COMPUTERISED DISTANCE RELAYING USING SYMMETRICAL COMPONENT DISCRETE FOURIER TRANSFORM TECHNIQUE

BY

MD. SAJJAD HOSSAIN

A THESIS

SUBMITTED TO THE DEPARTMENT OF ELECTRICAL & ELECTRONIC ENGINEERING, BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY, DHAKA, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF SCIENCE IN ELECTRICAL & ELECTRONIC ENGINEERING

JANUARY, 1987

DECLARATION

I do hereby declare that neither this thesis nor any part thereof has been submitted or is being concurrently submitted in candidature for any degree at any other University.

Candidate

CERTIFICATE OF RESEARCH

Certified that the work presented in this Thesis is the result of the investigation carried out by the candidate under the Supervision of Dr. Md. Mujibur Rahman, Professor and Head, Department of Electrical and Electronic Engineering, BUET, Dhaka.

Candidate

Supervisor

Accepted as satisfactory for partial fulfilment of the requirements for the degree of M.Sc. Engineering in Electrical and Electronic Engineering:

Board of Examiners:

(Dr. Md. Mujibur Rahman)
Professor & Head
Department of Electrical & Electronic Engineering, BUET, Dhaka, Bangladesh.

Chairman
(Supervisor)

[illegible]
Head
Department of Electrical & Electronic Engineering, BUET, Dhaka, Bangladesh.

Member

3/1/87
(Dr. Quamrul Ahsan)
Associate Professor
Department of Electrical & Electronic Engineering, BUET, Dhaka, Bangladesh.

Member

3/1/87
(Dr. Samsuddin Ahmed)
Professor and Head
Department of Electrical & Electronic
ICTVTR, Tongi, Dhaka.

Member
(External)

ACKNOWLEDGEMENT

The author expresses his indebtedness and deep sense of gratitude to Dr. Md. Mujibur Rahman, Professor and Head, Department of Electrical and Electronic Engineering, BUET, Dhaka for his continuous encouragement, constant guidance and keen supervision throughout the course of this study.

The author also wishes to express his sincere gratitude and thanks to Professor A.M. Patwari, Vice-Chancellor, Professor A.M. Zahoorul Hoq, Professor S.F. Rahhaman, Dr. Quamrul Ahsan for their advices rendering all possible help.

The author is especially indebted to Mr. S.M. Lutful Kabir, Assistant Professor, Department of E.E.E., BUET, Dhaka for his help, advice, suggestions and discussions rendered throughout the course of this work.

The author expresses his sincere gratitude to all those people who have collaborated in this work. Among those he wishes to mention a few but thanks all others not mentioned here.

ABSTRACT

The symmetrical component discrete fourier transform, has been used as the basis for computerized distance relaying in order to detect type and location of fault in a complicated power system network. The biggest advantage of computerized distance relaying using symmetrical component is the use of a single performance equation for handling all types of fault which are likely to occur on a three-phase power system. The beauty of the symmetrical component distance relay (SCDR) lies in the fact that is a high speed relay and simple to apply.

The input to the SCDR are the symmetrical components of voltage and current. These can be readily obtained from their respective sample wave form data using DFT filtering technique. The DFT filtering must be accomplished in such a way so that fundamental frequency component can be extracted from the sampled data without introducing excessive delay in the over all relaying process.

The work starts with an explanation of different types of faults which usually occur in a power system and the different type of protective relays which are involved in overcoming these faults. A comparitive study of the available methods is also provided.

A computer program is developed for detecting type and location of fault. The program is first validated on a model two bus power system. The performance under different system conditions is investigated to check the correctness of the response. The method is than applied on a realistic power system. The simulated data are fed in to the program and fault results obtained are discussed.

LIST OF PRINCIPAL SYMBOLS AND ABBREVIATIONS

CT	Current Transformer
PT	Potential Transformer.
DFT	Discrete Fourier Transform.
SCDFT	Symmetrical Component Discrete Fourier Transform.
SCDR	Symmetrical Component Distance Relay.
HZ	Hertz
C/S	Cycle Per Second.
P.U	Per Unit.
π	Pai, 3.1414927
W	Angular Frequency.
T	Time Period
K	Fault Distance
ε	(Epsilon) Tolerance
N	Data Window.
Z_{BUS}	Bus Impedance Matrix.
$E^{0,1,2}_{(F)}$	Zero, Positive and Negative Sequence Voltage.
ΔW	Incerement in Angular Frequency rad/sec.

CONTENTS

Page

APPENDICS

CHAPTER - 1

1.0 INTRODUCTION

1.1 GENERAL

Detailed analysis of the conditions under which fault occurs in a power-system and a thorough understanding of the methods for clearing these faults, are of vital importance in ensuring reliable operation of power systems. Availability of different types of protective equipments enables the system engineer to take proper step for detection of fault and clearing this fault by disconnecting the faulty section or equipment if necessary.

In a power-system, consisting of generators, transformers, transmission and distribution circuits, it is inevitable that sooner or later some failure will occur somewhere in the system. When a failure occurs on any part of the system, it must be quickly detected so that appropriate and timely measures may be taken to avoid, or at least to menimize, damage to the system. The anticipated damage includes not only the physical damages that may occur to the system components but also probable loss of revenue, lack of reliability and service interruptions etc. The detection of a fault and disconnection of a faulty section or apparatus, if necessary, can be achieved by using fuses or relays in conjunction with circuit breakers. The relay detects the fault and may initiate the operation of the circuit breaker to isolate the defective element from the rest of the system. Permanent or temporary isolation of the faulty section or equipment from rest of the system may be decided upon by the nature and severity of the fault. Under normal operating conditions of the system, a protective relay is required to keep itself alert so that in case of any emergency almost instantaneous action may be taken[4,5].

Each relay in a protection scheme performs a certain function and responds in a pre-specified manner to a certain type of change in the circuit quantities. Various combinations of these electrical quantities could be worked out accoring to the requirement of a particular situation because for every type and location of failure there is some distinctive difference in these quantities. There are various type of protective relaying equipments available, each of which is designed to recognize a particular difference and to operate in response to it[7]. Different types of protective relaying such as over-current relay, directional relay, differential relay, distance relay etc are used to protect different type of power system apparatus, feeder and transmission and distribution equipments. The choice depends upon some factors such as nature of fault, accuracy, simplicity, economy, speed etc.

Transmission lines form a major part of a power system. Different types of relays are used to protect these lines. The most commonly used relays are from the family of distance relays. Because distance protection are non-unit type of protection[3]. Moreover it is a high speed relay and is simple to apply. Computer implementation of this relay is attractive, potential and economic. Basically the objective of a high speed relaying scheme is to estimate the fundamental frequency components from the corrupted voltage and current signals following the fault occurrance. For distance relaying, these components are used to determine the apparant impedance to the fault and hence the fault location.

1.2 TYPE OF PROTECTION(2,4).

There are two types of protection. They are primary protection and Back-up protection. Primary protection is the essential protection provided for protecting an equipment or machine. The primary protection is the first to act and the Back-up protection is the next in the line of defence-meaning that if primary protection fails, the Back-up protection comes into action and removes the faulty part from the healthy system. When primary protection is made inoperative for the purpose of maintenance or testing etc; the Back-up protection acts as if it was primary protection.

1.3 PROTECTION SCHEMES

1.3.1 BASIC REQUIREMENTS OF PROTECTIVE SCHEMES(1,4,5).

A well-designed and efficient protective relay should posses the characteristics having minimum clearing time and voltage to operate, maximum continuity of service by disconnecting the faulty part of the system. This should have the capability of operating reliably under the actual desired condition and should always alert to operate under any condition of anticipated trouble. It should have simplified circuitry and minimum equipments and posses maximum service at minimum cost.

These characteristics are properly known as speed, selectivity, sensitivity, reliability, simplicity and Economy respectively.

1.3.2 TYPE OF PROTECTIVE RELAYING

1.3.2.1 OVERCURRENT RELAYING(2,3,4,5)

Overcurrent protection is that protection in which the relay picks up when the magnitude of current exceeds the pick up level. The basic element in overcurrent protection is an overcurrent relay. For any fault, the current would usually rise tremendously causing the actuating quantity of the relay to exceed the normal quantity. The relay would operate and close the contacts so as to complete the trip circuit of the breaker.

The choice of relay for overcurrent protection depends upon the time-current characteristic and other features desired. Depending upon these characteristic the relays used are

Instantaneous overcurrent relay, Time graded overcurrent relay, Inverse definite minimum time relay, Directional overcurrent relay. Instantaneous overcurrent relay is one in which no intentional time dely is provided for operation. The time of operation of such relay is approximately 0.1 see[2]. For Time graded overcurrent relay the time interval necessary between successive relays is governed by the factors such as fault clearance time of circuit breaker, finite contact gap to ensure non-operation, over shoot of the relays, relay and CT tolerance. The operation of directional relay depends upon both the magnitude and direction of the fault current through the protected equipment. Directional relay must have high speed of operation, high selectivity, adequate short-time, thermal rating.

The technique of overcurrent relaying is used as a means of detecting fault on distribution systems and on radial transmission lines fed from one end. In the case of lines fed from both ends it is used along with directional relays. Overcurrent relays are also used in conjunction with distance relays to provide back-up protection. Overcurrent relays offer the cheapest and the simplest protection.

1.3.2.2 <u>DIFFERENTIAL RELAYING</u> [1,2,3]

A differential relay is one that operates when the vector difference of two or more electrical quantities exceeds a predetermined value. The principle of operation depends on a simple circulating current principle where the difference of the currents of the two CTS flows through the relay under normal conditions or even under faults outside the protected section. Otherwise the fundamental principle of differential or balanced system of protection is that, under healthy conditions, the current entering at one end of the protected equipment is identical both in phase and magnitude with that leaving the other end. On the occurance of a fault, this balance is altered and the difference of the two currents works as the actuating quantity of the relay. The relay operates and the circuit is tripped.

Two fundamental system of differential Relays are current balance differential relay and voltage balance differential relay. A current differential rely is one that compares the current entering a section of the system with the current leaving the section. Under normal conditions the two currents are more or less equal but as soon as a fault occurs, this condition no longer applies. The difference between the incomming and outgoing currents is arranged to flow through the operating coil of the relay. If this differential current is equal to or greater than the pick up value, the relay will operate and open the circuit breaker to isolate the faulty section.

Differential protection is generally unit protection. The unit protection responds to internal faults only. The protected zone is exactly determined by location of CTS. The vector difference is achieved by suitable connections of CT or PT,s secondaries. Differential Relays are idealy suited for the protection of compact items of electrical plant such as generators, busbars, transformers, reactors, capacitors, motors, short transmission lines etc.

1.3.2.3 DISTANCE RELAYING (2,3,7)

Due to the complexity of the systems having a number of infeeds from generating stations, and the need for faster clearing times as the fault level increases the use of high speed distance relays on modern systems has become imperative. The difficulty in grading time-overcurrent relays with increasing number of switching stations, also overcome by distance Relay. The performance of distance relays is governed by the ratio of voltage to current at the relay location and the operating time of the relay automatically increases with an increase of this ratio. Now the impedance or the reactance of the circuit between the relay and the fault is proportional to the distance between them provided the relay actuating quantities (voltage and current) are properly chosen. This is the reason why such a relay is known as a distance relay.

Strictly speaking the impedance seen by the relay is not exactly proportional to the distance between the relay and the fault in general. The main reason for this is due to the presence of resistance at the fault location and presence of loads and generating sources between the relay and the fault location etc.

The factors to be considered for the selection of a distance scheme can be enumerated as speed of operation, measuring relay characteristics, fault coverage, economic considerations.[2]

In applying distance relays to transmission system it is necessary to state the relay characteristic in the same terms that the system conditions are stated. If the relay characteristics are thought of in terms of volts and amperes, than the system conditions should be stated in the same terms. With the distance relay, however, it is difficult to think in terms of volts and ampers because these values vary widely for the same relay response. It, therefore, simplified matters greatly to think of the distance relay response in terms of the ratio of voltages to amperes. However in designing distance relays it is necessary to think in terms of the volts, amperes and phase angle to which it must respond because these are the quantities which actually operate the contact actuating parts. Fig. 1.1 shows the variety of characteristic available. The names are derived from the fundamental torque equations which, when solved for the particular characteristic desired. The relay will operate whenever the combination of R & x falls within its characteristic. Relay location is the origin of the plot. The transmission line being protected can be drawn directly on the plot in the first quadratant and so the extent of the relay protection is immediately apparent.

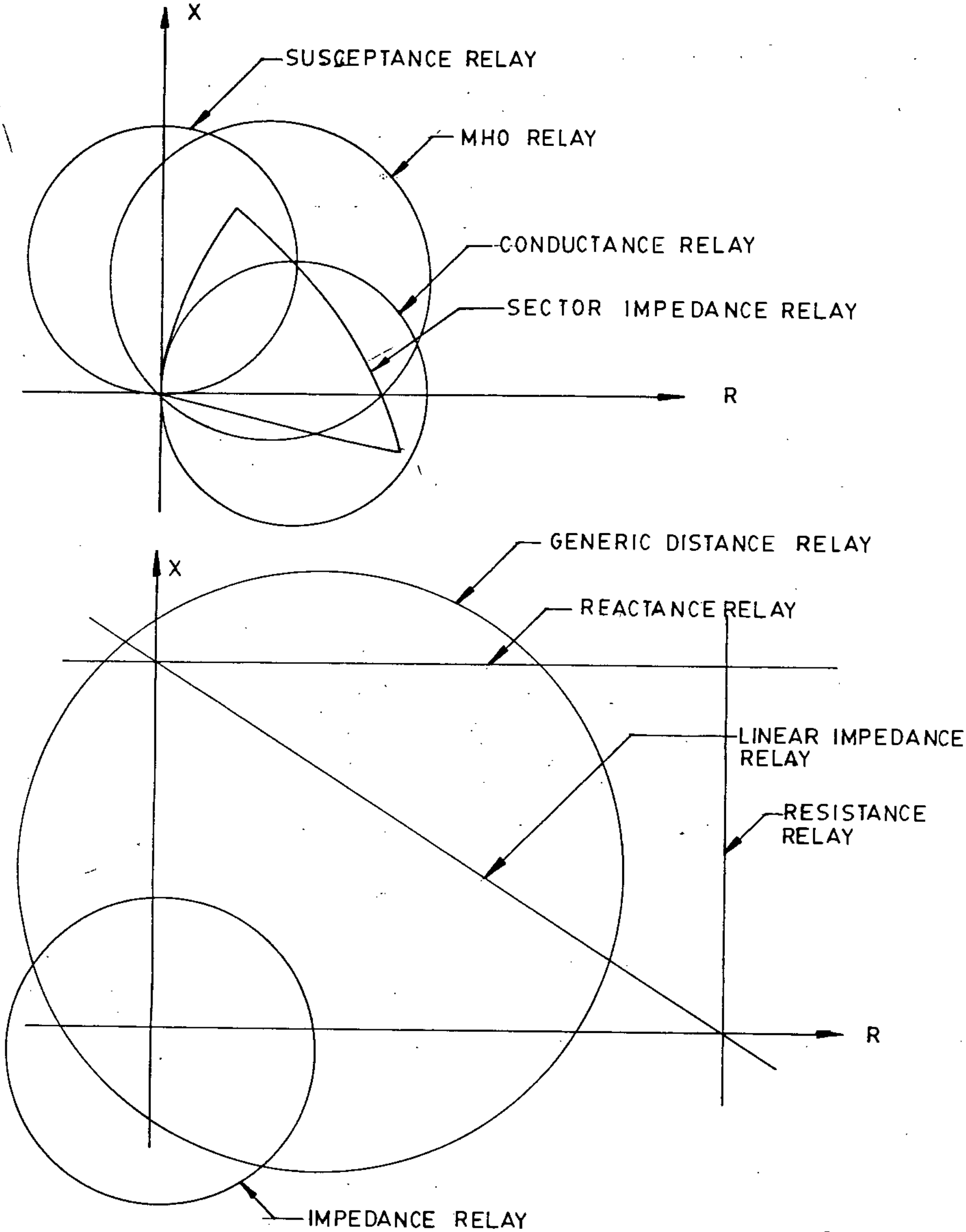


Fig. 1.1. General operating characterestics of distance relay.

Depending upon the characteristic, principle types of distance Relays are impedance, reactance, admittance, ohm and off set mho. The impedance relay compares the magnitude of the voltage and the current, the ratio being the indicated impedance. The reactance relay compares the magnitude of that component of the voltage 90 degree out of phase with the current and the magnitude of the current, the ratio being the indicated reactance.

For fault near the remote end of the section, the relay is unable to determine whether the fault is just within or just beyond the end of the section. Hence an intermediate class has been introduced to include faults in the immediate neighbourhood of the end of the section on either side. If a fault falls in the first class the circuit breaker is tripped instantly. If a fault falls in the second or intermediate class, a definite time delay is introduced before the circuit breaker is tripped and if the fault falls in the third class, the circuit breaker either is not tripped or is tripped only after a considerably greater-time-delay. This is shown in fig. 1.2.

Distance protection is non-unit protection. It is a high speed and simplified protection. It can be used as a primary and Back-up protection. Distance Relay is widely used in protection of transmission lines.

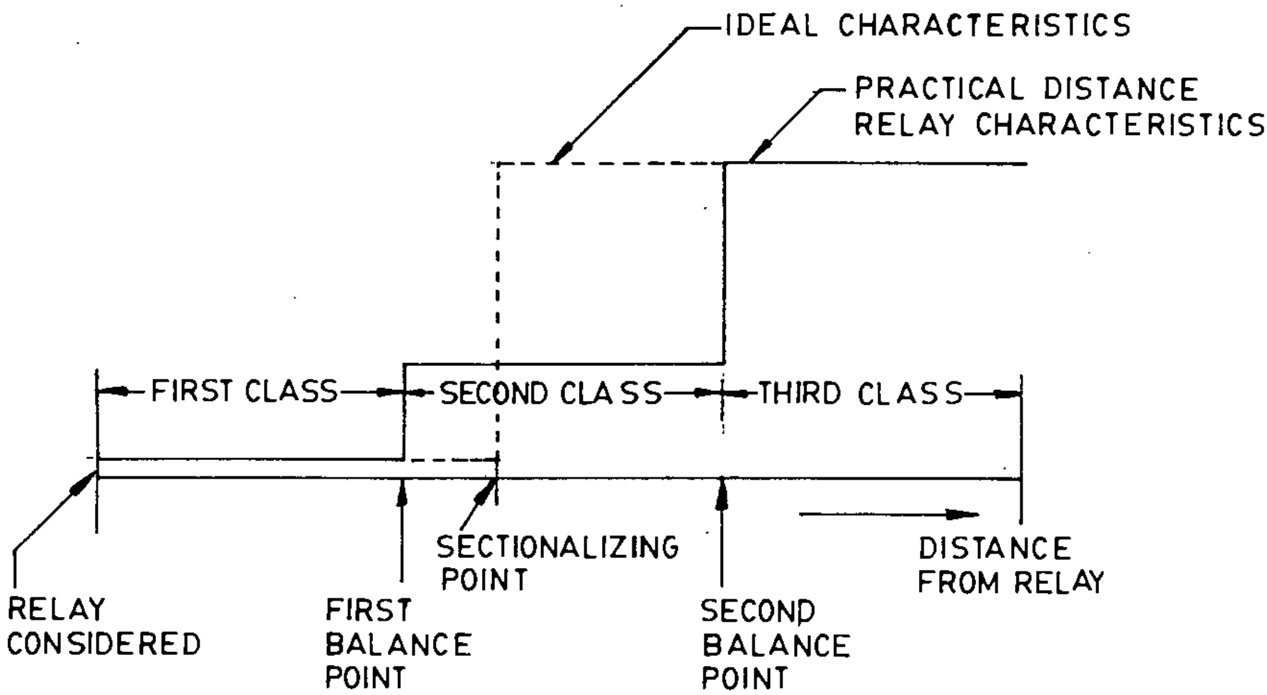


Fig. 1.2. Ideal and practical distance relay characteristics.

1.3.3 COMPARISONS BETWEEN DIFFERENT SCHEMES

Protective relaying is necessary with almost every electrical plant and hardly any part of the power system is left unprotected. The choice of protection depends upon several aspects such as type and rating of the protected equipment, its importance, location, probable abnormal conditions, cost etc[3].

The operation of the overcurrent relay depends upon the excess of current. So these relays are less sensitive because they can not make correct distinction between heavy load conditions and minor fault condition. But differential relays are free from these difficulties. Overcurrent protection includes the protection from over loads. Over loading of a machine or equipment means the machine is taking more current than its rated current. Hence with over loading there is an associated temperature rise. The permissible temperature rise has a limit based on insulation class and material problem[3]. On the other hand, overcurrent relays have the advantage that they offer the cheapest and the simplest protection for line.

Differential protection is generally unit protection[2]. Unit protection provides fast selective clearing. The protected zone is exactly determined by location of CTS. The impedance of the pilot cables of a current differential relay generally cause a slight difference between the currents at the two ends of the section to be protected. If the relay is very sensitive than the small differential current flowing through the relay may cause it to operate even under no fault conditions•pilot cable capacitance cause incorrect operation of the relay. Differential protection is suitable for protection of cables of relatively short lengths due to the capacitance of pilot wire.

The distance relay is a non-unit form of protection offering considerable economic and technical advantages on medium voltage and high voltage feeder. Being of the non unit types distance schemes automatically provide back-up protection to adjacent feeder section. Selectivity is often achieved by a directional feature which is either inherent to the distance relay itself. Distance relaying is employed where time and current graded overcurrent relaying is too slow or selectivity is not obtainable from them.[1]

Time graded overcurrent relaying is not suitable for ring mains or interconnected long distance transmission lines where rapid fault clearing is necessary to ensure stability of system but this system is suitable for radial feeder in which power flow is only in one direction. Different types of distance relays are suitable for different length lines. For very short lines reactance type is preferable because it is practically unaffected by arc resistance. Impedance relay is better suited for phase fault relaying for lines of moderate lengths (2,3). The effect of arc on impedance is more than in a reactance relay but less than a mho relay. Mho relays are suitable for longer lines.

1.4 DIGITAL DISTANCE RELAY (6,7,8)

The use of digital computers for protection of power system equipment is of relatively recent origin. A computer have several inherent advantage that make it attractive and provide incentive for further work on digital protection of transmission lines. For relaying this is particularly desireable since it permits constant monitoring and self checking. It also has the ability to consolidate logical functions of many devices in one processor unit, thus possibily avoiding duplication in situation where many separate piece of equipment use identical inputs or perform similar function. Finally in an integrated station concept there is potential for significant economics.

Computers relaying however is not inherently free of many of the problems that beset electro-mechanical or solid state relays. Input signal errors caused by transient dc offsets and CT saturation must still be recognized and considerable.

Distance relays form a key element of a protection system,and consequently a great deal of attention has been given to the problem of implimenting distance relay on digital computers[7]. Some relays which use a digital processor for computing the impedance and making decision have been developed in the last few years. The algorithms used to calculate the apparant impedance used in this relays can be catagorized into four groups. The first group is developed assuming that the waveforms presented to the relay are pure sinusoids. The second group of algorithm use fourier analysis and the third group used digital filters to extract the fundamental frequency information from the input. The last group of algorithms numerically solve a differential equation which describes the behaviour of the transmission lines[8].

In all digital relays, voltage and current outputs of the transducers are preprocessed and converted to milli-volts lvel. Preprocessed signals of the milli volt level are converted to numerical values by analog-to-digital converter. The digital information is then provided to a processor which analyzes the information and makes appropriate decision. Fig. 1.3 shows the block diagram representation of digital Relay.

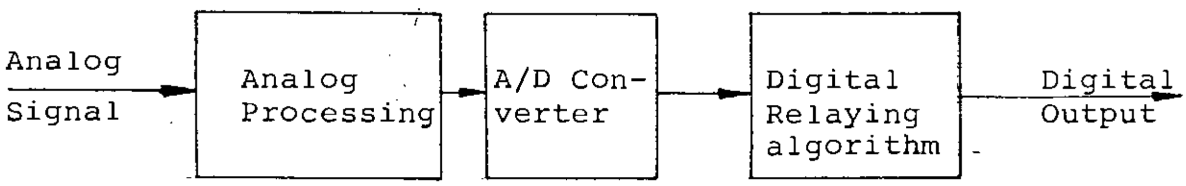


Fig. 1.3 Simplified Block diagram of a digital relay.

The line protection with digital computer working group developed a set of criteria to describe the performance of digital distance relays. The special criteria are speed (algorithm time, total time), selectivity (fault locations, fault type), Accuracy, reliability, Fault wave form specifications. Other important characteristics that should be considered are special processor requirements, memory requirement, substation environment requirement, power supply constraints, compatibility with other system used in the substation, adaptability, diagnostics, self-cheeking and the man machine interfaces[6].

1.5 LITERATURE SURVEY

The field of power system protection has been the subject of a great deal of analysis and different types of protective Relays have been developed for this purpose. Of these, the distance relay is one of the major tools for power system protection. Research abstracts and many references to such work are found in the literature. Some of the more important ones, relivant to the present study, are discussed in this section.

In 1947, W.A. Lewis and L.S. Tippett have presented a paper[9] on fundamental basis for distance relaying on 3-phase system. In this paper, they have discussed that the faults occurring on any power system are devided into two general types; the first consisting of line fault involving two or more conductors and the second consisting of ground faults involving one conductor and ground. They have then demonstrated the use of different relaying technique to obtain the relaying current and voltage for relay operation. The analyses has been based upon the assumption of sine wave currents and voltages, constant circuit impedance and negligible distributed capacitance in the faulted sections of the line. They also assumed further that the fault impedance consists of resistance only and is effectively constant throughout a cycle. They, however, do not provide any justification for these assumptions.

In 1958, W.K. Sonnemann and H.W. Lensner developed a methodology[10] for distance relaying based upon compensator technique. In this system, they proposed the use of two polyphase relay units—one of the units responding to all phase-to-phase faults, regardless of which pair of phases is faulted, and the other unit responding to 3-phase faults. They claim this to be a high speed distance relaying scheme for use with or without power line carrier or microwave. But they do not provide any scheme for single phase to ground fault.

In 1966, G.D. Rockefeller developed a basis[11] for designing distance relays that would detect ground faults in a preset zone of transmission lines. Used in conjunction with timers, the proposed scheme would provide step-distance protection.

These relays were inherently directional and are non reactance type which was the key to schemes simplicity. The relays would, however, be unable to detect a phase to phase fault. He also advocated in his paper that directional sensing as well as a phase selector must be added in these relays so as to be able to detect which phases in grounded. Because of these supervision requirements, a single zone relay becomes excessively complex.

In 1971, Barry J. Mann and I.F. Morrison proposed a method of distance type protection suitable for on line digital computer protection of transmission lines[12]. The basic principle is the predictive calculation of peak fault current and voltage from a small number of sample values. From these the transmission line impedance can be calculated and fault condition detected and measured by the drop in impedance. The author, however, noted that different inherent numerical errors due to numerical differentiation, presence of noise etc may give rise to problems and it is essential to avoid these errors for proper operation.

G.B. Gilerest, G.D. Rockefeller and E.A. Udren in their paper[13,14], suggested a method which provides high-speed phase and ground distance fault protection of 230 KV transmission lines. In this method the stored program performs all of the relaying functions using the output of an A/D converter which reads the instantaneous values of the power system currents and voltages.

M.S. Sachdev and M.A. Baribean in their paper[8] present a new algorithm suitable for calculating impedances from digitized voltages and currents sampled at a relay location. The algorithm assumes that the input is composed of a fundamental frequency component, a decaying d.c. and harmonics of specified order. Parameters of a digital filter, determined by using the least error squares approach, are then used to compute the real and imaginary components of the voltage and current phasors. Impedances as seen from a relay location are than calculated. They also mention that for development of algorithm it is essential to choose a proper sampling rate, data window, time references etc.

Adly A. Girgis and R. Grover Brown in their papers [15] proposed a method of digital distance relaying technique using kalman filtering. Kalman filters, as recursive optimal estimators, are used to optimally estimate the 60HZ voltage and current components. They pointed out that the kalman filtering based algorithm is especially well suited to on-line digital processing because the noisy input data being processed recursively. The filter is initialized with an initial estimate of the signal and its error coveriance. The paper, however, does not discuss the relative accuracy of this method.

A series of papers [16,17,18] by A.G. Phadke, T. Hlibka, M.G. Adamiak and M. Ibrahim discussed digital distance relaying technique using symmetrical component theory. In their first paper [16] they developed a single performance equation of distance relay for handling all types of faults which are likely to occur on a three-phase system. In this paper they also mentioned that symmetrical component relay is suitable for digital computer application and it is a high speed distance relay and is simple to apply. In their second paper [17] they discussed about digital computer implementation of the symmetricals component distance relay (SCDR) and a micro computer based hardware system suitable for this task. In their third paper [18] they describe the field tests of a micro computer based ultra high speed distance relay.

1.6 SCOPE OF THE PRESENT WORK

Computerised relaying is becoming a well-known research area for power system engineers. Computerised relays have the great advantages of accuracy in detecting fault and operation of relay over mechanically operated relays. Different methods are being investigated in devising a suitable way of calculating fault distance and in fault-type detection. Of these, the symmetrical component approach is found to be very sound and reliable in these respects. Some research is being carried out in exploring a method of distance relaying using symmetrical component. But practical application has not yet been established in this area.

The objective of this research is to present an analytical basis for distance relaying using symmetrical component concept. The biggest advantage of computerized distance relaying using symmetrical component is the use of a single performance equation for arbitrary types of faults. Conceptually, the use of a single equation to determine the distance to a fault is equivalent to using a single impedance unit which responds correctly to all fault types. The input to the symmetrical component distance relay are the symmetrical components of voltage and current. The symmetrical components of voltages and currents can be readily obtained from their respective sample waveform data under steady state as well as transient systems condition using discrete fourier transform (D.F.T) filtering technique. The D.F.T. filtering must be accomplished in such a way so that fundamental frequency component must be extracted from their sampled data without introducing excessive delay in the overall relaying process. The symmetrical component discrete fourier transform (S.C.D.F.T) is, therefore, chosen as the basis of the investigation reported here.

The work starts with an explanation of different type of faults which usually occur in a power system and the different type of protective relays which are involved in overcoming these faults. A comparative study of the available methods is also provided.

The next step is a detailed investigation into the discrete fourier transform technique and an attempt at refinement of the method so as to develop it as the basic tool of analysis in the present work.

Finally, a computer program is developed for detecting the type of fault and the distance of fault from the relay location. The program, is then tested on a model power system. The performance under different system conditions is investigated to check the correctness of the response. The method is then applied to a realistic power system. The simulated data are fed in to the program and fault results obtained is investigated.

CHAPTER - 2

2.0 FUNDAMENTAL BASIS FOR DISTANCE RELAYING USING SYMMETRICAL COMPONENT

2.1 INTRODUCTION

This chapter consist of development of distance relay performance equation based upon the theory of symmetrical components. This performance equation is used to determine location of fault, detection of type and phase of fault.

Fig. 2.1 shows a block diagram representation of the method. In section 2.5 expression for the distance up to fault for different type of faults are developed. Finally flow diagram (fig. 2.8) for calculating type and location of fault are discussed in section 2.7.

2.2 BLOCK DIAGRAM REPRESENTATION OF THE PRESENT WORK

First of all a computer program for SCDFT will be developed in order to obtain symmetrical component voltages and currents from the sample wave form data. Next, the computer program for symmetrical component distance relay will be developed and the symmetrical component data will be fed into the SCDR program in order to obtain fault results such as location of fault, type of fault and phases of fault. Finally the developed computer program will apply on a model power system and a large power system for investigation. The block diagram for the method is shown in Fig. 2.1.

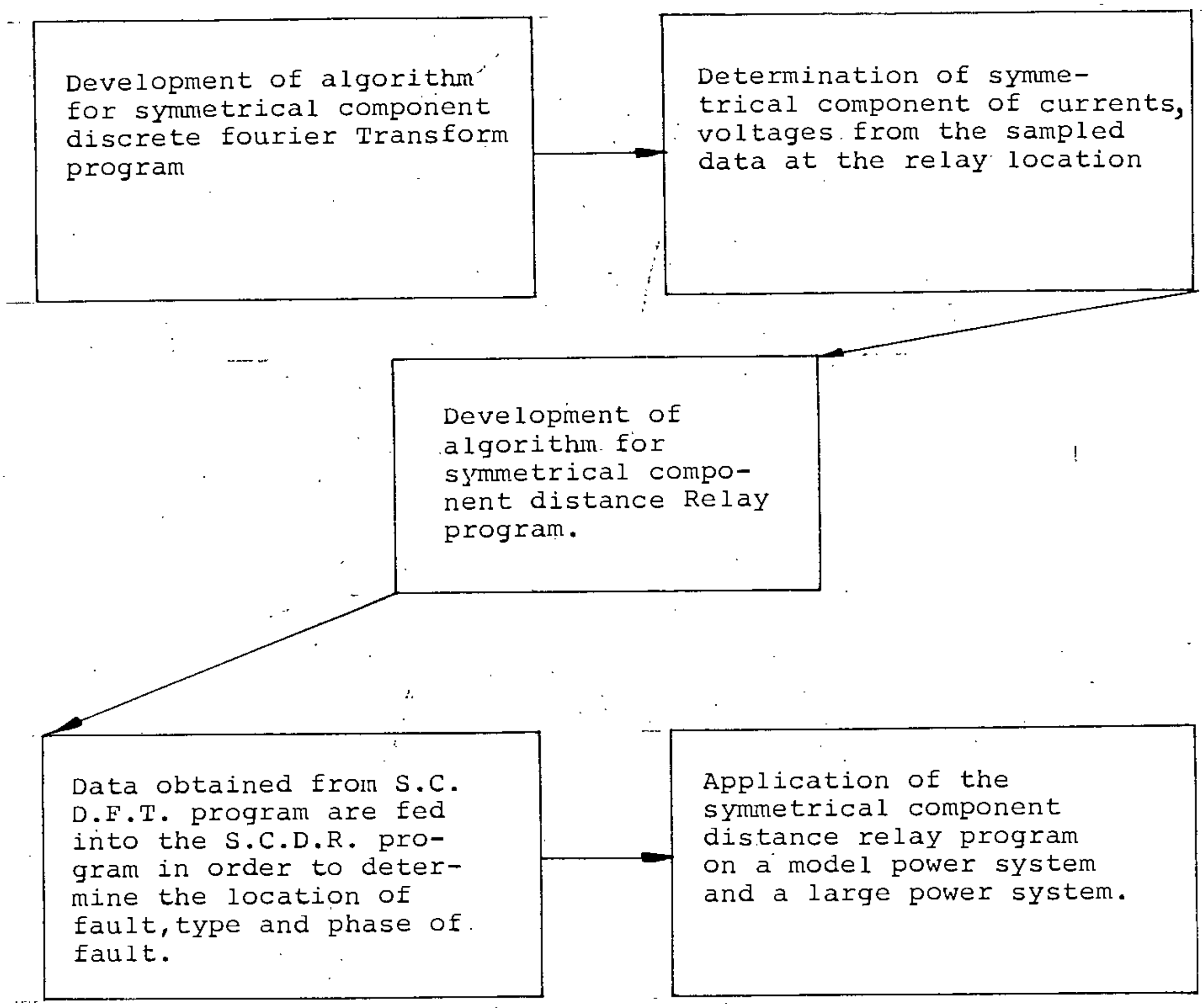


Fig. 2.1: Block diagram representation of the present work

2.3 BASIS FOR SYMEETRICAL COMPONENT FAULT ANALYSIS

An unbalanced system of n related phasors can be resolved into n systems of balanced phasors called the symmetrical components of the original phasors. This is the fundamental concept of symmetrical components which was introduced by Dr. Fortescue.(19) The n phasors of each set of components are equal in magnitude and the angular displacement between adjacent phasors of the set are equal. A more convenient method of analyzing unbalanced operation is through symmetrical components where the three phase voltages (and currents) which may be unbalanced are transformed into three sets of balanced voltages (and currents). Fortunately, in such a transformation the impedances presented by various power system elements (synchronous generators, transformers, lines) to symmetrical components are decoupled from each other resulting in independent system networks for each component (balanced set). This is the basic reason for the simplicity of the symmetrical component method of analysis.

Most of the faults that occur on power systems are unsymmetrical faults which may consists of unsymmetrical short circuit,unsymmetrical faults through impedances. Unsymmetrical faults occur as single line to ground faults,line-to-lie-faults or Double line-to-ground fault. Since any unsymmetrical fault causes unbalance currents to flow in the system, the method of symmetrical components is very useful in an analysis to determine the current and voltages in all parts of the system after the occurrence of the fault.

The utility of symmetrical component theory follows from the simplicity it introduces in calculation of unbalanced system fault conditions for an otherwise balanced system. For all unbalanced fault which are symmetric with respect to the reference phase, the resulting symmetrical component equations and equivalent circuits are especially simple. For unbalanced faults which are unsymmetric with respect to the reference phase the coresponding equations and equivalent circuits contain complex multiple of α and α^2 (See Appendix -A). This complication is of no consequence in most fault studies where the fault can always be assumed to be symmetric with respect to the reference phase without any loss of generality.

2.4 DEVELOPMENT OF THE DISTANCE RELAYING FORMULA

In order to develop the performance equation of the symmetrical component distance relay let us consider a sample system (see Fig. 2.2) consisting of two buses P & Q with the power system behind buses P & Q represented by three phase Thevenin sources E_G (Z_{0G}, Z_{1G}, Z_{2G}) and E_H (Z_{0H}, Z_{1H}, Z_{2H}) respectively. The relay under consideration is assumed to be at the P-terminal of the line. Various type of faults will be placed at B which is assumed to be at a fractional distance k from bus P, K being the ratio of the distance between P and B to that between the total distance PQ. The fault at B will be assumed to have a resistance R_f in the fault path. Bus W is a fictitious bus within the fault arc path.

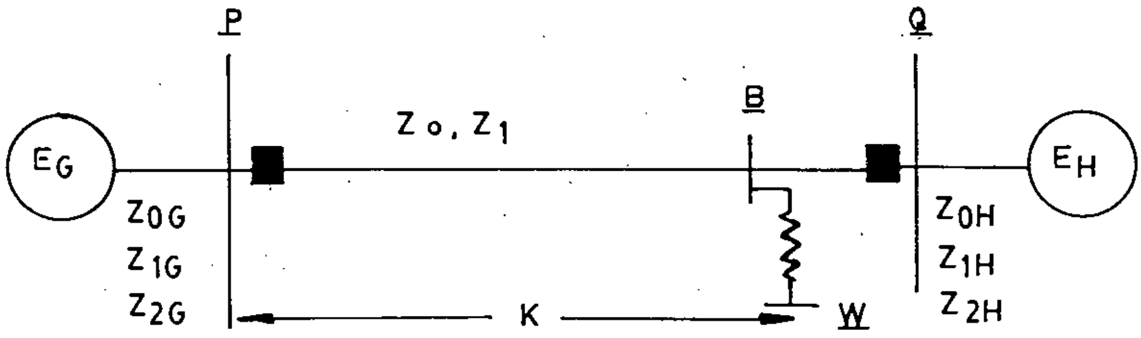


Fig. 2.2 Sample system;single line diagram

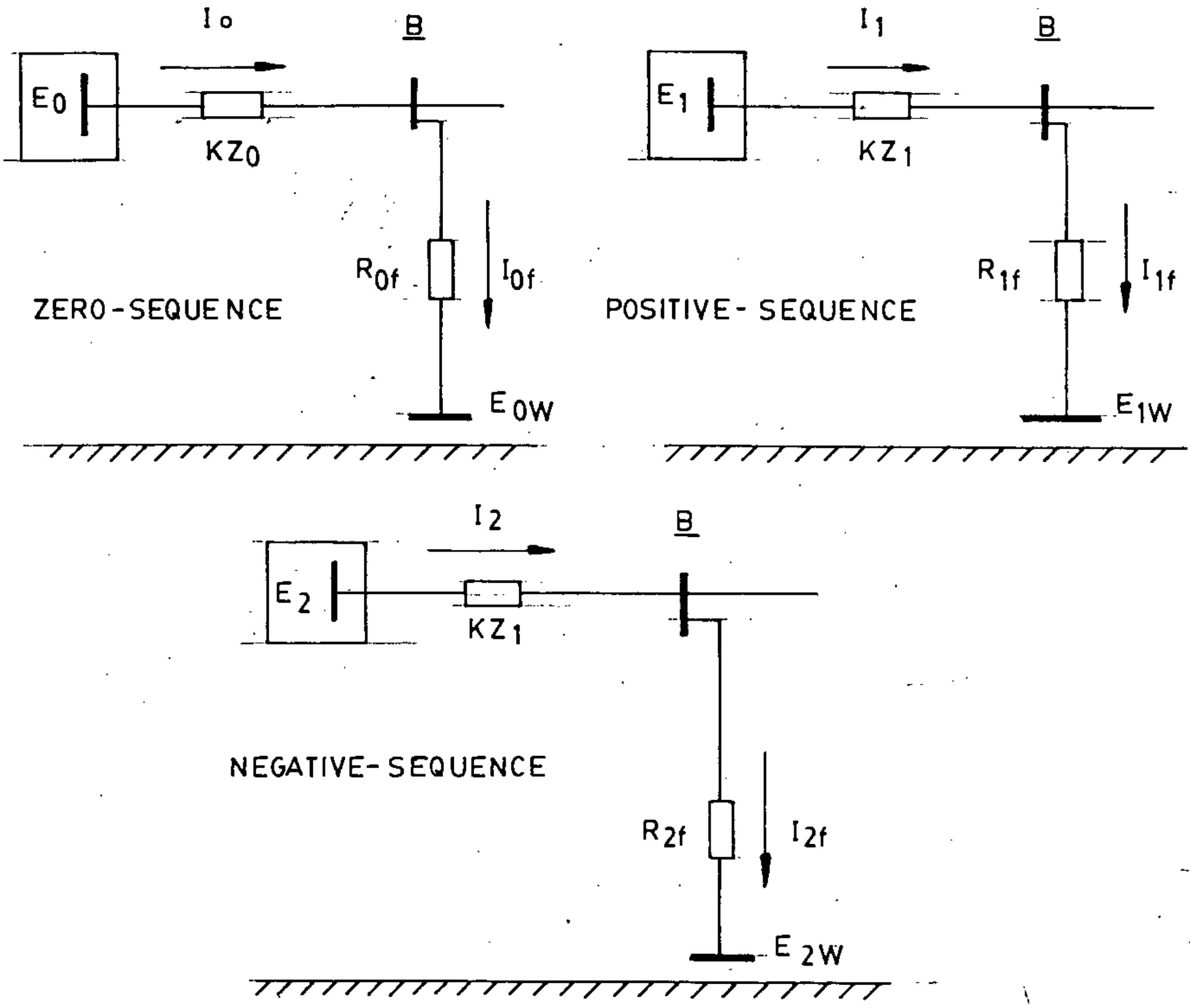


Fig. 2.3 Voltages and currents during fault at $\overline{B}$

The symmetrical components of voltages and current at terminal P of the line will be considered to be the input to the relay under consideration. Consider the occurrence of a fault at B through the fault path resistance. The resulting voltages and currents in the network are shown in fig. 2.3. The relevent performance equations are (See Appendix-B).

$$E_{ow} = E_o - KI_oZ_o - R_{of}\,I_{of}$$

$$E_{1w} = E_1 - KI_1Z_1 - R_{1f}\,I_{1f} \qquad 2.1$$

$$E_{2w} = E_2 - KI_2Z_2 - R_{2f}I_{2f}$$

For a transmission line, $Z_1=Z_2$; I_{of}, I_{1f}, I_{2f} are the symmetrical component of the fault current.

The change of line currents because of the fault are

$$\Delta I_o = I_o - \bar{I}_o \simeq I_o$$

$$\Delta I_1 = I_1 - \bar{I}_1 \qquad 2.2$$

$$\Delta I_2 = I_2 - \bar{I}_2 \simeq I_2$$

where $\bar{I}_o$, $\bar{I}_1$, $\bar{I}_2$ are prefault currents

using ΔI,S in equation 2.1.

$$E_{ow} = E_o - K\Delta I_oZ_o - R_{of}\,I_{of}$$

$$E_{1w} = E_1 - K\Delta I_1Z_1 - K\bar{I}_1Z_1 - R_{1f}I_{1f} \qquad 2.3$$

$$E_{2w} = E_2 - K\Delta I_2Z_2 - R_{2f}\,I_{2f}$$

The voltage drops are then,

$$\Delta E_o = \Delta I_oZ_o$$

$$\Delta E_1 = \Delta I_1 Z_1$$

$$\Delta E_2 = \Delta I_2 Z_2 \qquad 2.4$$

and the ratios are

$$K_o = \frac{E_o}{\Delta E_o}$$

$$K_1 = \frac{E_1}{\Delta E_1}$$

$$K_2 = \frac{E_2}{\Delta E_2} \qquad 2.5$$

$$K_L = \frac{Z_1 \bar{I}_1}{\Delta E_1}$$

Equation 2.3 can now be expressed in terms of these rations as

$$E_{ow} = \Delta E_o (K_o - K) - R_{of} I_{of}$$

$$E_{1w} = \Delta E_1 [K_1 - K(1+K_L)] - R_{1f} I_{1f} \qquad 2.6$$

$$E_{2w} = \Delta E_2 (K_2 - K) - R_{2f} I_{2f}$$

The first three ratios introduced in equation 2.5 are between voltages and voltage drops of the same sequence and the last ratio k_L is between currents of the same sequence.

2.5 EXPRESSION FOR DISTANCE UPTO FAULT

2.5.1 THREE PHASE TO GROUND FAULT

The symmetrical component representation for this fault is shown in fig. 2.4. It is obvious that only the positive sequence network is of significance. The fault imposes the boundary condition $E_{1w} = 0$ at bus W. Substituting this condition in second of equations 2.6 leads to (See Appendix-B).

$$K = \frac{K_1}{1+k_L} + \varepsilon_r \qquad 2.7$$

where $$\varepsilon_r = \frac{-R_{1f} I_{1f}}{\Delta E_1 (1+k_L)} \qquad 2.8$$

ε_r denotes the term depending upon R_{1f}.

2.5.2 SINGLE LINE TO GROUND FAULT

The symmetrical component representation for single phase to ground faults is shown in fig. 2.5. Boundary conditions imposed:

i) Phase 'a' to ground fault.

$$E_{1w} + E_{2w} + E_{ow} = 0 \qquad 2.9$$

$$\Delta E_1 = \Delta E_2$$

ii) Phase 'b' to ground fault.

$$\alpha^2 E_{1w} + \alpha E_{2w} + E_{ow} = 0$$

$$\alpha^2 \Delta E_1 = \alpha \Delta E_2 \qquad 2.10$$

iii) Phase 'c' to ground fault

$$\alpha E_{1w} + \alpha^2 E_{2w} + E_{ow} = 0$$

$$\alpha \Delta E_1 = \alpha^2 \Delta E_2 \qquad 2.11$$

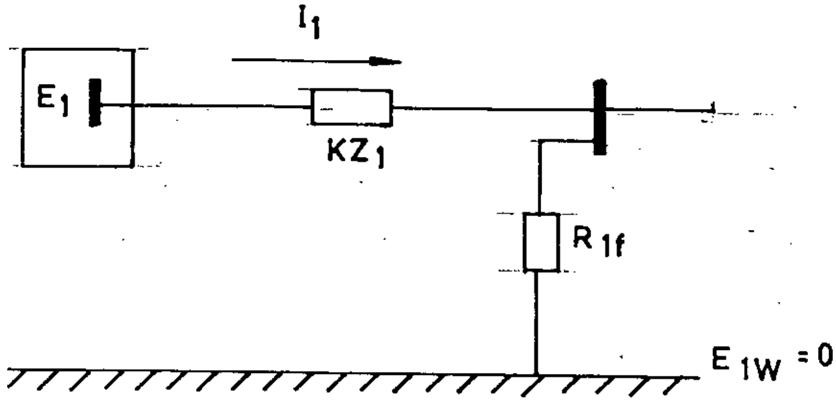
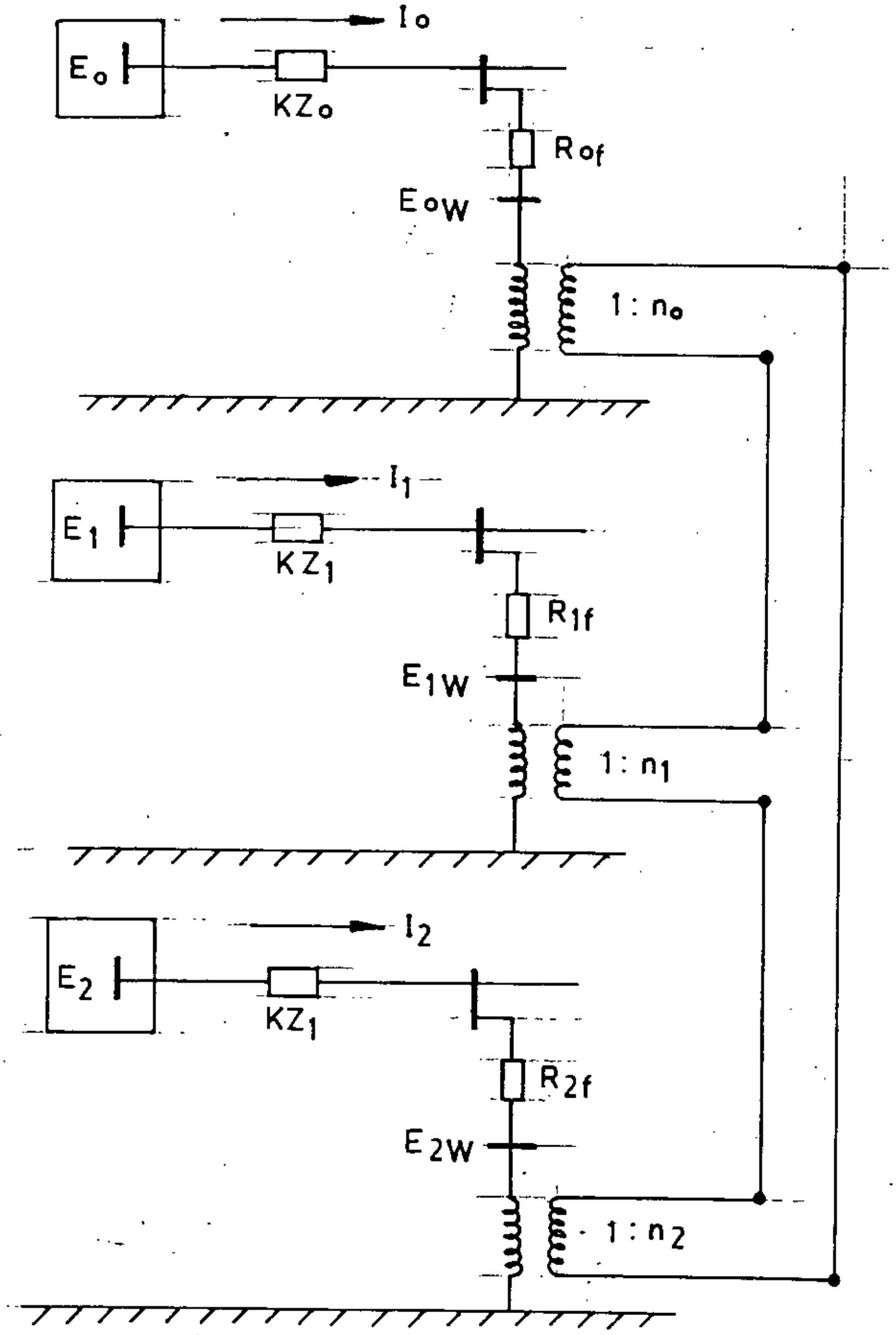


Fig. 2.4. Symmetrical component representation for A three phase fault



FAULT	n_o	n_1	n_2
a - g	1	1	1
b - g	1	α^2	α
c - g	1	α	α^2

Fig. 2.5. Symmetrical component reresentation for phase to ground fault

Using these boundary conditions in equation 2.6 leads to the following expression for K (See Appendix-B)

$$K = \frac{K_1 + K_2 + K_o K_o'}{2 + K_L + K_o'} + \varepsilon_r \qquad 2.12$$

where, for a-g fault

$$\varepsilon_r = \frac{-(R_{of}\, I_{of} + R_{1f}\, I_{1f} + R_{2f}\, I_{2f})}{\Delta E_1\ (2 + K_L + K_o')} \qquad 2.13$$

for b-g fault

$$\varepsilon_r = \frac{-(R_{1f}'\, I_{1f} + \alpha^2 R_{2f}\, I_{2f} + \alpha R_{of}\, I_{of})}{\Delta E_1\ (2 + K_L + K_o')} \qquad 2.14$$

for c-g fault

$$\varepsilon_r = \frac{-(R_{1f}\, I_{1f} + \alpha R_{2f}\, I_{2f} + \alpha^2 R_{of}\, I_{of})}{\Delta E_1\ (2 + K_L + K_o')} \qquad 2.15$$

and $K_o' = \dfrac{\Delta E_o}{\Delta E_1}$ 2.16

2.5.3 <u>LINE TO LINE FAULT</u>

The symmetrical component representation for the three phase to phase faults in shown in fig. 2.6. Boundary conditions imposed are

i) 'b' - 'c' fault

$$E_{1w} = E_{2w} \qquad 2.17$$

$$\Delta E_1 = -\Delta E_2$$

ii) 'a' - 'b' fault

$$\alpha E_{1w} = \alpha^2 E_{2w} \qquad 2.18$$

$$\alpha \Delta E_1 = -\alpha^2 \Delta E_2$$

iii) 'a' - 'c' fault

$$\alpha^2 E_{1w} = \alpha E_{2w} \qquad 2.19$$

$$\alpha^2 \Delta E_1 = -\alpha \Delta E_2$$

Substituting these boundary conditions in equation 2.6 the expression for K becomes (See Appendix -B)

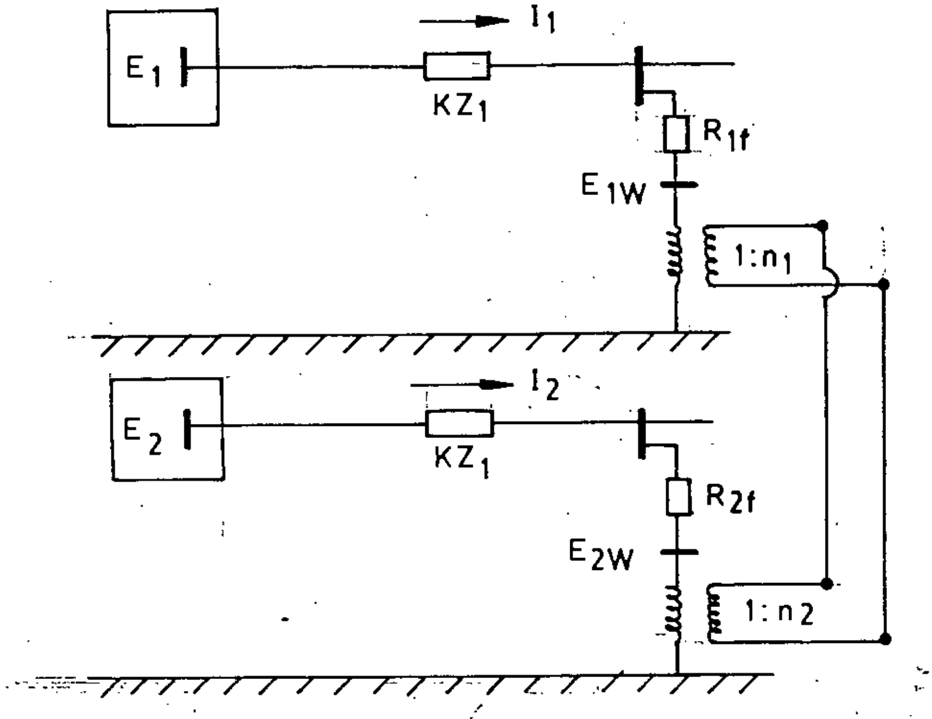
$$K = \frac{K_1 + K_2}{2+K_L} + \varepsilon_r \qquad 2.20$$

where, for b-c fault:

$$\varepsilon_r = \frac{-(R_{1f}\ I_{1f} - R_{2f}\ I_{2f})}{\Delta E_1\ (2 + K_L)} \qquad 2.21$$

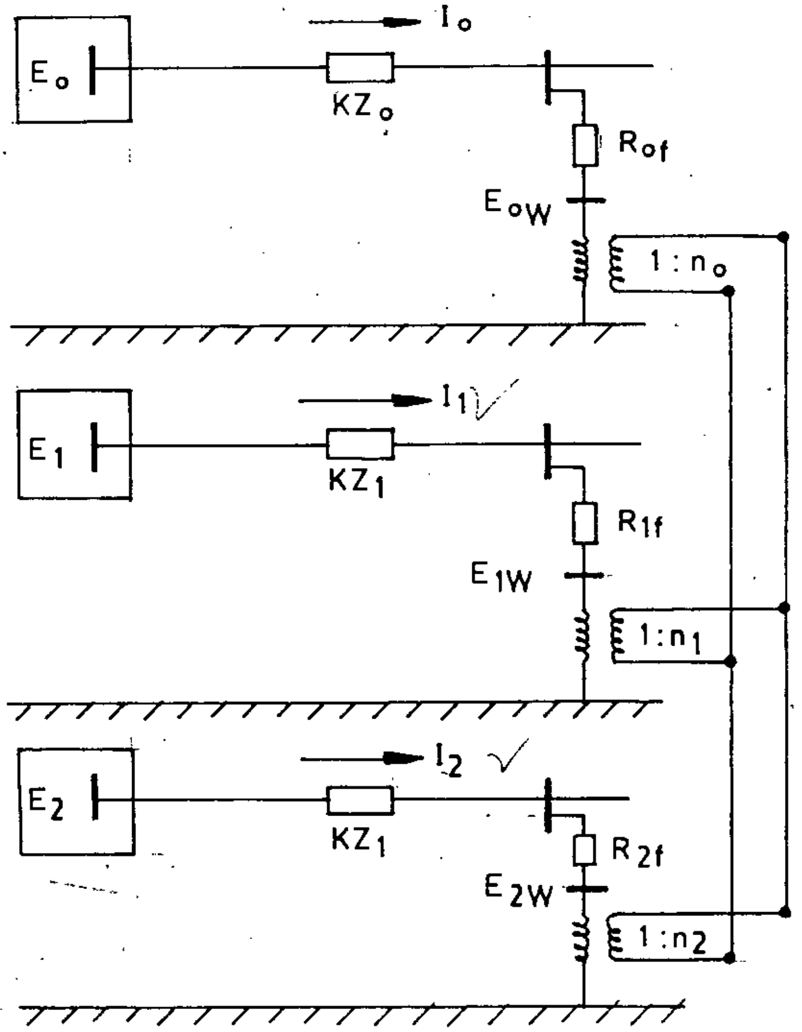
for a-b fault:

$$\varepsilon_r = \frac{-(R_{1f}\ I_{1f} - \alpha R_{2f}\ I_{2f})}{\Delta E_1\ (2 + K_L)} \qquad 2.22$$



FAULT	n_1	n_2
b - c	1	1
a - b	α	α^2
a - c	α^2	α

Fig. 2.6 Symmetrical component representation for phase to phase faults.



FAULT	n_o	n_1	n_2
b-c-g	1	1	1
a-b-g	1	α	α^2
a-c-g	1	α^2	α

Fig. 2.7 Symmetrical component representation for double phase to ground faults

for a-c fault:

$$\varepsilon_r = - \frac{(R_{1f}\ I_{1f} - \alpha^2 R_{2f}\ I_{2f})}{\Delta E_1\ (\ 2 + K_L)} \qquad 2.23$$

2.5.4 DOUBLE LINE TO GROUND FAULT

The symmetrical component representation for double phase to ground faults is shown in fig. 2.7. The boundary conditions are:

i) b-c-G fault:

$$E_{1w} = E_{2w} = E_{ow} \qquad 2.24$$

ii) a-b-g fault:

$$\alpha E_{1w} = \alpha^2 E_{2w} = E_{ow} \qquad 2.25$$

iii) a-c-g fault:

$$\alpha^2 E_{1w} = \alpha E_{2w} = E_{ow} \qquad 2.26$$

Using equation 2.6 and boundary condition the expression for K becomes (See Appendix - B).

$$K = \frac{K_1 + K_o' K_o}{1 + K_o' + K_L} + \varepsilon_r' \qquad 2.27$$

where for the b-c-g fault:

$$\varepsilon_r = \frac{R_{of}\ I_{of} - R_{1f}\ I_{1f}}{\Delta E_1 (1 + K_o' + K_L)} \qquad 2.28$$

for the a-b-g fault:

$$\varepsilon_r = \frac{\alpha^2 R_{of}\, I_{of} - R_{1f}\, I_{1f}}{\Delta E_1 \,(1+K_o' + K_L)} \qquad 2.29$$

and for the a-c-g fault

$$\varepsilon_r = \frac{\alpha R_{of}\, I_{of} - R_{1f}\, I_{1f}}{\Delta E_1 \,(1 +K_o' + K_L)} \qquad 2.30$$

2.5.5 GENERALISED EXPRESSION

The expression for K for all types of faults are given by equations 2.7, 2.12, 2.20, 2.26. Unification of these four equation is possible with the introduction of a new parameter K_2' defined as

$$K_2' = 1 \text{ when } |\Delta E_1| = |\Delta E_2| \qquad 2.31$$
$$= 0 \text{ otherwise.}$$

It will further modify the definitions of K_o and K_2 such that they are identically zero when ΔE_o and ΔE_2 are zero. The four expressions for K as indicated above are now equivalent to the single expression - (See Appendix - B):

$$K = \frac{K_1 + K_2\, K_2' + K_o\, K_o'}{1 + K_o' + K_2' + K_L} + \varepsilon_r \qquad 2.32$$

The expression represent by equation 2.32 is the generalized expression for the operating equation of symmetrical component distance relay. This equation represents per unit distance (expressed in terms of total line length) to any balanced or unbalanced fault on the transmission line.

2.6 DIFFERENT APPROXIMATIONS

In order to develop the generalized expression for distance relay a number of approximations were made. This simplifies the formulation of the problem. The main assumptions are the following:

i) The part of the system behind the buses are represented by three phase thevenin sources.

ii) Positive sequence voltages and currents are the only significant variables for balanced pre-fault conditions.

iii) The phase angle of ΔI_o and ΔI_1, $\alpha \Delta I_1$, $\alpha^2 \Delta I_1$ in three cases for phase to ground fault are approximately equal.[16]

$$\frac{\Delta E_o}{\Delta E_1}\Big|_{a-g} = \frac{\Delta E_o}{\alpha \Delta E_1}\Big|_{b-g} = \frac{\Delta E_o}{\alpha^2 \Delta E_1}\Big|_{c-g} = K'_o = \Big|\frac{\Delta E_o}{\Delta E_1}\Big| e^{J(\theta_o - \theta_1)}$$

The ratio of $\frac{\Delta E_o}{\Delta E_1}$ in a phasor with phase angle of approximately 0, $- 2\pi/3$ or $+ 2\pi/3$ depending upon whether the fault is on phase a, phase b or phase c.

v) In the operating equation of the distance relay the error due to fault resistance ε_r is neglected. Since the arc is likely to be short during the first cycle of the fault, the error due to the fault path resistance may be expected to be small for a high-speed relay. ε_r showed be neglible. So the final form of the performance equation from eqn. 2.32 is

$$K = \frac{K_1 + K_2 K_2' + K_o K_o'}{1 + K_o' + K_2' + K_L}$$

2.7 DEVELOPMENT OF THE COMPUTER PROGRAM

Fig. 2.8(a) shows the flow-diagram for calculating location and type of faults. The signals input to the relay program are symmetrical components of voltages and currents. The signals proportional to the voltage drops produced by phase and zero sequence impedances of the transmission line. The value of the ratio K_o, K_1, K_2, K_o' are than calculated from the ratio of E_o and ΔE_o, E_1 and ΔE_1, E_2 and ΔE_2, ΔE_o and ΔE_1. The magnitude of the difference of ΔE_1 and ΔE_2 is next compared against a tolerance ε_1. If this differences is greater than ε_1 in magnitude the value of K_2' is set equal to zero, otherwise the value of K_2' is one. Finally the value of K which is the location of fault is calculated. The choice of the tolerance ε_1 are discussed in section 2.8. The value of K_2' is now compared with zero. For a value of K_2' equal to zero, the magnitude of ΔE_o is compared against a second tolerance ε_2. If ΔE_o magnitude is greater than ε_2, than the type of fault is double line to ground fault, otherwise it is a three phase fault. Again for a value of K_2' not equal to zero, the magnitude of ΔE_o is compared against the tolerance ε_2. If ΔE_o magnitude is greater than ε_2, it is a phase to ground fault, otherwise it is phase to phase fault. The selection of the tolerance ε_2 are also discussed in section 2.8.

Fig. 2.8.(b) shows the flow chart for detection of phases for differnts type of faults. For single line to ground fault the magnitude of the angle of the ratio $\Delta E_1/ \Delta E_2$ is first compared with a tolerance ε_3. If magnitude of this angle is less than ε_3, it is phase 'a' to ground fault. If this angle is greater than ε_3, than the magnitude of the difference of the angle between the ratio $\Delta E_1/ \Delta E_2$ and 120^o is compared with the same tolerance ε_3. If this magnitude of the angle is greater than ε_3, it is phase 'b' to ground fault, otherwise it is phase 'c' to ground fault.

For phase to phase fault, the magnitude of the difference between the angle of the ratio $\Delta E_1/ \Delta E_2$ and 180^o is first compared with the tolerance ε_3. If the magnitude of this difference is less than ε_3, it is phase 'b' to phase 'c' fault. Again if this difference is greater than ε_3, than the difference of the angle between the ratio $\Delta E_1/ \Delta E_2$ and 60^o is compared with ε_3. If this difference is greater than ε_3, it is phase 'a' to phase 'b' fault, otherwise it is phase 'a' to phase 'c' fault.

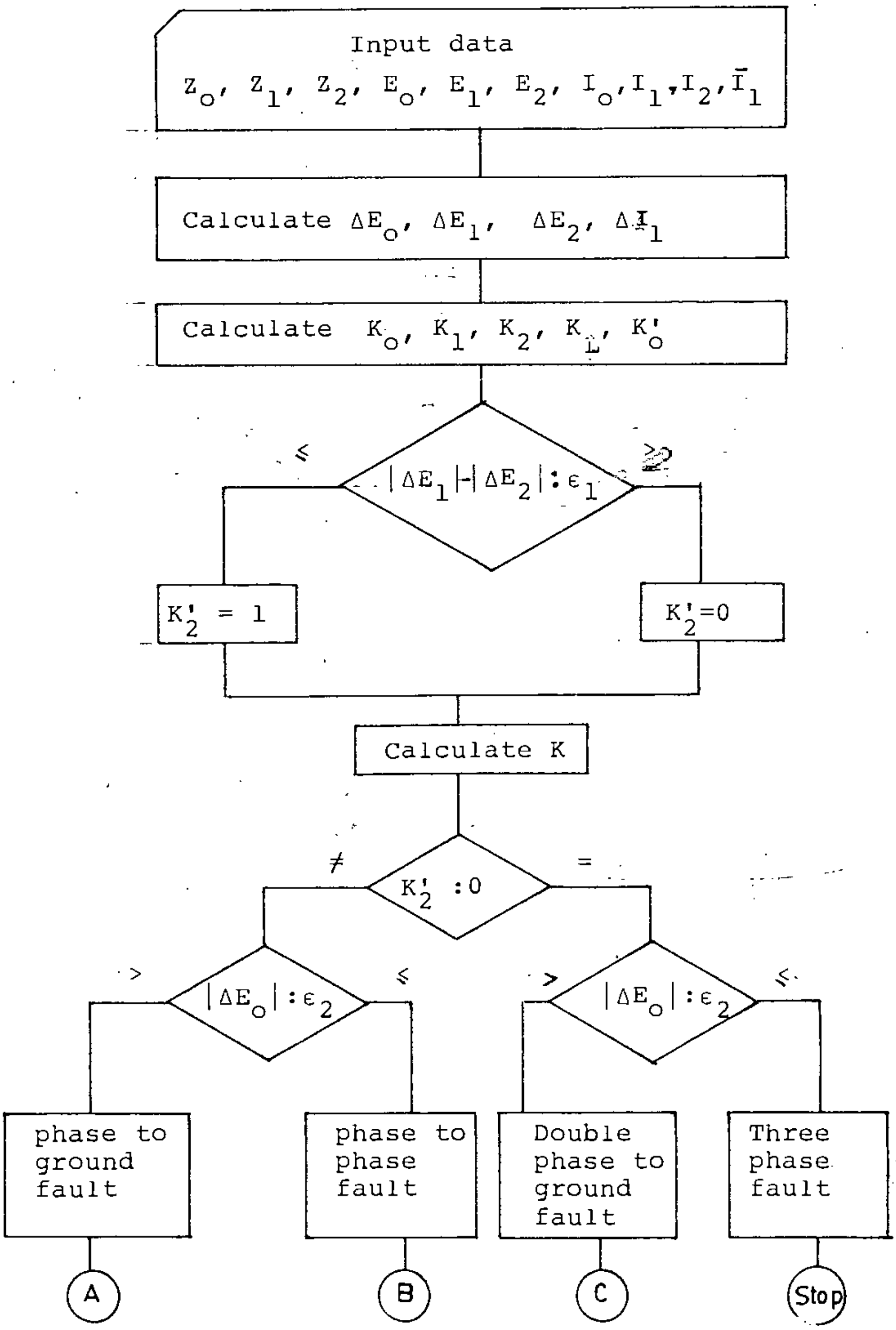
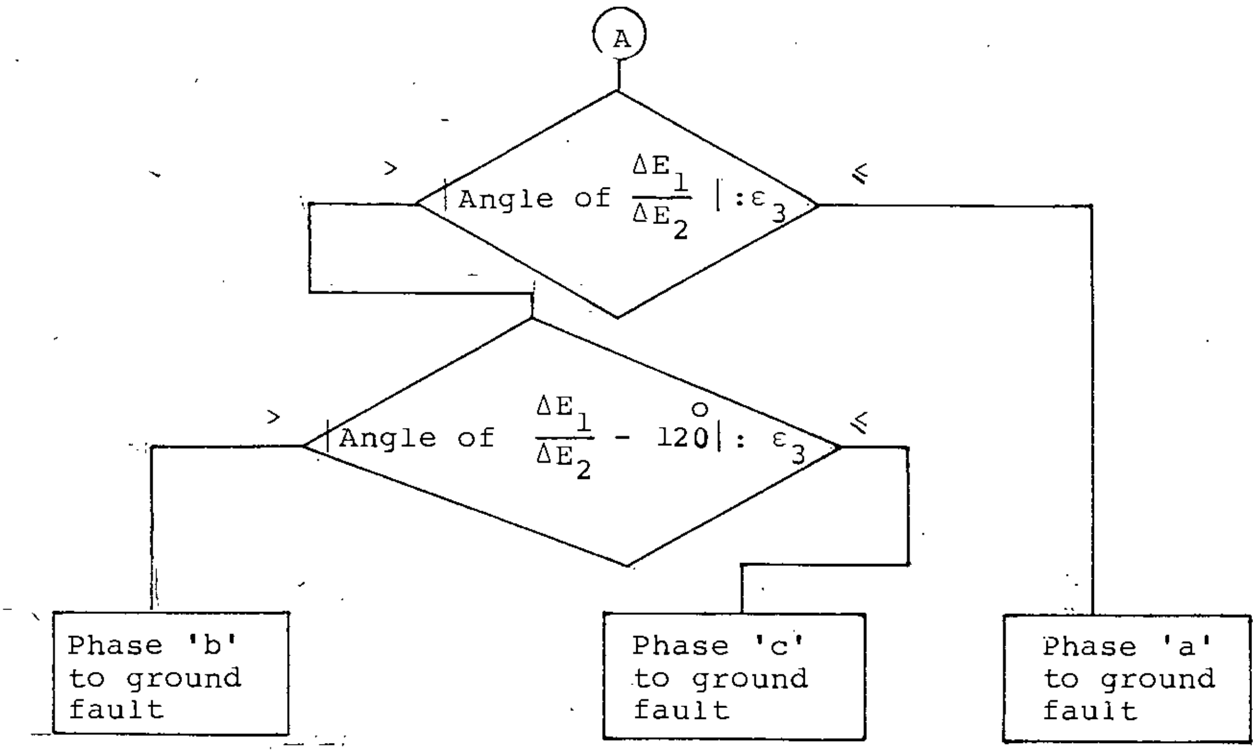
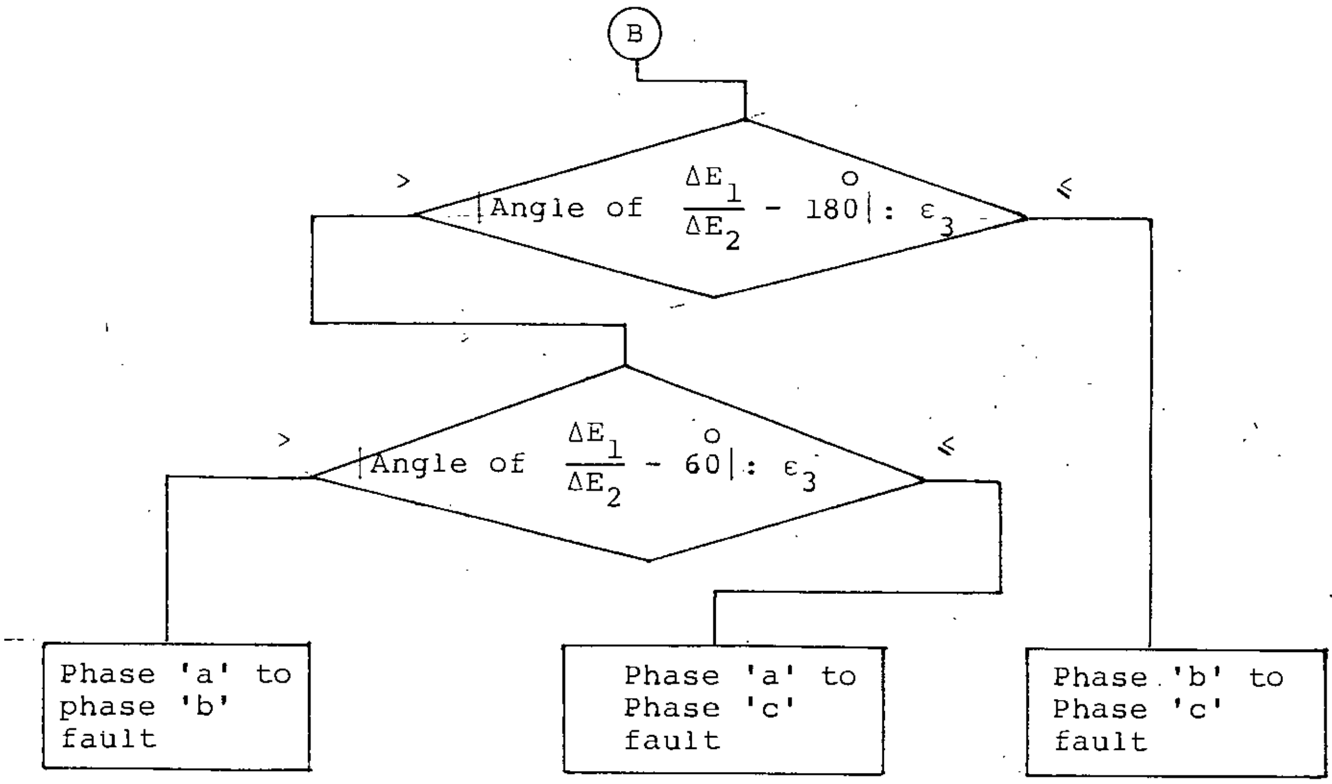


Fig. 2.8(a) Flow diagram for calculating location & type of fault


A
>
|Angle of ΔE1/ΔE2 |: ε3
≤
>
|Angle of ΔE1/ΔE2 - 120°|: ε3
≤
Phase 'b' to ground fault
Phase 'c' to ground fault
Phase 'a' to ground fault


B
>
|Angle of ΔE1/ΔE2 - 180°|: ε3
≤
>
|Angle of ΔE1/ΔE2 - 60°|: ε3
≤
Phase 'a' to phase 'b' fault
Phase 'a' to Phase 'c' fault
Phase 'b' to Phase 'c' fault

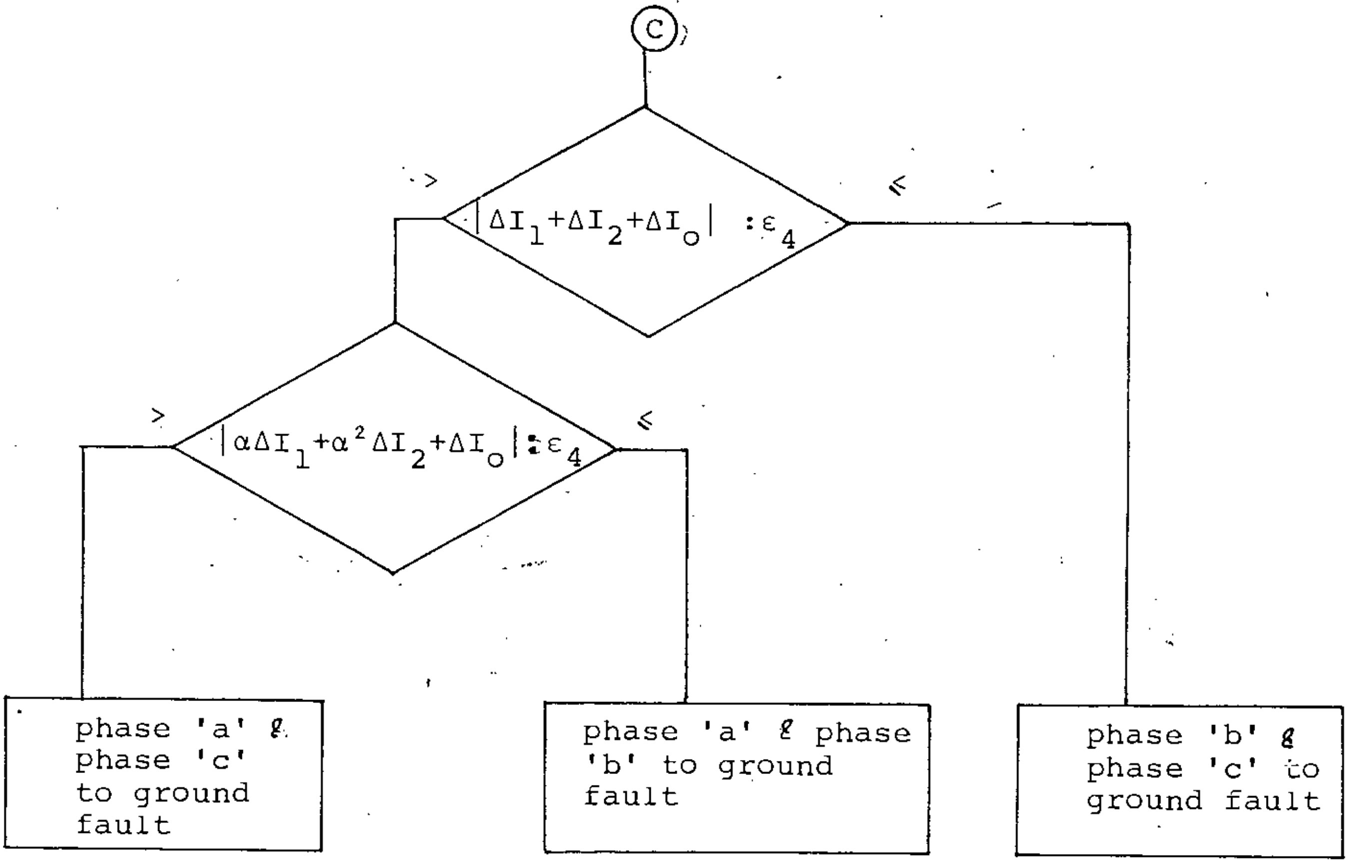


Fig.2.8(b): Flow diagram for detecting phases in different types of fault.

For double phase to ground fault, first the magnitude of the sum ($\Delta I_1 + \Delta I_2 + \Delta I_o$) is compared with the tolerance ε_4. If this sum is less than ε_4, it is phase 'b' and phase 'c' to ground fault. If this sum is greater than ε_4 than the magnitude of the sum $(\alpha\Delta I_1 + \alpha^2\Delta I_2 + \Delta I_o)$ is compared with the same tolerance ε_4. If this sum is greater than ε_4, it is phase 'a' and phase 'c' to ground fault, otherwise it is phase 'a' and phase 'b' to ground fault. (The computer program developed for this flow chart is shown in Appendix - C).

2.8 SETTING FOR TOLERANCES ε_1 AND ε_2 [17]

The tolerance ε_1 is set such that for any type of unbalanced fault on the system, the negative sequence voltage drop ΔE_2 is greater than $\varepsilon_1 . \Delta E_1$. The critical fault to consider is a double phase to ground fault, since for all other unbalanced faults, $|\Delta E_1| \simeq |\Delta E_2|$. The negative sequence voltage drop for the double phase to ground fault depends upon the ratio (Z_o/Z_1). Figure (2. 9) shows a plot of (I_2/I_1) as a function of (Z_2/Z_1). Taking the worst possible system configuration, a safe value for ε_1 can be determined. In our system ε_1 = 25% has been found to be a secure setting for all possible system conditions.

The ε_2 setting helps distinguish between ground faults and non-ground faults. This setting is also determined by considering the variation of $(|\Delta E_o| \;/\; |\Delta E_1|)$ as a function of Z_o/Z_1 for the system. Fig. (2.9) also shows the variation of (I_o/I_1) for all possible values of (Z_o/Z_1). From a consideration of worst case (Z_o/Z_1), the value of ε_2 can be determined. In our case, a value of 50% has been found to be a reliable setting for ε_2.

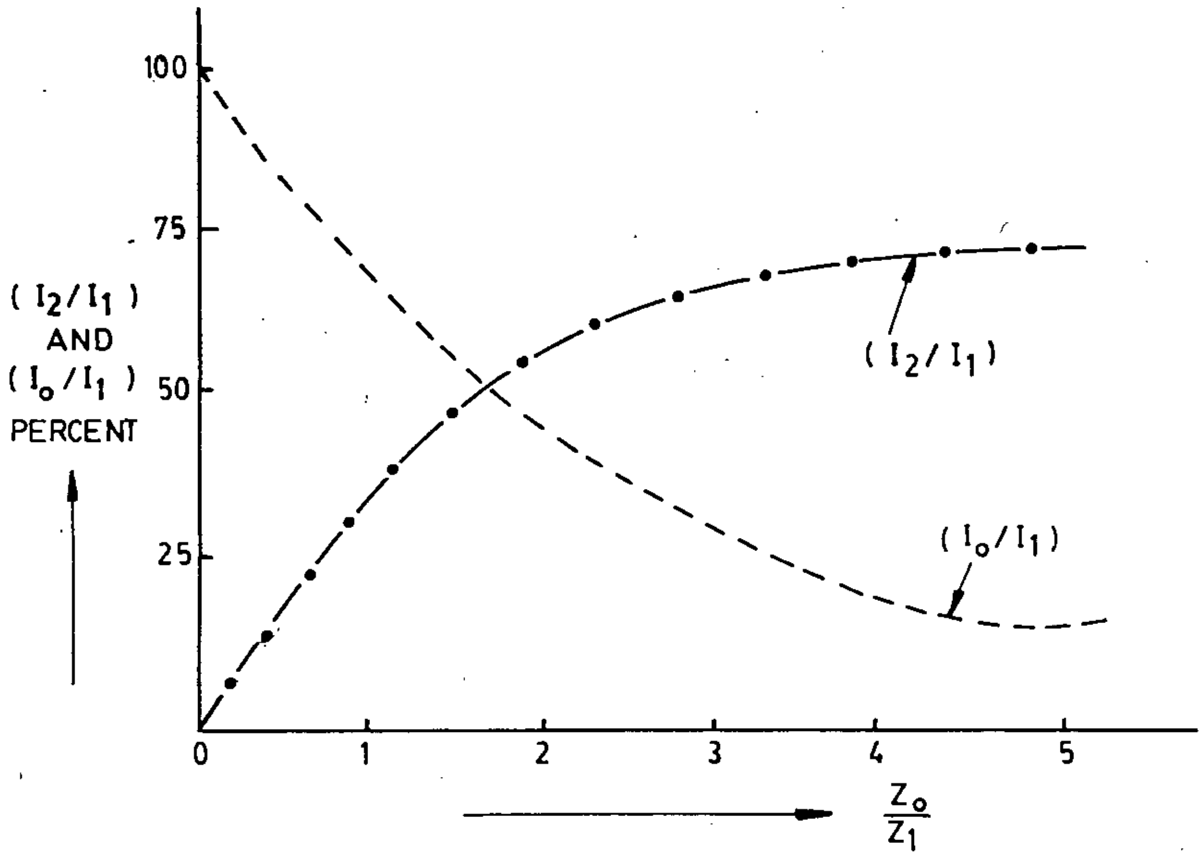


Fig.2.9 Settings for tolerances $\varepsilon_1, \varepsilon_2$

CHAPTER - 3

3.0 SYMMETRICAL COMPONENT DISCRETE FOURIER TRANSFORM

3.1 INTRODUCTION

In this chapter the analysis of discrete fourier transform technique, the algorithm for symmetrical component discrete fourier transform using DFT technique and Recursive Algorithm for SCDFT are presented. Section 3.2 consists of the description of D.F.T. technique, sampling theoreom. The choice of sampling rate, data window and time reference for S.C.D.F.T program are also discussed in this section. The development of algorithm for SCDFT and Recursive Algorithm are presented in section 3.3. Finally an algorithm for computer program for SCDFT is written which is presented in section 3.4.

3.2 DISCRETE FOURIER TRANSFORM

3.2.1 DESCRIPTION OF THE TECHNIQUE

The discrete fourier transform is a special case of contineous fourier transform. It approximates the contineous fourier transform and is easily amenable to machine computation. The most important concept to keep in mind is that the discrete fourier transform implies periodicity in both the time and frequency domain.[20]

Considering the discrete signal X(KT), which can be result of sampling a contineous signal x(t) or can occur in herently as a sequence of numbers.

The approximate fourier transform pair can be written as:

$$X(JW) \simeq \sum_{K=0}^{N-1} TX(t_k) \exp(-JWt_k) \qquad 3.1$$

and
$$X(t) \simeq \frac{\Delta W}{2\pi} \sum_{n=-M}^{M-1} X(JW_n) \exp(JW_n t) \qquad 3.2$$

If the signal has a finite number of points and its values are used in the approximate fourier transform, then Eq. (3.1) and Eq. (3.2) yields the approximate frequency and time information about the signal at the N discrete frequency and time values respectively. Eq. (3.1) and Eq. (3.2) can be written as:

$$X(JW_n) = T \sum_{K=0}^{N-1} X(t_k) \exp(-JW_n t_k)$$

$$\text{for } n = 0,1,2,\ldots\ N-1 \qquad (3.3)$$

and
$$X(t_k) = \frac{\Delta W}{2\pi} \sum_{n=-N/2}^{N/2-1} X(JW_n) \exp(JW_n t_k)$$

$$\text{for } k = 0,1,2,\ldots\ N-1 \qquad (3.4)$$

where for convenience and without loss of generality, M in Eq. (3.2) is replaced by N/2, so that the same number of data points in both the time and frequency domain is obtained. Since the frequency function $X(JW_n)$ in Eq. (3.3) is periodic with period N, the summation in Eq. (3.4) can be written as:

$$X(t_k) = \frac{\Delta W}{2\pi} \sum_{n=0}^{N-1} X(JW_n) \exp (JW_n t_k) \quad \text{for } k=0,1,2.. . N-1 \tag{3.5}$$

Now, the relationship between the time interval T and the frequency interval ΔW for sampling the contineous signal $X(t)$ in order to obtain discrete signal $X(KT)$ is

$$\Delta W = \frac{2\pi}{NT} \tag{3.6}$$

Then $\frac{\Delta W}{2\pi} = \frac{1}{NT}$ and $W_n t_k = \frac{nk2\pi}{N}$ (3.7)

Now let us consider

$$X_k = TX(t_k) \; ; \quad K = 0,1, \ldots . \quad N-1 \tag{3.8}$$

and $X_n = X(JW_n) \; ; \quad n = 0,1, \ldots \quad N-1$ (3.9)

Then Eq. (3.3) and Eq. (3.5) becomes

$$X_n = \sum_{K=0}^{N-1} X_k \exp (-(J2\pi/N)\, nk) \quad n= 0,1,\ldots N-1 \tag{3.9}$$

and $X_k = \frac{1}{N} \sum_{n=0}^{N-1} X_n \exp ((J2\pi/N)kn) \quad K = 0,1,\ldots \quad N-1$

(3.10)

The two expressions in Eq. (3.10) and Eq. (3.11) are called the discrete fourier transform (DFT) pair. Notation X_n = DFT (X_k) is used to denote the direct discrete fourier transform in Eq. (3.10) and X_k = IDFT (X_n) is used to denote the inverse discrete fourier transform in Eq. (3.11). (For detailed see Appendix-D).

3.2.2 SMAPLING THEOREM

"A band-limited periodic function with no hamonics of order higher than N is uniquely specified by its value at 2N+1 instants within one period" [21].

According to the sampling theorem, in order for a band limited signal to be recoverable from the samples of the signal the sampling frequency must be equal to at least twice the highest frequency component in the signal. [20]

That is:

$$f_s = \frac{1}{T} > 2\, f_h \qquad (3.12)$$

where $f_s = \frac{1}{T}$ = sampling frequency in HZ.

f_h = highest frequency content of signal in HZ.

Therefore, $T < \frac{1}{2f_h}$

This relation places an upper limit on the sampling interval in the time-domain. The requirement that $T = \frac{1}{2f_h}$

is simply the maximum spacing between samples for which the theorem holds. Frequency $\frac{1}{T} = 2f_h$ is known as Nyquist sampling rate. If $T > \frac{1}{2f_h}$, then aliasing will result. In practice the sampling interval is chosen to be much lower than the limiting value of $\frac{1}{2f_h}$ in order to reduce the aliasing error.

3.2.3 CHOICE OF SAMPLING RATE

Choice of sampling rate is one of the important consideration in sampling technique. Theoretical consideration dictate that the sampling frequency must be at least twice the largest frequency present in the sampled information to avoid aliasing.[20]

For symmetrical component calculation, using SCDFT in our present work, any multiple of 180 HZ is a suitable sampling rate. In symmetrical component calculation for sampled data, a sampling rate of 720 HZ is used to sample the current and voltage wave forms. This sampling rate has many advantage from a computational point of view in the present application. The adoptation of this sampling rate because: (i) It is within the range of practical analog/ digital conversion equipment available at the mini and microcomputer level. (ii) It produces sufficient redundancy in the calculations over a period of 1/2-1 cycle so that the results can be trust-worthy in the distance relaying sence. (iii) It involves a very small number of full (i.e., with irrational fourier co-efficient) multiplication.

In addition a most pertinent advantage of this sampling rate is the fact that the symmetrical components can be calculated with trivial extra arithmatic if this sampling rate is used. This discovery that the symmetrical component can be calculated from sampled data obtain at 720 HZ gave the initial empetus to the development of our relaying algorithm.

The noise contained in the sampling wave form must be band limited to 360 HZ to satisfy the Nyquist condition associated with the sampling rate of 720 HZ[17].

3.2.4 CHOICE OF DATA WINDOW AND TIME REFERENCE

The choice of data window is also an important factor for sampling. The width of the data window should be chosen in such a manner that there is an inverse relationship between the expected error of an estimate and the width of the data window[16]. Also a slight increase in data window creates much more stable system. On the other hand, increase of data window, increases the operating time of the relay.

In our present work, we have concentrated on data window of the order of a cycle or 12 samples per cycle. It produces only irrational number in the multiplication operation. Half cycle data window (6 sample/cycle) may also use. There is no special significance to a one-cycle window when the input signals are likely to contain harmonic as well as non-harmonic noice component. Certainly there is no merit in using a one-cycle data window if one intends to use result when the data window contains partial data from the pre-fault period.

Another degree of freedom allowed in the choice of the time reference, when is t equal to zero. Theoretically it is an arbitrary choice.

3.3 SYMMETRICAL COMPONENT DFT

3.3.1 DESCRIPTION OF THE TECHNIQUE

In symmetrical component discrete fourier transform method the theory of familiar discrete fourier transform technique is utilized in order to obtain the symmetrical component quantities. symmetrical component discrete fourier transform is a filtering technique of producing symmetrical components of the filtered quantities without adding to the delay of the filtering process.

Immediately after the occurance of a fault (order of a cycle), the voltage and current wave forms contain significant amounts of transient components in addition to the fundamental frequency components. It is necessary to remove these transient component from input wave forms so that fundamental frequency components alone are presented to the distance relay. This filtering must be accomplished without introducing excessive delay in the overall relaying process. The symmetrical component of voltages and currents can be readily obtained from their respective sampled wave from data under steady state as well as transient system conditions using this filtering technique.

3.3.2 DEVELOPMENT OF THE ALGORITHM OF THE METHOD

Recall that the symmetrical components of three phase quantities X_a, X_b, X_c are given as:

$$
\begin{aligned}
X_o &= \frac{1}{3}(X_a + X_b + X_c) \\
X_1 &= \frac{1}{3}(X_a + \alpha X_b + \alpha^2 X_c) \\
X_2 &= \frac{1}{3}(X_a + \alpha^2 X_b + \alpha X_c)
\end{aligned}
\qquad (3.13)
$$

where X stands for either a voltage or current phasor and it is implied that steady state conditions prevail. The time dependent function X(t) of which X is a phasor representation is assumed to be a pure fundamental frequency sinusoid. The coefficients α and α^2 are (-0.5 + J0.866) and (-0.5 - J0.866) respectively

In general, the functions X(t) are not pure sine waves during transient condition. Assume that such a non-sinusoidal X(t) is sampled at t = KT, (K=0,1,2 ....) and X_k are the corresponding samples.

$$X_k = X\ (KT),\ K = 0,1,2\ \ldots \tag{3.14}$$

T being the sampling interval. Phasor representation for the fundamental frequency component of X(t) is a function of X_k.

$$X = f\ (X_k) \qquad K = 0,1,2,\ \ldots \tag{3.15}$$

For an inpure signal X(t), X must be viewed as the optimum estimate of the phasor representation. When the signal X(t) is suitably band-limited, and the sample set (X_k) spans a multiple of one-half the fundamental frequency period, the optimum estimate X is the familiar discrete fourier transform (See Appendix-E)

$$X = \frac{2}{N} \sum_{k=0}^{N-1} X_k\ B_k \tag{3.16}$$

where $$B_k = \exp\ \left(-j\ \frac{2\pi T}{T_o}\ K\right) \tag{3.17}$$

T_o being the period of the fundamental frequency wave. The factor 2 in the expression for X comes about from combining X(1) and X(-1) to form X in the usual manner.

Equation 3.16 for a one cycle data window (N=12) and a sampling rate of 720 HZ becomes-

$$X(1) = \frac{1}{6} \sum_{K=0}^{11} X_k\ \exp\ \left(-j\ \frac{K\pi}{6}\right) \tag{3.18}$$

where X(1) is the phasor representation for the fundamental frequency for an impure signal X(t).

Recall that the conventional phasor representation of a sinusoidal wave X(t):

$$X(t) = \sqrt{2}\, X \,\mathrm{Sin}\,(Wt + \phi) \quad (3.19)$$

is X, where

$$X = |X|\; e^{J\phi} = |X|\;(\mathrm{Cos}\phi + j\,\mathrm{Sin}\phi) \quad (3.20$$

Taking samples X_k from equation 3.7 (where $Wt = \frac{K\pi}{6}$) and substituting these values of X_k in equation 3.18 and finally comparing the resulting expression for X(1) with equation 3.20 we get:

$$X = \frac{J}{\sqrt{2}}\, X(1) \quad (3.21)$$

using the notation $W_k = \frac{J}{6\sqrt{2}}\, e^{-J\,\frac{K\pi}{6}}$ (3.22)

and combining equations 3.18 and 3.21 we get:

$$X = \sum_{K=0}^{11} X_k\, W_k \quad (3.23)$$

Considering two new phasors Y and Z obtained from X through the complex multiplier α and α^2. Recalling that $\alpha = \exp\,(\,J\,\frac{2\pi}{3}\,)$;

$$Y = \alpha X = \sum_{k=0}^{11} X_k W_{k-4} \qquad (3.24)$$

Similarly,

$$Z = \alpha^2 X = \sum_{k=0}^{11} X_k W_{k+4} \qquad (3.25)$$

Now substituting equation 3.23, 3.24, 3.25 in equation 3.13.

$$X_o = \frac{1}{3} \sum_{k=0}^{11} W_k \,(X_{ak} + X_{bk} + X_{ck})$$

$$X_1 = \frac{1}{3} \sum_{k=0}^{11} (W_k X_{ak} + W_{k-4} X_{bk} + W_{k+4} X_{ck}) \qquad (3.26)$$

$$X_2 = \frac{1}{3} \sum_{k=0}^{11} (W_k X_{ak} + W_{k+4} X_{bk} + W_{k-4} X_{ck})$$

Equation 3.26 represents filtered symmetrical components obtained from sampled wave form data. The set (W) contains only the irrational number : ($\sqrt{3}/2$). The remaining multiplications consists of $\pm$ 1, 0 $\pm$ 1/2 . Equation 3.26 can be implemented on a digital computer utilizing very few arithmatic operation.

3.3.3. RECURSIVE ALGORITHM FOR SCDFT

In order to increase the accuracy of SCDFT program, a recursive algorithm is developed where the phasor estimate corresponding to a data set ending with X_{L+1} is obtained interms of the phasor estimate corresponding to the data set ending with X_L where X_L and X_{L+1} are the sampled data respectively. The expression for familiar discrete fourier transform for a half-cycle date window (N=6) is:

$$X = \frac{1}{3} \sum_{k=0}^{5} X_k \exp\left(-J \frac{K\pi}{6}\right) \qquad (3.27)$$

Let us consider a pure sine wave signal shown in figure 3.1(a) sampled at (K=0,...5). The corresponding X as computed with equation 3.27 is shown in figure 3.1(b).

The waveform of figure 3.1(a) is sampled contineously: when X_6 is obtained at K=6, the data window must be moved over to span the sample set { X_1, ...X_6 }. The corresponding phasor representation X(new) for this sample set can also be computed with equation 3.27.

$$X(\text{new}) = \frac{1}{3} \sum_{k=0}^{5} X_{k+1} \exp\left(-J \frac{K\pi}{6}\right) \qquad 3.28$$

Recall however that the DFT of a set $\{X_k\}$ may be multipled by a constant without affecting its information content. Defining $\left[X^6 = \exp\left(-J \frac{\pi}{6}\right) \cdot X(\text{new})\right]$ as the phasor representation of the set $\{X_1, \ldots\ldots X_6\}$

$$X^6 = \exp\left(-J \frac{\pi}{6}\right) X(\text{new})$$

$$= \frac{1}{3} \sum_{k=0}^{5} X_{k+1} \exp\left\{-J \frac{(K+1)\pi}{6}\right\}$$

$$= X^5 + \frac{1}{3} \exp\left(-J \frac{6\pi}{6}\right) \{ X_6 + X_o \} \qquad (3.29)$$

where X^5 is the phasor representation given by equation 3.27 corresponding to the data set $\{X_o, \ldots\ldots X_5\}$.

Defining $\Delta X_6 = X_6 + X_o$ we obtain the recursion relation for the phase X^6 as

$$X^6 = X^5 + \frac{1}{3} \exp\left(-J \frac{6\pi}{6}\right) \Delta X_6 \qquad (3.30)$$

In general, the phasor estimate corresponding to a data set ending with X_{L+1} is given in terms of the phasor estimate corresponding to the data set ending with X_L by the recursion relation

$$X^{L+1} = X^L + \frac{1}{3} \exp\left(-J \frac{(L+1)\pi}{6}\right) \cdot \Delta X_{L+1} \qquad (3.31)$$

where $\Delta X_{L+1} = X_{L+1} + X_{L-5}$

Using equation 3.27 on sample sets which shift as each new data sample becomes available, produces a phasor which turns in the complex plane by the sampling interval angle. This is illustrated by the dotted line representing X(new) in figure 3.1(b). The phase angle between X and X(new) is $(\frac{2\pi T}{T_o}).X^{L+1}$ obtained from the recursion relation is stationary in the complex place if the sampling frequency is an exact multiple of the power frequency.

The recursion relations for the symmetrical components are:

$$X_o^{L+1} = X_o^{L} + W_{L+1}\ (\Delta X_{a,L+1} + \Delta X_{b,L+1} + \Delta X_{c,L+1})$$

$$X_1^{L+1} = X_1^{L} + W_{L+1}\ \Delta X_{a,L+1} + W_{L-3}\ \Delta X_{b,L+1} + W_{L+5}\ \Delta X_{c,L+1}$$

(3.32)

$$X_2^{L+1} = X_2^{L} + W_{L+1}\ \Delta X_{a,L+1} + W_{L+5}\ \Delta X_{b,L+1} + W_{L-3}\ \Delta X_{c,L+1}$$

3.3.4. TRANSIENT MONITOR FUNCTION

When the data window of the DFT filter spans the on set of a transient, it contains two partial sample sets belonging to pre-and post transient system states. It is important to recognize this condition, so that no relaying decisions can be made during this period. A convenient method of achieving this control is through the use of a transient monitor function. Briefly, a transient monitor function tests for consistency of the samples being used in forming the phasor estimates. If the transient monitor function t is above a threshold value, this indicates that the data being used is not consistent in the sense of being close to a 60 HZ wave. The use of a transient monitor function has proved to be extremely useful in inhibiting the relay decision process during periods when data is highly inconsistent. Consider a sample set $\{X_k\}$ which is obtained from a signal which is predominatly a pure sine wave at fundamental frequency. Its phasor representation is given by equation 3.27 for a 6 sample data window. Consider the application of the inverse DFT to this phasor representation. The inverse DFT produces a sample set $\{\tilde{\tilde{X}}_k\}$ which differes from $\{X_k\}$ to the extent that the input signal differs from a pure fundamental frequency sine wave. The inverse DFT is given as:

$$\tilde{X}_k = \text{Re}\ \{X \exp\ (\ J\ \frac{2K\pi}{6}\ )\} \tag{3.33}$$

Substituting the value of X from equation 3.27

$$\tilde{X}_k = \frac{1}{3}\ \text{Re}\Big[\{\exp\ (\ J\ \frac{2K\pi}{6}\ )\ \sum_{l=0}^{5} X_L \exp\ (-J\ \frac{2l\pi}{6})\}\Big] \tag{3.34}$$

Equation 3.34 represents the application of a transformation to the vector $\{X_o, \ldots\ldots\ldots\ X_5\}^T$ to produce the vector $\{\bar{X}_o, \ldots\ldots\ \tilde{X}_5\}^T$:

$$[\tilde{X}] = [M][X] \tag{3.35}$$

where the m_{kl} entry of M is given by exp $\{J \frac{2\pi}{6} (k-\ell)\}$, and k,L range from 0 through 5.

Figure 3.2 illustrates the $\{X_k\}$ and $\{\tilde{X}_k\}$ sets for a noisy input signal. The input signal is represented by the solid line, and its sample set is shown by solid dots. The DFT calculation from $\{X_k\}$ produces the phasor representation X, which represents the dotted function in fig. 3.2. The sample set of this signal is represented by open dots in figure 3.2. The difference between $\{X\}$ and $\{\bar{X}\}$ is a measure of the non-sinusoidal components of X(t). Denoting this difference by a residual vector $\{r\}$:

$$[r] = [\bar{X} - X] = [M-1][X] \qquad (3.36)$$

The one form of $[r]$ is a convenient transient monitor function t:

$$t = \|r\|_1 = \sum_{k=0}^{5} |r_k| \qquad (3.37)$$

It can be shown from equation 3.36 that the residuals r_k obey a recursion relation similar to that given by equation.

When the data window lies completely in the pre-or post-transient period, the three phase current 't - function' have a small value. When the data-window contains partial

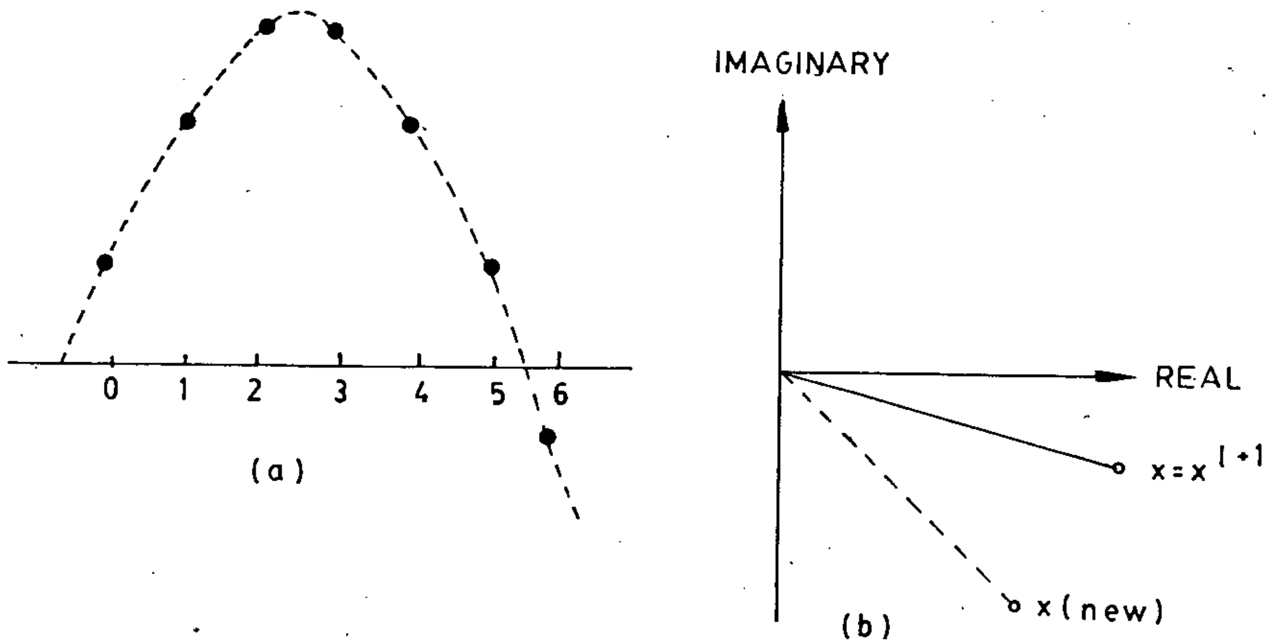


Fig. 3.1 (a) A pure sinusoidal signal sampled over a half cycle (b) Phasor representation

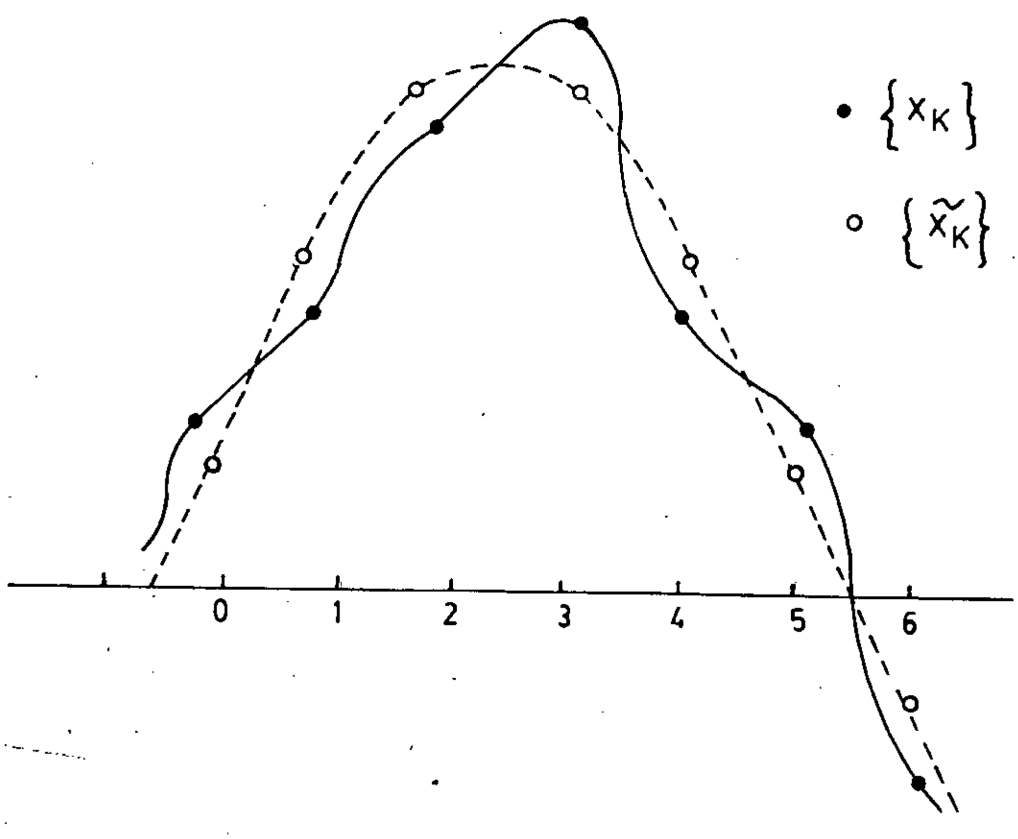


Fig. 3.2. Transient monitor function concepts.

data from the two system states, the t-functions assume a high value. Thus, whenever one of the t-functions is high it can be assumed that the phasor estimates are not reliable. The relay program is by passed under these conditions. In numerous tests of this algorithm, the -t-functions have proven to be very effective control parameters.

3.4 ALGORITHM FOR COMPUTER PROGRAM

A computer program (See Appendix-F) has been written to calculate the symmetrical component of the voltage and current from their respective sampled data using discrete fourier transform. The algorithm for the computer program is given below:

Step 1: Input data for the value of data window (no of sample) N, angular frequency W, normal frequency F, and the constant C_1 and C_2 which are the parameter of the equation. $W_k = JC_2\, e^{-JC_1K}$ where $C_1 = \frac{\pi}{6}$ and $C_2\ \frac{1}{6\sqrt{2}}$

Step 2: Set the value of the phase shift operator A_1 and A_2 as (-0.5+J0.866) and (-0.5-J0.866)

Step 3: Set the value of sampling interval as 1/sampling rate.

Step 4: Calculate the sampled data from their wave form.

Step 5: Repeat step 4 for all data window and store them.

Step 6: Set the initial value of K as one and initial value of symmetrical component of voltage as zero.

Step 7: Compute the value of W_k, W_{k+4} and W_{k-4} from their respective equation and store them in W_{k1}, W_{k2}, W_{k3}.

Step 8: Repeat step 6 for all sampled data.

Step 9: Computer the value of symmetrical component of voltages E_1, E_2, E_o from the information obtained using the equation 3.26.

Step 10: Repeat the whole procedure from 1 to 9 for current wave form.

An example for the performance of the SCDFT program are given in Appendix-G.

CHAPTER - 4

4.0 DISTANCE RELAYING FOR A MODEL POWER SYSTEM

4.1 A MODEL POWER SYSTEM

Let us consider a model power system shown in figure 4.1. The transmission line is assumed to be connected between two buses P & Q with the power system behind the buses P & Q represented by three phase thevnin sources E_G (Z_{OG}, Z_{1G}, Z_{2G}) and E_H (Z_{OH}, Z_{1H}, Z_{2H}) respectively.

The impedance and source data for model system of fig. 4.1 is given in table 4.1. The pre fault load current is I_1 = -.832-J.258.

TABLE 4.1
Sample System Data

Equivalent Generators		Transmission Lines	
E_G	100+J0		
E_H	86.67+J50	Z_1, Z_2	2.5+J30
Z_{1G}, Z_{2G}	0 +J10		
Z_{1H}, Z_{2H}	0 +J20	Z_o	20 +J90
Z_{OG}	0 +J5		
Z_{OH}	0 +J20		

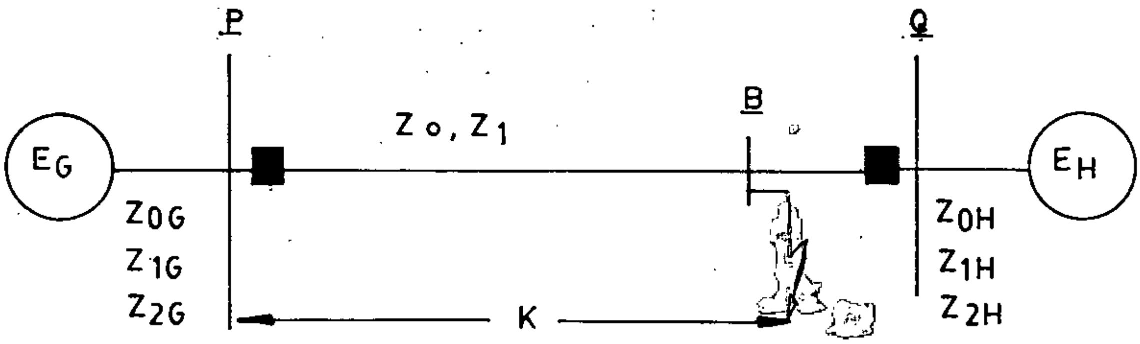


Fig. 4.1 Sample system;single line diagram

It has been assumed that the input to the relay is obtained with a symmetrical component filter so that the relay inputs consists of E_o, E_1, E_2 and I_o, I_1, I_2. This quantities have been calculated for the sample system for a three phase fault, single phase to ground fault, phase to phase fault, Double phase to Ground fault. The calculated results for all the K,s and the final value of K for each case is shown in the table of section 4.2. The fault was placed at K=0.9. It can be seen that the single performance equation calculated the K correctly for each of the fault considered.

4.2 CASE STUDY

4.2.1 SINGLE PHASE TO GROUND FAULT

TABLE 4.2.1

Results for Sample System Fault: Single Phase to Ground Fault.

Distance Relay Input and Output		Fault Type
E_o	-2.14-J1.13	Phase 'A' to ground fault
E_1	90.64+J5.23	
E_2	-6.8 -J3.01	
I_o	.227-J.427	
I_1	-.522-J.936	
I_2	.301-J.681	
K_L	-.13 - J1.16	
K_o	-.05 - J.01	
K'_o	1.98 - J.27	
K_2	-.33 - J.03	
K'_2	1.0	
K_1	3.91 - J1.11	
K	0.9	

4.2.2 PHASE TO PHASE FAULT

TABLE 4.2.2

Results for Sample System Fault: Phase to Phase Fault.

Distance Relay Input and Output		Fault Type
E_o	0 + J0	Phase 'B' to Phase 'C' fault
E_1	85.26 + J3.28	
E_2	12.2 + J4.94	
I_o	0 + J0	
I_1	-.328 - J1.47	
I_2	-.494 + J1.22	
K_{LF}	-.06 - J.66	
K_o	0	
K'_o	0	
K_2	-.33 - J.03	
K'_2	1.0	
K_1	2.09 - J.57	
K	0.9	

4.2.3 DOUBLE PHASE TO GROUND FAULT

TABLE 4.2.3

RESULTS FOR SAMPLE SYSTEM FAULT: DOUBLE PHASE TO GROUND FAULT

Distance Relay Input and Output		Fault Type
E_o	1.82 + J1.027	
E_1	82.28 + J1.91	
E_2	9.34 + J3.57	
I_o	-.205 + J.364	
I_1	-.192 - J1.77	
I_2	-.36 + J.933	
K_L	-.05 - J.52	Phase 'B' and Phase 'C' to ground fault
K_o	-.05 - J.01	
K'_o	.77 - J.11	
K_2	-.33 - J.03	
K'_2	0	
K_1	1.60 - J.48	
K	0.9	

4.2.4 THREE PHASE FAULT

TABLE 4.2.4

Results for Sample System Fault: 3 Phase Fault

Distance Relay Input and Output		Fault Type
E_o	0 + J0	3-Phase fault
E_1	73.06 - J1.64	
E_2	0 + J0	
I_o	0 + J0	
I_1	.164 - J2.693	
I_2	0 + J0	
$K_{\hat{L}}$	-.03 - J.33	
K_o	0	
K'_o	0	
K_2	0	
K'_2	0	
K_1	.88 - J.29	
K	0.9	

4.3 FAULTS AT VARYING DISTANCES

Table 4.3(a) shows the symmetrical component value of voltages and currents for single phase ground fault for varying distance and Table 4.3(b) shows the fault results for the data input of table 4.3(a). The result of Table 4.3(a) is obtained from a computer program (See Appendix-H)

TABLE 4.3(a)

Symmetrical Component of Voltage and Current for Single Phase to ground fault.

Symmetrical Component voltage	Symmetrical Component current	Distance p.u.
E_o = -12.87 - J2.31 E_1 = 74.47 + J4.15 E_2 = -22.96 - J4.07	I_o = .46 - J2.57 I_1 = -.41 - J2.56 I_2 = .41-J2.30	0.1
E_o = -8.99 - J2.13 E_1 = 80.92 + J4.38 E_2 = -16.51 - J3.85	I_o = .43 - J1.80 I_1 = -.44- J1.91 I_2 = .39 - J1.65	0.2
E_o = -6.82 - J1.93 E_1 = 84.47 + J4.65 E_2 = -12.95 - J3.58	I_o = 0.39 - J1.36 I_1 = .46 - J1.56 I_2 = .36 - J1.30	0.3
E_o = -5.42 - J1.75 E_1 = 86.70 + J4.86 E_2 = -10.73 - J3.36	I_o = .35 - J1.08 I_1 = -.49 - J1.33 I_2 = .34 - J1.07	0.4

Table 4.3(a) Contd.

Symmetrical Component voltage	Symmetrical Component current	Distance P.U.
E_o = -4.44 - J1.61 E_1 = 88.19 + J5.02 E_2 = -9.24 - J3.20	I_o = .32 - J.89 I_1 = -.50 -J1.18 I_2 = .32 - J.92	0.5
E_o = -3.70 - J1.48 E_1 = 89.23 + J5.14 E_2 = -8.20 - J3.09	I_o = .30 - J.74 I_1 = -.51 - J1.08 I_2 = .31 - J.82	0.6
E_o = -3.10 - J1.36 E_1 = 89.94 + J5.20 E_2 = -7.48 - J3.02	I_o = .27 - J.62 I_1 = -.52 - J1.01 I_2 = .30 - J.75	0.7
E_o = -2.60 - J1.25 E_1 = 90.41 + J5.23 E_2 = -7.01 - J2.99	I_o = .25 - J.52 I_1 = -.52 - J.96 I_2 =.30 - J.70	0.8
E_o = -2.13 - J1.13 E_1 = 90.63 + J5.22 E_2 = -6.79 - J3.00	I_o = .23 - J.43 I_1 =-.52 - J.94 I_2 = .30 - J.68	0.9
E_o = -1.65 - J1.01 E_1 = 90.56 + J5.17 E_2 = -6.86 - J3.05	I_o = .20 - J.33 I_1 = -.52 - J.95 I_2 = .31 - J.69	1.10

TABLE 4.3(b)

Fault Results For Data Input of Table 4.3(a)

Distance Relay Output						Fault distance P.U.
K_L	K_o	K_o'	K_2	K_2'	K_1	K
.05-J.37	-.05-J.01	3.39-J.46	-.33-J.03	1.0	1.06-J.04	0.1
.04-J.51	-.05-J.01	3.31-J.45	-.33-J.03	1.0	1.58-J.15	0.2
.02-J.64	-.05-J.01	3.18-J.43	-.33-J.03	1.0	2.06-J.29	0.3
.00-J.77	-.05-J.01	3.07-J.42	-.33-J.03	1.0	2.53-J.43	0.4
-.04-J.89	-.05-J.01	2.94-J.40	-.33-J.03	1.0	2.94-J.61	0.5
-.07-J.99	-.05-J.01	2.75-J.38	-.33-J.03	1.0	3.28-J.77	0.6
-.09-J1.07	-.05-J.01	2.53-J.34	-.33-J.03	1.0	3.57-J.92	0.7
-.13-J1.13	-.05-J.01	2.29-J.31	-.33-J.03	1.0	3.78-J1.07	0.8
-.14-J1.15	-.05-J.01	1.98-J.27	-.33-J.03	1.0	3.87-J1.14	0.9
-.14-J1.14	-.05-J.01	1.55-J.21	-.33-J.03	1.0	3.83-J1.11	1.0

4.4 CALCULATION OF FAULT DISTANCE FROM OTHER TERMINAL OF THE LINE

In order to calculate the fault distance from the relay placed at bus Q of fig. 4.1, the symmetrical component data obtained at bus Q are fed into the computer program for SCDR and the fault results are investigated. The fault distance should be 0.1. The results for sample system faults are shown in Table 4.4.

TABLE 4.4

Fault Results for Sample System

Distance Relay Input & Output	Fault Type			
	a-g	b-c	b-c-g	3 Phase
E_o	-27.45 - J10.073	0 + J0	23.57 + J9.29	0 + J0
E_1	69.41 + J24.98	51.77 + J19.64	42.27 + J15.79	11.73 + J5.69
E_2	-22.39 - J8.59	40.04 + J13.95	30.40 + J9.91	0 + J0
I_o	.50 - J1.37	0 + J0	-.46 + J1.18	0 + J0
I_1	1.25 - J.86	1.52- J1.74	1.71 - J2.22	2.22 - J3.74
I_2	.43 - J1.12	-.69 + J2.00	-.496 + J1.52	0 + J0
K_L	.04 + J.72	.01 + J.41	.01 + J.33	.01 + J.20
K_o	-.21 - J.05	0	-.21 - J.05	0
K'_o	3.69 - J.50	0	1.46 - J.20	0
K_2	-.66 - J.05	-.66 - J.06	-.66 - J.06	0
K'_2	1.0	1.0	0	0
K_1	2.04 + J.13	.86 + J.09	.57 + J.05	.1 + J.02
K	0.1	0.1	0.1	0.1

4.5 EFFECT OF DIFFERENT APPROXIMATION

4.5.1 UNEQUAL BUS VOLTAGES:

In order to investige the effect of unequal bus voltage on the fault result of model power system of fig. 4.1, let us assume that the two bus voltages are

$$E_G = 100 + J0$$

$$E_H = 95.263 + J55$$

Considering this bus voltage the fault results for the model power system are shown in table 4.5(a).

TABLE 4.5(a)

Fault Results for the Model System Considering Unequal Bus Voltage

Relay Input & Output	Fault Type			
	a-g	b-c	b-c-g	3-phase
E_o	-2.25 - J1.23	0 + J0	1.93 + J1.11	0 + J0
E_1	91.65 + J5.85	85.94 + J3.73	82.88 + J2.26	73.08 - J1.64
E_2	-7.18 - J3.27	12.88 + J5.38	9.79 + J3.89	0 + J0
I_o	.25 - J.45	0 + J0	-.22 + J.39	0 + J0
I_1	-.59 - J.84	-.37 - J1.41	-.23 - J1.71	.164 - J2.69
I_2	.33 - J.72	-.54 + J1.29	-.39 + J.98	0 + J0
K_L	-.33 - J1.12	-.17 - J.63	-.14 - J.51	-.09 - J.32
K_o	-.05 - J.01	0	-.05 - J.01	0
K'_o	1.98 - J.27	0	.79 - J.11	0
K_2	-.33 - J.03	-.33 - J.03	-.33 - J.03	0
K'_2	1.0	1.0	0	0
K_1	3.73 - J1.04	1.97 - J.54	1.52 - J.46	.82 - J.29
K	0.9	0.9	0.9	0.9

4.5.2 REPLACEMENT OF LINE IMPEDANCES BY REAL QUANTITIES

In order to investige the effect of replacing the line impedances by their real quantities the system data of model system of fig. 4.1 are changes as shown in table 4.5(b).

TABLE 4.5(b)

System Data Replacing the Impedance by Real Quantities

Equivalent Generator		Transmission Lines	
Z_{1G}, Z_{2G}	10 Ω	Z_1, Z_2	30.1 Ω
Z_{1H}, Z_{2H}	20 Ω		
Z_{OG}	5 Ω	Z_o	92.2 Ω
Z_{OH}	20 Ω		

Considering this real quantities of impedances the fault results for the model power system are shown in table 4.5(c).

TABLE 4.5(C)

Fault Results for the Model System Considering Impedances by their Real Quantities.

Distance Relay Input & Output	Fault Type			
	a-g	b-c	b-c-g	3-phase
E_o	- 2.28 - J.77	0 + J0	1.96 + J.66	0 + J0
E_1	90.80 + J5.98	85.38 + J4.16	82.38 + J3.14	73.04 + J0.0
E_2	-6.98 - J2.35	12.42 + J4.17	9.34 + J3.15	0 + J0
I_o	.46 + J.15	0 + J0	-.39 - J.13	0 + J0
I_1	.92 - J.59	1.46 - J.42	1.76 - J.314	2.69 + J0.0
I_2	.69 + J.24	-1.24 - J.42	-.93 - J.32	0 + J0
K_L	-.07 - J1.16	-.04 - J.66	-.04 - J.53	-.02 - J.33
K_o	-.05 + J0	0	-.05 - J0.0	0
K'_o	2.01 + J0.0	0	.77 + J0.0	0
K_2	-.33 + J0.0	-.33 + J0.0	-.33 + J0.0	0
K'_2	1.0	1.0	0	0
K_1	3.97 - J1.02	2.1 - J.58	1.62 - J.48	.88 - J.30
K	0.9	0.9	0.9	0.9

4.5.3 EQUAL BUS VOLTAGE REPLACING LINE IMPEDANCES BY REAL QUANTITIES AND NEGLECTING PRE-FAULT CURRENT

The fault results for the model power system for equal bus voltage and neglecting pre fault current are shown in table 4.5(d)

TABLE 4.5(d)

Fault Results: For the Model Power System

Distance Relay Input & Output	Fault Type			
	a-g	b-c	b-c-g	3-phase
E_o	-2.48 + J0.0	0 + J0	2.15 + J0.0	0 + J0
E_1	92.39 + J0.0	86.52 + J0.0	83.22 + J0.0	73.04 + J0.0
E_2	-7.61 + J0.0	13.49 + J0.0	10.19 + J0.0	0 + J0
I_o	.495 + J0.0	0 + J0	.43 + J0.0	0 + J0
I_1	.761 + J0.0	1.35 + J0.0	1.68 + J0.0	2.69 + J0.0
I_2	.761 + J0.0	-1.35 + J0.0	-1.02 + J0.0	0 + J0
K_L	0	0	0	0
K_o	-.05 + J0.0	0	-.05 + J0.0	0
K'_o	1.97 + J0.0	0	.78 + J0.0	0
K_2	-.33 + J0.0	-.33 + J0.0	-.33 + J0.0	0
K'_2	1.0	1.0	0	0
K_1	4.04 + J0.0	2.13 + J0.0	1.65 + J0.0	.90 + J0.0
K	0.9	0.9	0.9	0.9

4.6 DISCUSSION ON RESULTS

In this chapter, the performance of distance relay program were investigated by using a model power system having two bus. First of all, the simulated data (symmetrical component voltages and currents) were fed into the distance relay program and the fault results obtained were investigated for different type of fault occurred on the model system. The fault results include the location of fault distance, detection of type of fault and phases at which fault occurred. Finally, different approximation such as unequal bus voltages, replacement of line impedances by their real quantities, neglecting pre fault current were made on the system and the effect of these approximation were investigated.

Simulated data for single phase to ground fault, for phase-'A' to 'G' fault, phase 'B' to 'G' fault and phase 'C' to 'G' fault were fed into the computer program and fault result obtained were investigated. For each case we got some fault distance and correct phase. Fault results for phase 'A' to ground fault were presented in table 4.2.1. Similarly for phase to phase fault, double phase to ground fault, and 3-phase fault, the fault results obtained from the computer program were investigated. For each case we got correct detection. The fault results were presented in section 4.2.

The performance of the program was also checked for different fault distance and each case we got the proper distance. The performance of the distance relay program was also tested by feeding the data obtained from the other terminal of the line and we got the expected distance. These are presented in section 4.3 and 4.4.

Finally, the effect of different approximation which were made on the system were investigated and the computer program performed well and we got the expected results. The result of these effects were presented in section 4.5.

CHAPTER - 5

5.0 FAULT ANALYSIS OF A PRACTICAL POWER SYSTEM AND ITS DETECTION

5.1 INTRODUCTION TO FAULT ANALYSIS

Short circuit studies and hence the fault analysis are very important for the power system studies since they provide data such as voltages, and currents during and after the various types of faults which are necessary in designing the protective schemes of the power system.

The currents and voltages resulting from various type of faults occuring at different locations through out the power system network must be calculated in order to provide sufficient data for designing the protective scheme i.e. data both the protective relays and circuit breakers. Because of extensive calculations of voltages and currents due to different faults at different locations of the power system, it became necessary to use some sort of computer and to day most of the short circuit studies and hence fault analysis are performed on the digital computer. However the early approach to the short circuit studies employed the bus frame of reference in the admittance form but this method could not become popular because it was time consuming. Today most of the short circuit studies and hence fault calculations of the power system are formulated in the bus frame of reference using bus impedance matrix 'Z_{BUS}' becuase this method is simpler and less time consuming.

The development of techniques for applying a digital computer to form the bus impedance matrix made it feasible to use Thevenin's theorem for short circuit calculations [23]. This approach provided an efficient means of determining short circuit currents and voltage because these values can be obtained with few arithmatic operations involving only related portions of the bus impedance matrix.

5.2 FORMATION OF BUS IMPEDANCE MATRIX Z_{BUS}

For short circuit calculation of large power system it is necessary to form bus impedance matrix of the power system. In our present power system, fault calculations of the network were formulated in the bus frame of reference using bus impedance matrix 'Z_{BUS}' because the computer implementation of this method is simpler and less time consuming. Let us assume that Z_{BUS} matrix exists for a part of the primitive network known as partial network and the corresponding network equation for this partial network in the bus frame of reference is

$$\bar{E}_{BUS\ m\times 1} = Z_{BUS\ m\times m}\ \bar{I}_{BUS\ m\times 1} \qquad 5.1$$

From the above equation, it is clear that out of say n-buses of the primitive network, m buses are included in the partial network for which Z_{BUS} matrix exists.

We shall take one element at a time from the remaining portion of the primitive network which are not included in the partial network for which the Z_{BUS} matrix is available and add it to the partial network and in this way gradually Z_{BUS} matrix for the entire primitive network will be developed. However, the added element say p-q between buses p and q may be a branch or a link.

In case the partial network for which Z_{BUS} matrix is available includes only the bus p, then added element p-q will naturally be a branch and in this way a new bus q will be added up to the partial network. Thus if p-q is a branch, then a new bus q is added to the partial network and dimension of Z_{BUS} which was of the order of mxm will now be of the order (m+1) (m+1). And hence corresponding to this new bus q , a new row or column(say q th row/column) is added up in the Z_{BUS} matrix. In this way, the branch p-q is simulated by calculating the elements in this new row or column.

However, in the case both the bus p and q were already included in the partial network but the element p-q was not included, then the added element p-q from the primitive network to the partial network will naturally be a link. Thus when the added element p-q is a link, no new buses are added to the partial network as both the buses p and q are already included in the partial network for which Z_{BUS} matrix exists and hence dimension of the matrix Z_{BUS} will remain unchanged. However, the elements of the Z_{BUS} matrix will be modified in order to simulate the addition of this link. (For detailed see reference 22,23).

The computer program for the formation of Bus impedance matrix Z_{BUS} are given in Appendix-I .

5.3 SHORT CIRCUIT STUDIES OF A LARGE POWER SYSTEM NETWORK

In case of a large power system containing more than two bus, it is difficult to obtain the short circuit currents and voltages by applying network reduction technique. In order to obtain short circuit currents and voltages in symmetrical component form in a large system, it is necessary to perform short circuit study on the system. By performing short circuit study, we can obtain different bus voltages and branch currents. This short circuit data is essential for our present analysis of the system.

In short circuit study of a large power system, certain assumptions are made. These are:

i) Representing each machine by a constant voltage source behind proper reactances which may be X", X' or X.

ii) Neglecting all the shunt connections such as static loads, line charging and transformer magnetizing circuits. With this assumption, the power system network become open circuited and thus the normal load currents (i.e., pre fault currents) are automatically neglected and therefore, all the prefault bus voltages will have the same magnitude and phase angle. Thus to work on perunit system, the prefault bus voltages are set equal to $1\angle 0$.

iii) Setting all the transormers to nominal taps (i.e. transformer tappings are neglected). Since we work in per unit system, with this representation, transformers will automatically be out of circuit.

iv) Normally neglecting widing resistance and line resistances etc. with this assumption the system will contain only reactances and hence the power system is represented by its most simplified reactance diagram.

v) Equating the positive sequence impedance equal to negative sequence impedance also for 3-phase rotating elements.even though these sequence impedances are equal only in the case at 3-phase stationary elements.

The computer program developed for short circuit study is given in Appendix-I. (For detailed about short circuit study see reference 22,23).

5.4 A MULTI BUS POWER SYSTEM

The computer program developed for performing short circuit studies has been applied to a large power system in order to obtain the faulted bus voltages and fault current in different branch of the power system. The method developed in section 2 was then applied on the power system for detection of fault and location of fault.

The grid mainly consists of five buses among which bus no one is taken as reference bus. The single line diagram of the network is shown in Fig. 5.1. The system data (i.e. element no, bus code, self impedances) are given in table 5.1. The impedances are in P.U. and the bus voltages are $1 \angle 0$ P.U.

TABLE 5.1

System Data

Element	Bus-code	Self impedances $Z_{pq}^{0,1,2}$		
1	1-2	0.05	0.20	0.20
2	2-3	0.05	0.15	0.15
3	3-4	0.06	0.25	0.25
4	4-5	1.02	0.50	0.50
5	3-5	1.50	0.80	0.80
6	1-5	2.50	1.50	1.50

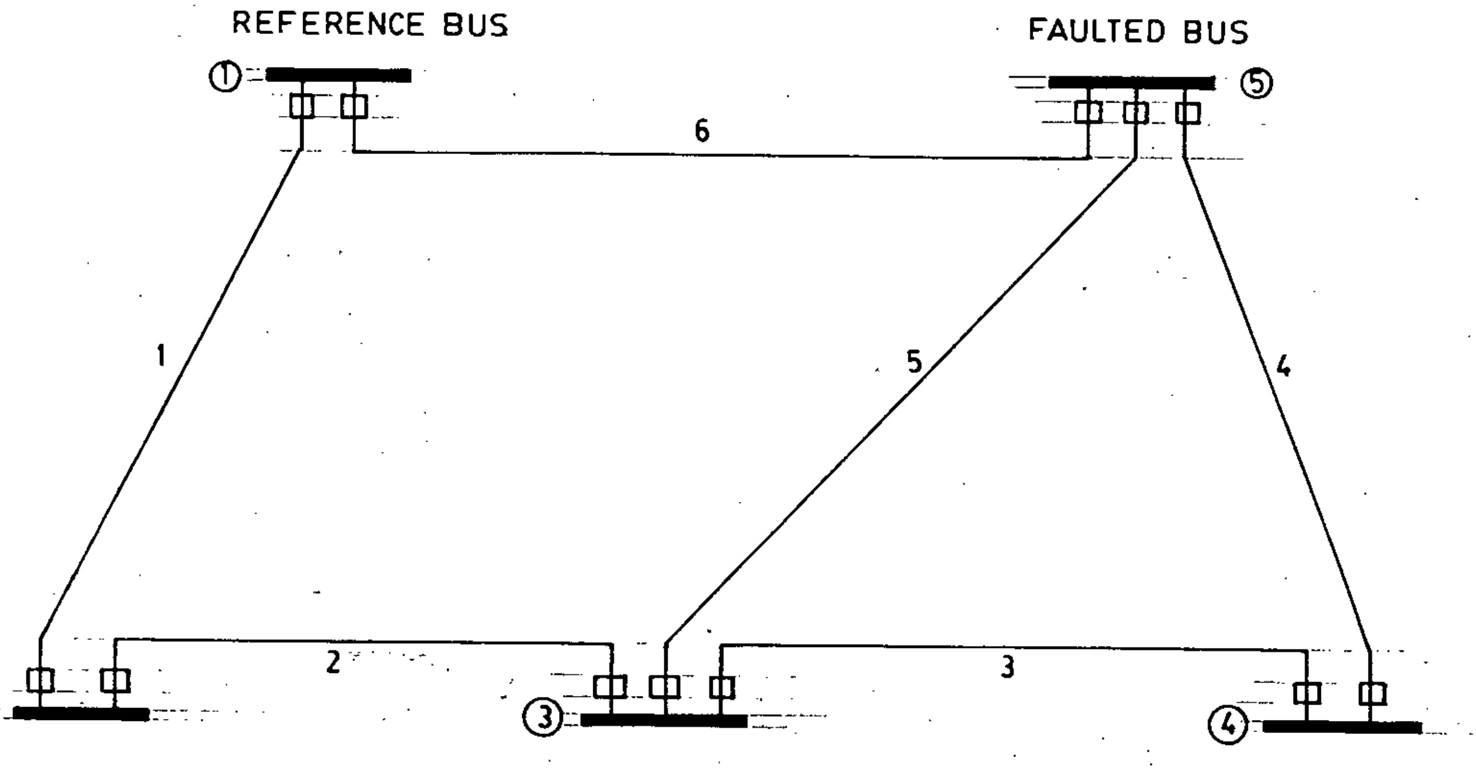


Fig. 5.1. Single line diagram of three phase system for fault occured on the bus

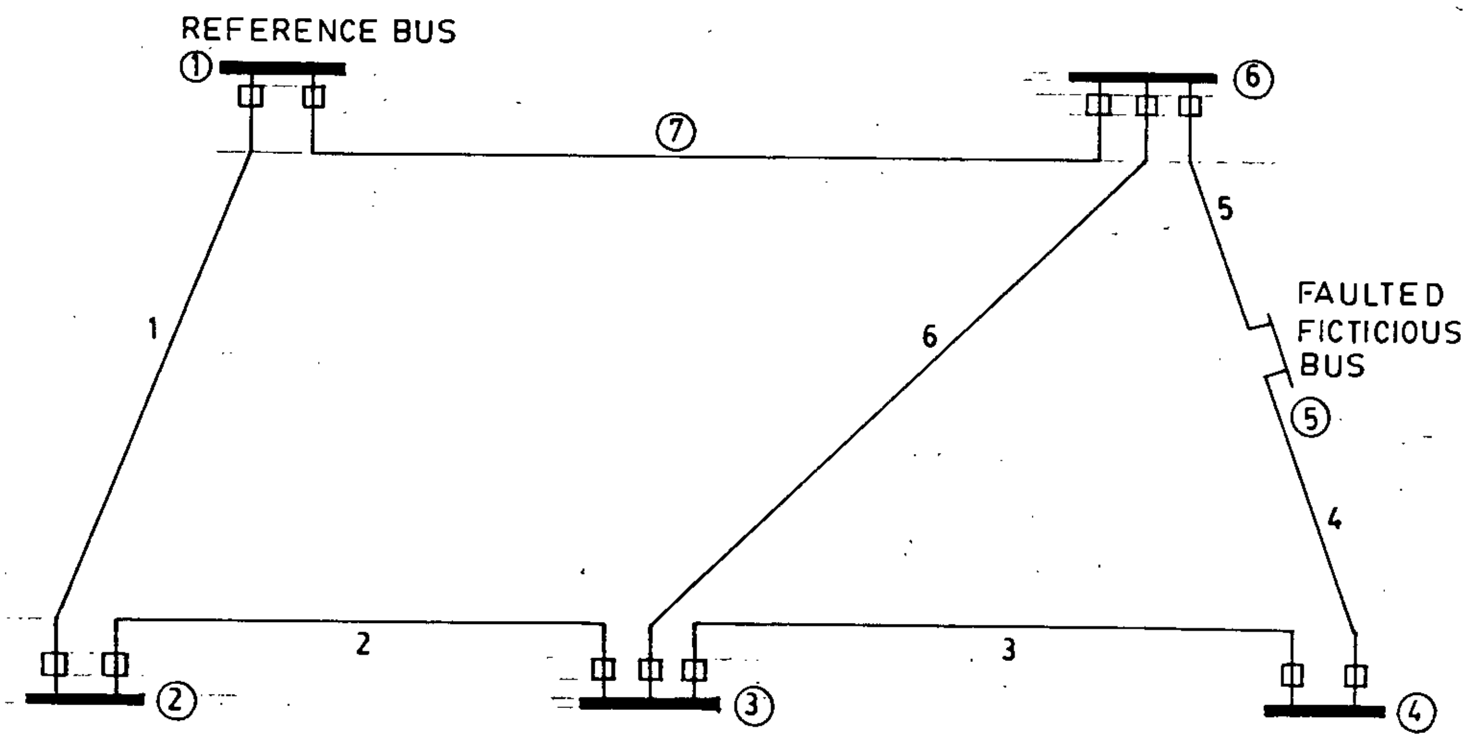


Fig. 5.2. Revised single line digram of three phase system for fault occured on the line between two buses.

5.5 CASE STUDY

5.5.1 FAULT OCCURED ON THE BUS

Assume that fault occured on bus no. 5 (shown in fig. 5.1). For this fault condition, the different bus voltages and fault current in different branches of the system are calculated. This fault result are than applied on the distance relay program in order to calculate fault distance and detection of fault.

The bus voltages and fault currents for different type of faults are shown in table 5.2 and 5.3.

TABLE 5.2: Different Bus Voltages

Bus No.	Bus Voltage $E_{(F)}^{0,1,2}$			Fault Type
1	0	0	0	-
2	0	1.262	0	3-phase
3	0	0.909	0	fault
4	0	0.606	0	
5	0	0	0	
1	0	0	0	Single phase
2	-.043	1.582	-.149	to ground fault
3	-.086	1.470	-.262	
4	-.117	1.374	-.358	
5	-.629	1.181	-.552	
1	0	0	0	
2	0	1.497	.235	Phase-to-phase
3	0	1.321	.411	fault
4	0	1.169	.563	
5	0	.866	.866	

TABLE 5.3 : Fault Currents For Different Branches

Bus Code p-q	Fault Current $I_{(F)}^{0,1,2}$			Fault Type
1-2	0	- 6.310	0	3-phase fault
2-3	0	2.349	0	
3-4	0	1.213	0	
4-5	0	1.213	0	
3-5	0	1.137	0	
1-5	0	0	0	
1-2	.864	-7.912	.748	Single phase to-ground fault
2-3	.864	.748	.748	
3-4	.503	.386	.386	
4-5	.503	.386	.386	
3-5	.362	.362	.362	
1-5	.252	-.787	.367	
1-2	0	-7.485	-1.174	Phase-to-phase fault
2-3	0	1.175	-1.174	
3-4	0	.606	-.606	
4-5	0	.606	-.606	
3-5	0	.589	-.568	
1-5	0	-.577	-.577	

In order to detect the fault type and location of fault, the short-circuit results are fed into the distance relay program and the corresponding fault results are shown in table 5.4.

Table 5.4: Fault Results for Fault Occured on Bus.

Relay Location	Relay Input						Relay Output							Fault type
	E_o	E_1	E_2	I_o	I_1	I_2	K_L	K_o	K'_o	K_2	K'_2	K_1	K	
Relay placed at bus No (4) and element No. 4	0	.606	0	0	1.213	0	0	0	0	0	0	1.01	1.0	3-P-fault
	-.117	1.374	-.358	.503	.386	.386	0	-.24	2.62	-1.85	1.0	7.03	1.0	L-G-fault
	0	1.169	.563	0	.606	-.606	0	0	0	-1.84	1.0	3.84	1.0	L-L-fault
Relay placed at bus No (3) and element No 5	0	.909	0	0	1.137	0	0	0	0	0	0	1.0	1.0	3-P-fault
	-.086	1.470	-.262	.362	.362	.362	0	-.17	1.88	-.90	1.0	5.10	1.0	L-G-fault
	0	1.321	.411	0	.589	-.568	0	0	0	-.90	1.0	2.89	1.0	L-L-fault
Relay placed at bus No. (5) and element No-4	0	0	0	0	-1.213	0	0	0	0	0	0	0	0	3-P-fault
	-.629	1.181	-.552	-.503	-.386	-.386	0	1.58	2.04	2.82	1.0	-6.05	0	L-G-fault
	0	.866	.866	0	-.606	.606	0	0	0	2.85	1.0	-2.85	0	L-L-fault
Relay placed at bus No(5) and element No -5	0	0	0	0	-1.137	0	0	0	0	0	0	0	0	3-P-fault
	-.629	1.181	-.552	-.362	-.362	-.362	0	1.17	1.88	1.91	1.0	-4.1	0	L-G-fault
	0	.866	.866	0	-.589	.568	0	0	0	1.91	1.0	-1.91	0	L-L-fault
Relay placed at bus No (4) and element No-3	0	.606	0	0	-1.213	0	0	0	0	0	0	-2.02	2.0	3-P-fault
	-.117	1.374	-.358	-.503	-.386	-.386	0	4.0	0	3.69	1.0	-14.05	4.0	L-G-fault
	0	1.169	.563	0	-.606	.606	0	0	0	3.67	1.0	-7.67	2.0	L-L-fault
Relay placed at bus No (3) and element No - 3	0	.909	0	0	1.213	0	0	0	0	0	0	3.01	3.0	3-P-fault
	-.086	1.470	-.262	.503	.386	.386	0	-3.0	.31	-2.67	1.0	15.08	5.0	L-G-fault
	0	1.321	.411	0	.606	-.606	0	0	0	-2.69	1.0	8.66	3.0	L-L-fault

Table 5.4 contd.

Relay Location	Relay Input						Relay Output							Fault type
	E_o	E_1	E_2	I_o	I_1	I_2	K_L	K_o	K'_o	K_2	K'_2	K_1	K	
Relay placed	0	.909	0	0	-2.349	0	0	0	0	0	0	-2.58	2.6	3-P-fault
at bus No (3)	-.086	1.470	-.262	-.864	-.748	-.748	0	2.09	.38	2.31	1.0	-13.07	4.2	L-G-fault
and element No - 2	0	1.321	.411	0	-1.175	1.174	0	0	0	2.34	1.0	-7.52	2.6	L-L-fault
Relay placed	0	1.262	0	0	2.349	0	0	0	0	0	0	3.57	3.6	3-P-fault
at bus No (2)	-.043	1.582	-.149	.864	.748	.748	0	-.93	.38	-1.33	1.0	14.04	5.2	L-G-fault
and element No - 2	0	1.497	.235	0	1.175	-1.174	0	0	0	-1.37	1.0	8.55	3.6	L-L-fault

5.5.2 FAULT OCCURED ON THE LINE BETWEEN THE BUSES

Assume that fault occured on the line between the buses 4 and 5 (shown in fig. 5.1). The redrawn fig. for this fault is shown in fig. 5.2 and system data are given in table 5.5. Let us assume that fault occured on ficticious bus 5 on the line between the bus 4 and 6 (See fig. 5.2).

TABLE 5.5: System Data

Element Number	Bus-Code p-q	Self impedance $Z_{pq}^{0,1,2}$		
1	1-2	0.05	0.20	0.20
2	2-3	0.05	0.15	0.15
3	3-4	0.06	0.25	0.25
4	4-5	0.61	0.30	0.30
5	5-6	0.41	0.20	0.20
6	3-6	1.50	0.80	0.80
7	1-6	2.50	1.50	1.50

The bus voltages and fault current for fault occurs on the line for different fault condition are shown in table 5.6 and 5.7.

TABLE 5.6: Different Bus Voltages

Bus No	Bus Voltage $E_{(F)}^{0,1,2}$			Fault Type
1	0	0	0	3-phase fault
2	0	1.259	0	
3	0	.905	0	
4	0	.494	0	
5	0	0	0	
6	0	.331	0	
1	0	0	0	Single line to-ground fault
2	-.047	1.574	-.158	
3	-.094	1.456	-.276	
4	-.137	1.318	-.414	
5	-.575	1.153	-.579	
6	-.418	1.264	-.468	
1	0	0	0	Line-to-line fault
2	0	1.496	.236	
3	0	1.319	.414	
4	0	1.113	.619	
5	0	.866	.866	
6	0	1.031	.701	

TABLE 5.7: Fault Current for Different Branches

Bus-Code p-q	Fault Current $I_{(F)}^{0,1,2}$			Fault-Type
1-2	0	-6.297	0	3-Phase fault
2-3	0	2.363	0	
3-4	0	1.645	0	
4-5	0	1.645	0	
5-6	0	-1.652	0	
3-6	0	.718	0	
1-6	0	-.220	0	
1-2	.935	-7.871	.789	Single-line-to-ground fault
2-3	.935	.789	.789	
3-4	.718	.549	.549	
4-5	.718	.549	.549	
5-6	-.382	-.552	-.552	
3-6	.216	.239	.239	
1-6	.167	-.843	.312	
1-2	0	-7.479	-1.182	Line-to-line fault
2-3	0	1.182	-1.182	
3-4	0	.823	-.823	
4-5	0	.823	-.823	
5-6	0	-.826	.826	
3-6	0	.359	-.359	
1-6	0	-.688	-.467	

In order to detect the fault type and location of fault, the short-circuit results are fed into the distance relay program and the corresponding fault results are shown in Table 5.8.

Table 5.8: Fault Results for Fault Occured on the Line Between the Buses.

Relay Location	Relay Input						Relay Output							Fault type
	E_o	E_1	E_2	I_o	I_1	I_2	K_L	K_o	K'_o	K_2	K'_2	K_1	K	
Relay placed at bus No (4) and element No-4	o	.494	0	0	1.645	0	0	0	0	0	0	.59	.6	3-P-fault
	-.137	1.318	-.414	.718	.549	.549	0	-.19	2.67	-1.49	1.0	4.8	.6	L-G-fault
	0	1.113	.619	0	.823	-.823	0	0	0	-1.51	1.0	2.71	.6	L-L-fault
Relay placed at bus No (6) and element No - 5	0	.331	0	0	1.652	0	0	0	0	0	0	-.40	.4	3-P-fault
	-.418	1.264	-.468	.383	.552	.552	0	-1.08	1.41	-1.71	1.0	4.58	.4	L-G-fault
	0	1.031	.701	0	.826	-.826	0	0	0	-1.69	1.0	2.48	.4	L-L-fault
Relay placed at bus No (4) and element No-3	0	.494	0	0	-1.645	0	0	0	0	0	0	-1.19	1.2	3-P-fault
	-.137	1.318	-.414	-.718	-.549	-.549	0	3.24	.31	2.98	1.0	-9.6	2.4	L-G-fault
	0	1.113	.619	0	-.823	.823	0	0	0	3.02	1.0	-5.42	1.2	L-L-fault
Relay placed at bus No (2) and element No-2	0	1.259	0	0	2.363	0	0	0	0	0	0	3.56	3.6	3-P-fault
	-.047	1.574	-.158	.935	.789	.789	0	-1.06	.40	-1.35	1.0	13.25	4.8	L-G-fault
	0	1.495	.236	0	1.182	-1.182	0	0	0	-1.36	1.0	8.47	3.6	L-L-fault
Relay placed at bus No (3) and element No-2	0	.905	0	0	-2.363	0	0	0	0	0	0	-2.54	2.6	3-P-fault
	-.094	1.456	-.276	-.935	-.789	-.789	0	1.91	.40	2.36	1.0	-12.32	3.8	L-G-fault
	0	1.319	.414	0	-1.182	1.182	0	0	0	2.32	1.0	-7.46	2.6	L-L-fault
Relay placed at bus No (3) and element No.6	0	.905	0	0	.718	0	0	0	0	0	0	1.56	1.6	3-P-fault
	-.094	1.456	-.276	.216	.239	.239	0	-.27	1.72	-1.46	1.0	7.60	1.5	L-G-fault
	0	1.319	.414	0	.359	-.359	0	0	0	-1.42	1.0	4.58	1.6	L-L-fault
Relay placed at bus No (3) and element No - 3	0	.905	0	0	1.645	0	0	0	0	0	0	2.18	2.2	3-P-fault
	-.094	1.456	-.276	.718	.549	.549	0	-2.08	.31	-2.04	1.0	10.62	3.4	L-G-fault
	0	1.319	.414	0	.823	-.823	0	0	0	-2.00	1.0	6.44	2.2	L-L-fault

5.6 DISCUSSION ON RESULTS

The computer program developed for distance relay was applied in a large power system having more than two bus and different fault results were investigated. The results were presented in section 5.5. The different approximation, the effect of which were discussed for two bus system in chapter 4 were also applied for this large power system.

The power system which was chosen for present analysis consists ~~of 5 bus of which~~ bus 1 is the reference bus. First of all, considered that fault occured on bus no. 5 (see fig. 5.1) and for this fault condition short circuit study were performed on the system in order to compute different bus voltages and fault currents. The short circuit results were presented in Table 5.2 & 5.3. The data obtained from short circuit study were fed into the distance relay program and the performance of the program were investigated and the fault results obtained were presented in Table 5.4.

From the results of Table 5.4, it was observed that for relay location on buses 4, element 4 and bus no. 3, element 5, the distance of the fault which occured on bus no.5 were 1 (one) P.U. for all type of faults. (3Ø fault, L-G fault, L-L fault etc.) Bus no. 4 and 3 were connected to the faulted bus 5 with element 4 and 5. Again for all the relays located on bus no. 5 , fault distance was 0 (Zero) for fault occuring on bus 5. Finally for relay located on bus no. 2 , 3 , 4 and element 2, 3 which were not connected to the faulted bus 5, the fault distance were greater than one. So we conclude that for relay location on faulted bus, the fault distance is zero, relay located to the adjacent buses and lines which are connected to the faulted bus is one. And relay located to the buses and the lines, not connected to the faulted bus is greater than one.

Secondly, considered that fault occured on the line between the buses 4 and 6 (see fig. 5.2) and for this fault condition short circuit study were performed in order to obtain different bus voltages and fault currents. The short circuit results were presented in table 5.6 and 5.7. The data obtained from short circuit study were fed in to the distance relay program and the fault results obtained were presented in table 5.8. From the results of table 5.8, it was observed that for relay located on bus no. 4 and element no 4 the fault distance was 0.6 (P.U.) and for relay located on bus no 6 and element 5, the fault distance was 0.4 (P.U.) for a fault occured on the line between the buses 4 and 6 i.e. (on fic-ticious bus 5) for different types of fault. Relay located other than the faulted line were greater than one. So for fault occured on the line between two bus the distance of fault from one bus is fractional distance 0.4 and from the other bus, the fault distance is (1-0.4) or 0.6.

From the result discussed above we conclude that:

i) $0 < K < 1$, i.e. when K has a value between 0 and 1, the fault occurs on the line between two buses.

ii) K = 0 or 1, fault occurs on the bus

a) K = 0 i.e. K has a value equal to zero, the fault occurs on the bus where the relay is located.

b) K = 1, i.e. when K has a value equal to one, fault occurs on the bus adjacent to the bus where the relay placed but connected with the relaying bus.

iii) K >1, i.e., when K has a value greater than 1, no fault occurs on the lines or bus connected to the relaying bus.

CHAPTER - 6

6.0 CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

6.1 CONCLUSIONS

A detailed investigation into the detection and localization of the various kinds of faults using symmetrical component distance relay, has been presented in the present work. The method used is well- ammenable to digital computer implementation. Symmetrical component discrete fourier transform technique was chosen as the basic tool because of a number of advantages compared to conventional technique of using phase and ground relays. Among these is the availability of negative and zero sequence currents which are useful in their own right in relaying applications with particularly difficult coordination problems. Another advantage of this formulation is that for a fault directly in front of a circuit breaker, symmetrical component voltages are non-zero (except of curse, for a closing three phase fault), and consequently the distance computation in this instance is highly directional at all values including zero. In case of a three phase fault adjacent to the breaker, memory voltages must be used with symmetrical component technique as they are with conventional relay.

The symmetrical component relay is even more attractive when digital computer based relaying system are considered. The problem of sequentially processing fault equations for different phase and ground faults (with attendant computational burden) is eliminated since the symmetrical component relay uses a single performance equation for all fault types. Symmetrical components of voltages and currents are generated recursively from sample data. This recursive computation implies ongoing processing of data at all times.

The main feature of the symmetrical component distance relay is use of a single equation to determine the distance to a fault from a transmission line terminal regardless of the type of fault. The performance equation uses the symmetrical components of line parameters, and a single equation is valid for all types of faults. The single performance equation eliminates the need for multiple impedance units or relaying systems with switched signals. The phases involved in a fault are identified as a by product of the distance equation evaluation rom the performance equation of the symmetrical component distance relay, it is shown that its accuracy is identical to that of a conventional phase and ground distance relay. The symmetrical component relay is specially suitable for digital computer application.

On the basis of through investigations the method developed for symmetrical component distance relay program has been applied for the calculation of location and type of fault on a large power system. It has revealed from the results that the distance of fault from the relay location represents the per unit distance (expressed in terms of total line length) to any balanced or unbalanced fault on the transmission line. For a fault on bus, the distance of the fault from the relay location is one, P.U., for fault on line, the distance of the fault from the relay location is less than one P.U. and for a fault beyond the protective zone of the relay the distance is greater than one P.U.

Finally we conclude that the main function provided by the SCDR program are:

i) Phase and ground distance protection.

ii) High speed relaying speed of 1/2-1 cycle.

iii) Fault classification.

iv) Fault localization.

v) Phase detection.

vi) Single pole trip output.

6.2 SUGGESTIONS FOR FUTURE WORK

Further research work in the field of power system protection, using symmetrical component distance relay could concentrate on the following:

1) Study on the development of micro-computer based S.C. distance relay using a plessey MIPROC -16 micro processor. This processor has 16 bit data and instruction words and its circuitry uses tri-state scholtky TTL device. Versions of the processor with 350, 300 and 250 n sec cycle time are available. It uses separate program and data memories and most instructions execute in one or two clock cycle.

2) Study on the development of ultra high speed micro-computer based distance relay using SCDFT and transient monitor functions.

3) Further study on the method of present analysis using different relay operating speed and mean and standard diviation of distance estimation will be compare.

4) Study of the application of the method in the BPDP power system.

5) Investigation of the method considering the effect of fault path resistance on the location of fault.

APPENDIX

APPENDIX - A

SYMMETRICAL COMPONENT TRANSFORMATION

A set of three balanced voltages (phasors) V_a, V_b, V_c is characterized by equal magnitudes and interphase differences of 120^o. The set is said to have a phase sequence abc (positive sequence) if V_b lags V_a by 120^o and V_c lags V_b by 120. The three phasors can then be expressed in terms of the reference phasor V_a as

$$V_a = V_a,\ V_b = \alpha^2 V_a,\ V_c = \alpha V_a \qquad \text{A.1}$$

where the complex number operator is defind as

$$\alpha = e^{J120^o}$$

If the phase sequence is acb (negative sequence)

$$V_a = V_a,\ V_b = \alpha V_a\ ,\ V_c = \alpha^2 V_a \qquad \text{A.2}$$

Thus a set of balanced phasors is fully characterized by its reference phasor (say V_a) and its phase sequence (Positive or negative).

Suffex 1 is commonly used to indicate positive sequence. A set of (balanced) positive sequence phasors is written as:

$$V_{a1},\ V_{b1} = \alpha^2 V_{a1},\ V_{c1} = \alpha V_{a1} \qquad \text{A.3}$$

Similarly, suffix 2 is used to indicate negative sequence. A set of (balanced) negative sequence phasors is written as:

$$V_{a2},\ V_{b2} = \alpha V_{a2},\ V_{c2} = \alpha^2 V_{a2} \qquad \text{A.4}$$

A set of three voltages (phasors) equal in magnitude and having the same phase is said to have zero sequence. Thus a set of zero sequence phasors is written as:

$$V_{ao},\ V_{bo} = V_{ao},\ V_{co} = V_{ao} \qquad \text{A.5}$$

Consider now a set of three voltages (phasors) V_a, V_b, V_c which in general may be unbalanced. According to Fortesques theoreom , the three phasors can be expressed as the sum of positive, negative and zero sequence phasors defined above. Thus

$$\begin{aligned} V_a &= V_{a1} + V_{a2} + V_{ao} \\ V_b &= V_{b1} + V_{b2} + V_{bo} \qquad \text{A.6} \\ V_c &= V_{c1} + V_{c2} + V_{co} \end{aligned}$$

The three phasor sequences (positive, negative, and zero) are called the symmetrical component. The addition of symmetrical components as per equation A.6 to generate V_a,V_b, V_c is indicated by the phasor diagram of fig. A.1.

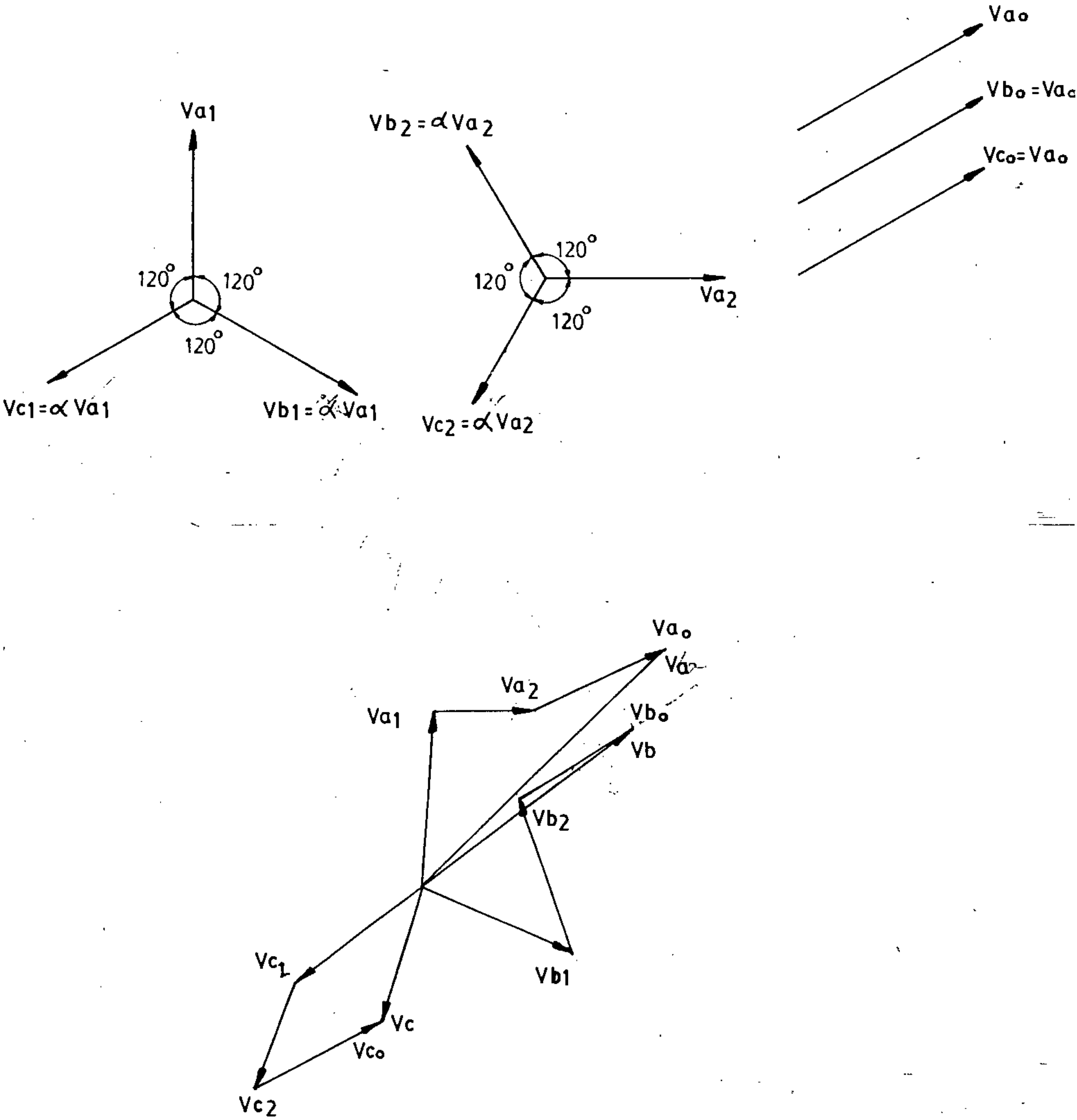


Fig. A.1. Graphical addition of the symmetrical components to obtain the set of phasor Va, Vb, Vc .

Let us express equation A.6 in terms of reference phasors V_{a1}, V_{a2} and V_{ao}. Thus

$$V_a = V_{a1} + V_{a2} + V_{ao}$$

$$V_b = \alpha^2 V_{a1} + \alpha V_{a2} + V_{ao} \qquad \text{A.7}$$

$$V_c = \alpha V_{a1} + \alpha^2 V_{a2} + V_{ao}$$

These equations can be expressed in the matrix form as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix} \begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{ao} \end{bmatrix} \qquad \text{A.8}$$

Invector form:

$$V_p = AV_s \qquad \text{A.9}$$

$$V_s = A^{-1} V_p$$

Computing A^{-1} and utilizing relation A.8

$$V_{a1} = \frac{1}{3} (V_a + \alpha V_b + \alpha^2 V_c)$$

$$V_{a2} = \frac{1}{3} (V_a + \alpha^2 V_b + \alpha V_c) \qquad A.10$$

$$V_{ao} = \frac{1}{3} (V_a + V_b + V_c)$$

Equation A.10 give the necessary relationships for obtaining symmetrical components of the original phasors.

APPENDIX - B

DERIVATION OF THE PERFORMANCE EQUATION OF SYMMETRICAL COMPONENT DISTANCE RELAY.

Fig. 2.1 shows the single line diagram of a sample system having two bus P and Q. Let us assume that fault occured at points B at a fractional distance K from the bus P. Under the occurance of a fault at point B through the fault resistance R_f, the resulting voltages and currents in the network are shown in fig. 2.2 and the relevant performance equations are as:

$$E_{ow} = E_o - K I_o Z_o - R_{of} I_{of}$$

$$E_{1w} = E_1 - K I_1 Z_1 - R_{1f} I_{1f} \qquad \text{B.1}$$

$$E_{2w} = E_2 - K I_2 Z_2 - R_{2f} I_{2f}$$

Where, R_{of}, R_{1f}, R_{2f} are symmetrical component fault resistances and I_{of}, I_{1f}, I_{2f} are the symmetrical component fault current.

For Transmission line $Z_1 = Z_2$

The line currents change because of the fault by the amounts:

$$\Delta I_o = I_o - \bar{I}_o \simeq I_o$$

$$\Delta I_1 = I_1 - \bar{I}_1 \qquad \text{B.2}$$

$$\Delta I_2 = I_2 - \bar{I}_2 \simeq I_2$$

Using ΔI'S in equation B.1:

$$E_{ow} = E_o - K\Delta\ I_o\ Z_o - R_{of}\ I_{of}$$

$$E_{1w} = E_1 - K\ \Delta\ I_1\ Z_1 - K\bar{I}_1\ Z_1 - R_{1f}\ I_{1f} \qquad \text{B.3}$$

$$E_{2w} = E_2 - K\Delta I_2 Z_2 - R_{2f}\ I_{2f}.$$

It is convenient to define the following voltage drops:

$$\Delta E_o = \Delta I_o Z_o$$

$$\Delta E_1 = \Delta I_1 Z_1 \qquad \text{B.4}$$

$$\Delta E_2 = \Delta I_2 Z_2$$

Using these drops, equation B.3 reduces to:

$$E_{ow} = E_o - K\Delta E_o - R_{of}\ I_{of}$$

$$E_{1w} = E_1 - K\Delta E_1 - K\bar{I}_1 Z_1 - E_{1f}\ I_{1f} \qquad \text{B.5}$$

$$E_{2w} = E_2 - K\Delta E_2 - R_{2f}\ I_{2f}$$

Let us define the ratios:

$$K_o = \frac{E_o}{\Delta E_o}\ ,\quad K_1 = \frac{E_1}{\Delta E_1}\ ,\ K_2\ \frac{E_2}{\Delta E_2}\ ,\ K_L = \frac{\bar{I}_1 Z_1}{\Delta E_1} \qquad \text{B.6}$$

Equation B.5 can now be expressed in terms of these ratios:

$$E_{ow} = \Delta E_o \left(\frac{E_o}{\Delta E_o} - K \right) - R_{of} I_{of}$$

$$= \Delta E_o \left(K_o - K \right) - R_{of} I_{of} \qquad \text{B.7(a)}$$

$$E_{1w} = \Delta E_1 \left(\frac{E_1}{\Delta E_1} - K - K \frac{\bar{I}_1 Z_1}{\Delta E_1} \right) - R_{1f} I_{1f}$$

$$= \Delta E_1 \left(K_1 - K - KK_L \right) - R_{1f} I_{1f}$$

$$= \Delta E_1 \{ K_1 - K (1 + K_L) \} - R_{1f} I_{1f} \qquad \text{B.7(b)}$$

$$E_{2w} = \Delta E_2 \left(\frac{E_2}{\Delta E_2} - K \right) - R_{2f} I_{2f}$$

$$= \Delta E_2 \left(K_2 - K \right) - R_{2f} I_{2f} \qquad \text{B.7(c)}$$

We will now develop expressions for the fractional distance to the fault K in terms of the above ratios for all types of faults.

i) <u>Three Phase Fault</u>:

Fig. 2.3 shows the symmetrical component representation for 3 phase fault. The fault imposes the boundary condition $E_{1w} = 0$.

Substituting this condition in equation B.7(b) leads to:

$$E_{1w} = 0 = \Delta E_1 \{ K_1 - K (1+K_L) \} - R_{1f} I_{1f}$$

or $$K_1 - K (1 + K_L) - \frac{R_{1f} I_{1f}}{\Delta E_1} = 0$$

or $$K (1 + K_L = K_1 - \frac{R_{1f} I_{1f}}{\Delta E_1}$$

$$\therefore K = \frac{K_1}{-1 + K_L} - \frac{R_{1f} I_{1f}}{\Delta E_1 (1+K_L)}$$

$$= \frac{K_1}{1 + K_L} + \varepsilon_r \qquad \text{B.8}$$

where $$\varepsilon_r = - \frac{R_{1f} I_{1f}}{\Delta E_1 (1+K_L)} \qquad \text{B.9}$$

ii) Phase to Ground Fault

Fig. 2.4 represents the symmetrical component representation for the single phase to ground faults. Boundary conditions for this fault are:

i) For phase 'a' to ground fault:

$$E_{1w} + E_{2w} + E_{ow} = 0$$

$$\Delta E_1 = \Delta E_2 \qquad \text{B.10}$$

ii) For phase 'b' to ground fault:

$$\alpha^2 E_{1w} + \alpha E_{2w} + E_{ow} = 0$$

$$\alpha^2 \Delta E_1 = \alpha \Delta E_2 \qquad \text{B.11}$$

iii) For phase 'c' to ground fault:

$$\alpha E_{1w} + \alpha^2 E_{2w} + E_{ow} = 0$$

$$\alpha \Delta E_1 = \alpha^2 E_2 \qquad \text{B.12}$$

Using these boundary conditions in equation B.7 leads to the following expressions for K:

For a-g fault:

$$E_{1w} + E_{2w} + E_{ow} = 0$$

$$\Delta E_o(K_o - K) - R_{of}I_{of} + \Delta E_1\{K - K(1+K_L)\} - R_{1f}I_{1f} + \Delta E_2(K_2 - K) - R_{2f}I_{2f} = 0$$

or $$\Delta E_o(K_o - K) - R_{of}I_{of} + \Delta E_1\{K_1 - K(1+K_L) + K_2 - K\} - R_{1f}I_{1f} - R_{2f}I_{2f} = 0$$

or $$\Delta E_o K_o + \Delta E_1 (K_1 + K_2) - (R_{of}I_{of} + R_{1f}I_{1f} + R_{2f}I_{2f}) = K\{\Delta E_o + \Delta E_1(2+K_L)\}$$

or $$K = \frac{\Delta E_o K_o + \Delta E_1(K_1+K_2)}{\Delta E_o + \Delta E_1(2+K_L)} - \frac{(R_{of}I_{of} + R_{1f}I_{1f} + R_{2f}I_{2f}}{\Delta E_o + \Delta E_1(2+K_L)}$$

$$= \frac{K_1 + K_2 + K_o \frac{\Delta E_o}{\Delta E_1}}{2 + K_L + \frac{\Delta E_o}{\Delta E_1}} - \frac{(R_{of}I_{of} + R_{1f}I_{1f} + R_{2f}I_{2f})}{(2 + K_L + \frac{\Delta E_o}{\Delta E_1})\ \Delta E_1} \qquad B.13$$

Let us define $K_0' = \frac{\Delta E_o}{\Delta E_1} = \left| \frac{\Delta E_o}{\Delta E_1} \right| e^{J\ (\theta_o - \theta_1)}$ B.14

Where θ_o and θ_1 are the phase angle of Z_o and Z_1. Using K_o' in equation B.13, the expression for K becomes:

$$K = \frac{K_1 + K_2 + K_o K_o'}{2 + K_L + K_o'} - \frac{(R_{of}I_{of} + R_{1f}I_{1f} + R_{2f}I_{2f})}{(2 + K_L + K_o')\ \Delta E_1}$$

$$= \frac{K_1 + K_2 + K_o K_o'}{2 + K_L + K'_o} + \varepsilon_r \qquad B.15$$

where $\varepsilon_r = - \frac{R_{of}I_{of} + R_{1f}I_{1f} + R_{2f}I_{2f}}{\Delta E_1 (2 + K_L + K_o')}$ B.16

Similarly for c-g fault:

$$\varepsilon_r = - \frac{(R_{1f}I_{1f} + \alpha R_{2f}I_{2f} + \alpha^2 R_{of}I_{of})}{\Delta E_1 (2 + K_L + K_o')} \qquad B.17$$

and for b-g fault:

$$\varepsilon_r = - \frac{R_{1f}I_{1f} + \alpha^2 R_{2f}I_{2f} + \alpha R_{of}I_{of})}{\Delta E_1 (2 + K_L + K_o')} \qquad B.18$$

iii) Phase to phase fault

Fig 2.5 shows the symmetrical component representation for phase to phase faults. Boundary conditions are:

i) For 'b' - 'c' fault:

$$E_{1w} = E_{2w} \qquad \text{B.19}$$

$$\Delta E_1 = - \Delta E_2$$

ii) For 'a' - 'b' fault:

$$\alpha E_{1w} = \alpha^2 E_{2w}$$

$$\alpha \Delta E_1 = -\alpha^2 \Delta E_2 \qquad \text{B.20}$$

iii) For 'a' - 'c' fault:

$$\alpha^2 E_{1w} = \alpha E_{2w}$$

$$\alpha^2 \Delta E_1 = - \alpha \Delta E_2 \qquad \text{B.21}$$

Substituting these boundary conditions in equation B.7, the expression for K becomes:

$$E_{1w} = E_{2w}$$

or $\Delta E_1 \{K_1 - K (1+K_L)\} - R_{1f}I_{1f} = \Delta E_2 (K_2 - K) - R_{2f}I_{2f}$

or $\Delta E_1 \{K_1 - K (1+K_L)\} - R_{1f}I_{1f} + \Delta E_1 (K_2 - K) + R_{2f}I_{2f} = 0$

or $\Delta E_1 K_1 + \Delta E_1 K_2 - K(2+K_L)\Delta E_1 - R_{1f}I_{1f} + R_{2f}I_{2f} = 0$

or $K(2+K_L)\Delta E_1 = \Delta E_1 (K_1+K_2) - (R_{1f}I_{1f} - R_{2f}I_{2f})$

or $K = \dfrac{K_1+K_2}{2+K_L} - \dfrac{R_{1f}I_{1f} - R_{2f}I_{2f}}{\Delta E_1 (2+K_L)}$

$$= \frac{K_1+K_2}{2+K_L} + \varepsilon_r \qquad \text{B.22}$$

$$\text{where } \varepsilon_r = -\frac{R_{1f}I_{1f} - R_{2f}I_{2f}}{\Delta E_1 (2+K_L)} \qquad \text{B.23}$$

Similarly for a-b fault:

$$\varepsilon_r = -\frac{R_{1f}I_{1f} - \alpha R_{2f}I_{2f}}{\Delta E_1 (2+K_L)} \qquad \text{B.24}$$

and for a-c fault:

$$\varepsilon_r = -\frac{R_{1f}I_{1f} - \alpha^2 R_{2f}I_{2f}}{\Delta E_1 (2+K_L)} \qquad \text{B.25}$$

iv) <u>Double phase to ground fault:</u>

Fig 2.6 represent the symmetrical component representation for double phase to ground fault. The boundary conditions are:

i) b-c-g fault:

$$E_{1w} = E_{2w} = E_{ow} \qquad \text{B.26}$$

ii) a-b-g fault:

$$\alpha E_{1w} = \alpha^2 E_{2w} = E_{ow} \qquad \text{B.27}$$

iii) a-c-g fault:

$$\alpha^2 E_{1w} = \alpha E_{2w} = E_{ow} \qquad \text{B.28}$$

Using these boundary conditions and equation B.7, the expression for K becomes:

$$\Delta E_1 \{K_1 - K(1+K_L)\} - R_{1f} I_{1f} = \Delta E_o (K_o - K) - R_{of} I_{of}.$$

$$\Delta E_1 K_1 - \Delta E_o K_o - R_{1f} I_{1f} + R_{of} I_{of} = K(1+K_L) \Delta E_1 - \Delta E_o K$$

or $K\{(1+K_L)\Delta E_1 - \Delta E_o\} = \Delta E_1 K_1 - \Delta E_o K_o - (R_{1f} I_{1f} - R_{of} I_{of})$

or $$K = \frac{\Delta E_1 K_1 - \Delta E_o K_o}{\Delta E_1 (1+K_L) - \Delta E_o} - \frac{(R_{1f} I_{1f} - R_{of} I_{of})}{\Delta E_1 (1+K_L) - \Delta E_o}$$

$$= \frac{K_1 - K_o \frac{\Delta E_o}{\Delta E_1}}{1 + K_L - \frac{\Delta E_o}{\Delta E_1}} + \frac{(R_{of} I_{of} - R_{1f} I_{1f})}{\Delta E_1 \left(1 + K_L - \frac{\Delta E_o}{\Delta E_1}\right)} \qquad \text{B.29}$$

Using the value of K_o' of eqn. B.14 in eqn. B.29 we have the expression for K as:

$$\frac{\Delta E_o}{\Delta E_1} = -\left|\frac{\Delta E_o}{\Delta E_1}\right| e^{J(\theta_o - \theta_1)} = -K_o' \qquad \text{B.30}$$

$$K = \frac{K_1 + K_o K_o'}{1 + K_L + K_o'} + \frac{R_{of} I_{of} - R_{1f} I_{1f}}{\Delta E_1 (1 + K_L + K_o')}$$

$$= \frac{K_1 + K_o K_o'}{1 + K_o' + K_L} + \varepsilon_r \qquad \text{B.31}$$

where $$\varepsilon_r = \frac{R_{of} I_{of} - R_{1f} I_{1f}}{(1 + K_o' + K_L)\ \Delta E_1} \qquad \text{B.32}$$

Similarly for a-b-g fault:

$$\varepsilon_r = \frac{\alpha^2 R_{of} I_{of} - R_{1f} I_{1f}}{\Delta E_1\ (1 + K_o' + K_L)} \qquad \text{B.33}$$

and for a-c-g fault:

$$\varepsilon_r = \frac{\alpha R_{of} I_{of} - R_{1f} I_{1f}}{\Delta E_1 (1 + K_o' + K_L)} \qquad \text{B.34}$$

Using equation B.8, B.15, B.22 and B.31 the general expression for the expression for K are as:

$$K = \frac{K_1 + K_2 K_2' + K_o K_o'}{1 + K_o' + K_2 + K_L} + \varepsilon_r \qquad \text{B.35}$$

APPENDIX - C

```
C..........................................................................
C      THIS PROGRAM IS DONE BY MD SAJJAD HOSSAIN                          .
C           PROGRAM FOR SCDF                                               .
C..........................................................................
C--------------------------------------------------------------------------
C      Z1,Z2,Z3 ARE POSITIVE,NEGATIVE,ZERO SEQUENCE IMPEDANCE              .
C      E1,E2,E3 ARE POSITIVE,NEGATIVE,ZERO SEQUENCE BUS VOLTAGE            .
C      CN1,CN2,CN3 ARE POSITIVE,NEGATIVE,ZERO SEQUENCE CURRENT             .
C      CNB=PRE FAULT CURRENT                                               .
C      C1=K1,C2=K2,C3=K3,CL=KL,C3P=K0',C=K                                 .
C--------------------------------------------------------------------------
C..........................................................................
       COMPLEX Z1,Z2,E1,E2,E3,CN1,CN2,CN3,CNB,C1,C2,C3,CL,C3P,C,R,DI,APH1
      1,APH2,Z3,DE1,DE2,DE3
       READ(1,1) EPS1,EPS2,EPS3,EPS4
       READ(1,2) Z1,Z2,Z3,CNB
       DO 57 LL=1,10
       READ(1,3) E1,E2,E3,CN1,CN2,CN3
       DI=CN1-CNB
       DE1=Z1*DI
       DE2=Z2*CN2
       DE3=Z3*CN3
C      WRITE(3,78) DE1,DE2,DE3
C 78   FORMAT(6(3X,F8.2))
C--------------------------------------------------------------------------
       APH1=CMPLX(-.5,.866)
       APH2=CMPLX(-.5,-.866)
       VV=CABS(DI*APH1+CN2*APH2+CN3)
C      WRITE(3,81) VV
C 81   FORMAT(5X,'VV=',F10.4)
       IF(CABS(E2).EQ.0.0.AND.CABS(DE2).EQ.0.0) GO TO 211
       R=DE1/DE2
C      WRITE(3,222) R
C222   FORMAT(5X,'R=',2E9.2)
       AN=ATAN(AIMAG(R)/REAL(R))*57.3
C      WRITE(3,79) AN
C 79   FORMAT(10X,'AN=',F10.4)
       IF(AIMAG(R).GT.0.0.AND.REAL(R).LT.0.0) AN=180.0+AN
       IF(AIMAG(R).LE.0.0.AND.REAL(R).LE.0.0) AN=180.0+AN
C      WRITE(3,80) AN
C 80   FORMAT(5X,F10.4)
       T1=ATAN(AIMAG(Z3)/REAL(Z3))
       T2=ATAN(AIMAG(Z1)/REAL(Z1))
       GM=CABS(DE3/DE1)
       RC3P=GM*COS(T1-T2)
       CC3P=GM*SIN(T1-T2)
       C2=E2/DE2
       GO TO 212
  211  C2=0.0
  212  C1=E1/DE1
       CL=Z1*CNB/DE1
       IF(CABS(E3).EQ.0.0.AND.CABS(DE3).EQ.0.0) GO TO 113
       C3=E3/DE3
       GO TO115
   113 C3=0.0
       C3P=0.0
       GO TO 213
   115 C3P=CMPLX(RC3P,CC3P)
   213 DIFF=ABS(CABS(DE1)-CABS(DE3))
C      WRITE(3,77) DIFF
C 77   FORMAT(5X,'DIFF =',F10.4)
       IF(ABS(CABS(DE1)-CABS(DE2)).GT.EPS1) GO TO 10
       C2P=1.0
       GO TO 20
   10  C2P=0.0
   20  C=(C1+C2*C2P+C3*C3P)/(1.0+C2P+C3P+CL)
       WRITE(3,111)
  111  FORMAT(5X,'THE VALUES OF DIFFERENT K ARE --C INDICATE K'.//)
       WRITE(3,5) C1,C2,C3,CL,C3P,C
    1  FORMAT(4F10.4)
    2  FORMAT(8(F6.2,1X))
    3  FORMAT(6(F5.2,1X))
```

```
2    FORMAT(8(F6.2,1X))
3    FORMAT(6(F6.2,1X))
5    FORMAT(4(5X,F8.2))
5    FORMAT(5X,'C1=',F8.2,'+J',F8.2,5X,'C2=',F8.2,'+J',F8.2,5X,'C3=',F8
    1.2,'+J',F8.2/5X,'CL=',F8.2,'+J',F8.2,5X,'C3P=',F8.2,'+J',F8.2,5X,'
    1C=',F8.2,'+J',F8.2///)
-------------------------------------------------------------------------
     IF(C2P.EQ.0.0) GO TO 30
```



```
     IF(CABS(DE3).LE.EPS2) GO TO 40
     WRITE(3,6)
     GO TO 100
0    WRITE(3,7)
     GO TO 110
30   IF(CABS(DE3).LE.EPS2) GO TO 50
     WRITE(3,8)
     GO TO 120
50   WRITE(3,9)
     GO TO 130
100  IF(ABS(AN).LE.EPS3) GO TO 200
     IF(ABS(AN-120.0).LE.EPS3) GO TO 210
     WRITE(3,11)
     GO TO 130
200  WRITE(3,12)
     GO TO 130
0    WRITE(3,13)
     GO TO 130
0    IF(ABS(AN-180.0).LE.EPS3) GO TO 220
     IF(ABS(AN-60.0).LE.EPS3) GO TO 230
     WRITE(3,14)
     GO TO 130
0    WRITE(3,15)
     GO TO 130
0    WRITE(3,16)
     GO TO 130
0    IF(CABS(DI+CN2+CN3).LE.EPS4) GO TO 240
     IF(CABS(DI*APH1+CN2*APH2+CN3).LE.EPS4) GO TO 250
     WRITE(3,17)
     GO TO 130
40   WRITE(3,18)
     GO TO 130
50   WRITE(3,19)
)    FORMAT(10X,'PHASE-TO-GROUND FAULT'//)
7    FORMAT(10X,'PHASE-TO-PHASE FAULT'//)
3    FORMAT(10X,'DOUBLE PHASE-TO-GROUND FAULT'//)
9    FORMAT(10X,'3-PHASE FAULT'//)
.1   FORMAT(10X,'PHASE-B-TO-GROUND-FAULT'//)
2    FORMAT(10X,'PHASE-A-TO-GROUND-FAULT'//)
.3   FORMAT(10X,'PHASE-C-TO-GROUND-FAULT'//)
.4   FORMAT(10X,'PHASE-A-TO-PHASE-B-FAULT'//)
.5   FORMAT(10X,'PHASE-B-TO-PHASE-C-FAULT'//)
.6   FORMAT(10X,'PHASE-C-TO PHASE-A-FAULT'//)
.7   FORMAT(10X,'PHASE-A-AND-PHASE-C-TO-GROUND-FAULT'//)
.8   FORMAT(10X,'PHASE-B-AND-PHASE-C-TO-GROUND-FAULT'//)
.9   FORMAT(10X,'PHASE-A-AND-PHASE-B-TO-GROUND-FAULT'//)
30   F=CABS(C)
     WRITE(3,45) F
5    FORMAT(10X,'THE FAULT HAS OCCURED AT A FRACTIONAL DISTANCE
    1OF',F3.1/10X,60('-')//)
7    CONTINUE
     STOP
     END
```

APPENDIX - D

DERIVATION OF DISCRETE FOURIER TRANSFORM

Consider the fourier transform pair of fig. B.1(a). To discretize this transform pair it is necessary to sample the wave form h(t).

The sampled function can be written as:

$$h(t)\,\Delta_o(t) = h(t)\sum_{k=-\infty}^{\infty}\delta(t-KT)$$

$$= \sum_{k=-\infty}^{\infty} h(KT)\,\delta(t-KT) \qquad D.1$$

where $\Delta_o(t)$ is the time domain sampling function shown in fig. D.1(b) and T is the sampling Interval.

Next, the sampled function is truncated by multiplication with the rectangular function X(t) shown in fig. D.1(d) as:

$$X(t) = 1 \quad -T/2 < t < T_o - T/2 \qquad D.2$$

$$= 0 \quad \text{otherwise}$$

where T_o is the duration of the truncation function. Truncation yields:

$$h(t)\,\Delta_o(t)\,X(t) = \left\{\sum_{k=-\infty}^{\infty} h(KT)\,\delta(t-KT)\right\} X(t)$$

$$= \sum_{k=0}^{N-1} h(KT)\,\delta(t-KT) \qquad D.3$$

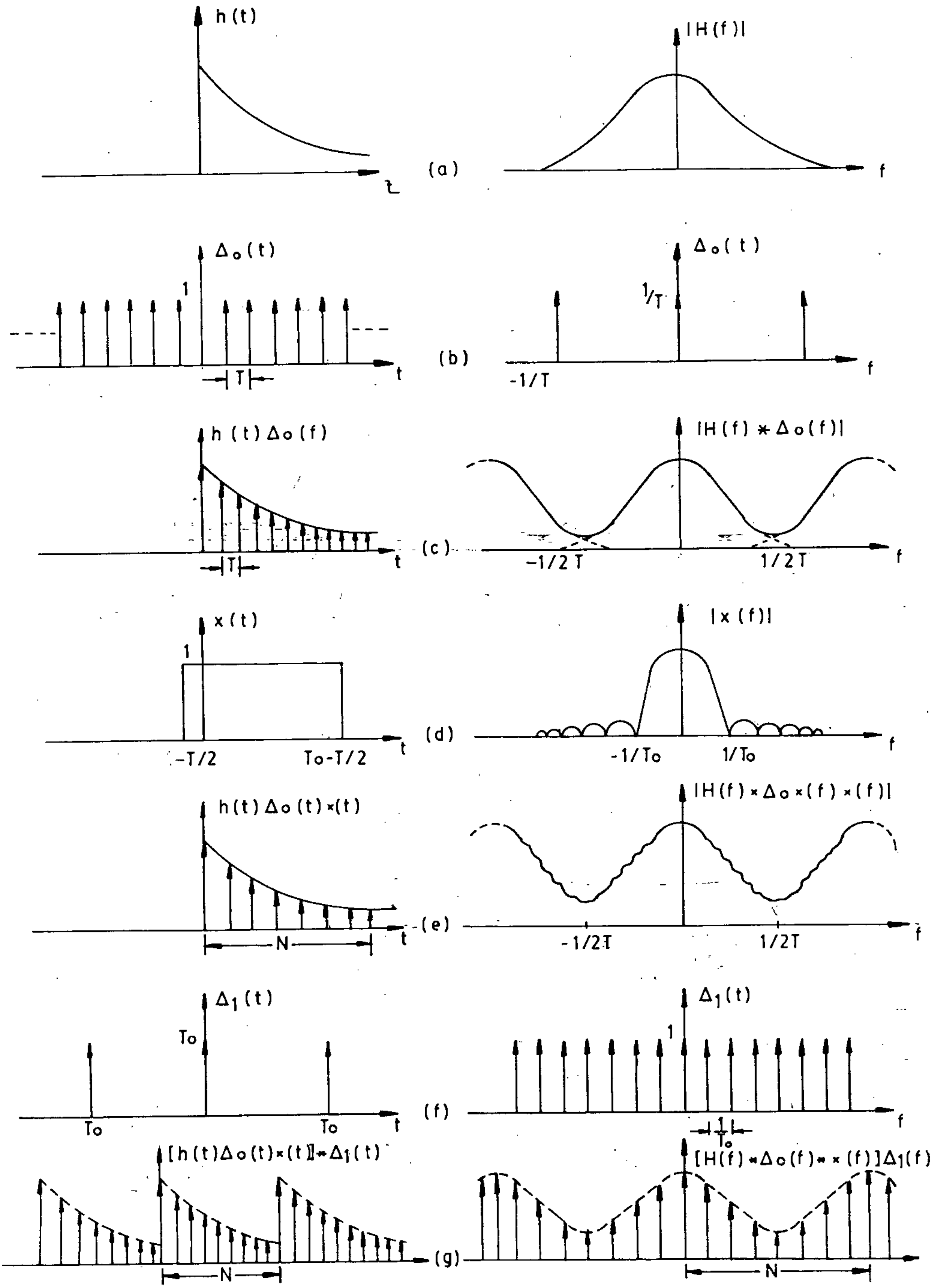


Fig. D.1 Graphical derivation of the discrete foarier transform pair

Assuming N equidistant impulse functions lying within the truncation interval i.e., $N = T_o/T$.

In order to modified the original fourier transform pair to a discrete fourier transform pair the truncated wave form of eq. D.3 and the time function $\Delta_1(t)$ as shown in fig. D.1(i) are corvolved. Function $\Delta_1(t)$ is given by fourier transform pair as:

$$\Delta_1(t) = T_o \sum_{r=\infty}^{\infty} \delta(t - r\, T_o) \qquad \text{D.4}$$

The discrete fourier transform is as follows:

$$\bar{h}(t) = \{h\ (t)\ \Delta_o(t)\ X(t)\} * \Delta_1(t)$$

$$= \{\sum_{k=0}^{N-1} h(KT)\ \delta(t-KT)\} * \{T_o \sum_{r=\infty}^{\infty} \delta(t - r\, T_o)\}$$

$$= \ldots \quad + T_o \sum_{k=0}^{N-1} h(KT)\ \delta(t+T_o-KT)$$

$$+ T_o \sum_{k=0}^{N-1} h(KT)\ \delta(t-KT)$$

$$+ T_o \sum_{k=0}^{N-1} h(KT)\ \delta(t-T_o-KT) + \ldots \qquad \text{D.5}$$

This equation can be reduced as:

$$\bar{h}(t) = T_o \sum_{r=\infty}^{\infty} \{ \sum_{k=0}^{N-1} h(KT)\,\delta\ (t-KT-rT_o) \} \qquad \text{D.6}$$

To develop the fourier transform of equation D.6 the fourier transform of a periodic function h(t) is a sequence of equi-distan empulses:

$$\bar{H}\left(\frac{n}{T_o}\right) = \sum_{n=\infty}^{\infty} \alpha_n \, \delta(f-nf_o), \quad f_o = \frac{1}{T_o} \qquad D.7$$

where $$\alpha_n = \frac{1}{T_o} \int_{-T/2}^{T_o-T/2} \bar{h}(t) \, e^{-J2\pi nt/T_o} \, dt, \quad n=0,\pm 1,\pm 2 \qquad D.8$$

Substituting of D.6 in D.8 yields

$$\alpha_n = \frac{1}{T_o} \int_{-T/2}^{T_o-T/2} T_o \sum_{r=\infty}^{\infty} \sum_{k=0}^{N-1} h(KT) \, \delta(t-KT-rT_o) \, e^{-J2\pi nt/T_o} \, dt \qquad D.9$$

Integration is only over one period, hence

$$\alpha_n = \int_{-T/2}^{T_o-T/2} \sum_{k=0}^{N-1} h(KT) \, \delta(t-KT) \, e^{-J2\pi nt/T_o} \, dt$$

$$= \sum_{k=0}^{N-1} h(KT) \int_{-T/2}^{T_o-T/2} e^{-J2\pi nt/T_o} \, \delta(t-KT) \, dt$$

$$= \sum_{k=0}^{N-1} h(KT) \, e^{-J2\pi knt/T_o} \qquad D.10$$

Since $T_o = NT$, equation D.10 can be written as

$$\alpha_n = \sum_{k=0}^{N-1} h(KT) \, e^{-J2\pi kn/N} \qquad n=0, \pm 1, \pm 2 \qquad D.11$$

and the fourier transform of D.7 is

$$\bar{H}\left(\frac{n}{NT}\right) = \sum_{n=\infty}^{\infty} \sum_{k=0}^{N-1} h(KT) \, e^{-J2\pi kn/N} \qquad D.12$$

From a cursory evaluation of D.12 it is not obvious that the fourier transform $\bar{\bar{H}}$ (n/NT) is periodic. However, there are only N distinct complex values computable from equation D.12.

To establish this fact, let n=r where r is an arbitrary integer. Equation D.12 becomes:

$$\bar{\bar{H}}\left(\frac{r}{NT}\right) = \sum_{k=0}^{N-1} h(KT)\, e^{-J2\pi kr/N} \qquad D.13$$

Now let n=r+N ,

$$\bar{\bar{H}}\left(\frac{r+N}{NT}\right) = \sum_{k=0}^{N-1} h(KT)\, e^{-J2\pi k(r+N)/N}$$

$$= \sum_{k=0}^{N-1} h(KT)\, e^{-J2\pi kr/N}\, e^{-J2\pi k}$$

$$= \sum_{k=0}^{N-1} h(KT)\, e^{-J2\pi kr/N}$$

$$= \bar{\bar{H}}\left(\frac{r}{NT}\right) \qquad D.14$$

Since $e^{-J2\pi k} = 1$ for K integer valued.

Therefore, there are only N distinct value for which eqn. D.12 can be evaluated; $\bar{\bar{H}}$ (r/NT) is periodic with a period of N samples. Fourier transform D.12 can be expressed equivalently as:

$$\bar{\bar{H}}\left(\frac{n}{NT}\right) = \sum_{k=0}^{N-1} h(KT)\, e^{-J2\pi nk/N} \qquad n=0,\ldots N-1 \qquad D.15$$

APPENDIX- E

DERIVATION OF SYMMETRICAL COMPONENT DISCRETE FOURIER TRANSFORM

The discrete fourier transform is as:

$$X = \frac{2}{N} \sum_{k=0}^{N-1} X_k \; B_k \qquad \text{E.1}$$

where $B_k = \exp\left(-J \frac{2\pi T}{T_o} K\right)$ E.2

For N = 12

$$X(1) = \frac{2}{12} \sum_{k=0}^{11} X_k \exp\left(J- \frac{2\pi T}{12T} K \right)$$

$$= \frac{1}{6} \sum_{k=0}^{11} X_k \exp\left(-J \frac{\pi K}{6} \right) \qquad \text{E.3}$$

The conventional phasor representation of a sinusoidal wave X(t):

$$X(t) = \sqrt{2}\, x \, \text{Sin} \left(Wt + \phi\right) \text{ is } x \qquad \text{E.4}$$

where $x = |X| \; e^{J\phi} = |X| \; (\text{Cos}\phi + J \, \text{Sin}\phi)$ E.5

Taking samples X_k from E.4 and substituting this values of X_k in E.3 and finally comparing the resulting expression for X(1) with equation E.5, we get:

$$X = \frac{J}{\sqrt{2}} \quad X(1) \qquad \text{E.6}$$

Substituting equation E.3 in equation E.6

$$X = \frac{J}{\sqrt{2}} \quad \frac{1}{6} \sum_{k=0}^{N} X_k \exp\left(-J\frac{\pi K}{6} \right)$$

$$= \Sigma \frac{J}{6\sqrt{2}} \quad X_k \exp\left(\quad \frac{\pi K}{6} \right)$$

$$= \Sigma \; X_k \; W_k \qquad \text{E.7}$$

$$\text{where } W_k = \frac{J}{6\sqrt{2}} \exp\left(-J \; \frac{\pi K}{6} \right) \qquad \text{E.8}$$

The two new phasor Y and Z obtained from X through the complex multiple of α and α^2.

$$Y = \alpha X = \exp\left(J \; \frac{2\pi}{3} \right) \cdot \sum_{k=0}^{11} \frac{J}{6\sqrt{2}} X_k \exp\left(-J \; \frac{\pi K}{6} \right)$$

$$= \sum_{k=0}^{11} \frac{J}{6\sqrt{2}} X_k \exp\left(J \; \frac{2\pi}{3} \right) \quad \exp\left(-J \; \frac{\pi K}{6} \right)$$

$$= \sum_{k=0}^{11} \frac{J}{6\sqrt{2}} X_k \exp\left\{ - \; \frac{J\pi}{6} \quad (K-4) \right\}$$

$$= \; \Sigma \, X_k \; W_k{-4} \qquad \text{E.9}$$

$$\text{where } W_k{-4} \quad = \frac{J}{6\sqrt{2}} \quad \exp\left\{ - \; \frac{J\pi}{6} \; (K-4) \right\}\} \qquad \text{E.10}$$

Similarly,

$$Z = \alpha^2 X = \exp\left(- \; \frac{J2\pi}{3} \right) \sum_{k=0}^{11} \frac{J}{6\sqrt{2}} X_k \exp\left(-J \; \frac{K\pi}{6} \right)$$

$$= \sum_{k=0}^{11} \frac{J}{6\sqrt{2}} X_k \exp\{-\frac{J\pi}{6} (K+4)\}$$

$$= \sum_{k=0}^{11} X_k W_{k+4} \qquad E.11$$

where $W_{k+4} = \frac{J}{6\sqrt{2}} \exp\{-\frac{J\pi}{6}(K+4)\}$ E.12

Now substituting X,Y,Z we get:

$$X_o = \frac{1}{3}\{X_a + X_b + X_c\}$$

$$= \frac{1}{3}\{\sum_{k=0}^{11} X_{ak} W_k + \sum_{k=0}^{11} X_{bk} W_k + \sum_{k=0}^{11} X_{ck} W_k\}$$

$$= \frac{1}{3}\{\sum_{k=0}^{11} (X_{ak} + X_{bk} + X_{ck}) W_k\} \qquad E.13$$

$$X_1 = \frac{1}{3}\{X_a + \alpha X_b + \alpha^2 X_c\}$$

$$= \frac{1}{3}\{\sum_{k=0}^{11} X_{ak} W_k + \sum_{k=0}^{11} X_{bk} W_{k-4} + \sum_{k=0}^{11} X_{ck} W_{k+4}\}$$

$$= \frac{1}{3}\{\sum_{k=0}^{11} (X_{ak} W_k + X_{bk} W_{k-4} + X_{ck} W_{k+4})\} \qquad E.14$$

and $X_2 = \frac{1}{3} \{ X_a + \alpha^2 X_b + \alpha X_c \}$

$$= \frac{1}{3}\{ \sum_{k=0}^{11} (X_{ak}W_k + \sum_{k=0}^{11} X_{bk}W_{k+4} + \sum_{k=0}^{11} X_{ck}W_{k-4}) \}$$

$$= \frac{1}{3}\{ \sum_{k=0}^{11} (X_{ak}W_k + X_{bk}W_{k+4} + X_{ck}W_{k-4}) \} \qquad \text{E.15}$$

APPENDIX - F

```
/ 360N-FO-479 3-8              MAINPGM              DATE    06/12/86        TIME      13.4

**************************************************************************
      THIS PROGRAM IS DONE BY MD SAJJAD HOSSAIN
             PROGRAM FOR SCDFT
**************************************************************************

        WK1= CONSTANT DUE TO WK
        WK2= CONSTANT DUE TO W(K-4)
        WK3= CONSTANT DUE TO W(K+4)
        E3= ZERO SEQUENCE VOLTAGE
        N= DATA WINDOW
        W=ANGULAR FREQUENCE
---------------------------------------------------------------------------
       COMPLEX WK1,WK2,WK3,E1,E2,E3,A1,A2,EA,EB,EC
       DIMENSION VA(20),VB(20),VC(20)
       DATA N,W,F,C1,C2/12,314.,50.,0.52356,0.11785/
       A1=CMPLX(-0.5,0.866)
       A2=CMPLX(-0.5,-0.866)
       DT=1.0/(F*FLOAT(N))
       T=DT
       DO 22 I=1,N
---------------------------------------------------------------------------
       VA(I)=1.7494*SIN(W*T+1.356021)+0.58313*SIN(3.*W*T-0.78534)
      1+0.3499*SIN(5.*W*T+1.9197)
       VB(I)=2.7973*SIN(W*T+4.71204)+0.4*SIN(2.*W*T-2.9668)+0.1*SIN(3.*W*
      1T-0.58813)
       VC(I)=1.7494*SIN(W*T+1.7853)-0.45*SIN(3.*W*T)+.2435*SIN(4.*W*T-3.2
      1123)
       WRITE(3,12) T,VA(I),VB(I),VC(I)
 12    FORMAT(10X,4(E10.2,5X))
---------------------------------------------------------------------------
 22    T=T+DT
       K=1
       E1=CMPLX(0.0,0.0)
       E2=CMPLX(0.0,0.0)
       E3=CMPLX(0.0,0.0)
       DO 33 I=1,N
---------------------------------------------------------------------------
       P1=SIN(K*C1)
       P2=COS(K*C1)
       WK1=CMPLX(P1,P2)*C2
       Q1=SIN((K-4)*C1)
       Q2=COS((K-4)*C1)
       WK2=CMPLX(Q1,Q2)*C2
       R1=SIN((K+4)*C1)
       R2=COS((K+4)*C1)
       WK3=CMPLX(R1,R2)*C2
---------------------------------------------------------------------------
       E1=E1+WK1*VA(I)+WK2*VB(I)+WK3*VC(I)
       E2=E2+WK1*VA(I)+WK3*VB(I)+WK2*VC(I)
       E3=E3+WK1*(VA(I)+VB(I)+VC(I))
       K=K+1
 33    CONTINUE
       E1=E1/3.
       E2=E2/3.
       E3=E3/3.
       WRITE(3,44)
4      FORMAT(10X,'THE SYMMETRICAL COMPONENT OF VOLTAGES ARE'/10X,44('-')
      1/////)
       WRITE(3,45)E1,E2,E3
5      FORMAT(10X,'E1=',2E12.3///10X,'E2=',2E12.3///10X,'E3=',2E12.3///)
       WRITE(3,43) E1,E2,E3
43     FORMAT(10X,2E12.3/)
---------------------------------------------------------------------------
       EA=E1+E2+E3
       EB=E3+A2*E1+A1*E2
       EC=E3+A1*E1+A2*E2
       WRITE(3,46)
>      FORMAT(10X,'THE PHASE VOLTAGES ARE'/10X,25('-')/////)
       WRITE(3,47) EA,EB,EC
7      FORMAT(10X,'EA=',2E12.3///10X,'EB=',2E12.3///10X,'EC=',2E12.3///)
       WRITE(3,43) EA,EB,EC
       STOP
       END
```

APPENDIX - G

AN EXAMPLE FOR THE PERFORMANCE OF SCDFT PROGRAM

Let us consider the voltage wave shape of a 3-phase system having fundamental frequency component and components having harmonics of order higher than one as:

$$V_a = 1.7494 \text{ Sin } (Wt + 77.69^\circ) + 0.58313 \text{ Sin } (3Wt - 45^\circ) + 0.3499 \text{ Sin } (5Wt + 110^\circ)$$

$$V_b = 2.7973 \text{ Sin } (Wt - 90^\circ) + 0.4 \text{ Sin } (2Wt - 170^\circ) + 0.1 \text{ Sin } (3Wt - 33.69^\circ)$$

$$V_c = 1.7494 \text{ Sin } (Wt + 102.29) - 0.45 \text{ Sin } (3Wt) + .2435 \text{ Sin } (4Wt - 184.05^\circ)$$

In order to obtain the symmetrical component of voltages from this 3-phase system, the computer program developed SCDFT is used.

The parameter chosen as:

Sampling number N = 12

Frequency of the wave F = 50 cycle per second.

Sampling rate = 50 x 12 HZ.

The symmetrical components of voltages obtained from the output of SCDFT program are:

$$E_1 = 1.05 + J.605$$

$$E_2 = -.787 + J.456$$

$$E_o = .000161 + J.147$$

In order to check the correctness of this result we have used the symmetrical component concepts as:

$$E_a = E_1 + E_2 + E_o = .263 + J1.21 = 1.238 \angle 77.740$$

$$E_b = \alpha^2 E_1 + \alpha E_2 + E_o = -.00313 - J1.98 = 1.98 \angle -90.09$$

$$E_c = \alpha E_1 + \alpha^2 E_2 + E_o = -.262 + J1.21 = 1.238 \angle 102.22$$

The fundamental frequency component of voltages obtained from the 3-phase wave are:

$$E_a = \frac{1.7494}{\sqrt{2}} \angle 77.7 = 1.237 \angle 77.7$$

$$E_b = \frac{2.7973}{\sqrt{2}} \angle -90.02 = 1.978 \angle -90.02$$

$$E_c = \frac{1.7494}{\sqrt{2}} \angle 102.29 = 1.237 \angle 102.29$$

Comparing the two set of data we conclude that the data obtained from the computer program is nearly same as the actual data.

APPENDIX - H

```
IV 360N FL 479 3-3          MAINPGM              DATE  09/12/86       TIME    15.14
C-----------------------------------------------------------------------------
C        THIS PROGRAM IS DONE BY MD SAJJAD HOSSAIN.
C        PROGRAM FOR CALCULATING SYMMETRICAL COMPONENT VOLTAGEAND
C        CURRENT AT VARING DISTANCE FOR SINGLE LINE TO GROUND FAULT
C.............................................................................
C-----------------------------------------------------------------------------
         COMPLEX CP1,ZD1,ZD,ZZ,I1,Z1,Z3,Z1,E1,E2,ZZ1,ZZ2,ZZ3,ZZ4
         READ(1,2) CP1,ZD1,ZD,IH1,ZZ,Z1,Z3,E1,E2
   2     FORMAT(2F10.5)
         P=0.
         ZZ1=Z1+P*Z1
         ZZ2=Z1+(1-P)*Z1
         ZZ3=ZS3+P*Z3
         ZZ4=ZS3+(1-P)*Z3
         WRITE(3,20) ZZ2
  20     FORMAT(10X,'ZZ2=',2F10.4)
         ZP1=1.0/(1.0/ZZ1+1.0/ZZ2)
         ZP2=1.0/(1.0/ZZ3+1.0/ZZ4)
         Z=1.0/(1.0/ZP1+1.0/ZP2)
         ZD=ZZ1*ZZ2+ZZ2*Z+Z*ZZ1
         ZD1=ZD/ZZ2
         ZD2=ZD/ZZ1
         ZD3=ZD/Z
         I1=E1/ZD1+(E1-E2)/ZD3
         I11=E2/ZD2+(E2-E2)/ZD3
         CD=I1+I11
         CD1=CD*ZP2/(ZP1+ZP2)
         CD2=CD-CD1
         C2=-CD1*ZZ2/(ZZ1+ZZ2)
         C3=-CD2*ZZ4/(ZZ3+ZZ4)
         DI1=C1*CP1
         DI2=C2
         DI3=C3
         V1=E1-C1*ZD1
         V2=-C2*ZD2
         V3=-C3*ZD3
         DV1=DI1*P*Z1
         DV2=DI2*P*Z1
         DV3=DI3*P*Z3
         WRITE(3,10) C1,C2,C3,V1,V2,V3,DV1,DV2,DV3
  10     FORMAT(5(3X,F8.2))
         STOP
         END
```

APPENDIX - I

IV 360N-FO-479 3-8 MAINPGM DATE 30/08/86 TIME

```
      DIMENSION P(8),Q(8),ZELO(8),ZEL1(8),NCATAG(8),NES(8)
      COMPLEX ZELO,ZEL1,ZEL(8),Z(8,8),Z0(8,8),Z1(8,8),SCII,E0(8),E1(8),
     +E2(8),C0(8,8),C1(8,8),C2(8,8),B
      INTEGER P,Q,PP
      READ(1,20) NB,NE
   20 FORMAT(I2,5X,I2)
      READ(1,30) (NES(I),P(I),Q(I),NCATAG(I),ZELO(I),ZEL1(I),I=1,NE)
   30 FORMAT(4I2,1X,2F7.3,1X,2F7.3)
      NSEQ=1
   51 CONTINUE
      IF(NSEQ.EQ.1) GO TO 31
      DO 101 K=1,NE
  101 ZEL(K)=ZELO(K)
      GO TO 33
   31 DO 102 K=1,NE
  102 ZEL(K)=ZEL1(K)
   33 DO 10 K=1,NE
      NP=P(K)
      NQ=Q(K)
      NCAT=NCATAG(K)
      GO TO (11,12),NCAT
   11 M=NQ-1
      Z(1,1)=CMPLX(0.0,0.0)
      DO 13 I=1,M
      Z(NQ,I)=Z(NP,I)
      Z(I,NQ)=Z(NQ,I)
   13 CONTINUE
      Z(NQ,NQ)=Z(NP,NQ)+ZEL(K)
      GO TO 10
   12 N=M+1
      L=N+1
      DO 14 I=2,N
      Z(L,I)=Z(NP,I)-Z(NQ,I)
      Z(I,L)=Z(L,I)
   14 CONTINUE
      Z(L,L)=Z(NP,L)-Z(NQ,L)+ZEL(K)
      DO 15 I=2,N
      DO 15 J=2,N
   15 Z(I,J)=Z(I,J)-Z(I,L)*Z(L,J)/Z(L,L)
   10 CONTINUE
      IF(NSEQ.EQ.0) GO TO 50
      WRITE(3,21)
   21 FORMAT('1',///,30X,'THE POSITIVE SEQUENCE BUS IMPEDENCE MATRIX IN
     +P.U.',/,30X,53('-'),//)
      DO 16 I=2,NB
      DO 16 J=2,NB
      B=Z(I,J)
      Z1(I,J)=B
   16 CONTINUE
      WRITE(3,22) ((I,J,Z1(I,J),J=2,NB),I=2,NB)
   22 FORMAT(5(1X,'Z1(',I2,',',I2,')=',F7.4,'+J',F7.4)/)
C     ZERO SEQ
      NSEQ=0
      GO TO 51
   50 CONTINUE
      WRITE(3,23)
   23 FORMAT('1',///,30X,'THE ZERO SEQUENCE BUS IMPEDENCE MATRIX IN P.U
     +',/,30X,46('-'),//)
      DO 53 I=2,NB
      DO 53 J=2,NB
      B=Z(I,J)
      Z0(I,J)=B
   53 CONTINUE
      WRITE(3,24) ((I,J,Z0(I,J),J=2,NB),I=2,NB)
   24 FORMAT(5(1X,'Z0(',I2,',',I2,')=',F7.4,'+J',F7.4)/)
C     3 PHASE FAULT
      PP=5
      SCII=1/Z1(PP,PP)
      SCI=1/(Z0(PP,PP)+2*Z1(PP,PP))
      SRT=SQRT(3.0)
      WRITE(3,111) SCII,SCI,SRT
  111 FORMAT(5X,4F7.4,4X,F7.4)
      DO 70 II=2,NB
      IF(II.EQ.PP) GO TO 71
      E0(II)=CMPLX(0.0,0.0)
      E1(II)=CMPLX(SRT,0.0)-Z1(II,PP)*SCII*SRT
      WRITE(3,112) (E1(II))
  112 FORMAT(2F7.4)
```

```
      E2(II)=CMPLX(0.0,0.0)
   70 CONTINUE
      GO TO 72
   71 E0(II)=CMPLX(0.0,0.0)
      E1(II)=CMPLX(0.0,0.0)
      E2(II)=CMPLX(0.0,0.0)
      IF(II.EQ.6.) GO TO 72
      GO TO 70
   72 E0(1)=CMPLX(0.0,0.0)
      E1(1)=CMPLX(0.0,0.0)
      E2(1)=CMPLX( 0.0,0.0)
      WRITE(3,444)
  444 FORMAT('1',//,30X,'3-PHASE FAULT CALCULATION')
      DO 100 I=1,NB
      WRITE(3,75)
   75 FORMAT('1',///,30X,'THE BUS VOLTAGE IN P.U.')
      WRITE(3,76) I,E0(I),I,E1(I),I,E2(I)
  100 CONTINUE
   76 FORMAT(3X,'E0(',I2,')=',F7.4,'+J',F7.4,3X,'E1(',I2,')=',F7.4,'+J',
     +F7.4,3X,'E2(',I2,')=',F7.4,'+J',F7.4)
      DO 74 K=1,NE
      NP=P(K)
      NQ=Q(K)
      C0(NP,NQ)=CMPLX(0.0,0.0)
      C1(NP,NQ)=(E1(NP)-E1(NQ))/ZEL1(K)
      C2(NP,NQ)=CMPLX(0.0,0.0)
      C0(NQ,NP)=-C0(NP,NQ)
      C1(NQ,NP)=-C1(NP,NQ)
      C2(NQ,NP)=-C2(NP,NQ)
      WRITE(3,77)
   77 FORMAT('1',///,30X,'THE FAULT CURRENT IN P.U.')
      WRITE(3,104) NP,NQ,C0(NP,NQ),NP,NQ,C1(NP,NQ),NP,NQ,C2(NP,NQ),NQ,NP
     +,C0(NQ,NP),NQ,NP,C1(NQ,NP),NQ,NP,C2(NQ,NP)
  104 FORMAT(5X,'C0(',I2,',',I2,')=',F7.4,'+J',F7.4,3X,'C1(',I2,',',I2,'
     +)=',F7.4,'+J',F7.4,3X,'C2(',I2,',',I2,')=',F7.4,'+J',F7.4)
   74 CONTINUE
C     SINGLE LINE TO GROUND FAULT
      DO 40 II=2,NB
      IF(II.EQ.PP) GO TO41
      E0(II)=-Z0(II,PP)*SCI*SRT
      E1(II)=CMPLX(SRT,0.0)-Z1(II,PP)*SCI*SRT
      E2(II)=-Z1(II,PP)*SCI*SRT
   40 CONTINUE
      GO TO 42
   41 E0(II)=-Z0(PP,PP)*SCI*SRT
      E1(II)=(Z0(PP,PP)+Z1(PP,PP))*SCI*SRT
      E2(II)=-Z1(PP,PP)*SCI*SRT
      IF(II.EQ.6.) GO TO 42
      GO TO 40
    2 E0(1)=CMPLX(0.0,0.0)
      E1(1)=CMPLX(0.0,0.0)
      E2(1)=CMPLX(0.0,0.0)
      WRITE(3,555)
  555 FORMAT('1',///,30X,'SINGLE LINE TO GROUND FAULT CALCULATION')
      DO 45 I=1,NB
      WRITE(3,75)
      WRITE(3,76) I,E0(I),I,E1(I),I,E2(I)
   45 CONTINUE
      DO 43 K=1,NE
      NP=P(K)
      NQ=Q(K)
      C0(NP,NQ)=(E0(NP)-E0(NQ))/ZEL0(K)
      C1(NP,NQ)=(E1(NP)-E1(NQ))/ZEL1(K)
      C2(NP,NQ)=(E2(NP)-E2(NQ))/ZEL1(K)
      C0(NQ,NP)=-C0(NP,NQ)
      C1(NQ,NP)=-C1(NP,NQ)
      C2(NQ,NP)=-C2(NP,NQ)
      WRITE(3,77)
      WRITE(3,104) NP,NQ,C0(NP,NQ),NP,NQ,C1(NP,NQ),NP,NQ,C2(NP,NQ),NQ,NP
     +,C0(NQ,NP),NQ,NP,C1(NQ,NP),NQ,NP,C2(NQ,NP)
   43 CONTINUE
C     LINE TO LINE FAULT CALCULATION
      DO 80 II=2,NB
      IF(II.EQ.PP) GO TO 81
      E0(II)=CMPLX(0.0,0.0)
      E1(II)=CMPLX(SRT,0.0)-(Z1(II,PP)*SRT*SCII)/2.0
      E2(II)=(Z1(II,PP)*SRT*SCII)/2.0
   80 CONTINUE
```

```
      GO TO 82
 81   E0(II)=CMPLX(0.0,0.0)
      E1(II)=SRT/2.0
      E2(II)=SRT/2.0
      IF(II.EQ.6.) GO TO 82
      GO TO 80
 82   E0(1)=CMPLX(0.0,0.0)
      E1(1)=CMPLX(0.0,0.0)
      E2(1)=CMPLX(0.0,0.0)
      WRITE(3,666)
666   FORMAT('1',///,30X,'LINE TO LINE FAULT')
      DO 95 I=1,NB
      WRITE(3,75)
      WRITE(3,76) I,E0(I),I,E1(I),I,E2(I)
 95   CONTINUE
      DO 93 K=1,NE
      NP=P(K)
      NQ=Q(K)
      C0(NP,NQ)=(E0(NP)-E0(NQ))/ZEL0(K)
      C1(NP,NQ)=(E1(NP)-E1(NQ))/ZEL1(K)
      C2(NP,NQ)=(E2(NP)-E2(NQ))/ZEL1(K)
      C0(NQ,NP)=-C0(NP,NQ)
      C1(NQ,NP)=-C1(NP,NQ)
      C2(NQ,NP)=-C2(NP,NQ)
      WRITE(3,77)
      WRITE(3,104) NP,NQ,C0(NP,NQ),NP,NQ,C1(NP,NQ),NP,NQ,C2(NP,NQ),NQ,NP
     +,C0(NQ,NP),NQ,NP,C1(NQ,NP),NQ,NP,C2(NQ,NP)
 93   CONTINUE
      STOP
      END
```

REFERENCES

1. V.K. Mehta: "Principles of Power System", A Book published by S. Chand & Company Ltd. , 1982, PP(526-529) and PP (540-553).

2. B. Ravindranath and M.Chander: "Power System Protection and Switchgear", A Book published by Wiley eastern ltd., 1977, PP (52-124).

3. Sunil S. Rao: "Switchgear and Protection", A Book published by Khanna Publishers, Delhi, 1982, PP (607-657).

4. R.S.Jha: "Switchgear and Protection" A Book Published by Dhanpat Rai & Sons, 1979.

5. M.L. Soni, P.V. Gupta and U.S. Bhatnegar: "A course in Electrical Power", A Book published by Dhanpat Rai & Sons, 1979.

6. IEEE Power System Relaying Committee Workshop, "Criteria for the evaluation of digital impedance methods of Transmission line Protection", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-104, No. 1 January 1985.

7. Stanley H. Horowetz: "Protective Relaying for Power System", A Volume in the IEEE press selected reprint series.

8. M.S. Sachdev and M.A. Baribeau: "A New algorithm for Digital impedance Relays", IEEE Trans. on Power Apparatus and Systems, Vol. PAS -98, No. 6 Nov./Dec. 1979.

9. W.A. Lewis and L.S. Tippetl: "Fundamental Basis for distance Relaying on 3-Phase system", AIEE Proceeding, Vol. 66, 1947.

10. W.K. Sonnemann and H.W. Lensner: "Compensator Distance Relaying -I, General Principles of Operation", AIEE Trans. Part III: PAS, June 1958.

11. G.D. Rockefeller: "Zone-Packaged Ground Distance Relay: I Principles of Operation" IEEE Trans on Power Apparatus and Systems October 1966.

12. Barry J. Mann and I.F. Morrison: "Digital Calculation of Impedance for Transmission Line Protection" IEEE Trans on PAS, January/February 1971.

13. G.B. Gilcrest, G.D. Rockefeller and E.A. Udren: "High Speed Distance Relaying using a Digital Computer: I-System description", IEEE Trans on PAS, May/ June 1972.

14. G.D. Rockefeller and E.A. Udren: "High Speed Distance Relaying Using Digital Computer: II- Test results", Ibid.

15. Adley A.Girgis: "A New Kalman Filtering Based Digital Distance Relay", IEEE Trans on Power Apparatus and Systems Vol PAS -101, No. 9, September 1982.

16. A.G. Phadke, M. Ibrahim and T. Hlibka: "Fundamental Basis for Distance Relaying with Symmetrical component", IEEE Trans on PAS, Vol. PAS-96, No. 2, March/April 1977, PP (635-646).

17. A.G. Phadke et al: "A microcomputer Based Symmetrical Component distance Relay", Proceeding on PICA, April, 1979.

18. A.G. Phadke et al: "A Microcomputer Based ultra High-Speed Distance Relay:,Field Tests", IEE Trans, ON PAS, Vol. PAS -100, No. 4, April 1981.

19. I.J. Nagrath and D.P. Kothari: "Modern Power System Analysis", A Book Published by Tata McGraw Hill Publishing Company Ltd; 1980, PP (304-310).

20. E.Oran Brigham: "The First Fourier Transform", A Book Published by Prentic Hall, INC., Englewood Cliffs, New Jersey, USA, 1974.

21. M. Schwartz and L. Shaw: "Signal Processing: Discrete Spectral Analysis, Detection and Estimation", A Book Published by Mc Graw Hill Kogakusha, Ltd, Tokyo PP (50-60).

22. G.W. Stagg and A.H.El. Abiad: " Computer Methods in Power System Analysis", A Book Published by Mc Graw Hill Book Company, New York, Chapter- 4,6.

23. L.P. Singh: "Advanced Power System Analysis and Dynamics", A Book published by Willy Eastern Ltd., 1983, Chapter-2,4.