

ANALYSIS OF TRANSMISSION SYSTEM FAULTS IN THE PHASE DOMAIN

A Thesis

by

JUN ZHU

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2004

Major Subject: Electrical Engineering

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ABSTRACT

Analysis of Transmission System Faults in the Phase Domain.

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In order to maintain a continuous power supply, nowadays relays in transmission systems are required to be able to deal with complicated faults involving non-conventional connections, which poses a challenge to the short circuit analysis performed for the data settings of the relay. The traditional sequence domain method has congenital defects to treat such cases, which leads to a trend of using the actual phase domain method in fault calculation. Although the calculation speed of the phase domain method is not so fast and is memory consumable, it performs well when handling complicated faults. Today more and more commercial software involves phase domain calculation in their short circuit analysis to treat complicated cases. With the advanced development of computers, there is a possibility to totally get rid of the sequence method.

In this thesis, a short circuit analysis method based on phase domain is developed. After the three sequence admittance matrices of the system are built, all the data are transformed into phase domain to get the phase domain admittance matrix. The following fault calculations are performed purely in phase domain. The test results of different types of faults in 3 bus, 14 bus, and 30 bus transmission systems are presented and compared with the results of a commercial fault analysis software. The validation of this program is also presented.

To My Family and Parents

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First, I would like to express deep gratitude to my advisor, Dr. Ali Abur, who has given me a lot of help. Also, I would like to thank my parents for their never ending support, for I would not have had the chance to study here and finish this thesis.

TABLE OF CONTENTS

CHAPTER		Page
I	INTRODUCTION.....	1
II	REVIEW OF EXISTING METHODS	5
	A. Sequence Method.....	5
	a) Build system impedance matrices Z	5
	b) Calculate the fault current I_{fk}	5
	1. 3ϕ fault.....	6
	2. SLG fault	7
	3. Line-to-line fault.....	7
	4. Double line ground fault.....	8
	c) Calculate the post-fault voltages V	9
	d) Calculate the post-fault line current I_{ij}	9
	B. Example	9
	a) Build the system nodal impedance matrices	11
	b) Calculate the fault current I_{f2}	11
	c) Calculate the post-fault voltages V	11
	d) Calculate the post-fault line currents.....	12
	C. Phase Coordinate Method.....	13
III	FAULT CALCULATIONS IN THE PHASE DOMAIN.....	16
	A. Component Models.....	16
	a) Transmission lines	16
	b) Generators	17
	c) Shunt elements.....	17
	d) Transformers	18
	e) Loads	20
	B. Three-phase Y Matrix	21

CHAPTER	Page
C. Fault Calculations for Different Types of Faults	24
a) Non-grounded faults	25
b) Grounded faults	26
D. Proposed Algorithm.....	27
IV VALIDATION OF RESULTS	30
A. Case 1.....	30
a) Build Y matrices in sequence domain	31
b) Transform the Y matrices to phase domain	31
c) Including transformer branches	31
d) Calculate the fault current	31
e) Calculate the post-fault bus voltages	32
f) Calculate the post-fault branch currents	33
B. Case 2.....	34
a) Single-line-ground fault.....	36
b) Double-line-ground fault.....	36
c) 3-Phase ground fault.....	37
d) Line-line fault.....	37
e) 3-line fault	38
C. Case 3.....	38
a) Single-line-ground fault.....	40
b) Double-line-ground fault.....	40
c) 3-Phase ground fault.....	41
d) Line-line fault.....	41
e) 3-line fault	42
D. Case 4.....	42
a) Single-line-ground fault.....	47
b) Double-line-ground fault.....	47
c) 3-Phase ground fault.....	48

CHAPTER	Page
d) Line-line fault.....	48
e) 3-line fault	49
V IMPLEMENTATION OF THE FAULT ANALYSIS PROGRAM.....	50
A. Data File Specifications.....	50
a) Input files.....	50
b) Output files.....	54
B. User Interface Specifications	55
VI CONCLUSIONS.....	59
REFERENCES	61
APPENDIX A PROGRAM CODE.....	63
APPENDIX B DATA OF 14 BUS SYSTEM.....	83
APPENDIX C DATA OF 30 BUS SYSTEM.....	85
APPENDIX D DATA OF 30 BUS SYSTEM(WITH LOAD CURENTS)	90
APPENDIX E FLTOTP.DAT	92
APPENDIX F SCOUTPUT.DAT	93
APPENDIX G FLTBUSOTP.DAT.....	95
APPENDIX H FLTBRANCHOTP.DAT.....	96
VITA.....	97

LIST OF FIGURES

FIGURE		Page
1.	Sequence network connection for a 3-phase fault	6
2.	Sequence network connection for a SLG fault.....	7
3.	Sequence network connection for a line to line fault	8
4.	Sequence network connection for a LLG fault.....	8
5.	System diagram for the 3-bus system.....	10
6.	Transmission line model.....	16
7.	Generator model	17
8.	Shunt model Y_g connected.....	18
9.	Shunt model Y or delta connected.....	18
10.	Transformer model	20
11.	Load model.....	21
12.	Fault impedances	25
13.	Flow chart of calculation	28
14.	Three bus system	30
15.	Diagram of IEEE 14 bus test system.....	35
16.	Diagram of IEEE 30 bus test system.....	39
17.	Bus data window	44
18.	Transformer data window1.....	45
19.	Transformer data window2.....	45
20.	CAPE session setup window	46
21.	Input and output files of the program.....	55
22.	Line data window	56
23.	Generator data window.....	57
24.	Shunt element data window.....	57
25.	Fault data window	58
26.	Mutual data window	58

LIST OF TABLES

TABLE		Page
1.	Generator data.....	10
2.	Line data	10
3.	Fault type	10
4.	Definitions of Y_A , Y_B , Y_C for different transformer connections	19
5.	SLG fault results(14 bus system).....	36
6.	DLG fault results(14 bus system).....	36
7.	3-PG fault results(14 bus system).....	37
8.	LL fault results(14 bus system)	37
9.	3L fault results(14 bus system).....	38
10.	Mutual couplings(30 bus system).....	39
11.	SLG fault results(30 bus system).....	40
12.	DLG fault results(30 bus system).....	40
13.	3-PG fault results(30 bus system).....	41
14.	LL fault results(30 bus system)	41
15.	3L fault results(30 bus system).....	42
16.	SLG fault results(with load currents)	47
17.	DLG fault results(with load currents).....	47
18.	3-PG fault results(with load currents)	48
19.	LL fault results(with load currents)	48
20.	3L fault results(with load currents)	49

CHAPTER I

INTRODUCTION

Electric power is generated, transmitted and distributed via large interconnected power systems. The electric power is generated in the power plant. Then the voltage level of the power will be raised by the transformer before the power is transmitted. Since electric power is proportional to the product of voltage and current, high voltage is used in transmission in order to reduce the line currents and consequently the power transmission losses.

The primary objective of all power systems is to maintain the continuous power supply. However, lightning or other natural events like wind and ice, physical accidents, equipment failure, and other unpredictable events may cause an accidental connection between the phase wires of the transmission line or from the phase wires to ground, which is called a fault. The fault currents caused by short circuits are determined by the system impedance between the generator voltages and the fault, which may be several orders of magnitude larger than normal operating currents. In that case, if the fault persists, it may do severe damage to the equipment and lead to long-term power loss. In order to prevent such an accident, it is necessary to disconnect the faulted part from the whole system temporarily as soon as possible. This is accomplished by the protective relaying system.

Relays are usually installed at both ends of the transmission lines. When a relay detects that a fault occurs in its protection zone, the relay will trip the circuit breakers of that line to open. This way, the faulted line will be removed from the power system avoiding further damage. Since most short circuit faults are caused by lightning, they are temporary. So shortly after the breaker operation, the relay will attempt to re-close the breaker. If the fault is cleared, then the re-closing will be successful and the line will work properly; if the fault is still there, the breaker will open again and wait for the fault to be

This thesis follows the style and format of *IEEE Transactions of Power Systems*.

cleared. The relay system is designed as such in order to minimize the total outage time.

The crucial problem for the relay is how to sense the fault. An unreliable detection method will result in misoperation, which will cause unnecessary line outage. Fortunately, as mentioned above, there are significant changes in system quantities during the fault, which can be distinguished from the normal system swing. The criteria for fault sensing are calculated pre-fault and saved in the database of the relay. The relay will compare the values of the quantities it is sensing with these criteria to check whether there is a fault or not. These changing quantities include currents, voltages, power, power factor or phase angle, power or current direction or other physical quantities like temperature or pressure, and so on. The most obvious indicator is the significant change in the current. Because of that, the overcurrent protection is widely used.

Short circuit analysis provides currents and voltages in a power system during and after a fault, which can be used to design a protective relay system. In order to develop an efficient and reliable relay system, the currents and voltages must be calculated under various types of faults in every location of the power system. Considering that there are normally thousands of buses in one system it is not easy to calculate them without a computer. The first short circuit analysis program is proposed in 1956 [1]. Gradually, a formal calculation method is developed to handle the classical faults with high accuracy.

The traditional fault analysis approach of unbalanced power systems is based entirely on the symmetrical components. Before introducing this method, the power system model will be briefly described. The practical power system is designed in three phases because of its several advantages. Since in a three-phase balanced system the neutral current is nearly zero under normal operating conditions, the neutral conductors can be removed. However for security reason, neutral conductors are maintained to reduce the transient overvoltages and carry unbalanced currents during faults. They can be designed significantly small in size than normal phase conductors allowing cost savings. Another important reason is that a three-phase generator will have constant output power under balanced condition producing constant torque and thereby minimizing shaft vibration and noise.

Although the three-phase system has so many advantages, its analysis is more involved when the system is unbalanced during a fault. To solve this problem, the symmetrical components method is developed, which provides a means of analyzing the unbalanced system. The three phasors can be transformed into a new set of components called symmetrical components, which are defined as zero, positive and negative sequences. When the system is balanced, the sequence components are uncoupled. While the system is unbalanced, they are connected only at the point of unbalance. Taking this advantage, by transferring the three-phase network into three separate sequence networks, the calculation is simplified.

Applying the symmetrical components method to fault analysis involves several steps. Firstly the components in the system, such as transmission lines, generators, transformers and loads are modeled in three-sequence networks, and subsequently they are combined as dictated by network topology to build zero, positive, and negative sequence impedance (or admittance) matrices to model the fault. Faulted power system voltages and currents can then be determined easily for various fault types as discussed in [2]. In the end, those sequence network results will be transferred back to obtain the three-phase network results.

Many commercial short circuit analysis programs using symmetrical components method work well for structurally symmetrical electric power systems. The main computational advantage of the conventional symmetrical components method is that the three sequence matrices are treated separately. However, in certain cases such as when the transmission line is not completely transposed, the three sequence elements of that line will be coupled with each other. As a result, such cases cannot be solved by using sequence network method.

The other problem is the mutual coupling between transmission lines. Mutual couplings are common elements in the power system, and in short circuit analysis it is necessary to include these elements. If there is a fault on the mutually coupled line, then the current produced by the mutual coupling in another line cannot be omitted. This current may cause the relay of that line to operate, which should be prevented. However, introducing the mutual coupling effects into the sequence network results in an increase in

the number of non-zero elements in the nodal admittance matrix. This makes the zero-sequence networks much more difficult to handle than the other two sequences, especially for the unbalanced system, which critically counteracts the computational advantage of this method.

To solve these problems, Rao and Roy presented an alternative fault analysis method involving phase domain [3] in 1982, which is based on the previous pure phase domain fault calculation method. It did not involving Z matrix and performed the calculation totally in phase domain. This method can handle complex fault in unbalanced network involving large mutual coupled groups.

The main obstacle of the phase domain computation is the amount of the calculation. For an n-bus system, the sequence method only need to handle three $[n] \times [n]$ matrices, while the phase domain method have to deal with a $[3n] \times [3n]$ nodal admittance matrix. However, with the increase in the speed and power of computers nowadays, three-phase network models are becoming manageable in representing unbalanced power systems in many steady-state power system analysis programs including fault analysis. The method proposed in this thesis is also using the three-phase method. In this method, after the three-phase nodal admittance matrix is obtained, all of the fault calculation is performed in three-phase domain. The computation of this method is based on the sparse nodal admittance matrix and therefore avoids the storage of the impedance matrix.

In this thesis, firstly a brief review of the general existing approaches in fault analysis will be presented in the next chapter. Then the calculation technique of this method will be given in chapter III. Case studies of 14 and 30 bus systems are presented in chapter IV to illustrate the effectiveness of this method. In chapter V the implementation of the program will be given and the thesis will end with a short conclusion.

CHAPTER II

REVIEW OF EXISTING METHODS

A. Sequence Method

This thesis is mainly concerned about the fault analysis in transmission systems. The most common method used for this purpose is the sequence method. In this method, the unbalanced three-phase system will be decomposed into three symmetrical zero, negative and positive sequence networks and the corresponding sequence impedance or admittance matrices will be built. After the sequence fault current and node voltages are found, they will be transformed into phase domain components. Several implementations of this method can be found in [4]-[12]. Refs. [4]-[10] directly use the sequence method, while Refs. [11] and [12] do some modification of it for the computer program application.

The generalized steps of the sequence method are:

a) Build system impedance matrices Z

For each sequence network, we define the impedance matrix Z by the equation

$$V = Z \cdot I \quad (2.1)$$

where V is the node voltage and I is the injecting node current.

b) Calculate the fault current I_{fk}

The faults are calculated by connecting the faulted node k to the ground through fault impedance Z_f . Since during the fault all node currents except I_k are zero, by solving the equation (2.1),

$$I_k = V_k / Z_{kk} = -I_{fk} \quad (2.2)$$

Note that the fault current I_{fk} is the negative of the injecting node current I_k .

From the way the node k is terminated, another equation can be written as

$$V_k = Z_f I_{fk} - V_s \quad (2.3)$$

From the equations (2.2) and (2.3), the fault current can be solved

$$I_{fk} = V_s / Z_T \quad (2.4)$$

where V_s is the Thevenin voltage of that bus before fault occurs. Since before fault the system is balanced, only the positive sequence has non-zero Thevenin voltage. So the equation (2.4) is used only for calculating positive sequence fault current, the currents of the other two sequences can be solved by the positive sequence fault current. And $Z_T = Z_{kk} + Z_f$. The Z_T has different expressions according to different fault types.

1. 3ϕ fault

From the boundary conditions

$$\begin{aligned} V_a &= Z_f I_a + Z_g (I_a + I_b + I_c) \\ V_b &= Z_f I_b + Z_g (I_a + I_b + I_c) \\ V_c &= Z_f I_c + Z_g (I_a + I_b + I_c) \end{aligned} \quad (2.5)$$

the sequence network connections are shown in Figure 1.

Then the fault current can be solved.

$$I_{a1} = \frac{V_s}{Z_{kk-1} + Z_f} \quad (2.6)$$

and $Z_T = Z_{kk-1} + Z_f$, where k is the faulted bus number.

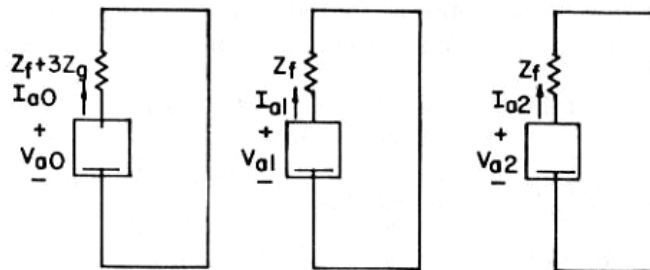


Figure 1. Sequence network connection for a 3-phase fault

2. SLG fault

From the boundary conditions (Assume fault is in phase A)

$$I_b = I_c = 0$$

$$V_a = Z_f I_a \quad (2.7)$$

the sequence network connections are shown in Figure 2.

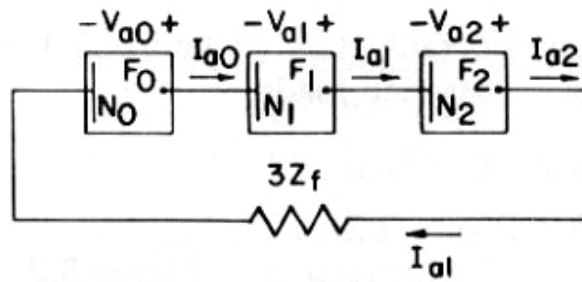


Figure 2. Sequence network connection for a SLG fault

Then the fault current can be solved.

$$I_{a0} = I_{a1} = I_{a2} = \frac{V_s}{Z_{kk-0} + Z_{kk-1} + Z_{kk-2} + 3Z_f} \quad (2.8)$$

and $Z_T = Z_{kk-0} + Z_{kk-1} + Z_{kk-2} + Z_f$.

3. Line-to-line fault

From the boundary conditions (Assume the faulted phases are phase B and C)

$$I_a = 0$$

$$I_b = -I_c \quad (2.9)$$

$$V_b - V_c = I_b Z_f$$

the sequence network connections are shown in Figure 3.

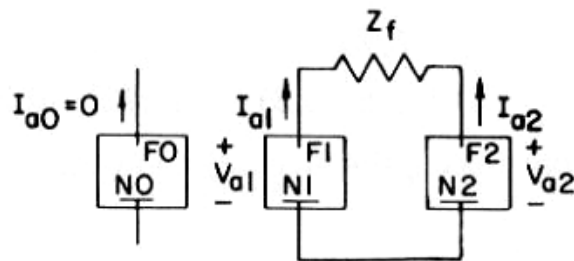


Figure 3. Sequence network connection for a line to line fault

Then the fault current can be solved.

$$I_{a1} = -I_{a2} = \frac{V_s}{Z_{kk-1} + Z_{kk-2} + Z_f} \quad (2.10)$$

and $Z_T = Z_{kk-1} + Z_{kk-2} + Z_f$.

4. Double line ground fault

From the boundary conditions(Assume the faulted phases are phase B and C)

$$\begin{aligned} I_a &= 0 \\ V_b &= (Z_f + Z_g)I_b + Z_g I_c \\ V_c &= (Z_f + Z_g)I_c + Z_g I_b \end{aligned} \quad (2.11)$$

the sequence network connections are shown in Figure 4.

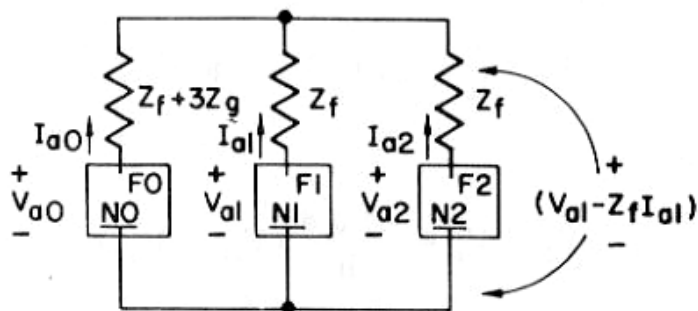


Figure 4. Sequence network connection for a LLG fault

Then the fault current can be solved.

$$I_{a1} = \frac{V_s}{Z_{kk-1} + Z_f + \frac{(Z_{kk-2} + Z_f)(Z_{kk-0} + Z_f + 3Z_g)}{Z_{kk-0} + Z_{kk-2} + 2Z_f + 3Z_g}} \quad (2.12)$$

$$\text{and } Z_T = Z_{kk-1} + Z_f + \frac{(Z_{kk-2} + Z_f)(Z_{kk-0} + Z_f + 3Z_g)}{Z_{kk-0} + Z_{kk-2} + 2Z_f + 3Z_g}.$$

c) Calculate the post-fault voltages V

$$V_i^{0,2} = -Z_{ik}^{0,2} I_{fk}^{0,2}, \quad i = 1, 2, \dots, n \quad (2.13)$$

$$V_i^1 = V_s - Z_{ik}^1 I_{fk}^1, \quad i = 1, 2, \dots, n \quad (2.14)$$

where n is the number of buses in the system, 0, 1, 2 represent the zero, positive and negative sequences.

d) Calculate the post-fault line current I_{ij}

$$I_{ij}^{0,1,2} = \frac{V_i^{0,1,2} - V_j^{0,1,2}}{z_{ij}^{0,1,2}} \quad (2.15)$$

where z_{ij} is the primitive impedance element between nodes i and j .

After all these sequence quantities are obtained, they must be transferred to the phase domain to get the phase components.

In the following we will present a small example to illustrate the sequence method.

B. Example

Consider a 3-bus transmission system. The system diagram is shown in Figure 5. The data of this system is listed in Tables 1, 2, and 3.

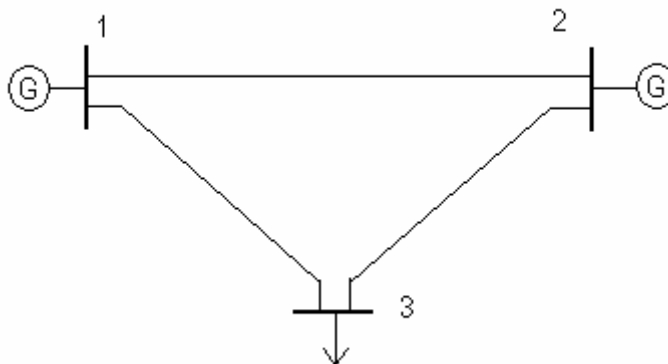


Figure 5. System diagram for the 3-bus system

Table 1 Generator data (3 Bus system)

Bus #	Gen. connection	Generator impedance(p.u.)		
		P	N	Z
1	Y-grounded	0.05j	0.05j	0.15j
2	Y-grounded	0.10j	0.10j	0.30j

Table 2 Line data (3 Bus system)

Line #	End Bus	Type	Line impedance(p.u.)			Line shunt admittance(p.u.)		
			P	N	Z	P	N	Z
1	1-2	Line	0.10j	0.10j	0.30j	0	0	0
2	2-3	Line	0.15j	0.15j	0.45j	0	0	0
3	1-3	Line	0.105j	0.105j	0.315j	0	0	0

Table 3 Fault type (3 Bus system)

Fault type	Fault bus	z_a (p.u.)	z_b (p.u.)	z_c (p.u.)	z_g (p.u.)
SLG	2	0	∞	∞	0.1j

The pre-fault bus voltages are assumed to be 1 per unit.

a) Build the system nodal impedance matrices

$$Y_1 = Y_2 = j \begin{bmatrix} -39.52 & 10 & 9.52 \\ 10 & -26.67 & 6.67 \\ 9.52 & 6.67 & -16.19 \end{bmatrix}$$

$$Y_0 = j \begin{bmatrix} -13.17 & 3.33 & 3.17 \\ 3.33 & -8.88 & 2.22 \\ 3.17 & 2.22 & -5.39 \end{bmatrix}$$

$$Z_1 = Z_2 = Y_1^{-1} = j \begin{bmatrix} 0.0387 & 0.0225 & 0.0321 \\ 0.0225 & 0.0549 & 0.0359 \\ 0.0321 & 0.0359 & 0.0954 \end{bmatrix}$$

$$Z_0 = Y_0^{-1} = j \begin{bmatrix} 0.1162 & 0.0676 & 0.0962 \\ 0.0676 & 0.1648 & 0.1076 \\ 0.0962 & 0.1076 & 0.2862 \end{bmatrix}$$

b) Calculate the fault current I_{f2}

Since this is a single line to ground fault, the equation (2.8) should be used.

$$Z_f = 0.1$$

$$Z_T = Z_{0-22} + Z_{1-22} + Z_{2-22} + 3Z_f = j0.5746$$

$$I_{a1} = I_{a2} = I_{a0} = \frac{1}{Z_T} = -j1.74$$

$$I_{fa} = 3I_{a1} = -j5.221$$

c) Calculate the post-fault voltages V

$$\begin{bmatrix} V_{a0-1} \\ V_{a0-2} \\ V_{a0-3} \end{bmatrix} = -I_{a0} \cdot \begin{bmatrix} Z_{0-12} \\ Z_{0-22} \\ Z_{0-32} \end{bmatrix} = j1.74 \cdot \begin{bmatrix} j0.0676 \\ j0.1648 \\ j0.1076 \end{bmatrix} = \begin{bmatrix} -0.1177 \\ -0.2867 \\ -0.1873 \end{bmatrix}$$

$$\begin{bmatrix} V_{a1-1} \\ V_{a1-2} \\ V_{a1-3} \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - I_{a1} \cdot \begin{bmatrix} Z_{1-12} \\ Z_{1-22} \\ Z_{1-32} \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} + j1.74 \cdot \begin{bmatrix} j0.0225 \\ j0.0549 \\ j0.0359 \end{bmatrix} = \begin{bmatrix} 0.9608 \\ 0.9044 \\ 0.9376 \end{bmatrix}$$

$$\begin{bmatrix} V_{a2-1} \\ V_{a2-2} \\ V_{a2-3} \end{bmatrix} = -I_{a2} \cdot \begin{bmatrix} Z_{2-12} \\ Z_{2-22} \\ Z_{2-32} \end{bmatrix} = j1.74 \cdot \begin{bmatrix} j0.0225 \\ j0.0549 \\ j0.0359 \end{bmatrix} = \begin{bmatrix} -0.0392 \\ -0.0956 \\ -0.0624 \end{bmatrix}$$

Then transform the sequence domain voltages to the phase domain.

$$\begin{bmatrix} V_{1a} \\ V_{1b} \\ V_{1c} \end{bmatrix} = T \cdot \begin{bmatrix} V_{a0-1} \\ V_{a1-1} \\ V_{a2-1} \end{bmatrix} = \begin{bmatrix} 0.8039 \\ -0.5786 - j0.866 \\ -0.5786 + j0.866 \end{bmatrix}$$

$$\begin{bmatrix} V_{2a} \\ V_{2b} \\ V_{2c} \end{bmatrix} = T \cdot \begin{bmatrix} V_{a0-2} \\ V_{a1-2} \\ V_{a2-2} \end{bmatrix} = \begin{bmatrix} 0.5221 \\ -0.6911 - j0.866 \\ -0.6911 + j0.866 \end{bmatrix}$$

$$\begin{bmatrix} V_{3a} \\ V_{3b} \\ V_{3c} \end{bmatrix} = T \cdot \begin{bmatrix} V_{a0-3} \\ V_{a1-3} \\ V_{a2-3} \end{bmatrix} = \begin{bmatrix} 0.6879 \\ -0.6249 - j0.866 \\ -0.6249 + j0.866 \end{bmatrix}$$

where matrix A is the synthesis matrix,

$$T = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$$

where $a = 1 \angle 120^\circ$

d) Calculate the post-fault line currents

$$I_{1-12} = I_{2-12} = \frac{V_{1-1} - V_{1-2}}{Z_{1-12}} = -j0.564$$

$$I_{0-12} = \frac{V_{0-1} - V_{0-2}}{Z_{0-12}} = -j0.563$$

$$I_{1-23} = I_{2-23} = \frac{V_{1-2} - V_{1-3}}{Z_{1-23}} = j0.221$$

$$I_{0-12} = \frac{V_{0-2} - V_{0-3}}{z_{0-23}} = j0.221$$

$$I_{1-13} = I_{2-13} = \frac{V_{1-1} - V_{1-3}}{z_{1-13}} = -j0.221$$

$$I_{0-13} = \frac{V_{0-1} - V_{0-3}}{z_{0-13}} = -j0.221$$

Then transform them to the phase domain.

$$\begin{bmatrix} I_{12a} \\ I_{12b} \\ I_{12c} \end{bmatrix} = T \cdot \begin{bmatrix} I_{0-12} \\ I_{1-12} \\ I_{2-12} \end{bmatrix} = \begin{bmatrix} -j1.691 \\ j0.001 \\ j0.001 \end{bmatrix}$$

$$\begin{bmatrix} I_{23a} \\ I_{23b} \\ I_{23c} \end{bmatrix} = T \cdot \begin{bmatrix} I_{0-23} \\ I_{1-23} \\ I_{2-23} \end{bmatrix} = \begin{bmatrix} j0.663 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} I_{13a} \\ I_{13b} \\ I_{13c} \end{bmatrix} = T \cdot \begin{bmatrix} I_{0-13} \\ I_{1-13} \\ I_{2-13} \end{bmatrix} = \begin{bmatrix} -j0.663 \\ 0 \\ 0 \end{bmatrix}$$

C. Phase Coordinate Method

While the sequence method contributes a lot to the analysis of the short circuit system, it still has some shortcomings that limit its application. The traditional sequence method cannot handle complex faults where there is mutual coupling between sequence networks. To solve this problem, Alvarado presented an important algorithm involving the phase domain [13] in 1985. In the same year, Tinney also presented a mixed method [14] for short circuit analysis, which is almost the same with Alvarado's method. And there is other similar method based on them [15].

In their methods, the sequence nodal admittance matrix is first transformed to the phase domain, and then overlapped with the fault matrix. A new 3 by 3 matrix will be obtained by collapsing the phase matrix as indicated by the fault. Then the phase domain

voltages at the fault point will be solved by this new matrix. After that, the phase domain voltages will be transformed back into sequence domain, and it will be used to calculate the fault current and post-fault voltages in the sequence domain. It is clear that only part of its calculation is in the phase domain.

On the other hand, an alternative method in the phase domain was developed [16,17] in 1968. It includes two solution methods for the fault calculation, the source transformation method and the distributed source method. This method is the early phase domain method for the fault analysis. Later, a generalized phase domain method [3] was presented as mentioned in the first chapter, which is based on the distributed source method. In this method, all the power system components are modeled in phase domain and then the three-phase admittance matrix is obtained. After the fault, the admittance matrix Y will be modified to Y' to include the changes in the network configuration according to the fault. Then the voltage drops produced by the fault can be calculated:

$$Y' \cdot V' = I' - Y_k' V_k \quad (2.16)$$

where k is the fault node. n is the total bus number. And there are 3 phases p, q, r included in this node.

Y' is the $(n-3)$ by $(n-3)$ modified admittance matrix, it excludes the p th, q th and r th rows and columns.

V' is the voltage drops requested.

$I' = 0$; since I_k' is removed from that vector.

Y_k' is the p th, q th and r th columns of Y' but not included Y_{pp}' , Y_{qq}' , Y_{rr}' .

V_k is the pre-fault voltage of node k including three elements V_p' , V_q' , V_r' .

The post-fault bus voltages can be got:

$$E_i = V_i + V_i' \quad i = 1, 2, \dots, n \quad (2.17)$$

The fault current I_k will be obtained from:

$$I_k = \sum_{i=1}^n Y_{ki}' \cdot E_i \quad k = p, q, r \quad (2.18)$$

Although this method successfully generalized the phase domain fault analysis approach, it is only taken as an alternative method since at that time the computer is not powerful enough to handle the phase domain calculation.

In this thesis, a short circuit analysis algorithm, which involves calculations strictly in the phase domain, will be presented. This algorithm will not involve the sequence domain networks since the three-phase nodal admittance matrix will be built. Since it performs the fault calculations in phase domain, it can handle complicated fault scenarios. This method is not the same with the method in [3]. It does not modify the admittance matrix but use the sub-impedance matrix of the fault node to calculate the fault current. The detailed calculations will be presented in the next chapter.

CHAPTER III

FAULT CALCULATIONS IN THE PHASE DOMAIN

A. Component Models

Before the fault calculation, the sequence nodal admittance matrices are to be obtained. For this purpose, the component models will firstly be presented for building the admittance matrices. In this method, the sequence admittance matrices without transformers will be built and transformed into three-phase domain admittance matrix. Then the transformer admittance matrices will be incorporated into it. So, the transformer model is built in three-phase domain and all the other components models are created in the sequence domain. Models for each component will be briefly discussed next.

a) Transmission lines

The model for a transmission line connected between buses k and m is shown in Figure 6.

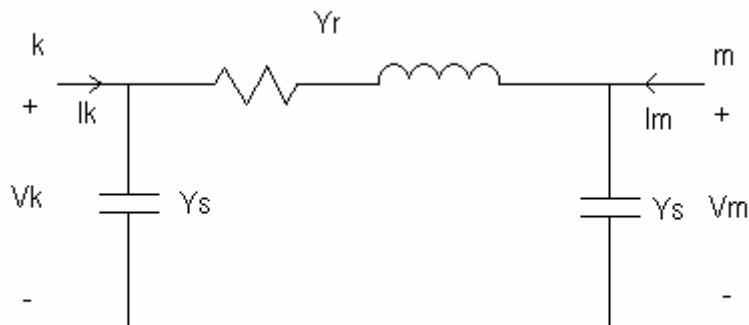


Figure 6. Transmission line model

Writing the model equations relating the terminal voltages and currents:

$$\begin{bmatrix} Y_r + Y_s & -Y_s \\ -Y_s & Y_r + Y_s \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix} = \begin{bmatrix} I_k \\ I_m \end{bmatrix}. \quad (3.1)$$

Note that the nodal equation and the associated nodal admittance matrix can be written for each sequence. The admittance values Y_r and Y_s will be replaced by the corresponding sequence values in the model for each sequence.

b) Generators

The generators are modeled as shown in Figure 7. If the generator is Y connected with a grounded neutral, then the model will be as shown in Figure 3-2 in each sequence, except for the fact that the value of Y_g will be different in each sequence.

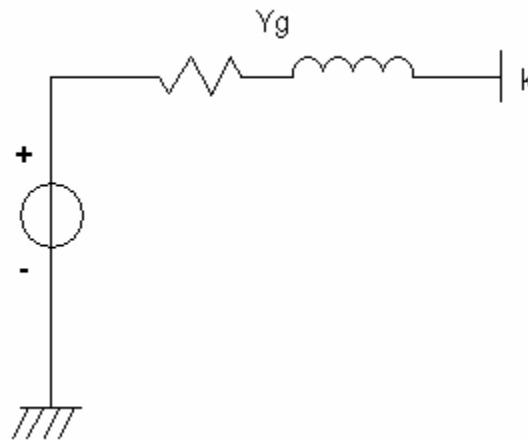


Figure 7. Generator model

However, if the generator is not Y-grounded, then the zero-sequence admittance will be replaced by zero.

c) Shunt elements

If they are Y connected with a grounded neutral, then their model in each sequence will be as shown in Figure 8. If they are Δ connected or Y connected with a floating neutral, then their model in positive and negative sequence are the same with Figure 8, and their model in zero sequence will be as given in Figure 9.

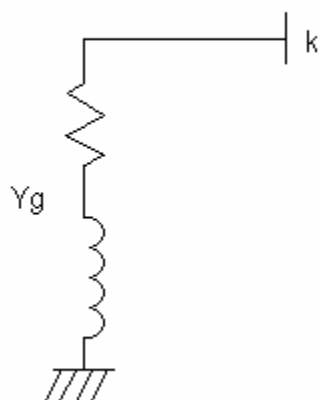
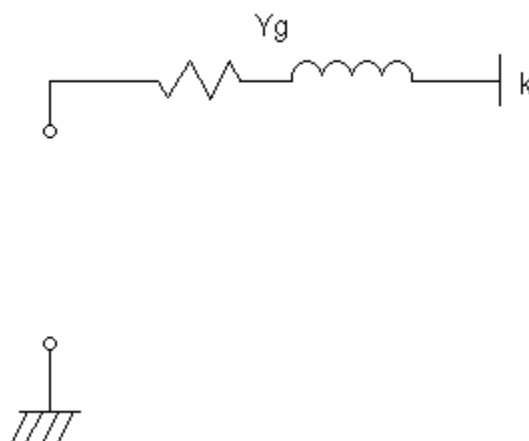
Figure 8. Shunt model Y_g connected

Figure 9. Shunt model Y or delta connected

d) Transformers

The transformer can be modeled by the following admittance matrix [18, 19]:

$$Y_T = \begin{bmatrix} \frac{1}{\alpha^2} Y_A & -\frac{1}{\alpha\beta} Y_C \\ -\frac{1}{\alpha\beta} Y_C^T & \frac{1}{\beta^2} Y_B \end{bmatrix} \quad (3.2)$$

where α and β are the primary & secondary side off-nominal taps respectively. The matrices Y_A , Y_B and Y_C are given by Y_I , Y_{II} and Y_{III} for different transformer connections according to the rules, which are listed in Table 4.

Table 4 Definitions of Y_A , Y_B , Y_C for different transformer connections

Connection	Y_A	Y_B	Y_C
Yg-Yg	Y_I	Y_I	Y_I
Yg-Y	Y_I	Y_{II}	Y_{II}
Yg-D	Y_I	Y_{II}	Y_{III}
Y-Y	Y_{II}	Y_{II}	Y_{II}
Y-D	Y_{II}	Y_{II}	Y_{III}
D-D	Y_{II}	Y_{II}	Y_{II}

where Yg: Y-connected with grounded neutral; Y: Y-connected with floating neutral;
D: Delta connected.

$$Y_I = \frac{1}{3} \begin{bmatrix} y_0 + 2y_1 & y_0 - y_1 & y_0 - y_1 \\ y_0 - y_1 & y_0 + 2y_1 & y_0 - y_1 \\ y_0 - y_1 & y_0 - y_1 & y_0 + 2y_1 \end{bmatrix} \quad (3.3)$$

$$Y_{II} = \frac{1}{3} \begin{bmatrix} 2y_1 & -y_1 & -y_1 \\ -y_1 & 2y_1 & -y_1 \\ -y_1 & -y_1 & 2y_1 \end{bmatrix} \quad (3.4)$$

$$Y_{III} = \frac{1}{\sqrt{3}} \begin{bmatrix} y_1 & -y_1 & 0 \\ 0 & y_1 & -y_1 \\ -y_1 & 0 & y_1 \end{bmatrix} \quad (3.5)$$

where for Y_A and Y_B , $y_1 = y_{l1} + \frac{1}{2}y_{m1}$; and for Y_C , $y_1 = y_{l1}$. y_0 is always equal to y_{l0} .

The subscripts 1 and 0 represent the positive and zero sequence respectively.

In each sequence, the transformer is assumed to be modeled as shown in Figure 10, where y_l is the leakage (series) admittance and y_m is the magnetizing (shunt) admittance in the respective sequence.

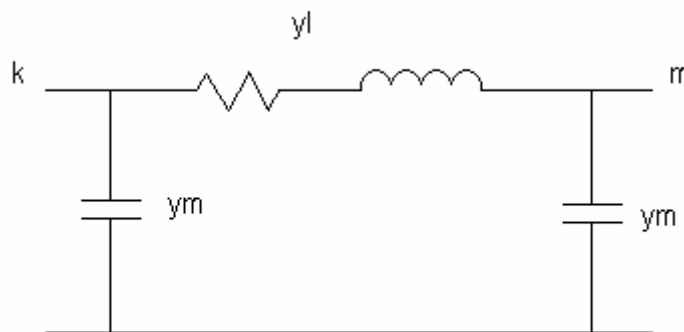


Figure 10. Transformer model

e) Loads

For the fault analysis, each static load is converted into an equivalent impedance when the load currents are taken in account. Since it is a real load, the load impedance for each sequence is the same. The load model is shown in Figure 11.

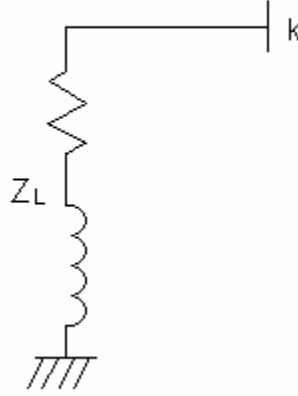


Figure 11. Load model

B. Three-phase Y Matrix

After all the components are modeled, the admittance matrices in three sequences can be built. First, the primitive impedance matrices are to be built. For example, the zero sequence primitive impedance matrix is given by:

$$z_0 = \begin{matrix} 1 \\ 2 \\ 3 \\ \dots \\ m \end{matrix} \begin{bmatrix} z_{r1} & 0 & 0 & \dots & 0 \\ 0 & z_{r2} & z_{mu} & \dots & 0 \\ 0 & z_{mu} & z_{r3} & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & z_{rm} \end{bmatrix} \quad (3.6)$$

where z_r is the series impedance of the line, z_{mu} is the mutual impedance of line 2 and line 3 and m is the total line number. If the line p is a transformer branch, z_{rp} will be replaced by 1.0.

The primitive admittance matrix of the zero sequence will then be:

$$y_0 = z_0^{-1} \quad (3.7)$$

and if the line p is a transformer branch, let $y_{pp} = 1$. This step is to make sure that the element of the transformer branch will not influence the other elements in the matrix while the step in equation (3-9) is performed.

Then the nodal branch-to-branch incidence matrix is defined as,

$$A = \begin{matrix} & \begin{matrix} 1 & 2 & \dots & n \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ \dots \\ m \end{matrix} & \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} \end{matrix} \quad (3.8)$$

$$\text{where } a_{pq} = \begin{cases} 1 & \text{if } q \text{ is the sending - end bus of branch } p \\ -1 & \text{if } q \text{ is the receiving - end bus of branch } p \\ 0 & \text{otherwise} \end{cases}$$

where m is the total line number and n is the total bus number.

Then the nodal admittance matrices for each sequence i can be obtained by

$$Y_{l-i} = A^i \cdot y_i \cdot A \quad (3.9)$$

Note that this admittance matrix does not include the shunt elements, generators and the shunt capacitances of the transmission lines.

Adding the line shunt capacitances,

$$Y_s = \begin{matrix} p \\ q \end{matrix} \begin{bmatrix} Y_{l-pp} + y_s & Y_{l-pq} - y_s \\ Y_{l-qp} - y_s & Y_{l-qq} + y_s \end{bmatrix} \quad (3.10)$$

where p and q are nodes of that line and y_s is the shunt admittance of that line.

Adding shunt elements and generators,

$$Y_{pp} = Y_{s-pp} + y_g \quad (3.11)$$

where p is the node that the generator or the other shunt element is connected, y_g is the admittance of the generator or the shunt element. Notice that if the connection of the

generator is not Y-grounded, the zero sequence admittance of the generator y_{g0} will be set as zero.

Performing all the steps above for all the three sequences, the nodal sequence admittance matrices Y_0 , Y_1 and Y_2 without transformer branches will be obtained.

Then these sequence admittance matrices will be combined and transformed into phase domain. For a single bus, such as bus 1, the diagonal element of the admittance matrix in phase domain can be expressed as

$$Y_{11}^{(a,b,c)} = \begin{bmatrix} Y_{a1a1} & Y_{a1b1} & Y_{a1c1} \\ Y_{b1a1} & Y_{b1b1} & Y_{b1c1} \\ Y_{c1a1} & Y_{c1b1} & Y_{c1c1} \end{bmatrix} = T \cdot \begin{bmatrix} Y_{0-11} & 0 & 0 \\ 0 & Y_{1-11} & 0 \\ 0 & 0 & Y_{2-11} \end{bmatrix} \cdot T^{-1} \quad (3.12)$$

where T is the symmetrical component transformation matrix given by:

$$T = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \quad (3.13)$$

where $a = 1 \angle 120^\circ$.

Then the entire three-phase admittance matrix will be:

$$Y_{abc} = \begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1n} \\ Y_{21} & Y_{22} & \dots & Y_{2n} \\ \dots & \dots & \dots & \dots \\ Y_{n1} & Y_{n2} & \dots & Y_{nn} \end{bmatrix} \quad (3.14)$$

The final admittance matrix can then be obtained by combining Y_{abc} and all the transformer matrices as given by eqn. (3.2).

$$Y_{final} = Y_{abc} + \sum_{j=1}^N Y_{Tj} \quad (3.15)$$

$$\text{where } Y_{Tj}' = \begin{bmatrix} p_j & & & \\ & \frac{1}{\alpha_j^2} Y_{Aj} & & -\frac{1}{\alpha_j \beta_j} Y_{Cj} \\ & & & \\ q_j & -\frac{1}{\alpha_j \beta_j} Y_{Cj}^T & & \frac{1}{\beta_j^2} Y_{Bj} \end{bmatrix} \quad (3.16)$$

N: number of transformers;

Y_{Aj} , Y_{Bj} , Y_{Cj} : parameters of transformer j;

α_j , β_j : off-nominal taps for transformer j.

p_j and q_j are terminal buses of the transformer j.

C. Fault Calculations for Different Types of Faults

Assume that the fault occurs at bus k. The rows and columns corresponding to the faulted bus are recorded to be the last in the three-phase admittance matrix Y.

$$Y' = \begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1k} \\ Y_{21} & Y_{22} & \dots & Y_{2k} \\ \dots & \dots & \dots & \dots \\ Y_{k1} & Y_{k2} & \dots & Y_{kk} \end{bmatrix} \quad (3.17)$$

Applying LU factorization to the Y' matrix, the 3×3 impedance sub-matrix Z_{kk} will be easily obtained.

For different types of faults at bus k, the fault impedance can be defined as shown in Figure 12.

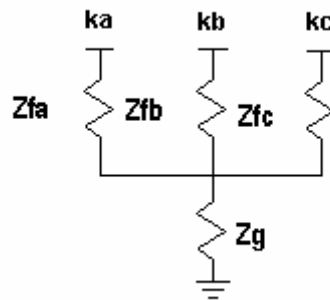


Figure 12. Fault impedances

The fault current for the grounded and on-grounded faults can be calculated as follows:

a) Non-grounded faults

Non-grounded faults include Line-line fault and 3-phase fault.

$$\begin{aligned} V_a - (Z_{akak} + Z_{fa})I_{fa} - Z_{akbk}I_{fb} - Z_{akck}I_{fc} &= V_b - Z_{bkak}I_{fa} - (Z_{bkbk} + Z_{fb})I_{fb} - Z_{bkck}I_{fc} \\ V_b - Z_{bkak}I_{fa} - (Z_{bkbk} + Z_{fb})I_{fb} - Z_{bkck}I_{fc} &= V_c - Z_{ckak}I_{fa} - Z_{ckbk}I_{fb} - (Z_{ckck} + Z_{fc})I_{fc} \end{aligned} \quad (3.18)$$

$$I_{fa} + I_{fb} + I_{fc} = 0$$

where k is the faulted bus number.

Z_{akak} , Z_{bkbk} and so on are the three-phase impedance elements related to the faulted bus, which are obtained in the previous step.

V_a , V_b , V_c are pre-fault voltages of the faulted bus.

Z_{fa} , Z_{fb} , Z_{fc} are fault impedances of phase A, B, C.

I_{fa} , I_{fb} and I_{fc} can be solved from eqn. (3.18).

b) Grounded faults

Grounded faults include Single-line-ground fault, Line-line-ground fault and 3-phase-ground fault.

$$\begin{bmatrix} I_{fa} \\ I_{fb} \\ I_{fc} \end{bmatrix} = \begin{bmatrix} Z_{akak} + Z_{fa} & Z_{akbk} & Z_{akck} \\ Z_{bkak} & Z_{bkbk} + Z_{fb} & Z_{bkck} \\ Z_{ckak} & Z_{ckbk} & Z_{ckck} + Z_{fc} \end{bmatrix}^{-1} \cdot \begin{bmatrix} V_a - Z_g (I_{fa} + I_{fb} + I_{fc}) \\ V_b - Z_g (I_{fa} + I_{fb} + I_{fc}) \\ V_c - Z_g (I_{fa} + I_{fb} + I_{fc}) \end{bmatrix} \quad (3.19)$$

where k is the faulted bus number, and Z_g is the fault impedance between the neutral and the ground.

I_{fa} , I_{fb} and I_{fc} can be solved from eqn. (3.19).

Once the fault currents in each phase are solved, the changes in the post fault bus voltages can be obtained by:

$$Y \cdot \Delta V = -I_f \quad (3.20)$$

Factorizing Y into its LU factors will yield:

$$L \cdot U \cdot \begin{bmatrix} \Delta V_{1a} \\ \Delta V_{1b} \\ \Delta V_{1c} \\ \dots \\ \Delta V_{ka} \\ \Delta V_{kb} \\ \Delta V_{kc} \\ \dots \\ \Delta V_{nc} \\ \Delta V_{nb} \\ \Delta V_{nc} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \dots \\ -I_{fa} \\ -I_{fb} \\ -I_{fc} \\ \dots \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (3.21)$$

where k is the faulted bus number.

By applying the LU factorization to the admittance matrix Y, the need to build and store the impedance matrix Z is avoided. In a typical power system, most of the buses are connected to less than 10 neighbors, yielding a very sparse nodal admittance matrix Y. However, the impedance matrix Z is in general a full matrix. By performing the LU

factorization, not only the storage space is saved but also the calculation speed is increased by avoiding the inversion of the matrix.

Since Y is a sparse matrix, L and U are both sparse matrices, and I_f is a sparse vector, we can easily solve this equation to get all the ΔV s by forward and backward substitution. The post-fault bus voltages can thus be calculated as follows:

$$\begin{bmatrix} V_{pa}^{new} \\ V_{pb}^{new} \\ V_{pc}^{new} \end{bmatrix} = \begin{bmatrix} V_{pa} \\ V_{pb} \\ V_{pc} \end{bmatrix} + \begin{bmatrix} \Delta V_{pa} \\ \Delta V_{pb} \\ \Delta V_{pc} \end{bmatrix} \quad (3.22)$$

where p is the bus number.

The voltage drops along every lines in the system can be computed and saved in a vector as below:

$$V_{line} = A \cdot V^{new} \quad (3.23)$$

where A is the incidence matrix defined in eqn. (3.8).

Then build the primitive impedance matrices shown in equation (3.6), but in this case, include the transformer branch impedances as well. Transforming these three sequence matrices to the phase domain as in equations (3.12) - (3.14), the branch series admittance matrix Y_{line} will be obtained in phase domain. The post-fault branch currents can thus be calculated by:

$$I_{line} = Y_{line} \cdot V_{line} \quad (3.24)$$

This completes the fault analysis.

D. Proposed Algorithm

The following algorithm describes the overall fault analysis procedure that is described above.

The algorithm for short circuit calculation can be stated simply as:

1. Build Y matrix in phase domain for transmission lines.
2. Build admittance matrices in phase domain for transformers.
3. Overlap those matrices to build the final Y matrix in phase domain.

4. Using the admittance matrix calculate the fault current.
5. Calculate the post-fault bus voltages.
6. Calculate the post-fault branch currents.

The following flow chart, Figure 13, shows the main steps of the algorithm.

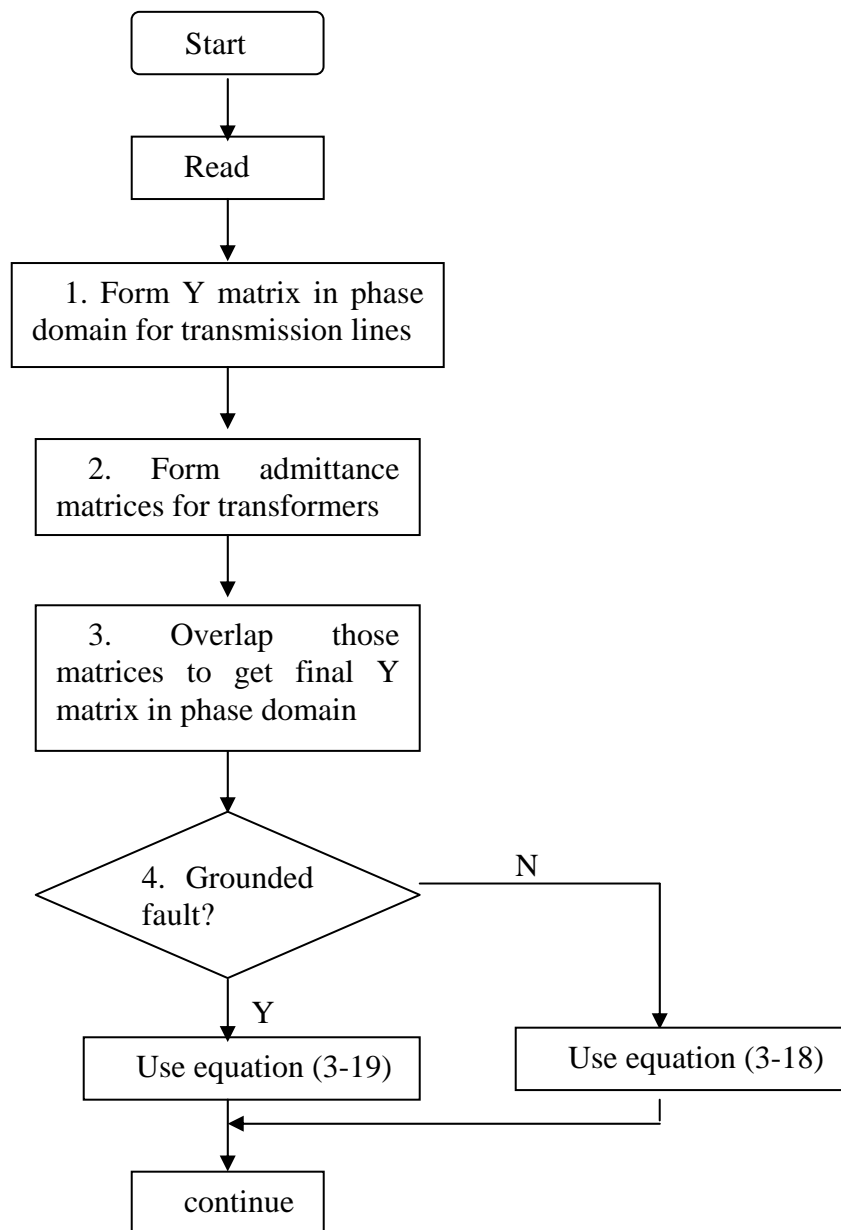


Figure 13. Flow chart of calculation

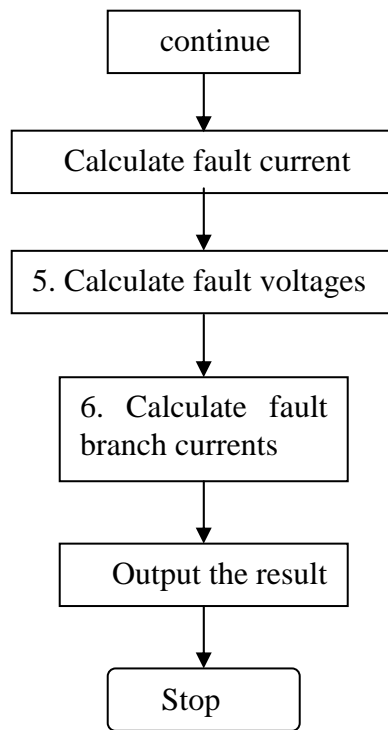


Figure 13. Continued

The program code of this approach for Matlab is shown in Appendix A. The main properties of this method are

- 1) to form the 3-phase admittance matrix and perform the fault calculation in phase domain.
- 2) to use the sub-impedance matrix of the fault node to calculate the fault currents.
- 3) to avoid using the full 3-phase impedance matrix.

Comparing with the method in [3], the approach presented here does not need to modify the admittance matrix according to the fault type, but the elements of the fault node impedance is requested. the calculation of eqn. (2.17) is substituted by the steps of (3.18) and (3.19).

The validation of this method will be presented in the next chapter.

CHAPTER IV

VALIDATION OF RESULTS

In this chapter, four cases will be illustrated to validate the presented method. The first case is a 3-bus system, and the following three ones are of IEEE-14 bus system and IEEE-30 bus systems. The first case will be calculated by hand following the steps introduced in the last chapter. The last three ones will be calculated by computer and the results will be checked by CAPE.

A. Case 1

In the first case, a 3 bus, 3 line system, which is shown in Figure 14, will be used as an example to illustrate the calculation steps of the method presented. The data of the system is the same with the system illustrated in the second chapter, which is listed in Tables 1, 2 and 3. Thus, the phase domain method can be compared with the sequence domain approach discussed in chapter II.

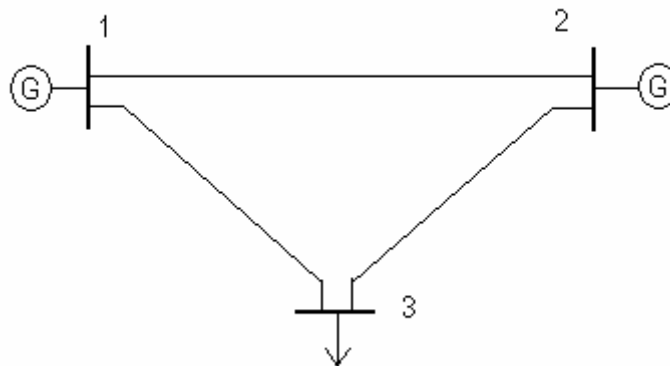


Figure 14. Three bus system

a) Build Y matrices in sequence domain

Since this system doesn't involve the mutual couplings and the line shunts, it is easy to get the three sequence admittance matrices.

$$Y_1 = Y_2 = j \begin{bmatrix} -39.52 & 10 & 9.52 \\ 10 & -26.67 & 6.67 \\ 9.52 & 6.67 & -16.19 \end{bmatrix}$$

$$Y_0 = j \begin{bmatrix} -13.17 & 3.33 & 3.17 \\ 3.33 & -8.88 & 2.22 \\ 3.17 & 2.22 & -5.39 \end{bmatrix}$$

b) Transform the Y matrices to phase domain

Perform sequence to phase domain transfer for every element in the admittance matrix like equation (3-12).

$$Y_{abc} = j \begin{bmatrix} -30.74 & 8.783 & 8.783 & 7.778 & -2.222 & -2.222 & 7.407 & -2.116 & -2.116 \\ 8.783 & -30.74 & 8.783 & -2.222 & 7.778 & -2.222 & -2.116 & 7.407 & -2.116 \\ 8.783 & 8.783 & -30.74 & -2.222 & -2.222 & 7.778 & -2.116 & -2.116 & 7.407 \\ \hline 7.778 & -2.222 & -2.222 & -20.74 & 5.926 & 5.926 & 5.185 & -1.482 & -1.482 \\ -2.222 & 7.778 & -2.222 & 5.926 & -20.74 & 5.926 & -1.482 & 5.185 & -1.482 \\ -2.222 & -2.222 & 7.778 & 5.926 & 5.926 & -20.74 & -1.482 & -1.482 & 5.185 \\ \hline 7.407 & -2.116 & -2.116 & 5.185 & -1.482 & -1.482 & -12.59 & 3.598 & 3.598 \\ -2.116 & 7.407 & -2.116 & -1.482 & 5.185 & -1.482 & 3.598 & -12.59 & 3.598 \\ -2.116 & -2.116 & 7.407 & -1.482 & -1.482 & 5.185 & 3.598 & 3.598 & -12.59 \end{bmatrix}$$

c) Including transformer branches

Since there is no transformer branch in the system, this Y_{abc} is the final nodal admittance matrix Y in phase domain. This step can be omitted.

d) Calculate the fault current

Then change the rows and columns of Y, since bus 2 is the faulted bus,

$$Y' = \begin{bmatrix} Y_{11} & Y_{13} & Y_{12} \\ Y_{31} & Y_{33} & Y_{32} \\ Y_{21} & Y_{23} & Y_{22} \end{bmatrix}$$

Applying the LU factorization, obtain the sub-matrix

$$Z_{22} = j \begin{bmatrix} 0.09153 & 0.03661 & 0.03661 \\ 0.03661 & 0.09153 & 0.03661 \\ 0.03661 & 0.03661 & 0.09153 \end{bmatrix}$$

Since the fault type is single-line-to-ground, equation (3-19) should be used to calculate the fault current:

$$I_{fa} = [Z_{akak} + Z_{fa}]^{-1} \cdot [V_a - Z_g I_{fa}] = -j5.221$$

e) Calculate the post-fault bus voltages

By using the eqn. (3.20),

$$Y \cdot \Delta V = -I_f = \begin{bmatrix} 0 \\ 0 \\ 0 \\ j5.221 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Solving for ΔV :

$$\Delta V = \begin{bmatrix} -0.1961 \\ -0.07845 \\ -0.07845 \\ -0.4779 \\ -0.1912 \\ -0.1912 \\ -0.3122 \\ -0.1249 \\ -0.1249 \end{bmatrix}$$

Post-fault voltages will then be:

$$V_{new} = V_{pre} + \Delta V = \begin{bmatrix} 0.8039 \\ -0.5785 - j0.866 \\ -0.5785 + j0.866 \\ 0.5221 \\ -0.6912 - j0.866 \\ -0.6912 + j0.866 \\ 0.6879 \\ -0.6249 - j0.866 \\ -0.6249 + j0.866 \end{bmatrix}$$

f) Calculate the post-fault branch currents

$$V_{line} = \begin{bmatrix} V_1^{abc} - V_2^{abc} \\ V_2^{abc} - V_3^{abc} \\ V_1^{abc} - V_3^{abc} \end{bmatrix} = \begin{bmatrix} 0.2818 \\ 0.1127 \\ 0.1127 \\ -0.1658 \\ -0.0663 \\ -0.0663 \\ 0.1160 \\ 0.0464 \\ 0.0464 \end{bmatrix}$$

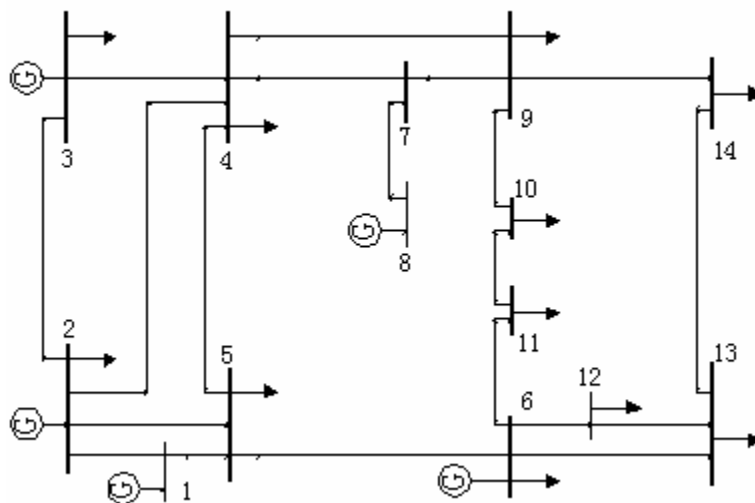


Figure 15. Diagram of IEEE 14 bus test system

In order to validate the phase domain method, the results of this approach will be compared with CAPE, the Computer-Aided Protection Engineering System, which is a commercial fault analysis software [20].

In this case, all the transformers are assumed to be connected in Y-Y with both neutrals grounded. All the line shunt capacitances will be omitted and all the pre-fault voltages are set as 1 per unit.

The zero sequence impedances are set as three times of the corresponding positive sequence impedances.

Different fault types will be checked. Fault bus is set as bus 13.

The test results are listed in Tables 5 – 9.

a) Single-line-ground fault

$$z_a = 0.1 + j0.1, z_b = \infty, z_c = \infty, z_g = 0$$

Table 5 SLG fault results(14 bus system)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	$2.2916 \angle -64.2^\circ$	0.0	0.0
Phase method	$2.2916 \angle -64.2^\circ$	0.0	0.0
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	$0.3241 \angle -19.2^\circ$	$1.1746 \angle -130.1^\circ$	$1.1255 \angle -132.2^\circ$
Phase method	$0.3241 \angle -19.2^\circ$	$1.1746 \angle -130.1^\circ$	$1.1255 \angle -132.2^\circ$

b) Double-line-ground fault

$$z_a = 0.1 + j0.1, z_b = 0.1 + j0.1, z_c = \infty, z_g = 0$$

Table 6 DLG fault results(14 bus system)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	$2.7569 \angle -51.0^\circ$	$2.8772 \angle 166.7^\circ$	0.0
Phase method	$2.7570 \angle -51.0^\circ$	$2.8772 \angle 166.7^\circ$	0.0
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	$0.3899 \angle -6.0^\circ$	$0.4069 \angle -148.3^\circ$	$1.2048 \angle 121.0^\circ$
Phase method	$0.3899 \angle -6.0^\circ$	$0.4069 \angle -148.3^\circ$	$1.2048 \angle 121.0^\circ$

c) 3-Phase ground fault

$$z_a = 0.1 + j0.1, z_b = 0.1 + j0.1, z_c = 0.1 + j0.1, z_g = 0$$

Table 7 3-PG fault results(14 bus system)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	$3.0786 \angle -61.7^\circ$	$3.0786 \angle 178.3^\circ$	$3.0786 \angle 58.3^\circ$
Phase method	$3.0786 \angle -61.7^\circ$	$3.0786 \angle 178.3^\circ$	$3.0786 \angle 58.3^\circ$
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	$0.4354 \angle -16.7^\circ$	$0.4354 \angle -136.7^\circ$	$0.4354 \angle 103.3^\circ$
Phase method	$0.4354 \angle -16.7^\circ$	$0.4354 \angle -136.7^\circ$	$0.4354 \angle 103.3^\circ$

d) Line-line fault

$$z_a = 0.1 + j0.1, z_b = 0.1 + j0.1, z_c = \infty, z_g = \infty$$

Table 8 LL fault results(14 bus system)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	$2.6661 \angle -31.7^\circ$	$2.6661 \angle 148.3^\circ$	0.0
Phase method	$2.6662 \angle -31.7^\circ$	$2.6662 \angle 148.3^\circ$	0.0
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	$0.7075 \angle -29.3^\circ$	$0.5327 \angle -102.7^\circ$	$1.0 \angle 120.0^\circ$
Phase method	$0.7075 \angle -29.3^\circ$	$0.5327 \angle -102.7^\circ$	$1.0 \angle 120.0^\circ$

e) 3-line fault

$$z_a = 0.1 + j0.1, z_b = 0.1 + j0.1, z_c = 0.1 + j0.1, z_g = \infty$$

Table 9 3L fault results(14 bus system)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	$3.0786 \angle -61.7^\circ$	$3.0786 \angle 178.3^\circ$	$3.0786 \angle 58.3^\circ$
Phase method	$3.0786 \angle -61.7^\circ$	$3.0786 \angle 178.3^\circ$	$3.0786 \angle 58.3^\circ$
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	$0.4354 \angle -16.7^\circ$	$0.4354 \angle -136.7^\circ$	$0.4354 \angle 103.3^\circ$
Phase method	$0.4354 \angle -16.7^\circ$	$0.4354 \angle -136.7^\circ$	$0.4354 \angle 103.3^\circ$

C. Case 3

In this case, IEEE-30 bus system is used as the test system. This system includes 30 buses, 41 lines and 6 generators. The single line diagram of the 14 buses system is shown in Figure 16.

In this case, the transformers connecting buses 6-10 and buses 28-27 are assumed to be connected in Y-Y with both neutrals grounded. The transformers connected between buses 6-9 and buses 4-12 are assumed to be connected in Y-Y with both floating neutrals. All the pre-fault voltages are set as 1 per unit.

The zero sequence impedances are set as three times of the corresponding positive sequence impedances. And the zero sequence line shunt capacitances are set as 1/3 of the corresponding positive sequence line shunt capacitances.

And there are three mutual couplings added to this system, which is listed in Table 10:

Table 10 Mutual couplings(30 bus system)

Mutual #	Line 1		Line 2		Mutual impedance	
	From bus	To bus	From bus	To bus	R(p.u.)	X(p.u.)
1	24	22	25	24	0	0.4
2	17	16	20	10	0	0.5
3	29	27	30	27	0	0.8

The detailed data for the 30 bus system is listed in Appendix C.

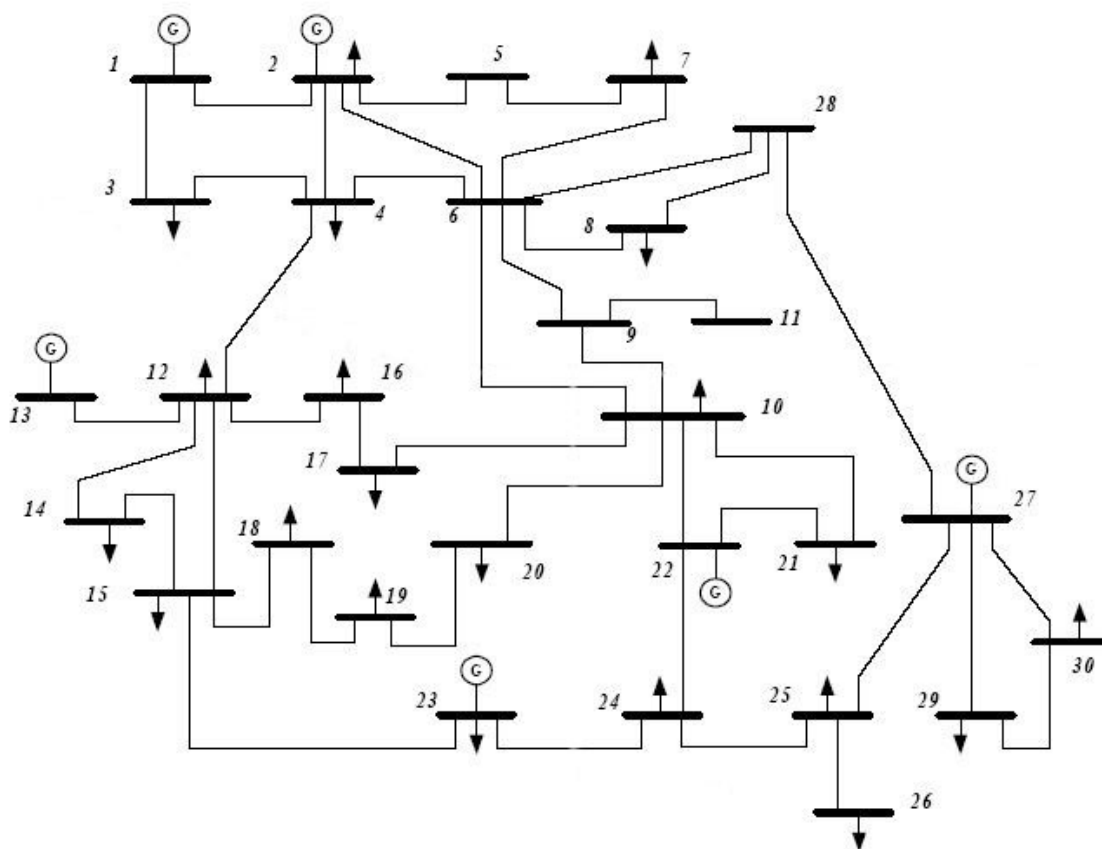


Figure 16. Diagram of IEEE 30 bus test system

Different fault types will be checked. Fault bus is set as bus 25.

The test results are listed in Tables 11 – 15.

a) Single-line-ground fault

$$z_a = 0.1 + j0.1, z_b = \infty, z_c = \infty, z_g = 0$$

Table 11 SLG fault results(30 bus system)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	1.9435 $\angle -60.3^\circ$	0.0	0.0
Phase method	1.9433 $\angle -60.3^\circ$	0.0	0.0
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	0.2749 $\angle -15.3^\circ$	1.1269 $\angle -130.1^\circ$	1.1337 $\angle 129.8^\circ$
Phase method	0.2748 $\angle -15.3^\circ$	1.1269 $\angle -130.1^\circ$	1.1337 $\angle 129.8^\circ$

b) Double-line-ground fault

$$z_a = 0.1 + j0.1, z_b = 0.1 + j0.1, z_c = \infty, z_g = 0$$

Table 12 DLG fault results(30 bus system)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	2.3223 $\angle -50.6^\circ$	2.3084 $\angle 169.4^\circ$	0.0
Phase method	2.3220 $\angle -50.6^\circ$	2.3081 $\angle 169.4^\circ$	0.0
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	0.3284 $\angle -5.6^\circ$	0.3265 $\angle -145.6^\circ$	1.1844 $\angle 119.9^\circ$
Phase method	0.3284 $\angle -5.6^\circ$	0.3264 $\angle -145.6^\circ$	1.1846 $\angle 119.9^\circ$

c) 3-Phase ground fault

$$z_a = 0.1 + j0.1, z_b = 0.1 + j0.1, z_c = 0.1 + j0.1, z_g = 0$$

Table 13 3-PG fault results(30 bus system)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	$2.5118 \angle -60.6^\circ$	$2.5118 \angle 179.4^\circ$	$2.5118 \angle 59.4^\circ$
Phase method	$2.5118 \angle -60.6^\circ$	$2.5118 \angle 179.4^\circ$	$2.5118 \angle 59.4^\circ$
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	$0.3552 \angle -15.6^\circ$	$0.3552 \angle -135.6^\circ$	$0.3552 \angle 104.4^\circ$
Phase method	$0.3552 \angle -15.6^\circ$	$0.3552 \angle -135.6^\circ$	$0.3552 \angle 104.4^\circ$

d) Line-line fault

$$z_a = 0.1 + j0.1, z_b = 0.1 + j0.1, z_c = \infty, z_g = \infty$$

Table 14 LL fault results(30 bus system)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	$2.1757 \angle -30.6^\circ$	$2.1757 \angle 149.4^\circ$	0.0
Phase method	$2.1753 \angle -30.6^\circ$	$2.1753 \angle 149.4^\circ$	0.0
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	$0.6539 \angle -33.1^\circ$	$0.5115 \angle -95.4^\circ$	$0.9998 \angle 120.0^\circ$
Phase method	$0.6539 \angle -33.1^\circ$	$0.5115 \angle -95.4^\circ$	$1.0 \angle 120.0^\circ$

e) 3-line fault

$$z_a = 0.1 + j0.1, z_b = 0.2 + j0.2, z_c = 0.3 + j0.3, z_g = \infty$$

Table 15 3L fault results(30 bus system)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	2.1854 $\angle -54.7^\circ$	1.8711 $\angle 174.1^\circ$	1.7009 $\angle 69.4^\circ$
Phase method	2.1854 $\angle -54.7^\circ$	1.8712 $\angle 174.1^\circ$	1.7010 $\angle 69.4^\circ$
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	0.4618 $\angle -18.0^\circ$	0.5061 $\angle -123.0^\circ$	0.5899 $\angle 106.1^\circ$
Phase method	0.4618 $\angle -18.0^\circ$	0.5061 $\angle -123.0^\circ$	0.5899 $\angle 106.1^\circ$

D. Case 4

In this case, IEEE-30 bus system, whose diagram is shown in Figure 16, is used to test the method and the detailed data is listed in Appendix D. The transformers connecting buses 6-9 and buses 4-12 are assumed to be connected in Y-Y with both neutrals grounded. The transformer connected between buses 6-10 is assumed to be connected in Y-Y with neutral grounded at bus 6 and floating neutral at bus 10. The transformer connected between buses 28-27 is assumed to be connected in Y-Y with both floating neutrals.

The zero sequence impedances and line shunt capacitances are set as the same as the data used in Case 3, and there is no mutual coupled branches in the system.

In this case, the load currents will be considered in the short circuit analysis and the pre-fault bus voltages will be set as the power flow results of this system. All the loads and pre-fault bus voltages are obtained for the IEEE-30 bus system.

CAPE's settings will be a little bit different from Case 2 and 3. First of all, the pre-fault bus voltages will be changed to the power flow results in the data window shown in Figure 17.

The transformer connected as Yg-Y will change the input data as shown in Figure 18.

The zero sequence series impedance is set as infinite. However, the shunt susceptance of the Y grounded side should be changed to:

$$B_0 = \frac{1}{Z_0} = \frac{1}{j0.556} = -j1.79856$$

This transformer can be specified using alternative input dialog box as shown in Figure 19.

In this window, after the transformer connections, leakage impedance and Base MVA are input, click the "Calculate" button, the correct data will be generated in the previous window. Notice that in CAPE the 30 degrees phase shift in the Yg-D and Y-D models is omitted, so there will be small difference between the results of CAPE and this method when those two transformer connections are involved.

All of the above system data will be edited in the database of CAPE. After that, when building the short circuit model in CAPE, the option "With load currents" will be chosen, while Case 2 and 3 are run under the mode "Without load currents". This window is shown in Figure 20.

Then apply the fault analysis using different fault types. Fault bus is set as bus 25.

The test results are listed in Tables 16 – 20.

The screenshot shows a software window titled "Bus Data: Query". At the top, there is a toolbar with navigation icons (back, forward, home, search, refresh) and buttons for "Copy Record", "Cancel", and "Original". The main area is divided into several sections:

- Bus Information:** Fields for "Bus Number" (10), "Substation" (1), "Bus Name" (Bus 10), "Category" (0), "Base kV" (100), and "Reference Angle" (0). A "Type" dropdown menu is set to "(Real) Conventional". A "<< Advanced" button is located at the bottom right of this section.
- Power Flow Data:** A tabbed interface with "Miscellaneous" selected. It contains fields for "Area", "Zone", and "Voltage Limit Set Number".
- Prefault Voltage:** Fields for "Magnitude" (1.045) and "Angle" (-16.01).
- Desired Voltage:** Fields for "Low" (0) and "High" (0).

Figure 17. Bus data window

XFMR Data: Query

Navigation: Copy Record, Cancel, Original, View Branch Set, Change To Line

Number	Name	Substation	Connection	Breaker Time	Tag: 11
Bus K: 6	Bus 6	1	Grounded Wye	0.00	Cycles
Bus M: 10	Bus 10	1	Ungrounded Wye	0.00	

Circuit Number: 1 ID:
 Equipment Name:
 Area:
 Zone:
 Xfmr Name:
 In Service Date:
 Out of Service Date:
 Category: 0

Transformer Model | Impedance Data | Power Flow Data | External Formats | Miscellaneous

View: Compact Full
 Max Load Current: 0 Worst Load Angle: 0
 All Impedances are in per-unit on the System base

	Series Impedance (Zkm)		Shunt Admittance (Yk)		Shunt Admittance (Ym)	
	R	X	G	B	G	B
+ Sequence	0	0.556	0	0	0	0
0 Sequence	999999	999999	0	-1.79856	0	0

Figure 18. Transformer data window1

XFMR Data: Query

Navigation: Copy Record, Cancel, Original, View Branch Set, Change To Line

Number	Name	Substation	Connection	Breaker Time	Tag: 11
Bus K: 6	Bus 6	1	Grounded Wye	0.00	Cycles
Bus M: 10	Bus 10	1	Ungrounded Wye	0.00	

Circuit Number: 1 ID:
 Equipment Name:
 Area:
 Zone:
 Xfmr Name:
 In Service Date:
 Out of Service Date:
 Category: 0

Transformer Model | Impedance Data | Power Flow Data | External Formats | Miscellaneous

Transformer Model Data

Leakage Impedance		Grounding Impedance (Zg in ohms)		Bus kV
	R	X		
+ Sequence	0	0.556	0	100
0 Sequence	0	0.556	0	100

Bus K Winding: R=0, X=0
 Bus M Winding: R=0, X=0

Impedances in p.u. on Transformer Base
 Transformer Base MVA: 100.000

Figure 19. Transformer data window2

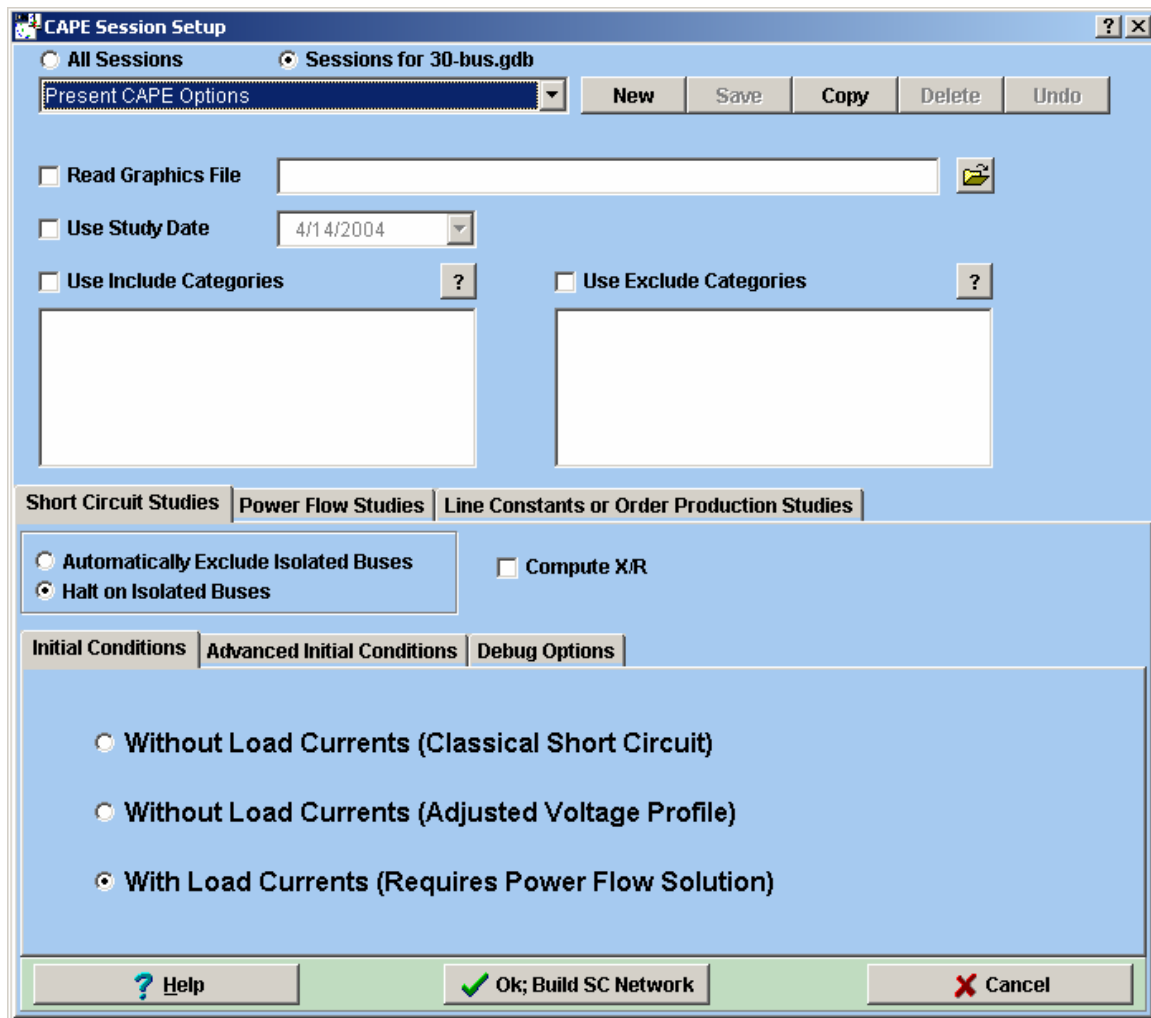


Figure 20. CAPE session setup window

a) Single-line-ground fault

$$z_a = j0.001, z_b = \infty, z_c = \infty, z_g = 0$$

Table 16 SLG fault results(with load currents)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	$1.9859 \angle -76.2^\circ$	0.0	0.0
Phase method	$1.9857 \angle -76.2^\circ$	0.0	0.0
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	$0.002 \angle 13.8^\circ$	$1.2948 \angle -157.7^\circ$	$1.3889 \angle 120.3^\circ$
Phase method	$0.002 \angle 13.8^\circ$	$1.2948 \angle -157.7^\circ$	$1.3888 \angle 120.3^\circ$

b) Double-line-ground fault

$$z_a = j0.001, z_b = j0.001, z_c = \infty, z_g = 0$$

Table 17 DLG fault results(with load currents)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	$3.5489 \angle -64.7^\circ$	$3.3088 \angle 137.3^\circ$	0.0
Phase method	$3.5498 \angle -64.7^\circ$	$3.3095 \angle 137.3^\circ$	0.0
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	$0.0035 \angle 25.3^\circ$	$0.0033 \angle -132.7^\circ$	$1.3552 \angle 102.3^\circ$
Phase method	$0.0035 \angle 25.3^\circ$	$0.0033 \angle -132.7^\circ$	$1.3552 \angle 102.3^\circ$

c) 3-Phase ground fault

$$z_a = j0.001, z_b = j0.001, z_c = j0.001, z_g = 0$$

Table 18 3-PG fault results(with load currents)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	$3.8869 \angle -84.1^\circ$	$3.8869 \angle 155.9^\circ$	$3.8869 \angle 35.9^\circ$
Phase method	$3.8869 \angle -84.1^\circ$	$3.8869 \angle 155.9^\circ$	$3.8869 \angle 35.9^\circ$
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	$0.0039 \angle 5.9^\circ$	$0.0039 \angle -114.1^\circ$	$0.0039 \angle 125.9^\circ$
Phase method	$0.0039 \angle 5.9^\circ$	$0.0039 \angle -114.1^\circ$	$0.0039 \angle 125.9^\circ$

d) Line-line fault

$$z_a = j0.001, z_b = j0.001, z_c = \infty, z_g = \infty$$

Table 19 LL fault results(with load currents)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	$3.3671 \angle -54.1^\circ$	$3.3671 \angle 125.9^\circ$	0.0
Phase method	$3.3661 \angle -54.1^\circ$	$3.3661 \angle 125.9^\circ$	0.0
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	$0.5071 \angle -76.0^\circ$	$0.5096 \angle -76.7^\circ$	$1.0167 \angle 103.6^\circ$
Phase method	$0.5072 \angle -76.0^\circ$	$0.5098 \angle -76.7^\circ$	$1.0170 \angle 103.6^\circ$

e) 3-line fault

$$z_a = j0.001, z_b = j0.002, z_c = j0.003, z_g = \infty$$

Table 20 3L fault results(with load currents)

	Fault current		
	Phase A	Phase B	Phase C
CAPE	$3.8784 \angle -84.1^\circ$	$3.8764 \angle 155.7^\circ$	$3.8648 \angle 35.9^\circ$
Phase method	$3.8784 \angle -84.1^\circ$	$3.8764 \angle 155.7^\circ$	$3.8648 \angle 35.9^\circ$
	Faulted bus voltage		
	Phase A	Phase B	Phase C
CAPE	$0.0059 \angle -4.9^\circ$	$0.0081 \angle -98.2^\circ$	$0.0097 \angle 119.2^\circ$
Phase method	$0.0059 \angle -4.9^\circ$	$0.0081 \angle -98.2^\circ$	$0.0097 \angle 119.2^\circ$

From the results of the cases presented above, the errors of the two methods, CAPE and the program of the approach presented here, are very small which prove that this approach is correct for the fault calculation. The detailed data input and output formats and the future-implementing interface will be presented in the next chapter.

CHAPTER V

IMPLEMENTATION OF THE FAULT ANALYSIS PROGRAM

This short circuit analysis program will be applied to practical use by being inserted into PET(Power Education Toolbox), which is power system analysis software. PET has many functions including power flow analysis and state estimation, and this program will be added into it to perform the short circuit analysis.

A. Data File Specifications

PET will generate 4 input files when the short circuit analysis data is input through the interface. The fault analysis program will read these data and perform the analysis, and generate 4 output files. As an additional function of PET, the data format of these files will be the same with PET's files. The data files of a 5-bus sample system will be listed below:

a) Input files

1. scparam.dat

1 100

-99

This file includes only two parameters. The first one is to control the mode of the fault calculation, that is, including the load currents or not in the calculation. The second one is the MVAbase of the system. -99 is the flag of the end of the data.

2. BUSOTP.dat

0

1 1.00000 0.000 1.00000 -120.000 1.00000 120.000

2 1.03130 0.000 1.03130 -120.000 1.03130 120.000

3 1.00000 0.000 1.00000 -120.000 1.00000 120.000

```

4  1.03350  0.000 1.03350 -120.000 1.03350  120.000
5  1.03750  0.000 1.03750 -120.000 1.03750  120.000

```

This file is generated by PET when you run the power flow analysis. It includes the bus voltages. If the calculation mode is chosen to consider the load currents in the scparam.dat, the prefault bus voltages will be read from this file.

0 is the flag to show there is no error during the power flow analysis.

1st column: the bus number.

2nd to 3rd columns: the magnitude and angle of bus voltage of phase A.

4th to 5th columns: the magnitude and angle of bus voltage of phase B.

6th to 7th columns: the magnitude and angle of bus voltage of phase C.

3. scinput.dat

```

1 0  1  0.000  0.30  0.000  0.10
3 0  1  0.000  0.36  0.000  0.12
-99
4 0  1  0.000  0.12  0.000  0.04
-99
1 5  10  10
-99
1 1 2  1  1  0  0  1  1  0.00000  0.60000  0.00000  0.01000  0.00000
0.20000  0.00000  0.03000
2 3 4  1  1  0  1  1  1  0.00000  0.36000  0.00000  0.01000  0.00000
0.12000  0.00000  0.03000
3 2 4  1  0 -1 -1 -1 -1  0.00000  0.30000  0.00000  0.01000  0.00000
0.10000  0.00000  0.03000
4 2 5  1  0 -1 -1 -1 -1  0.00000  0.45000  0.00000  0.01000  0.00000
0.15000  0.00000  0.03000

```

```

5 4 5 1 0 -1 -1 -1 -1 0.00000 0.60000 0.00000 0.01000 0.00000
0.20000 0.00000 0.03000
-99
4 5 2 5 4 5 0 0.1 0 0 0 0
-99

```

This file includes the network information, such as generator data, shunt element data, load data, line data and mutual data.

3.1) Generator data includes the generator connection type, location bus number and per sequence impedance.

1st column: the location bus number.

2nd column: the generator connection type (Yg or Y or Delta).

3rd column: a flag to show that the impedance of negative sequence is equal to positive sequence or not. If yes, then the negative sequence data will not be included. If no, then the negative sequence data will be added at the end of the data line.

4th to 5th columns: the resistance and reactance of the generator of zero sequence.

6th to 7th columns: the resistance and reactance of the generator of positive sequence.

3.2) Shunt element data includes the shunt connection type, location bus number and per sequence impedance.

1st column: the location bus number.

2nd column: the shunt element connection type (Yg or Y or Delta).

3rd column: a flag to show that the impedance of negative sequence is equal to positive sequence or not.

4th to 5th columns: the resistance and reactance of the shunt element of zero sequence.

6th to 7th columns: the resistance and reactance of the shunt element of positive sequence.

3.3) Load data includes the load location bus number, real and reactive power of the load.

1st column: the load number.

2nd column: the location bus number.

3rd to 4th columns: the real and reactive power of that load.

3.4) Branch data includes line number, terminal buses number, branch type, per sequence impedance, connection types and off nominal taps if it is a transformer branch.

1st column: the branch number.

2nd to 3rd columns: the terminal bus numbers.

4th column: a flag to show that the impedance of negative sequence is equal to positive sequence or not.

5th column: the branch type (transformer or transmission line).

6th to 7th columns: the transformer connection types of both sides (Yg, Y or Delta). If the branch type is not transformer, the data will be -1.

8th to 9th columns: the off-nominal taps of both sides of the transformer. If the branch type is not transformer, the data will be -1.

10th to 13th columns: the resistance, reactance, conductance and susceptance of the branch of zero sequence.

14th to 17th columns: the resistance, reactance, conductance and susceptance of the branch of positive sequence.

3.5) Mutual coupling data includes coupled lines number, terminal buses number and mutual sequence impedance.

1st to 2nd columns: the mutually coupled branch numbers.

3rd to 4th columns: the terminal bus numbers of the first branch.

5th to 6th columns: the terminal bus numbers of the second branch.

7th to 8th columns: the mutual resistance and reactance of zero sequence.

9th to 10th columns: the mutual resistance and reactance of positive sequence.

11th to 12th columns: the mutual resistance and reactance of negative sequence.

4. fltinput.dat

```
5 0 0.01 -1 0 -1 0 0 0
```

```
-99
```

This file includes the fault bus location, fault type and fault impedances.

1st column: the fault location bus number.

2nd to 3rd columns: the fault resistance and reactance of z_a .

4th to 5th columns: the fault resistance and reactance of z_b .

6th to 7th columns: the fault resistance and reactance of z_c .

8th to 9th columns: the fault resistance and reactance of z_g .

b) Output files

1. FLTOTP.dat

The detailed outputs is shown in Appendix E.

This file includes the fault bus, magnitudes and angles of the fault currents.

2. scoutput.dat

The detailed outputs is shown in Appendix F.

This is a detailed output file including post fault bus voltages and branch currents flowing from both terminals of the line.

3. FLTBUSOTP.dat

The detailed outputs is shown in Appendix G.

This is a brief output file of post fault bus voltages for quick reviewing.

4. FLTBRANCHOTP.dat

The detailed outputs is shown in Appendix H.

This is a brief output file of post fault branch currents for quick reviewing.

The diagram of the input and output files is shown in Figure 21.

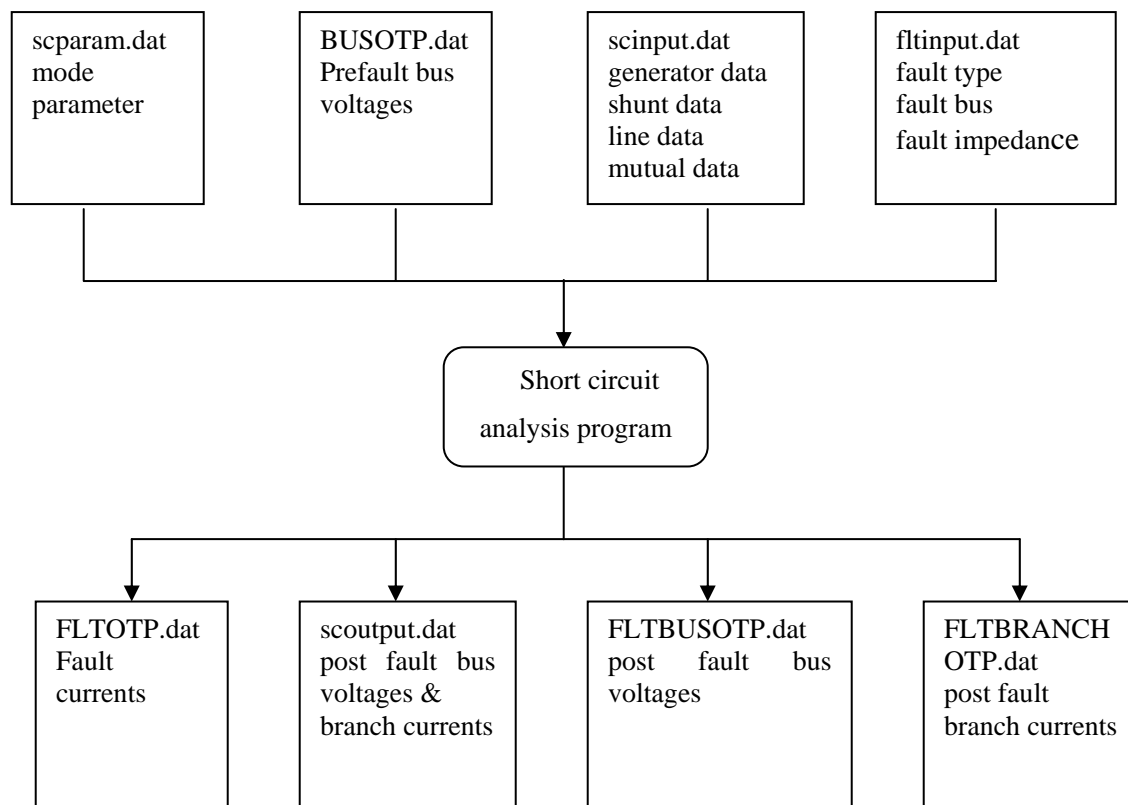


Figure 21. Input and output files of the program

B. User Interface Specifications

In the future PET's short circuit analysis mode, the data input interface will look like the following figures(see Figures 22 – 26).

Line Data [X]

Sequence Data(p.u.)

	Z	P	N
R:	<input type="text"/>	<input type="text"/>	<input type="text"/>
X:	<input type="text"/>	<input type="text"/>	<input type="text"/>
G:	<input type="text"/>	<input type="text"/>	<input type="text"/>
B:	<input type="text"/>	<input type="text"/>	<input type="text"/>

Type

Line
 Transformer

Enable Neg Seq.

Enable
 Disable

Terminations

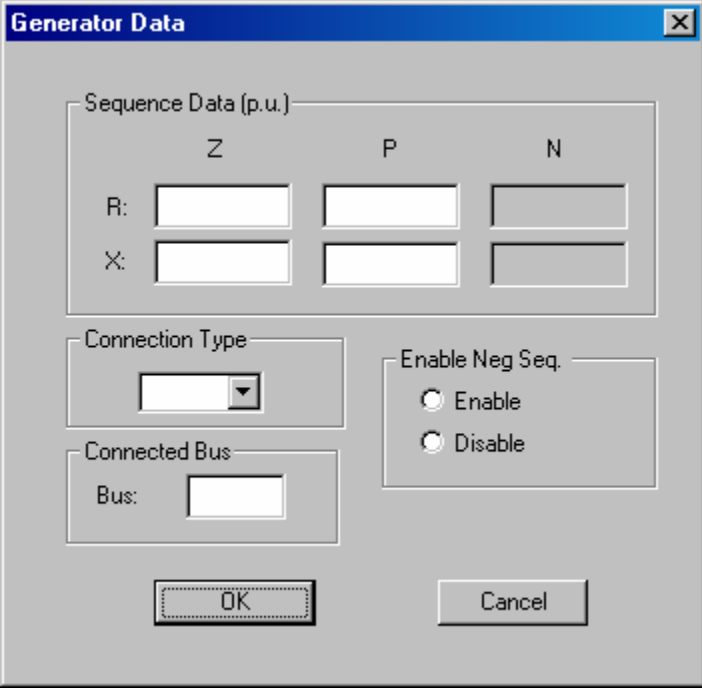
Bus1:
Bus2:

Transformer Data

Termination1: ▼
Termination2: ▼
Tap1:
Tap2:

OK Cancel

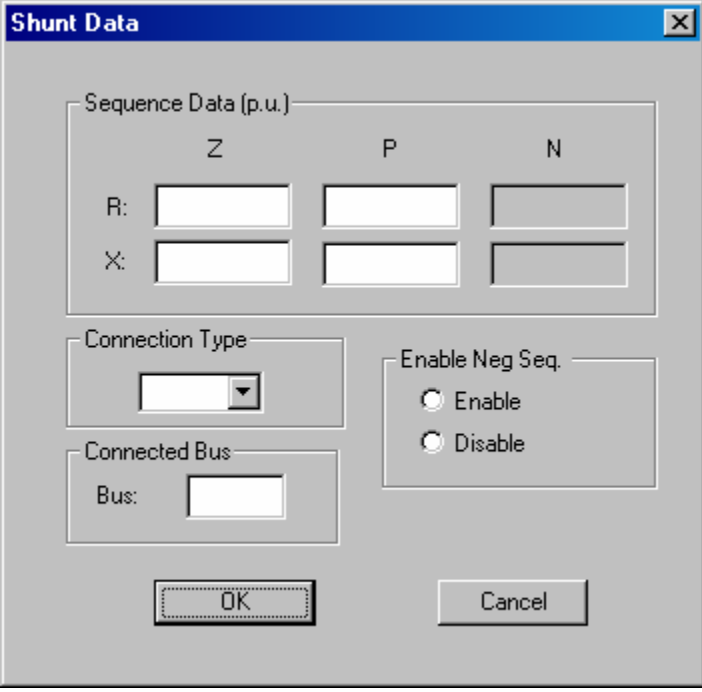
Figure 22. Line data window



The **Generator Data** dialog box is used to configure generator parameters. It features a title bar with a close button (X). The main content is organized into several sections:

- Sequence Data (p.u.):** A table with three columns labeled Z, P, and N. The rows are labeled R and X. Each cell contains an empty text input field.
- Connection Type:** A dropdown menu with a downward arrow.
- Connected Bus:** A section with the label "Bus:" followed by an empty text input field.
- Enable Neg Seq.:** A section containing two radio buttons: "Enable" and "Disable".
- Buttons:** "OK" and "Cancel" buttons are located at the bottom of the dialog.

Figure 23. Generator data window



The **Shunt Data** dialog box is used to configure shunt element parameters. It features a title bar with a close button (X). The main content is organized into several sections:

- Sequence Data (p.u.):** A table with three columns labeled Z, P, and N. The rows are labeled R and X. Each cell contains an empty text input field.
- Connection Type:** A dropdown menu with a downward arrow.
- Connected Bus:** A section with the label "Bus:" followed by an empty text input field.
- Enable Neg Seq.:** A section containing two radio buttons: "Enable" and "Disable".
- Buttons:** "OK" and "Cancel" buttons are located at the bottom of the dialog.

Figure 24. Shunt element data window

Fault Data

Faulted Bus:

Sequence Data (p.u.)

	Phase A	Phase B	Phase C	N-G
R:	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
X:	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

OK Cancel

Figure 25. Fault data window

Mutual Data

Mutual Impedance (p.u.)

	Z	P	N
R:	<input type="text"/>	<input type="text"/>	<input type="text"/>
X:	<input type="text"/>	<input type="text"/>	<input type="text"/>

Mutual Coupling Terminations

Bus1:

Bus2:

OK Cancel

Figure 26. Mutual data window

Through these data input windows, all the short circuit data will be input into PET and generate the 4 input files for the short circuit analysis program.

CHAPTER VI

CONCLUSIONS

This thesis investigates the problem of fault calculation in three phase power systems. The method that exist and currently in use by power engineers are reviewed first. These usually make use of a hybrid solution method where the solution is carried out both in the phase and sequence domain. The fault analysis algorithm strictly in phase domain appeared in late 60's and was developed to a generalized method later. However it was not widely used because of the limit of the hardware. With the highly improvement in the power of computers since that time, the phase domain method will be of more importance. In this work, a fault analysis algorithm, whose calculation is in pure phase domain, is developed. This algorithm has certain advantages over sequence domain methods. Also it is much easier to interlace this approach with a three-phase power flow solver.

The approach to short circuit analysis presented here is not a totally new one. As mentioned in chapter II, there was other phase domain method although there are differences between the fault calculation processes. Sine the proposed method of calculation is implemented completely in phase domain, it can deal with complicated faults between different phases. It improves the calculation speed and saves storage space by performing the LU factorization of the admittance matrix corresponding to the complete three-phase domain network. When building the admittance matrix, the model used for the transformer in this step is the phase domain model unlike most of the fault analysis algorithms. Since the phase domain transformer model takes into account the 30 degrees phase shift in the Yg-D or Y-D connections, which is omitted in the sequence transformer model, the results of this method do not need post processing to account for connection induced phase shifts for the transformers.

The method presented here is just a prototype program developed for phase domain short circuit analysis. It can be improved in many aspects. The sparse techniques are not fully exploited in this implementation since the software is intended to be used as a teaching software. Hence it is expected to only small systems. However, the sparsity

methods should be considered when large systems or many mutual couplings are involved.

The developed software so far can only calculate the fault at a given bus and deal with one fault at a time. One possible modification is to allow this program to handle the faults occurring in the middle of lines and the cases of simultaneous faults. Although it is probably not a common case in power systems, as a phase domain fault analysis program, it should be able to deal with simultaneous faults in different locations. Moreover, since the fault calculations are processed totally in phase domain, some uncommon faults can be calculated more easily by this method, such as phase A of a line shorted with phase B of another line. Such cases are more difficult to handle when using sequence methods.

When combined with PET, the short circuit analysis program cannot share the system network data with other functions. The sequence network data used by application functions such as power flow analysis and state estimation are the same. However, when the short circuit analysis mode is chosen, the network data must be entered separately since additional data are required. These include zero and negative sequence network data, mutual coupling data, transformer connection data, which are not part of the power flow analysis data. Since different modes read data from different input files generated by PET, the data of the power flow analysis and short circuit analysis must be entered separately although there will be a certain amount of overlap.

Another possible improvement is to develop a full three-phase power flow analysis program which will share the network data with the short circuit program. Both programs will be allowed to use the same data structure to save the network model and parameters. If the short-circuit program is required to account for load currents, then the results of the power flow analysis can readily be obtained corresponding to the same network.

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APPENDIX A

PROGRAM CODE

```

function shortcircuit()
% start to input data
finput=fopen('scparam.dat');      % input calculation mode and base MVA

ReadLine=fgets(finput);
BranchData=str2num(ReadLine);
while BranchData(1)~= -99
    prefaultv = BranchData(1);    % The calculation mode: including the load currents or not
    MVAbase= BranchData(2);
    ReadLine=fgets(finput);
    BranchData=str2num(ReadLine);
end

fclose(finput);

finput=fopen('scinput.dat');      % input generator data

ReadLine=fgets(finput);
BranchData=str2num(ReadLine);
I=1;
while BranchData(1)~= -99
    gennum(I)=BranchData(1);
    genconnect(I)=BranchData(2);
    negative(I)=BranchData(3);
    genzr(I)=BranchData(4);
    genzx(I)=BranchData(5);
    genpr(I)=BranchData(6);
    genpx(I)=BranchData(7);
    if negative(I)==1            % if data of negative sequence = positive sequence

```

```

    gennr(I)=genpr(I);      % use the same data
    gennx(I)=genpx(I);
else
    gennr(I)=BranchData(8);
    gennx(I)=BranchData(9);
end
ReadLine=fgets(finput);
BranchData=str2num(ReadLine);
I=I+1;
end
total_gen=I-1;

ReadLine=fgets(finput);      % input shunt elements data
BranchData=str2num(ReadLine);
I=1;
while BranchData(1)~-=-99
    shuntnum(I)=BranchData(1);
    shuntconnect(I)=BranchData(2);
    negative(I)=BranchData(3);
    shuntzr(I)=BranchData(4);
    shuntzx(I)=BranchData(5);
    shuntpr(I)=BranchData(6);
    shuntpx(I)=BranchData(7);
    if negative(I)==1
        shuntnr(I)=shuntpr(I);
        shuntnx(I)=shuntpx(I);
    else
        shuntnr(I)=BranchData(8);
        shuntnx(I)=BranchData(9);
    end
end
ReadLine=fgets(finput);
BranchData=str2num(ReadLine);
I=I+1;

```

```
end
total_shunt=I-1;

ReadLine=fgets(finput);          % input load data
BranchData=str2num(ReadLine);
I=1;
while BranchData(1)~-=-99
    loadnum(I)=BranchData(1);
    loadbus(I)=BranchData(2);
    loadP(I)=BranchData(3);
    loadQ(I)=BranchData(4);
    ReadLine=fgets(finput);
    BranchData=str2num(ReadLine);
    I=I+1;
end
total_load=I-1;
```

```
ReadLine=fgets(finput);          % input lines data
BranchData=str2num(ReadLine);
I=1;
while BranchData(1)~-=-99
    startbus(I) = BranchData(2);
    endbus(I) = BranchData(3);
    negative(I)=BranchData(4);
    branchtype(I) = BranchData(5);
    frombuscon(I) = BranchData(6);
    tobuscon(I) = BranchData(7);
    ratiop(I) = BranchData(8);
    ratios(I) = BranchData(9);
    zr(I) = BranchData(10);
    zx(I) = BranchData(11);
    zcon(I) = BranchData(12);
```

```

zsup(I) = BranchData(13);
pr(I) = BranchData(14);
px(I) = BranchData(15);
pg(I) = BranchData(16);
pb(I) = BranchData(17);
if negative(I)==1
    nr(I)=pr(I);
    nx(I)=px(I);
    ng(I)=pg(I);
    nb(I)=pb(I);
else
    nr(I)=BranchData(18);
    nx(I)=BranchData(19);
    ng(I)=BranchData(20);
    nb(I)=BranchData(21);
end
ReadLine=fgets(finput);
BranchData=str2num(ReadLine);
I=I+1;
end
total_line=I-1;
total_bus=max(max(startbus),max(endbus));

ReadLine=fgets(finput);          % input mutual couplings data
BranchData=str2num(ReadLine);
I=1;
while BranchData(1)~= -99
    mutualset(I,:)=BranchData(1:2);
    mutualendbus(I,:)=BranchData(3:6);
    mutualzim(I)=BranchData(7)+i*BranchData(8);
    mutualpim(I)=BranchData(9)+i*BranchData(10);
    mutualnim(I)=BranchData(11)+i*BranchData(12);
    ReadLine=fgets(finput);

```

```

    BranchData=str2num(ReadLine);
    I=I+1;
end
total_mutual=I-1;
if total_mutual==0
    mutual=0;
else
    mutual=1;
end

fclose(finput);

finput=fopen('fltinput.dat');    % input fault data

ReadLine=fgets(finput);
BranchData=str2num(ReadLine);
I=1;
while BranchData(1)~-99
    shortbus(I)=BranchData(1);
    za(I)=BranchData(2)+i*BranchData(3);
    zb(I)=BranchData(4)+i*BranchData(5);
    zc(I)=BranchData(6)+i*BranchData(7);
    zg(I)=BranchData(8)+i*BranchData(9);
    ReadLine=fgets(finput);
    BranchData=str2num(ReadLine);
    I=I+1;
end
total_fault=I-1;

fclose(finput);

if prefaultv==1    % not including load currents
    v=ones(total_bus,1);    % Initial value for bus voltages = desired voltage in data file

```

```

va=v;
vb=v*cos(-2/3*pi)+v*sin(-2/3*pi)*i;
vc=v*cos(2/3*pi)+v*sin(2/3*pi)*i;
else % including load currents
    finput=fopen('BUSOTP.DAT'); % Initial value for bus voltages = voltages of power flow
    results

    ReadLine=fgets(finput);
    BranchData=str2num(ReadLine);
    I=1;
    if BranchData(1)==0
        I=I+1;
        while I<=total_bus+1
            ReadLine=fgets(finput);
            BranchData=str2num(ReadLine);
            va(I-
1)=BranchData(2)*cos(BranchData(3)*pi/180)+BranchData(2)*sin(BranchData(3)*pi/180)*i;
            vb(I-
1)=BranchData(4)*cos(BranchData(5)*pi/180)+BranchData(4)*sin(BranchData(5)*pi/180)*i;
            vc(I-
1)=BranchData(6)*cos(BranchData(7)*pi/180)+BranchData(6)*sin(BranchData(7)*pi/180)*i;
            I=I+1;
        end
    end
end

    fclose(finput);
end

a=-0.5+sqrt(3)*j/2;
T=[1 1 1;1 a^2 a;1 a a^2]; % transforming matrix
S=inv(T);
C=1/sqrt(3)*[1 -1 0;0 1 -1;-1 0 1]; % matrix used in transformer model

% Build prefault three-phase voltage matrix
vpre=zeros(total_bus*3,1);

```

```

for x=1:total_bus
    vpre(x*3-2)=va(x);
    vpre(x*3-1)=vb(x);
    vpre(x*3)=vc(x);
end

% Build incidence matrix A
A=zeros(total_line,total_bus);
for x=1:total_line
    A(x,startbus(x))=1;
    A(x,endbus(x))=-1;
end

% Build the Y Matrix of zero-sequence
zz=zeros(total_line,total_line);
for x=1:total_line
    if branchtype(x)==0          % input elements data other than transformer
        zz(x,x)=zr(x)+zx(x)*i;
    else
        zz(x,x)=1;
    end
end
end
if total_mutual>0              % input mutual couplings data
    for x=1:total_mutual
        zz(mutualset(x,1),mutualset(x,2))=mutualzim(x);
        zz(mutualset(x,2),mutualset(x,1))=mutualzim(x);
    end
end
end
yz=inv(zz);
for x=1:total_line
    if branchtype(x)==1
        yz(x,x)=0;
    end
end

```

```

end
Ymatrixz=A'*yz*A;
if total_gen~=0
for x=1:total_gen          % add the generator admittance
    if genconnect(x)==0
        bus=gennum(x);
        Ymatrixz(bus,bus)=Ymatrixz(bus,bus)+1/(genzr(x)+genzx(x)*i);
    end
end
end
if total_shunt~=0
for x=1:total_shunt        % add the shunt element admittance
    if shuntconnect(x)==0
        bus=shuntnum(x);
        Ymatrixz(bus,bus)=Ymatrixz(bus,bus)+1/(shuntzr(x)+shuntzx(x)*i);
    end
end
end
for x=1:total_line        % add line shunt capacitance
    from=startbus(x);
    to=endbus(x);
    if branchtype(x)==0
        Ymatrixz(from,from)=Ymatrixz(from,from)+zcon(x)+zsup(x)*i;
        Ymatrixz(to,to)=Ymatrixz(to,to)+zcon(x)+zsup(x)*i;
    end
end
end

if prefaultv==0          % if considering load currents, add the equivalent load impedance
for x=1:total_load
    bus=loadbus(x);
    PQ=(loadP(x)-loadQ(x)*j)/MVAbase;
    zload(x)=va(bus)*conj(va(bus))/PQ;
    Ymatrixz(bus,bus)=Ymatrixz(bus,bus)+1/zload(x);
end

```



```

    end
end

% Build the Y Matrix of positive-sequence
zp=zeros(total_line,total_line);
for x=1:total_line
    if branchtype(x)==0          % input elements data other than transformer
        zp(x,x)=pr(x)+px(x)*i;
    else
        zp(x,x)=1;
    end
end
end
if total_mutual>0              % input mutual couplings data
    for x=1:total_mutual
        zp(mutualset(x,1),mutualset(x,2))=mutualpim(x);
        zp(mutualset(x,2),mutualset(x,1))=mutualpim(x);
    end
end
end
yp=inv(zp);
for x=1:total_line
    if branchtype(x)==1
        yp(x,x)=0;
    end
end
end
Ymatrixp=A'*yp*A;
if total_gen~=0
    for x=1:total_gen          % add the generator admittance
        bus=gennum(x);
        Ymatrixp(bus,bus)=Ymatrixp(bus,bus)+1/(genpr(x)+genpx(x)*i);
    end
end
end
if total_shunt~=0
    for x=1:total_shunt        % add the shunt element admittance

```

```

    bus=shuntnum(x);
    Ymatrixp(bus,bus)=Ymatrixp(bus,bus)+1/(shuntpr(x)+shuntpx(x)*i);
end
end
for x=1:total_line          % add line shunt capacitance
    from=startbus(x);
    to=endbus(x);
    if branchtype(x)==0
        Ymatrixp(from,from)=Ymatrixp(from,from)+pg(x)+pb(x)*i;
        Ymatrixp(to,to)=Ymatrixp(to,to)+pg(x)+pb(x)*i;
    end
end

if prefaultv==0            % if considering load currents, add the equivalent load impedance
    for x=1:total_load
        bus=loadbus(x);
        Ymatrixp(bus,bus)=Ymatrixp(bus,bus)+1/zload(x);
    end
end

% Build the Y Matrix of negative-sequence
zn=zeros(total_line,total_line);
for x=1:total_line
    if branchtype(x)==0    % input elements data other than transformer
        zn(x,x)=nr(x)+nx(x)*i;
    else
        zn(x,x)=1;
    end
end

if total_mutual>0        % input mutual couplings data
    for x=1:total_mutual
        zn(mutualset(x,1),mutualset(x,2))=mutualnim(x);
        zn(mutualset(x,2),mutualset(x,1))=mutualnim(x);
    end
end

```

```

    end
end
yn=inv(zn);
for x=1:total_line
    if branchtype(x)==1
        yn(x,x)=0;
    end
end
Ymatrixn=A'*yn*A;
if total_gen~=0
for x=1:total_gen            % add the generator admittance
    bus=gennum(x);
    Ymatrixn(bus,bus)=Ymatrixn(bus,bus)+1/(gennr(x)+gennx(x)*i);
end
end
if total_shunt~=0
for x=1:total_shunt        % add the shunt element admittance
    bus=shuntnum(x);
    Ymatrixn(bus,bus)=Ymatrixn(bus,bus)+1/(shuntnr(x)+shuntnx(x)*i);
end
end
for x=1:total_line        % add line shunt capacitance
    from=startbus(x);
    to=endbus(x);
    if branchtype==0
        Ymatrixn(from,from)=Ymatrixn(from,from)+ng(x)+nb(x)*i;
        Ymatrixn(to,to)=Ymatrixn(to,to)+ng(x)+nb(x)*i;
    end
end
end

if prefaultv==0            % if considering load currents, add the equivalent load impedance
    for x=1:total_load
        bus=loadbus(x);

```

```

        Ymatrixn(bus,bus)=Ymatrixn(bus,bus)+1/zload(x);
    end
end

% Convert to Y matrix in phase domain
Ymatrix=zeros(total_bus*3,total_bus*3);
for x=1:total_bus
    for y=1:total_bus
        if y<x
            Ymatrix(3*x-2:3*x,3*y-2:3*y)=Ymatrix(3*y-2:3*y,3*x-2:3*x);
        else
            Ymatrix(3*x-2:3*x,3*y-2:3*y)=T*[Ymatrixz(x,y) 0 0;0 Ymatrixp(x,y) 0;0 0
Ymatrixn(x,y)]*S;
        end
    end
end

% Add transformer components
for x=1:total_line
    from=startbus(x);
    to=endbus(x);
    if branchtype(x)==1
        ys1=1/(pr(x)+px(x)*i)+pg(x)+pb(x)*i;
        ys0=1/(zr(x)+zx(x)*i)+zcon(x)+zsup(x)*i;
        y1=1/(pr(x)+px(x)*i);
        y0=1/(zr(x)+zx(x)*i);
        alpha=ratiop(x);
        beta=ratios(x);
        Y1=1/3*[ys0+2*ys1 ys0-ys1 ys0-ys1;ys0-ys1 ys0+2*ys1 ys0-ys1;ys0-ys1 ys0-ys1 ys0+2*ys1];
        Y2=1/3*[2*ys1 -ys1 -ys1;-ys1 2*ys1 -ys1;-ys1 -ys1 2*ys1];
        Y1x=1/3*[y0+2*y1 y0-y1 y0-y1;y0-y1 y0+2*y1 y0-y1;y0-y1 y0-y1 y0+2*y1];
        Y2x=1/3*[2*y1 -y1 -y1;-y1 2*y1 -y1;-y1 -y1 2*y1];
        Y3=y1*C;
        Y3t=y1*C';
    end
end

```

```
fromco=frombuscon(x);
toco=tobuscon(x);
if fromco==0           % for different connections, use different functions
    switch toco
        case 0
            Ya=Y1;
            Yb=Y1x;
            Yc=Y1x;
            Yd=Y1;
        case 1
            Ya=Y1;
            Yb=Y2x;
            Yc=Y2x;
            Yd=Y2;
        otherwise
            Ya=Y1;
            Yb=Y3;
            Yc=Y3t;
            Yd=Y2;
    end
elseif fromco==1
    switch toco
        case 0
            Yd=Y1;
            Yb=Y2x;
            Yc=Y2x;
            Ya=Y2;
        case 1
            Ya=Y2;
            Yb=Y2x;
            Yc=Y2x;
            Yd=Y2;
        otherwise
```

```

        Ya=Y2;
        Yb=Y3;
        Yc=Y3t;
        Yd=Y2;
    end
else
    switch toco
    case 0
        Ya=Y2;
        Yb=Y3t;
        Yc=Y3;
        Yd=Y1;
    case 1
        Ya=Y2;
        Yb=Y3t;
        Yc=Y3;
        Yd=Y2;
    otherwise
        Ya=Y2;
        Yb=Y2x;
        Yc=Y2x;
        Yd=Y2;
    end
end
Ytr=[Ya/alpha^2 -Yb/(alpha*beta);-Yc/(alpha*beta) Yd/beta^2];    % build the final matrix
Ymatrix(from*3-2:from*3,from*3-2:from*3)=Ymatrix(from*3-2:from*3,from*3-
2:from*3)+Ytr(1:3,1:3);    % overlap it to the Y amtrix
Ymatrix(to*3-2:to*3,to*3-2:to*3)=Ymatrix(to*3-2:to*3,to*3-2:to*3)+Ytr(4:6,4:6);
Ymatrix(from*3-2:from*3,to*3-2:to*3)=Ymatrix(from*3-2:from*3,to*3-2:to*3)+Ytr(1:3,4:6);
Ymatrix(to*3-2:to*3,from*3-2:from*3)=Ymatrix(to*3-2:to*3,from*3-2:from*3)+Ytr(4:6,1:3);
end
end
Zmatrix=inv(Ymatrix);    % get the Z matrix

```

```

% Short circuit study
Ishort=zeros(total_bus*3,1);
for x=1:total_fault
    k=shortbus(x);
    if zg(x)==-1                % for non-grounded fault
        if za(x)==-1
            Zx=Zmatrix(3*k-1:3*k,3*k-1:3*k)+[zb(x) 0;0 zc(x)];
            Zf=[Zx(1,:)-Zx(2,:);1 1];
            Ip=inv(Zf)*[vb(k)-vc(k);0];
            If=[0;-Ip];
        elseif zb(x)==-1
            Zx=[Zmatrix(3*k-2,3*k-2)+za(x) Zmatrix(3*k-2,3*k);Zmatrix(3*k,3*k-2)
Zmatrix(3*k,3*k)+zc(x)];
            Zf=[Zx(1,:)-Zx(2,:);1 1];
            Ip=inv(Zf)*[va(k)-vc(k);0];
            If=[-Ip(1);0;-Ip(2)];
        elseif zc(x)==-1
            Zx=Zmatrix(3*k-2:3*k-1,3*k-2:3*k-1)+[za(x) 0;0 zb(x)];
            Zf=[Zx(1,:)-Zx(2,:);1 1];
            Ip=inv(Zf)*[va(k)-vb(k);0];
            If=[-Ip;0];
        else
            Zx=Zmatrix(3*k-2:3*k,3*k-2:3*k)+[za(x) 0 0;0 zb(x) 0;0 0 zc(x)];
            Zf=[Zx(1,:)-Zx(2,:);Zx(2,:)-Zx(3,:);1 1 1];
            Ip=inv(Zf)*[va(k)-vb(k);vb(k)-vc(k);0];
            If=-Ip;
        end
    else                % for grounded fault
        if (za(x)==-1)&(zb(x)==-1)
            Ic=vc(k)/(zc(x)+zg(x)+Zmatrix(3*k,3*k));
            If=[0;0;-Ic];
        elseif (za(x)==-1)&(zc(x)==-1)
            Ib=vb(k)/(zb(x)+zg(x)+Zmatrix(3*k-1,3*k-1));
            If=[0;-Ib;0];
        end
    end
end

```

```

elseif (zb(x)==-1)&(zc(x)==-1)
    Ia=va(k)/(za(x)+zg(x)+Zmatrix(3*k-2,3*k-2));
    If=[-Ia;0;0];
elseif za(x)==-1
    Zx=Zmatrix(3*k-1:3*k,3*k-1:3*k)+[zb(x) 0;0 zc(x)]+zg(x)*ones(2,2);
    Ip=inv(Zx)*[vb(k);vc(k)];
    If=[0;-Ip];
elseif zb(x)==-1
    Zx=[Zmatrix(3*k-2,3*k-2)+za(x) Zmatrix(3*k-2,3*k);Zmatrix(3*k,3*k-2)
Zmatrix(3*k,3*k)+zc(x)]+zg(x)*ones(2,2);
    Ip=inv(Zx)*[va(k);vc(k)];
    If=[-Ip(1);0;-Ip(2)];
elseif zc(x)==-1
    Zx=Zmatrix(3*k-2:3*k-1,3*k-2:3*k-1)+[za(x) 0;0 zb(x)]+zg(x)*ones(2,2);
    Ip=inv(Zx)*[va(k);vb(k)];
    If=[-Ip;0];
else
    Zx=Zmatrix(3*k-2:3*k,3*k-2:3*k)+[za(x) 0 0;0 zb(x) 0;0 0 zc(x)]+zg(x)*ones(3,3);
    Ip=inv(Zx)*[va(k);vb(k);vc(k)];
    If=-Ip;
end
end
end
Ishort(3*k-2:3*k)=If;          % calculate fault currents
end
deltaV=Zmatrix*Ishort;
Vshort=vpre+deltaV;          % calculate post-fault voltages
Iline=zeros(total_line*3,1);
Vline=zeros(total_line*3,1);
for x=1:total_line          % build the voltage difference matrix for the line
    from=startbus(x);
    to=endbus(x);
    Vline(3*x-2:3*x)=Vshort(from*3-2:from*3)-Vshort(to*3-2:to*3);
end
end
Yline=zeros(total_line*3,total_line*3); % build the line impedance matrix

```



```

for x=1:total_line
    if branchtype(x)==0
        Ym=T*[yz(x,x) 0 0;0 yp(x,x) 0;0 0 yn(x,x)]*S;
    else
        Ym=T*[1/(zr(x)+zx(x)*i) 0 0;0 1/(pr(x)+px(x)*i) 0;0 0 1/(nr(x)+nx(x)*i)]*S;
    end
    Yline(3*x-2:3*x,3*x-2:3*x)=Ym;
end
if total_mutual>0                % add mutual couplings
    for x=1:total_mutual
        a=mutualset(x,1);
        b=mutualset(x,2);
        for y=1:total_line
            Ym1=T*[yz(a,y) 0 0;0 yp(a,y) 0;0 0 yn(a,y)]*S;
            Ym2=T*[yz(b,y) 0 0;0 yp(b,y) 0;0 0 yn(b,y)]*S;
            Yline(3*a-2:3*a,3*y-2:3*y)=Ym1;
            Yline(3*b-2:3*b,3*y-2:3*y)=Ym2;
        end
    end
end
Iline=Yline*Vline;                % calculate the post-fault branch currents

shuntIline=zeros(total_line*3,2);    % calculate the flow in and out currents of the line
for x=1:total_line
    from=startbus(x);
    to=endbus(x);
    yshunt=T*[zcon(x)+zsup(x)*i 0 0;0 pg(x)+pb(x)*i 0;0 0 ng(x)+nb(x)*i]*S;
    shuntIline(3*x-2:3*x,1)=yshunt*Vshort(from*3-2:from*3);
    shuntIline(3*x-2:3*x,2)=yshunt*Vshort(to*3-2:to*3);
end

% Output the results
foutput = fopen('scoutput.dat','w');

```

```

fprintf(foutput,'\nResults of Short Circuit Study\n');
fprintf(foutput,'\n Post Fault Voltages \n');
fprintf(foutput,'\nBus No.   Phase-A Voltage   Phase-B Voltage   Phase-C Voltage \n');
fprintf(foutput,'\n      Abs   Abgle   Abs   Abgle   Abs   Abgle \n\n');
for x=1:total_bus
    fprintf(foutput,'\n%3d%12.4f%12.4f%12.4f%12.4f%12.4f%12.4f\n',x,abs(Vshort(x*3-2)),angle(Vshort(x*3-2))*180/pi,abs(Vshort(x*3-1)),angle(Vshort(x*3-1))*180/pi,abs(Vshort(x*3)),angle(Vshort(x*3))*180/pi);
end

fprintf(foutput,'\n Post Fault Line Currents \n');
fprintf(foutput,'\nBus No.   Phase-A Current   Phase-B Current   Phase-C Current \n');
fprintf(foutput,'\n      Abs   Abgle   Abs   Abgle   Abs   Abgle \n\n');
for x=1:total_bus
    fprintf(foutput,'\n%3d\n',x);
    for y=1:total_line
        if startbus(y)==x
            tobus=endbus(y);
            Ia=Iline(y*3-2)+shuntIline(y*3-2,1);
            Ib=Iline(y*3-1)+shuntIline(y*3-1,1);
            Ic=Iline(y*3)+shuntIline(y*3,1);

            fprintf(foutput,'TOBUS%3d%7.4f%12.4f%12.4f%12.4f%12.4f%12.4f\n',tobus,abs(Ia),angle(Ia)*180/pi,abs(Ib),angle(Ib)*180/pi,abs(Ic),angle(Ic)*180/pi);
            end
            if endbus(y)==x
                tobus=startbus(y);
                Ia=-(Iline(y*3-2)-shuntIline(y*3-2,2));
                Ib=-(Iline(y*3-1)-shuntIline(y*3-1,2));
                Ic=-(Iline(y*3)-shuntIline(y*3,2));

            fprintf(foutput,'TOBUS%3d%7.4f%12.4f%12.4f%12.4f%12.4f%12.4f\n',tobus,abs(Ia),angle(Ia)*180/pi,abs(Ib),angle(Ib)*180/pi,abs(Ic),angle(Ic)*180/pi);
            end
        end
    end
end

```

```

    end
end
fclose(foutput);

foutput = fopen('FLTOTP.dat','w');

fprintf(foutput,'\nFault Current \n');
fprintf(foutput,'\nFault Bus No.   Phase-A Current   Phase-B Current   Phase-C Current \n');
fprintf(foutput,'\n           Abs   Abgle   Abs   Abgle   Abs   Abgle \n');
for x=1:total_fault
    fprintf(foutput,'\n%8d%12.4f%12.4f%12.4f%12.4f%12.4f\n',shortbus(x),abs(-
Ishort(shortbus(x)*3-2)),angle(-Ishort(shortbus(x)*3-2))*180/pi,abs(-Ishort(shortbus(x)*3-1)),angle(-
Ishort(shortbus(x)*3-1))*180/pi,abs(-Ishort(shortbus(x)*3)),angle(-Ishort(shortbus(x)*3))*180/pi);
end
fclose(foutput);

foutput = fopen('FLTBUSOTP.dat','w');

fprintf(foutput,'\n0\n');
for x=1:total_bus
    fprintf(foutput,'%3d%7.4f%12.4f%12.4f%12.4f%12.4f\n',x,abs(Vshort(x*3-
2)),angle(Vshort(x*3-2))*180/pi,abs(Vshort(x*3-1)),angle(Vshort(x*3-
1))*180/pi,abs(Vshort(x*3)),angle(Vshort(x*3))*180/pi);
end
fclose(foutput);

foutput = fopen('FLTBRANCHOTP.dat','w');
fprintf(foutput,'\n0\n');
for x=1:total_line
    Iaf=Iline(x*3-2)+shuntIline(x*3-2,1);
    Ibf=Iline(x*3-1)+shuntIline(x*3-1,1);
    Icf=Iline(x*3)+shuntIline(x*3,1);

fprintf(foutput,'%3d%3d%12.4f%12.4f%12.4f%12.4f%12.4f\n',startbus(x),endbus(x),abs(Iaf),an
gle(Iaf)*180/pi,abs(Ibf),angle(Ibf)*180/pi,abs(Icf),angle(Icf)*180/pi);

```

```
Iat=-(Iline(x*3-2)-shuntIline(x*3-2,2));  
Ibt=-(Iline(x*3-1)-shuntIline(x*3-1,2));  
Ict=-(Iline(x*3)-shuntIline(x*3,2));  
  
fprintf(foutput,'%3d%3d%12.4f%12.4f%12.4f%12.4f%12.4f%12.4f\n',endbus(x),startbus(x),abs(Iat),angle(Iat)*180/pi,abs(Ibt),angle(Ibt)*180/pi,abs(Ict),angle(Ict)*180/pi);  
end  
fclose(foutput);
```

APPENDIX B

DATA OF 14 BUS SYSTEM

Generator impedances are all zero. Shunt elements impedances are all zero.

Transformer data:

Transformer. #	Connect. Bus		Connect. Type	Transformer impedance (p.u.)		
	From	To		0	1	2
1	5	6	Y -Y	j0.252	j0.252	j0.252
2	4	7	Y -Y	j0.2091	j0.2091	j0.2091
3	4	9	Y -Y	j0.5562	j0.5562	j0.5562

Line data:

Line. #	Connect. Bus		Line impedance (p.u.)		
	From	To	0	1	2
1	1	2	0.05814+j0.1775	0.01938+j0.05917	0.01938+j0.05917
2	2	3	0.1410+j0.5940	0.04699+j0.1980	0.04699+j0.1980
3	2	4	0.1743+j0.5289	0.05811+j0.1763	0.05811+j0.1763
4	1	5	0.1621+j0.6690	0.05403+j0.2230	0.05403+j0.2230
5	2	5	0.1709+j0.5217	0.05695+j0.1739	0.05695+j0.1739
6	3	4	0.2010+j0.5130	0.06701+j0.1710	0.06701+j0.1710
7	4	5	0.04005+j0.1263	0.01335+j0.04211	0.01335+j0.04211
8	7	8	j0.5286	j0.1762	j0.1762
9	7	9	j0.3300	j0.1100	j0.1100
10	9	10	0.9543+j0.2535	0.3181+j0.0845	0.3181+j0.0845
11	6	11	0.2849+j0.5967	0.09498+j0.1989	0.09498+j0.1989
12	6	12	0.3687+j0.7674	0.1229+j0.2558	0.1229+j0.2558
13	6	13	0.1985+j0.3909	0.06615+j0.1303	0.06615+j0.1303

Line. #	Connect. Bus		Line. #		
	From	To	0	1	2
14	9	14	0.3813+j0.8112	0.1271+j0.2704	0.1271+j0.2704
15	10	11	0.2462+j0.5763	0.08205+j0.1921	0.08205+j0.1921
16	12	13	0.6627+j0.5997	0.2209+j0.1999	0.2209+j0.1999
17	13	14	0.5127+j1.0440	0.1709+j0.3480	0.1709+j0.3480

Line shunt capacitances are omitted.

No mutually coupled branches.

APPENDIX C

DATA OF 30 BUS SYSTEM

Generator data:

Gen. #	Bus	Connect. Type	Generator impedance (p.u.)		
			0	1	2
1	1	Yg	j0.3	j0.1	j0.1
2	2	Yg	j0.36	j0.12	j0.12
3	5	Yg	j0.33	j0.11	j0.11
4	8	Yg	j0.45	j0.15	j0.15
5	11	Yg	j0.48	j0.16	j0.16
6	13	Yg	j0.42	j0.14	j0.14

Shunt element data:

Shunt. #	Bus	Connect. Type	Shunt impedance (p.u.)		
			0	1	2
1	10	Yg	j0.19	j0.19	j0.19
2	24	Yg	j0.043	j0.043	j0.043

Transformer data:

Transformer. #	Connect. Bus		Connect. Type	Transformer impedance (p.u.)		
	From	To		0	1	2
1	6	9	Y -Y	j0.2080	j0.2080	j0.2080
2	6	10	Yg -Yg	j0.5560	j0.5560	j0.5560
3	4	12	Y -Y	j0.2560	j0.2560	j0.2560
4	28	27	Yg -Yg	j0.3960	j0.3960	j0.3960

Line data:

Line. #	Connect. Bus		Line impedance (p.u.)		
	From	To	0	1	2
1	2	1	0.0576+j0.1725	0.0192+j0.0575	0.0192+j0.0575
2	3	1	0.1356+j0.5556	0.0452+j0.1852	0.0452+j0.1852
3	4	2	0.171+j0.5211	0.057+j0.1737	0.057+j0.1737
4	4	3	0.0396+j0.1137	0.0132+j0.0379	0.0132+j0.0379
5	5	2	0.1416+j0.5949	0.0472+j0.1983	0.0472+j0.1983
6	6	2	0.1743+j0.5289	0.0581+j0.1763	0.0581+j0.1763
7	6	4	0.0357+j0.1242	0.0119+j0.0414	0.0119+j0.0414
8	7	5	0.138+j0.348	0.046+j0.116	0.046+j0.116
9	7	6	0.0801+j0.246	0.0267+j0.082	0.0267+j0.082
10	8	6	0.036+j0.126	0.012+j0.042	0.012+j0.042
11	11	9	j0.624	j0.208	j0.208
12	10	9	j0.33	j0.11	j0.11
13	13	12	j0.42	j0.14	j0.14
14	14	12	0.3693+j0.7677	0.1231+j0.2559	0.1231+j0.2559
15	15	12	0.1986+j0.3912	0.0662+j0.1304	0.0662+j0.1304
16	16	12	0.2835+j0.5961	0.0945+j0.1987	0.0945+j0.1987
17	15	14	0.663+j0.5991	0.221+j0.1997	0.221+j0.1997
18	17	16	0.1572+j0.5769	0.0524+j0.1923	0.0524+j0.1923
19	18	15	0.3219+j0.6555	0.1073+j0.2185	0.1073+j0.2185
20	19	18	0.1917+j0.3876	0.0639+j0.1292	0.0639+j0.1292
21	20	19	0.102+j0.204	0.034+j0.068	0.034+j0.068
22	20	10	0.2808+j0.627	0.0936+j0.209	0.0936+j0.209
23	17	10	0.0972+j0.2535	0.0324+j0.0845	0.0324+j0.0845
24	21	10	0.1044+j0.2247	0.0348+j0.0749	0.0348+j0.0749
25	22	10	0.2181+j0.4497	0.0727+j0.1499	0.0727+j0.1499

Line. #	Connect. Bus		Line. #		
	From	To	0	1	2
26	22	21	0.0348+j0.0708	0.0116+j0.0236	0.0116+j0.0236
27	23	15	0.3+j0.606	0.1+j0.202	0.1+j0.202
28	24	22	0.345+j0.537	0.115+j0.179	0.115+j0.179
29	24	23	0.396+j0.81	0.132+j0.27	0.132+j0.27
30	25	24	0.5655+j0.9876	0.1885+j0.3292	0.1885+j0.3292
31	26	25	0.7632+j1.14	0.2544+j0.38	0.2544+j0.38
32	27	25	0.3279+j0.6261	0.1093+j0.2087	0.1093+j0.2087
33	29	27	0.6594+j1.2459	0.2198+j0.4153	0.2198+j0.4153
34	30	27	0.9606+j1.8081	0.3202+j0.6027	0.3202+j0.6027
35	30	29	0.7197+j1.3599	0.2399+j0.4533	0.2399+j0.4533
36	28	8	0.1908+j0.6	0.0636+j0.2	0.0636+j0.2
37	28	6	0.0507+j0.1797	0.0169+j0.0599	0.0169+j0.0599

Line. #	Connect. Bus		Line shunt capacitance (p.u.)		
	From	To	0	1	2
1	2	1	j0.0176	j0.0528	j0.0528
2	3	1	j0.0136	j0.0408	j0.0408
3	4	2	j0.0123	j0.0368	j0.0368
4	4	3	j0.0028	j0.0084	j0.0084
5	5	2	j0.0139	j0.0418	j0.0418
6	6	2	j0.0125	j0.0374	j0.0374
7	6	4	j0.003	j0.009	j0.009
8	7	5	j0.0068	j0.0204	j0.0204
9	7	6	j0.0057	j0.017	j0.017
10	8	6	j0.003	j0.009	j0.009
11	11	9	0	0	0

Line. #	Connect. Bus		Line. #		
	From	To	0	1	2
12	10	9	0	0	0
13	13	12	0	0	0
14	14	12	0	0	0
15	15	12	0	0	0
16	16	12	0	0	0
17	15	14	0	0	0
18	17	16	0	0	0
19	18	15	0	0	0
20	19	18	0	0	0
21	20	19	0	0	0
22	20	10	0	0	0
23	17	10	0	0	0
24	21	10	0	0	0
25	22	10	0	0	0
26	22	21	0	0	0
27	23	15	0	0	0
28	24	22	0	0	0
29	24	23	0	0	0
30	25	24	0	0	0
31	26	25	0	0	0
32	27	25	0	0	0
33	29	27	0	0	0
34	30	27	0	0	0
35	30	29	0	0	0
36	28	8	j0.0143	j0.0428	j0.0428
37	28	6	j0.0043	j0.013	j0.013

Mutual data:

Mutual #	Line 1		Line 2		Mutual impedance (p.u.)	
	From bus	To bus	From bus	To bus	R	X
1	24	22	25	24	0	0.4
2	17	16	20	10	0	0.5
3	29	27	30	27	0	0.8

APPENDIX D

DATA OF 30 BUS SYSTEM(WITH LOAD CURRENTS)

Generator data, shunt data and line data are the same with Appendix C.

There are no mutually coupled branches in the system.

Transformer data:

Transformer. #	Connect. Bus		Connect. Type	Transformer impedance (p.u.)		
	From	To		0	1	2
1	6	9	Yg -Yg	j0.2080	j0.2080	j0.2080
2	6	10	Yg -Y	j0.5560	j0.5560	j0.5560
3	4	12	Yg -Yg	j0.2560	j0.2560	j0.2560
4	28	27	Y -Y	j0.3960	j0.3960	j0.3960

Load data:

Load #	Bus	P (p.u.)	Q (p.u.)
1	2	21.7	12.7
2	3	2.4	1.2
3	4	7.6	1.6
4	5	94.2	19.0
5	7	22.8	10.9
6	8	30.0	30.0
7	10	5.8	2.0
8	12	11.2	7.5
9	14	6.2	1.6
10	15	8.2	2.5
11	16	3.5	1.8
12	17	9.0	5.8

Load #	Bus	P (p.u.)	Q (p.u.)
13	18	3.2	0.9
14	19	9.5	3.4
15	20	2.2	0.7
16	21	17.5	11.2
17	23	3.2	1.6
18	24	8.7	6.7
19	26	3.5	2.3
20	29	2.4	0.9
21	30	10.6	1.9

APPENDIX E

FLTOTP.DAT

This out put file is shown below.

Fault Current

Fault Bus No.	Phase-A Current		Phase-B Current		Phase-C Current	
	Abs	Angle	Abs	Angle	Abs	Angle
5	4.0014	-90.0000	0.0000	0.0000	0.0000	0.0000

APPENDIX F

SCOUTPUT.DAT

This out put file is shown below.

Results of Short Circuit Study

Post Fault Voltages

Bus No.	Phase-A Voltage		Phase-B Voltage		Phase-C Voltage	
	Abs	Angle	Abs	Angle	Abs	Angle
1	0.8661	0.0000	1.0292	-122.7345	1.0292	122.7345
2	0.5991	0.0000	1.0938	-127.7242	1.0938	127.7242
3	0.9626	0.0000	0.9906	-119.0691	0.9906	119.0691
4	0.7954	0.0000	1.0490	-124.3936	1.0490	124.3936
5	0.0400	0.0000	1.2736	-137.2502	1.2736	137.2502

Post Fault Line Currents

Bus No.	Phase-A Current		Phase-B Current		Phase-C Current	
	Abs	Angle	Abs	Angle	Abs	Angle
1						
TOBUS 2	0.7602	-90.0000	0.0390	-53.8826	0.0390	-126.1174
2						
TOBUS 1	0.8107	90.0000	0.0290	2.5058	0.0290	177.4942
TOBUS 4	1.2089	90.0000	0.0400	-39.5031	0.0400	-140.4969
TOBUS 5	1.9343	-90.0000	0.0289	-39.9684	0.0289	-140.0316
3						
TOBUS 4	0.6426	-90.0000	0.2213	-83.7106	0.2213	-96.2894
4						
TOBUS 3	0.6979	90.0000	0.1923	81.7190	0.1923	98.2810
TOBUS 2	1.1596	-90.0000	0.0217	-13.0993	0.0217	-166.9007
TOBUS 5	2.0405	-90.0000	0.0279	-42.1637	0.0279	-137.8363

5
TOBUS 2 1.9706 90.0000 0.0323 -22.7091 0.0323 -157.2909
TOBUS 4 2.0804 90.0000 0.0336 -21.5254 0.0336 -158.4746

APPENDIX G

FLTBUSOTP.DAT

This out put file is shown below.

1	0.8661	0.0000	1.0292	-122.7345	1.0292	122.7345
2	0.5991	0.0000	1.0938	-127.7242	1.0938	127.7242
3	0.9626	0.0000	0.9906	-119.0691	0.9906	119.0691
4	0.7954	0.0000	1.0490	-124.3936	1.0490	124.3936
5	0.0400	0.0000	1.2736	-137.2502	1.2736	137.2502

APPENDIX H

FLTBRANCHOTP.DAT

This out put file is shown below.

1	2	0.7602	-90.0000	0.0390	-53.8826	0.0390	-126.1174
2	1	0.8107	90.0000	0.0290	2.5058	0.0290	177.4942
3	4	0.6426	-90.0000	0.2213	-83.7106	0.2213	-96.2894
4	3	0.6979	90.0000	0.1923	81.7190	0.1923	98.2810
2	4	1.2089	90.0000	0.0400	-39.5031	0.0400	-140.4969
4	2	1.1596	-90.0000	0.0217	-13.0993	0.0217	-166.9007
2	5	1.9343	-90.0000	0.0289	-39.9684	0.0289	-140.0316
5	2	1.9706	90.0000	0.0323	-22.7091	0.0323	-157.2909
4	5	2.0405	-90.0000	0.0279	-42.1637	0.0279	-137.8363
5	4	2.0804	90.0000	0.0336	-21.5254	0.0336	-158.4746

VITA

Jun Zhu received his B.S. degree in electrical engineering from Shanghai Jiaotong University, Shanghai, China in 2000. During the following two years, he worked as a system engineer dealing with the control systems of power plants for Shanghai Automation Instrumentation Co. Ltd.. In the fall of 2002, he began work on his M.S. degree at Texas A&M University. His research areas are power transmission and state estimation.

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