            12.
12.          12.           12.           12.           12.           12.
1000.        400.          290.          250.          96.           47.
27.          14.           10.           6.5           4.7           2.8
.04          .01           .01           .01           .01           .01
    1
1.           2.25          2.97          4.82          7.3
    3      3     6       18
15.          60.           120.
2.           2.            1.33          1.33          1.            1.
1.9          1.9           2.4           2.            1.            1.
    1
1.1          1.1           1.15          1.3           1.4           1.6
2.           3.2           5.4           10.           10.3          11.
11.          11.5          14.           17.           20.           40.
1000.        250.          190.          150.          110.          80.
55.          38.           29.           24.           22.           20.
.222         .178          .142          .124          .12           .11
1.22         1.22          1.22          1.3           1.27          1.27
1.25         1.28          1.23          1.            1.            1.
1.55         1.55          1.55          1.5           1.43          1.43
1.6          1.56          1.57          1.            1.            1.
.9           .9            .9            1.2           1.6           2.
2.7          3.4           6.6           7.8           8.5           8.8
8.8          8.9           9.5           12.           20.           40.
1000.        210.          95.           52.           30.           22.
17.          14.           11.           9.6           8.2           7.
.087         .064          .0505         .0438         .0421         .0388
1.27         1.25          1.12          1.26          1.23          1.1
1.04         1.            1.            1.            1.            1.
1.56         1.56          1.56          1.56          1.47          1.35
1.22         1.48          1.            1.            1.            1.
```

```
   3
1.          2.33        3.05        5.          7.2
   3        3   6       18
15.         60.         120.
2.          2.          1.14        1.14        1.          1.
1.9         1.9         2.4         2.          1.          1.
   1
1.          1.4         1.7         1.9         2.5         3.1
3.6         4.          4.2         4.3         4.4         4.5
4.5         5.          6.          7.5         9.5         14.
1000.       300.        150.        110.        65.         45.
38.         31.         29.         28.         24.         18.
.2          .15         .12         .11         .1          .1
1.11        1.22        1.21        1.22        1.13        1.07
1.12        1.14        1.1         1.07        1.          1.
1.8         1.43        1.38        1.47        1.52        1.39
1.22        1.1         1.05        1.02        1.          1.
.9          1.          1.1         1.2         1.6         1.9
2.2         2.6         3.          3.1         3.2         3.36
3.36        3.7         4.6         5.5         7.5         14.
1000.       410.        200.        120.        64.         37.
25.         18.         14.         12.         9.          7.
.1          .05         .04         .035        .033        .033
1.28        1.31        1.34        1.26        1.28        1.08
1.15        1.15        1.07        1.05        1.          1.
1.67        1.55        1.45        1.33        1.18        1.16
1.26        1.26        1.1         1.07        1.05        1.
   8        3
270.        320.        410.
280.        350.        420.
300.        390.        495.
400.        490.        600.
490.        590.        740.
700.        870.        1100.
1000.       1250.       1700.
8000.       11000.      15000.
300.        430.        520.
320.        460.        580.
380.        500.        610.
450.        600.        710.
570.        720.        900.
700.        900.        1100.
1000.       1300.       1600.
10000.      13000.      18000.
400.        550.        700.
470.        600.        800.
600.        700.        920.
800.        1000.       1200.
```

```
1300.          1700.          2000.
3000.          3600.          4500.
7000.          8400.          10000.
20000.         23000.         27000.
1000.          300.           60.            10.
4.7            1.7            .6             .01
1000.          200.           58.            13.
5.             2.7            1.             .01
1000.          70.            13.            3.5
.8             .15            .04            .015
    10     18      18     11   18      18    8
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
1.             1.             .01            1.
```

(D) A Listing of the Output Data for Example IV.2

```
D3,K3,J3,KC,JC     8          1     0      0
X31,Y31,X32,Y32
        18.0000            1000.0000            23.2500            1000.0000
        21.0000             400.0000            25.5000             550.0000
        22.5000             290.0000            30.0000             300.0000
        23.2500             250.0000            35.2500             170.0000
        30.0000              96.0000            37.5000             130.0000
        37.5000              47.0000            45.0000              77.0000
        46.5000              27.0000            52.5000              55.0000
        66.0000              14.0000            64.5000              38.0000
        75.0000              10.0000            75.0000              28.0000
        97.5000               6.5000            90.0000              20.0000
       120.0000               4.7000           142.5000              10.0000
       123.6549               2.7998           152.9500               6.1992
       124.3267               0.0400           153.8181               0.0400
       124.3267               0.0100           170.2986               0.0300
       124.3267               0.0100           186.7791               0.0270
       124.3267               0.0100           203.2596               0.0250
       124.3267               0.0100           274.6750               0.0230
       124.3267               0.0100           878.9602               0.0230
EXTRA KC,JC,I(JJ-1)=3          8     1

D6,K6,J6,KC,JC     2          1     8      1
X61,Y61,X62,Y62
        53.8564            1000.0000            42.3409            1000.0000
        53.8564             250.0000            43.0176             210.0000
        56.3016             190.0000            48.0048              95.0000
        59.7247             150.0000            56.8838              52.0000
        65.8311             110.0000            77.6674              30.0000
        75.2240              80.0000           108.5172              22.0000
        95.5089              55.0000           154.8884              17.0000
       149.1580              38.0000           202.7848              14.0000
       261.7703              29.0000           262.1475               7.0000
       327.6025              20.0000           262.1475               7.0000
       327.6025              20.0000           262.1475               7.0000
       327.6025              20.0000           262.1475               7.0000
       330.0000               0.2220           263.9998               0.0870
       345.0000               0.1780           266.9998               0.0640
       420.0000               0.1420           285.0000               0.0505
       510.0000               0.1240           360.0000               0.0438
       600.0000               0.1200           600.0000               0.0421
      1200.0000               0.1100          1200.0000               0.0388
EXTRA KC,JC,I(JJ-1)=6          1     1
I AM IN FRONT OF STOP
```

```
D6,K6,J6,KC,JC          4     5     1        1                              104
X61,Y61,X62,Y62
                        8     1     0        0
      176.5370              1000.0000            151.1644          1000.0000
      211.9578               300.0000            159.8050           410.0000
      251.2945               150.0000            168.1315           200.0000
      292.8904               110.0000            173.1461           120.0000
      393.9402                65.0000            213.1093            64.0000
      460.1409                45.0000            250.1549            37.0000
      470.3486                18.0000            305.9998            25.0000
      470.3486                18.0000            351.3088             7.0000
      470.3486                18.0000            351.3088             7.0000
      470.3486                18.0000            351.3088             7.0000
      470.3486                18.0000            351.3088             7.0000
      470.3486                18.0000            351.3088             7.0000
      473.6843                 1.0000            353.6843             0.7200
      526.3159                 0.7500            389.4736             0.3600
      631.5791                 0.6000            484.2104             0.2880
      789.4739                 0.5500            578.9475             0.2520
     1000.0005                 0.5000            789.4739             0.2376
     1473.6848                 0.5000           1473.6848             0.2376
EXTRA KC,JC,I(JJ-1)=6           3     5
I AM IN FRONT OF STOP
I AM IN FRONT OF STOP

D7,K7,J7,KC,JC    2             2     3        5
X71,Y71,X72,Y72,X73,Y73
  320.0000   1000.0000     430.0000   1000.0000     550.0000   1000.0000
  350.0000    300.0000     460.0000    200.0000     600.0000     70.0000
  390.0000     60.0000     500.0000     58.0000     700.0000     13.0000
  490.0000     10.0000     600.0000     13.0000    1000.0000      3.5000
  590.0000      4.7000     720.0000      5.0000    1700.0000      0.8000
  870.0000      1.7000     900.0000      2.7000    3600.0000      0.1500
 1250.0000      0.6000    1300.0000      1.0000    8400.0000      0.0400
11000.0000      0.0100   13000.0000      0.0100   23000.0000      0.0150
```

VITA

Y. C. Frederick Hui was born in Swatow, Canton, China, on January 4, 1950, and moved with his family to Kowloon, Hong Kong, in 1956. He received his primary and secondary education from Munsang College in Kowloon, Hong Kong. After graduating from Munsang College in 1967, he came to the United States to attend Georgia Southern College in Statesboro, Georgia. After attending Georgia Southern College for five quarters, he transferred to The University of Tennessee where he received the Bachelor of Science degree in Electrical Engineering in June, 1972. In September, 1972, he obtained a graduate assistantship from the Electrical Engineering Department of The University of Tennessee to continue his studies toward his Master's degree in Electrical Engineering.