POWER SYSTEM FAULT ANALYSIS TOOL DEVELOPMENT USING SEQUENCE BUS IMPEDANCE MATRIX METHOD

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***Abstract*—This document provides the summary, and the process of a fault analysis tool developed for the power system analysis course. *Characters, Footnotes, or Math in Paper Title or Abstract*. (*Abstract*)**

Keywords—Fault analysis, Bus method, Sequence network

I. Introduction

Fault analysis in ac power systems is very crucial to prevent the power grid from withstanding major power outages. The fault analysis would tell the system conditions after a fault happens. There are various types of faults. some types of faults very common while some other are rare. The type and frequency of faults depends on the location, condition of the grid and other disturbances.

II. Methodology

A. Methodology overview

The following flow chart shows the overview of the fault analysis. When the user wanted to perform a fault analysis the system should meet the necessary conditions first. For example, it should be single frequency AC system. The system should be balanced three phase system before the fault condition etc. The faults in the power systems can be categorized into two major categories. Namely, symmetrical and unsymmetrical faults. following assumptions are made to simplify the problem[ref 1].

1. Transformer leakage and winding losses are neglected. Delta-Wye phase shift is neglected.
2. Series resistance, resistance and shunt admittance are neglected.
3. Synchronous machines (& large induction motors) are modelled as constant voltage source while the armature resistance and saliency are neglected.
4. Small induction motors and loads are neglected.

Figure 2 shows the superposition scenario of a node I showing the changes of current with respect to changes in voltages when a fault occurs. If we neglect the pre-fault current (typically very low compared to fault current), the nodal equation can be written as follows.

$$Z_{bus}I = E \qquad \text{Equation 1}$$

Symmetrical faults will have only positive sequence network. For unsymmetrical faults, based on the type of fault the sequence networks can be developed. Once the sequence networks have been developed, then the Y bus (bus admittance matrix) can be constructed. Once the Y bus is constructed then, the Z bus can be found using the following equation:

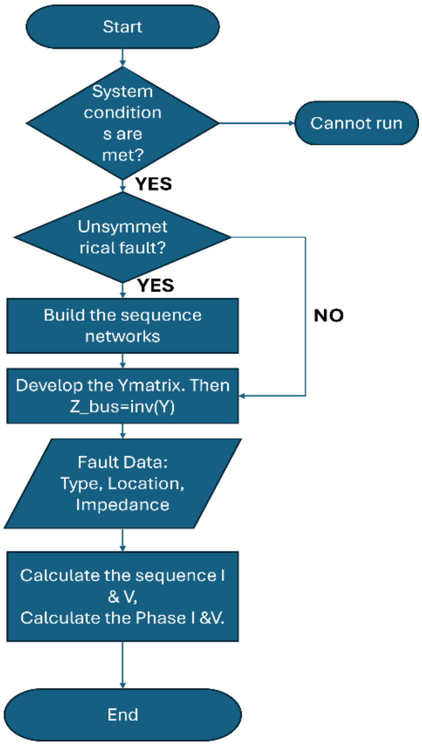

Figure II-1:Power system fault analysis overview flowchart.

$$Z_{bus} = Y_{bus}^{-1} \qquad \text{Equation 2}$$

The Equation 1 can be written in matrix format as in below[1]:

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1N} \\ Y_{21} & Y_{22} & \cdots & Y_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{N1} & Y_{N2} & \cdots & Y_{NN} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} \quad \textit{Equation 3}$$

However if we neglect the pre-fault current(which is relatively small compared to fault current typically). Then the Equation 3 can be re written (for balanced 3 phase fault) as:

$$\begin{bmatrix} \Delta V_1 \\ \vdots \\ \Delta V2 \\ \vdots \\ \Delta V_N \end{bmatrix} = \begin{bmatrix} Z_{11} & \cdots & Z_{1i} & \cdots & Z_{1N} \\ \vdots & \ddots & \vdots & ⋰ & \vdots \\ Z_{i1} & \cdots & Z_{ii} & \cdots & Z_{iN} \\ \vdots & ⋰ & \vdots & \ddots & \vdots \\ Z_{N1} & \cdots & Z_{Ni} & \cdots & Z_{NN} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ -I''_F \\ \vdots \\ 0 \end{bmatrix} \textit{Equation 4}$$

From Equation 4 the sub transient fault current can be calculated as:

$$I''_F = \frac{\Delta V_i}{Z_{ii}} \quad \text{Equation 5}$$

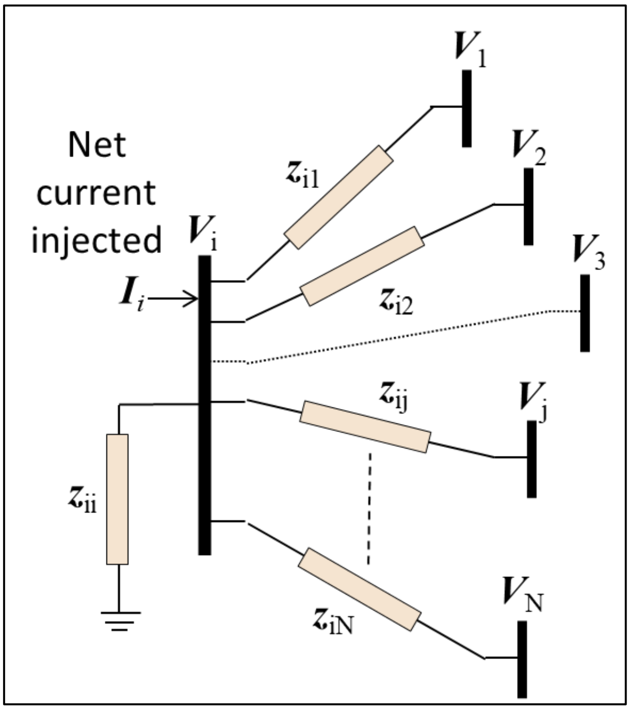

Figure 2: Superposition applied for a bus to develop a relationship between current and voltage. [Class Lecture slides].

Also, the voltage at any bus k can be written as:

$$V_k = \left(1 - \frac{Z_{kn}}{Z_{nn}}\right) V_F \text{ Equation 6}$$

The fault currents for different types of faults can be calculated using the developed sequence impedance matrix(Z_{bus}). Let's consider the sequence network for a Single line to ground (SLG) fault. The sequence network diagram can be drawn as in figure 3. The sequence currents can be calculated by using circuit theory as:

$$I_0^n = I_1^n = I_2^n = \frac{E_1}{Z_{nn}^1 + Z_{nn}^2 + Z_{nn}^0 + 3Z_F} \text{ Equation 7}$$

Similarly the sequence current for other types of faults also can be found. Also the voltage at any node can be calculated using the following equation:

$$\begin{bmatrix} V_{K-0} \\ V_{K-1} \\ V_{K-2} \end{bmatrix} = \begin{bmatrix} 0 \\ V_F \\ 0 \end{bmatrix} - \begin{bmatrix} Z_{Kn-0} & 0 & 0 \\ 0 & Z_{kn-1} & 0 \\ 0 & 0 & Z_{kn-2} \end{bmatrix} \begin{bmatrix} I_{n-0} \\ I_{n-1} \\ I_{n-2} \end{bmatrix} \text{ Equation8}$$

B. Fault happens anywhere in the line

When the fault happens in a line, a fictious bus is added at the faulted point and two lines are created between the busses where the line was connected previously and to the new fictious bus. Then the same zbus method can be used.

III. Case Studies

A. IEEE 14 bus test based fault study

The proposed algorithm was implemented using MATLAB. The user interface diagram of the developed tool is shown in the figure 4.different types fault were applied. First case study was a bus fault at bus 4 with different scenarios. Scenario 1-Balanced three phase fault, scenario 2-SLG, scenario 3-DLG,

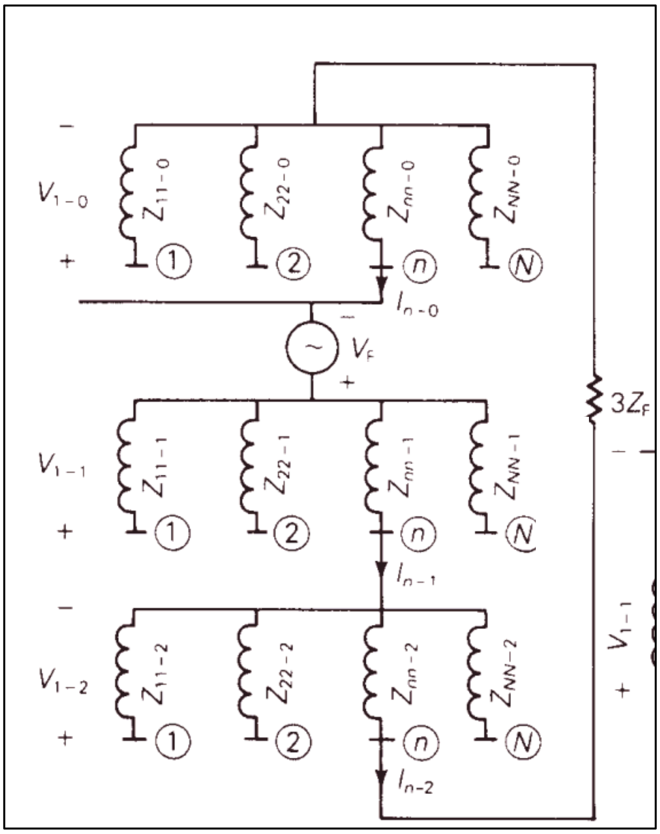

Figure3: Single Line to Ground (SLG) fault sequence network

scenario 4-LL fault. Similarly case 2 happened in the line which connects busses 3 and 4 with similar scenarios. The results were compared with power world software(commercially available state of the art tool. The fault imedance was 0 in each case. The fault location was 45% from

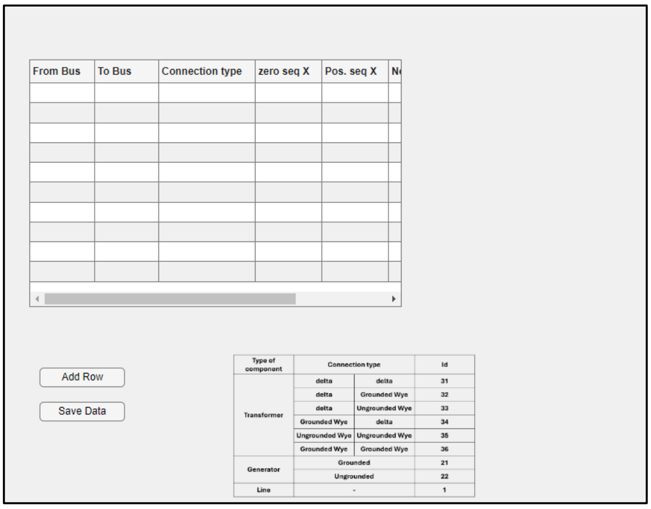

Figure 4: Screenshot of the GUI of the developed fault study tool

bus 3.

IV. Results and Discussion

The voltages of a selected faulty phase in each study together with the power world result is shown in the table 1.also the the error is calculated and plotted in the figure 5.

Table 1:The table compares the results of the developed tool with respect to the power world softwware.

Location	Fault at bus(bus 4, VF=1.0 p.u)							
	3PH balanced Phase A		SLG Phase A		LL Phase B		DLG Phase B	
	Current method	Power Wo	Current m	Power Wo	Current m	Power Wo	Current m	Power World
Bus 1	0.5375	0.46559	0.5266	0.5773	0.6832	0.62786	0.532	0.49146
Bus 2	0.4698	0.31198	0.4603	0.38212	0.6446	0.55197	0.465	0.32399
Bus 3	0.4627	0.20393	0.4597	0.25716	0.6408	0.54028	0.4612	0.20155
Bus 4	0	0	0	0	0.5	0.50884	0	0
Bus 5	0.2771	0.11657	0.2489	0.13737	0.5546	0.5031	0.2638	0.11779
Bus 6	0.7102	0.15481	0.6832	0.61562	0.7926	0.55002	0.6967	0.4691
Bus 7	0.3429	0.08783	0.3856	0.57863	0.5815	0.53349	0.3669	0.44293
Bus 8	0.4501	0.15736	0.5365	0.62708	0.634	0.55925	0.5006	0.47685
Bus 9	0.457	0.09064	0.4953	0.57758	0.6377	0.52743	0.4779	0.43805
Bus 10	0.5001	0.1011	0.5272	0.58019	0.6615	0.52669	0.5147	0.43945
Bus 11	0.6025	0.12689	0.6032	0.59566	0.7226	0.53532	0.6029	0.45149
Bus 12	0.6901	0.14831	0.6683	0.60495	0.7792	0.5416	0.6791	0.46111
Bus 13	0.6746	0.14328	0.6568	0.60022	0.769	0.53694	0.6656	0.45624
Bus 14	0.5518	0.11159	0.5656	0.57742	0.6916	0.52189	0.559	0.43777

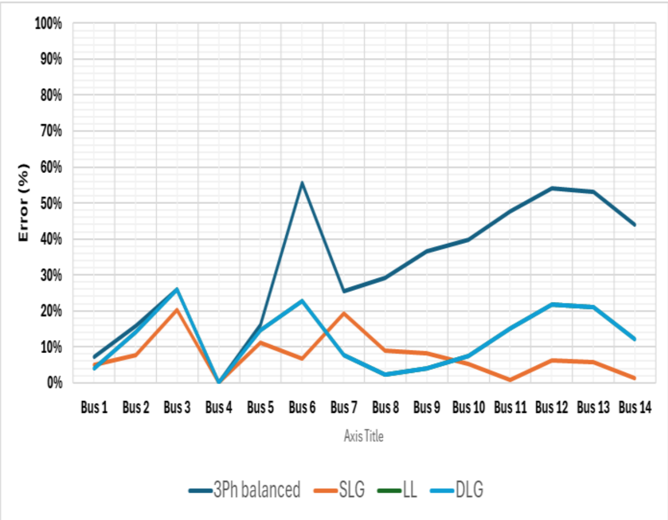

Figure5: :Error in voltages in various cases when a fault happens at bus 4 (for the developed tool compared to the power world.

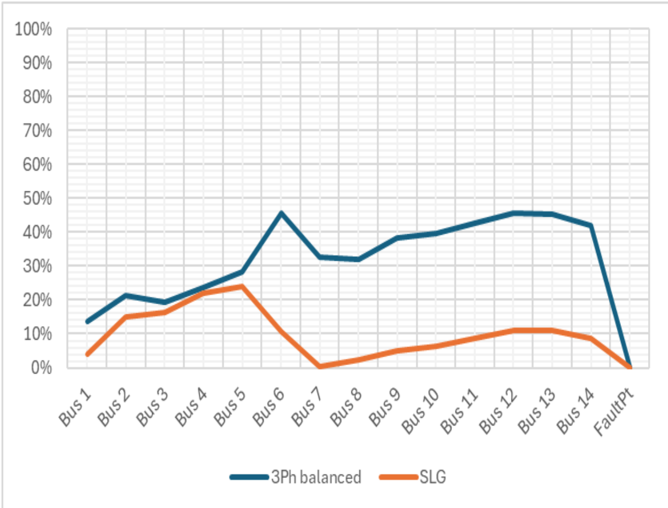

Figure6: :Error in voltages in various cases when a fault happens In the line between busses 3 &4 (for the developed tool compared to the power world.

V. CONCLUSIONS

The Fault analysis in power system plays crucial role to take proactive decisions to minimize the power system outages and unnecessary interruptions. There are various commercially available tools to solve the problem. However these tools are expensive and the proprietary of companies. In this work a fault analysis tool was developed using MATLAB software. The developed tool could handle when a fault happens at a bus or anywhere in the line. Developped tool results were compared with power world software. However in certain scenarios the error was high compared to the power world answers. This could be potentially due to some variable assignment issue or our models assumptions.

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Appendix 1:
The test system data

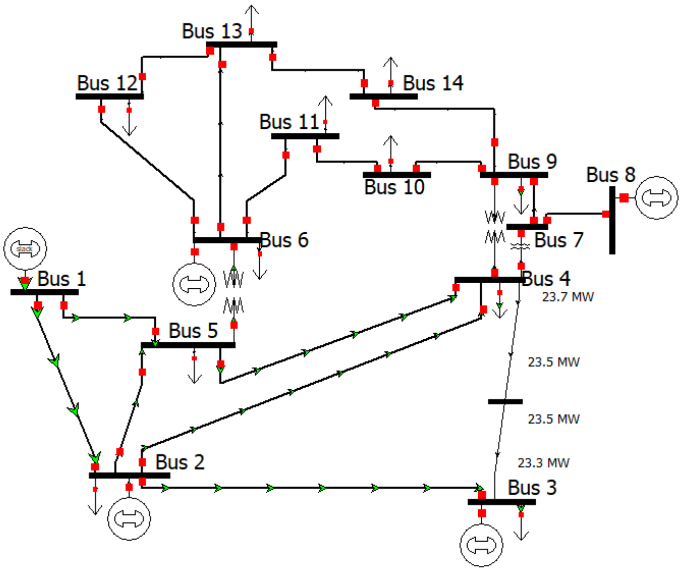

Table 2 - Transmission line characteristics of IEEE 14-bus system

Line		R [pu/m]	X [pu/m]	B [pu/m]
From Bus	To Bus			
1	2	1.94E-07	5.92E-07	5.28E-07
1	5	5.40E-07	2.23E-06	4.92E-07
2	3	4.70E-07	1.98E-06	4.38E-07
2	4	5.81E-07	1.76E-06	3.40E-07
2	5	5.70E-07	1.74E-06	3.46E-07
3	4	6.70E-07	1.71E-06	1.28E-07
4	5	1.34E-07	4.21E-07	1.00E-09
6	11	9.50E-07	1.99E-06	1.00E-09
6	12	1.23E-06	2.56E-06	1.00E-09
6	13	6.62E-07	1.30E-06	1.00E-09
7	8	1.00E-09	1.76E-06	1.00E-09
7	9	1.00E-09	1.10E-06	1.00E-09
9	10	3.18E-07	8.45E-07	1.00E-09
9	14	1.27E-06	2.70E-06	1.00E-09
10	11	8.21E-07	1.92E-06	1.00E-09
12	13	2.21E-06	2.00E-06	1.00E-09
13	14	1.71E-06	3.48E-06	1.00E-09

Results Screenshot

```
How many buses are in the system? ... ... 14
is the fault at a bus (0) or in the line(1) ? ... ... 0
What is the faulted bus? ... ... 4
What is the fault voltage ? ... ... 1
What is the fault impedance? ... ... 0
What is the fault type? ...answer should be a 4 digit number faulted phase will be 1 nonfaulted phase will be 0. The digit format is ABCG(Phases A,B,C & Ground). EG.: 3Phase to Ground:- 1111 , Phase B to Ground fau
3 phase fault

F_Current =

   0.0000 + 0.0000i   0.0000 -18.6540i   0.0000 + 0.0000i


Table =

  14×4 table
```

bus	Va	Vb	Vc
1	0.53754	0.53754	0.53754
2	0.46983	0.46983	0.46983
3	0.46272	0.46272	0.46272
4	1.1102e-16	1.1102e-16	1.1102e-16
5	0.27711	0.27711	0.27711
6	0.71019	0.71019	0.71019
7	0.34291	0.34291	0.34291
8	0.45013	0.45013	0.45013
9	0.45702	0.45702	0.45702
10	0.50011	0.50011	0.50011
11	0.60246	0.60246	0.60246
12	0.69009	0.69009	0.69009
13	0.67462	0.67462	0.67462
14	0.55178	0.55178	0.55178


```
3 phase fault

F_Current =

   0.0000 + 0.0000i   0.0000 -18.6540i   0.0000 + 0.0000i


Table =

  14×4 table
```

bus	Va	Vb	Vc
1	0.53754	0.53754	0.53754
2	0.46983	0.46983	0.46983
3	0.46272	0.46272	0.46272
4	1.1102e-16	1.1102e-16	1.1102e-16
5	0.27711	0.27711	0.27711
6	0.71019	0.71019	0.71019
7	0.34291	0.34291	0.34291
8	0.45013	0.45013	0.45013
9	0.45702	0.45702	0.45702
10	0.50011	0.50011	0.50011
11	0.60246	0.60246	0.60246
12	0.69009	0.69009	0.69009
13	0.67462	0.67462	0.67462
14	0.55178	0.55178	0.55178

SLG

F_Current =

0.0000 - 3.8871i   0.0000 - 3.8871i   0.0000 - 3.8871i

Table =

15×4 table

bus	Va	Vb	Vc
1	0.72688	0.99968	0.99968
2	0.67126	0.99888	0.99888
3	0.36218	0.9971	0.9971
4	0.52992	0.99355	0.99355
5	0.63041	1.0023	1.0023
6	0.8462	1.0049	1.0049
7	0.71038	0.98607	0.98607
8	0.78193	0.97697	0.97697
9	0.7612	0.98785	0.98785
10	0.77566	0.99069	0.99069
11	0.81003	0.99753	0.99753
12	0.83945	1.0035	1.0035
13	0.83426	1.0024	1.0024
14	0.79301	0.99412	0.99412
15	1.1102e-16	0.99532	0.99532

Appendix 3:Matlab Code:

```
%% Get the user input
clear all
bus = input('How many buses are in the system? ... ... ');
location = input('is the fault at a bus (0) or in the line(1) ? ... ... ');
if location == 0
F_bus = input('What is the faulted bus? ... ... ');
else
  In_bus = input('Enter two numbers(connected busses)  separated by space (enter small numer first): ', 's');
  busses= str2double(strsplit(In_bus));
   Z_loc = input(['Enter how far (in %) the fault is from bus ', num2str(busses(1)),': ']);Z_loc=Z_loc/100;
end
V_F = input('What is the fault voltage ? ... ... ');
Z_F = input('What is the fault impedance? ... ... ');
F_Type=input('What is the fault type? ...answer should be a 4 digit number faulted phase will be 1 nonfaulted phase will be 0. The digit format is ABCG(Phases A,B,C & Ground). EG.: 3Phase to Ground:- 1111 , Phase B to Ground fault:- 0101 ', 's');
        app=app2
       waitfor(app);
       T1= tableDataFromApp


%% Temp data
Define data for each column
FromBus   = T1(:,1);
ToBus     = T1(:,2);
ConnType  = T1(:,3);
ZeroSeqX  = T1(:,4);
PosSeqX   = T1(:,5);
NegSeqX   = T1(:,6);
NeutralX  = T1(:,7);

%% Uncomment this data to run for the ieee test (14 bus) system
% FromBus   = [1;	1;	2;	2;	2;	3;	4;	4;	4;	5;	6;	6;
	6;	7;	7;	9;	9;	10;	12;	13; 4;4;5; 1;2;3;6;8];
% ToBus     = [2;	5;	3;	4;	5;	4;	5;	7;	9;	6;	11;	12;
	13;	8;	9;	10;	14;	11;	13;	14; 8;9;6; 0;0;0;0;0];
% ConnType  = [1;	1;	1;	1;	1;	1;	1;	1;	1;	1;	1;	1;
	1;	1;	1;	1;	1;	1;	1;	1;	 34;34;36; 0;0;0;0;0];
% ZeroSeqX  = [0.06;	0.22;	0.20;	0.18;	0.17;	0.17;	0.04;	0.21;	0.56;	0.25;	0.20;	0.26;
	0.13;	0.18;	0.11;	0.08;	0.27;	0.19;	0.20;	0.35;	0.209;0.556;0.252; 0.2;0.2;0.2;0.2;0.2];
% PosSeqX   = [0.06;	0.22;	0.20;	0.18;	0.17;	0.17;	0.04;	0.21;	0.56;	0.25;	0.20;	0.26;
	0.13;	0.18;	0.11;	0.08;	0.27;	0.19;	0.20;	0.35;	0.209;0.556;0.252; 0.2;0.2;0.2;0.2;0.2];
% NegSeqX   = [0.06;	0.22;	0.20;	0.18;	0.17;	0.17;	0.04;	0.21;	0.56;	0.25;	0.20;	0.26;
	0.13;	0.18;	0.11;	0.08;	0.27;	0.19;	0.20;	0.35;	0.209;0.556;0.252; 0.2;0.2;0.2;0.2;0.2];
% NeutralX  = [0;	0;	0;	0;	0;	0;	0;	0;	0;	0;	0;	0;
	0;	0;	0;	0;	0;	0;	0;		0;0;0;0; 0;0;0;0;0];

   if location == 1
      bus=bus+1;F_bus=bus;
      rowToRemove=find(FromBus == busses(1) & ToBus == busses(2));  index1=rowToRemove;


ZeroSeqXR1=Z_loc*ZeroSeqX(index1);PosSeqXR1=Z_loc*PosSeqX(index1);NegSeqXR1=Z_loc*NegSeqX(index1);
NeutralXR1=Z_loc*NeutralX(index1);
   ZeroSeqXR2=(1-Z_loc)*ZeroSeqX(index1);PosSeqXR2=(1-Z_loc)*PosSeqX(index1);NegSeqXR2=(1-
Z_loc)*NegSeqX(index1); NeutralXR2=(1-Z_loc)*NeutralX(index1);
   end
% Create table

T = table(FromBus, ToBus, ConnType, ZeroSeqX, PosSeqX, NegSeqX, NeutralX);
```

```
Y0=zeros(bus,bus);Y1=zeros(bus,bus);Y2=zeros(bus,bus);

if location == 1
   %Y0=zeros(bus-2,bus-2);Y1=zeros(bus-2,bus-2);Y2=zeros(bus-2,bus-2);
T(rowToRemove, :) = [];
newRow1={busses(1), bus, 1, ZeroSeqXR1, PosSeqXR1, NegSeqXR1, NeutralXR1};
newRow2={bus, busses(2), 1, ZeroSeqXR1, PosSeqXR1, NegSeqXR1, NeutralXR1};
newRow1_Table=cell2table(newRow1,'VariableNames',T.Properties.VariableNames);
newRow2_Table=cell2table(newRow2,'VariableNames',T.Properties.VariableNames);
T=[T;newRow1_Table;newRow2_Table];
end
%% ZBus Construction
   % Zero sequence
   for i=1:height(T)
      comp=T{i,3} ;% Check for the component type
      if comp==1 % If line
         FB=(T{i,1}); TB=(T{i,2});
         Y0(FB,TB)=-1/T{i,4};Y0(TB,FB)=Y0(FB,TB);
         Y0(FB,FB)=Y0(FB,FB)+1/T{i,4};Y0(TB,TB)=Y0(TB,TB)+1/T{i,4};
         %%%%%%%%%%%%%%%%%%%%%%% positive seq
         Y1(FB,TB)=-1/T{i,5};Y1(TB,FB)=Y1(FB,TB);
         Y1(FB,FB)=Y1(FB,FB)+1/T{i,5};Y1(TB,TB)=Y1(TB,TB)+1/T{i,5};
         %%%%%%%%%%%%%%%%%%%% Neg Seq
         Y2(FB,TB)=-1/T{i,6};Y2(TB,FB)=Y2(FB,TB);
         Y2(FB,FB)=Y2(FB,FB)+1/T{i,6};Y2(TB,TB)=Y2(TB,TB)+1/T{i,6};
      elseif comp>30   %check whether= a transformer
         FB=(T{i,1}); TB=(T{i,2});X=(T{i,4});Xn=0;
         [Zbetween,Zself1,Zself2]=TrImp(comp,FB,TB,X,Xn);
         Y0(FB,TB)=-1/Zbetween;Y0(TB,FB)=Y0(FB,TB);
         Y0(FB,FB)=Y0(FB,FB)+1/Zself1;Y0(TB,TB)=Y0(TB,TB)+1/Zself2;
        %%%%%%%%%%%%%%%%%%%%%%% positive seq
         Y1(FB,TB)=-1/T{i,5};Y1(TB,FB)=Y1(FB,TB);
         Y1(FB,FB)=Y1(FB,FB)+1/T{i,5};Y1(TB,TB)=Y1(TB,TB)+1/T{i,5};
         %%%%%%%%%%%%%%%%%%%% Neg Seq
         Y2(FB,TB)=-1/T{i,4};Y2(TB,FB)=Y2(FB,TB);
         Y2(FB,FB)=Y2(FB,FB)+1/T{i,6};Y2(TB,TB)=Y2(TB,TB)+1/T{i,6};
      else
         CB=(T{i,1});%gen connected bus
         Y0(CB,CB)=Y0(CB,CB)+1/T{i,4};
         Y1(CB,CB)=Y1(CB,CB)+1/T{i,5};
         Y2(CB,CB)=Y2(CB,CB)+1/T{i,6};
      end
   end
Z0=j*inv(Y0);Z1=j*inv(Y1);Z2=j*inv(Y2);


%% Fault Analysis
   F_Type_B = str2double(cellstr(F_Type.')).';
   Bus=F_bus;Z0n=Z0(Bus,Bus);Z1n=Z1(Bus,Bus);Z2n=Z2(Bus,Bus);
[F_Current]=Fault_Analysis(F_Type_B,V_F,F_bus,Bus,Z0n,Z1n,Z2n,Z_F);
Table=table();
a=exp(1j*2*pi/3);
A=[1,1,1;1,a^2,a;1,a,a^2];

for k=1:bus
   Bus=k;
Z0kn=Z0(k,F_bus);Z1kn=Z1(k,F_bus);Z2kn=Z2(k,F_bus);
F_Voltage=[0,V_F,0]'+[Z0kn,0,0;0,Z1kn,0;0,0,Z2kn]*F_Current';
F_Voltage=A*F_Voltage;F_Voltage=abs(F_Voltage);
newRow = array2table(F_Voltage', 'VariableNames', {'Va','Vb','Vc'});
newRow.bus=k;
newRow=newRow(:,{'bus','Va','Vb','Vc'});
```

```
Table=[Table;newRow];
end

F_Current

Table


%% Functions
function[Zbetween,Zself1,Zself2]=TrImp(typeofTr,Bus1,Bus2,X,Xn)
if typeofTr==31
   Zbetween=inf;Zself1=inf;Zself2=inf;
elseif typeofTr==32
   Zbetween=inf;Zself1=inf;Zself2=X;
elseif typeofTr==33
   Zbetween=0;Zself1=0;Zself2=0;

elseif typeofTr==34
   Zbetween=inf;Zself1=X;Zself2=inf;
elseif typeofTr==35
   Zbetween=inf;Zself1=inf;Zself2=inf;
else
   Zbetween=X;Zself1=inf;Zself2=inf;
end
end

%%
function[F_Current]=Fault_Analysis(F_Type_B,V_F,F_bus,Bus,Z0n,Z1n,Z2n,ZF)
 numOnes = sum(F_Type_B);
     if numOnes == 4
       disp('3 phase fault');
       I0=0;I2=0;I1=V_F/(Z1n);
           elseif numOnes == 3
               disp('LLG');
               I1=V_F/(Z0n+Z1n+Z2n)
               a=Z2n*(Z0n+3*ZF);b=(Z0n+3*ZF+Z2n);
               I1=V_F/(Z1n+(a/b))
               I2=-I1*((Z0n+3*ZF)/(Z0n+3*ZF+Z2n))
               I0=-I1*((Z2n)/(Z0n+3*ZF+Z2n));

           elseif numOnes == 2
                if F_Type_B(4)==1
                   disp('SLG');
                   I1=V_F/(Z0n+Z1n+Z2n+ZF);I0=I1;I2=I0;
                else
                    disp('LL');
                   I1=V_F/(Z1n+Z2n+ZF);I2=-I1;I0=0;
                end

     end
     F_Current=[I0,I1,I2];

end
```