AUTOMATIC CONTINGENCY SELECTION

Ejebe/Wollenberg Method vs. PSS/E Method

EE 8725 Project

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Abstract

- Paper by G.C. Ejebe and B.F. Wollenberg submitted to the IEEE Transactions on Power Apparatus and Systems in 1979.
  - A fast technique for the automatic ranking and selection of contingency cases for a power system contingency analysis study.
  - Contingencies are ranked according to their expected severity as reflected in voltage level degradation and circuit overloads.
- Compared to PSS/E method, defined in a paper by T.A. Mikolinnas and B.F. Wollenberg completed in 1981.
  - Method seeks to improve Ejebe/Wollenberg contingency selection algorithm
- Complete contingency ranking on test case using both methods

Presentation Summary

- Introduction to Contingency Selection
- Ejebe/Wollenberg Method
- PSSE Method (Mikolinnas/Wollenberg)
- Test Case
- Conclusions

INTRODUCTION TO CONTINGENCY SELECTION

Purpose of Contingency Selection

- To identify critical contingencies from all possible contingencies
- To create system reliability by making system changes or upgrades to reduce the impact of the most critical contingencies
  - Protective device settings
  - Add backup generation
  - Line/transformer upgrades
  - Backup line for load switching during outage

Contingency Selection in Planning Studies

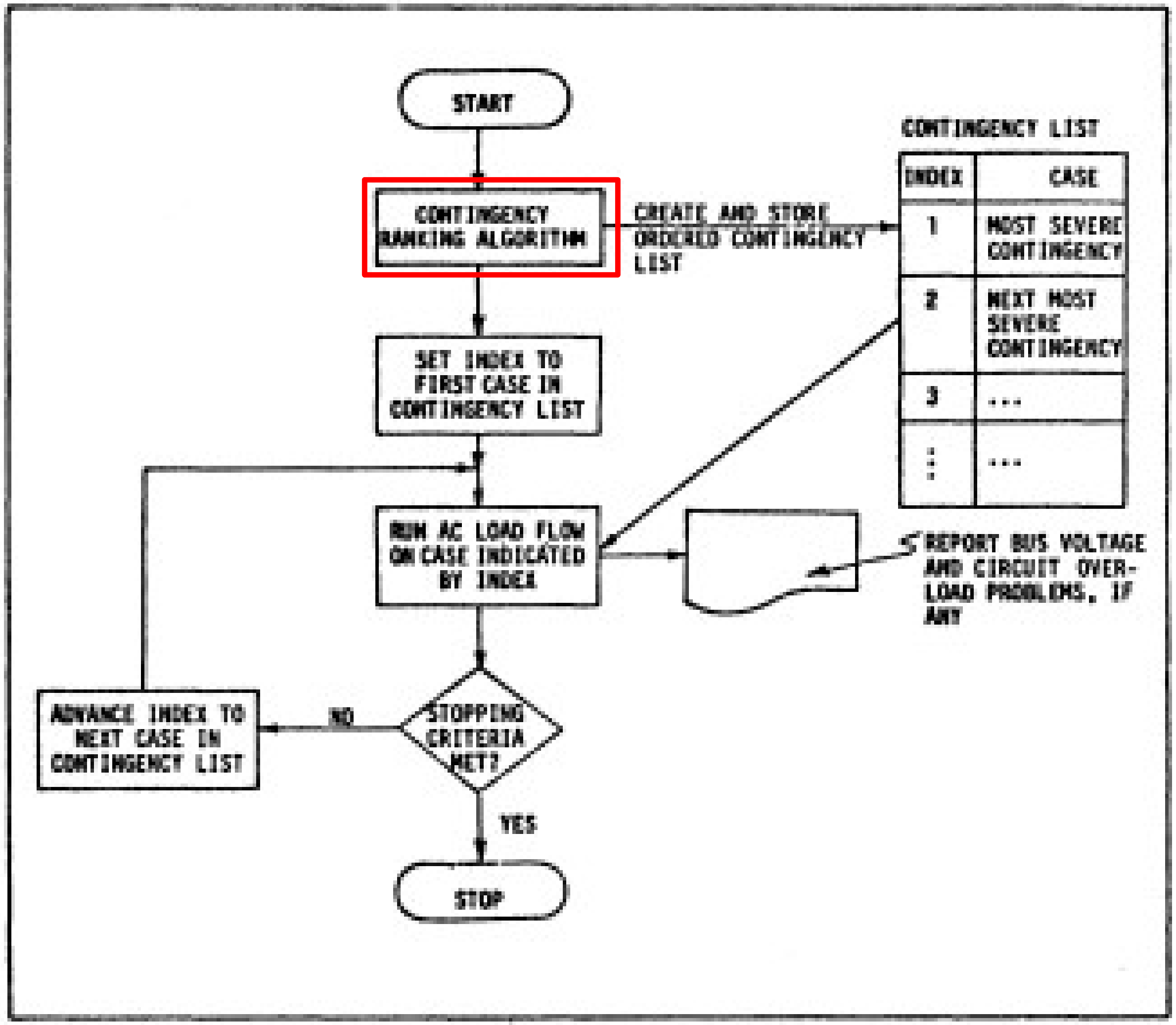
- Often involves testing of all possible combinations of outages
  - Even small systems can have many possibilities
- Contingency selection algorithms can be used to minimize the amount of cases that need to be looked at
- Can run algorithm to find worst case single outages, then take those lines out and run to find the worst case (n-2) outages

Real Time Contingency Selection

- Cases are complex because a single line outage may cause multiple circuit breaker options and other system changes due to system protection
- User only wants the one contingency that will cause the most issues for the system, not multiple contingencies
- Results are needed as quickly as possible

EJEBE/WOLLENBERG METHOD

Adaptive Contingency Processor



1. Index for Voltage Analysis

$$PI_V = \sum_{i=1}^{NB} \frac{W_{V_i}}{2n} \left(\frac{|V_i| - |V_i^{sp}|}{\Delta V_i^{Lim}} \right)^{2n}$$

where:

$|V_i|$ is the voltage magnitude at bus i

$|V_i^{sp}|$ is the specified (rated) voltage magnitude at bus i

ΔV_i^{Lim} is the voltage deviation limit, above which voltage deviations are unacceptable

n is the exponent of penalty function (n = 1 is preferred)

NB is the number of buses in the system

W_{V_i} is the real non-negative weighting factor

1. Index for Voltage Analysis

- Recall: ΔV_i^{Lim} is the voltage deviation limit, above which voltage deviations are unacceptable
  - If voltage is outside this limit, PI_V will be large
  - If voltage is within this limit, PI_V will be small
- Thus PI_V allows us to rank contingencies based on severity using the voltage limits on the system buses involved

- Problem: bus voltages depend on reactive power flow, which is not considered in this index
  - What if generators are driven to their reactive power (Q) limits?
- Solution: revised index to include reactive power constraints

1. Index for Voltage Analysis

$$PI_{VQ} = \sum_{i=1}^{NB} \frac{W_{V_i}}{2n} \left(\frac{|V_i| - |V_i^{sp}|}{\Delta V_i^{Lim}} \right)^{2n} + \sum_{i=1}^{NG} \frac{W_{Q_i}}{2n} \left(\frac{Q_i}{Q_i^{Max}} \right)^{2n}$$

where:

$|V_i|$ is the voltage magnitude at bus i

$|V_i^{sp}|$ is the specified (rated) voltage magnitude at bus i

ΔV_i^{Lim} is the voltage deviation limit, above which voltage deviations are unacceptable

n is the exponent of penalty function (n = 1 is preferred)

NB is the number of buses in the system

W_{V_i} is the real non-negative weighting factor

Q_i is the reactive power produced at bus i

Q_i^{Max} is the reactive power production limit

NG is the number of reactive power production units

W_{Q_i} is the real non-negative weighting factor (set to 0 if not required)

2. Index for Power Flow Analysis

$$PI_{MW} = \sum_{l=1}^{NL} \frac{W_l}{2n} \left(\frac{P_l}{P_l^{Lim}} \right)^{2n}$$

where:

P_l is the megawatt flow of line *l* (calculated by the DC load flow model)

P_l^{Lim} is the megawatt capacity of line *l*

NL is the number of lines in the system

n is the specified exponent (n = 1 is preferred)

W_l is the real non-negative weighting coefficient; may be used to reflect importance of some lines

2. Index for Power Flow Analysis

- Recall: P_l^{Lim} is the line capacity limit
  - If line flows exceed their limits, PI_{MW} will be large
  - If line flows are within their limits, PI_{MW} will be small
- The absolute value of PI_{MW} for each outage is not significant
  - Ranking is done by comparing PI_{MW} for each outage and looking at the relative change
  - This is done by looking at the results of the DC load flow solution before the outage (base case) and after the outage (adjoint power system)

Contingency List Options

Option	Performance Index	Outage Type
1	PI_V or PI_{VQ}	Line and/or generator outages
2	PI_{MW}	Line outages
3	PI_{MW}	Generator outages (Allows for redispatch of the lost generation)

- May focus on only one option, or repeat procedure to look at all three

Method Overview

Advantages

- Is able to rank all possible system contingencies
- Can be completed very quickly
- Gives planners a list of "worst case" contingencies to look at

Disadvantages

- Misrankings can occur
- Only identifies when overloads occur, so heavily loaded lines do not affect PI (masking)
- Gradient function of Tellegen's theorem is inaccurate because it uses a linear projection for a non-linear function

PSS/E CONTINGENCY SELECTION METHOD

Method Overview

- "An Advanced Contingency Selection Algorithm"
  - Mikolinnas & Wollenberg (1981)
- Algorithm ranks contingencies at a fraction of the calculation time of doing a complete DC load flow of each case
- Approach was to reduce the number of contingencies to look at rather than reducing the computation time for each one
- Sought to improve the algorithm identified by Ejebe/Wollenberg method in 1979

Method Comparison

Ejebe/Wollenberg

- Uses performance indices for real power, reactive power, and voltage
- Gradient technique (Tellegen's theorem)
- Capture rates* of 0.6-0.8

Mikolinnas/Wollenberg

- Uses performance indices for real power flow only
- Infinite Taylor series expansion
- Capture rates* of 0.9-1.0

**Capture rate is the fraction of the worst N contingencies appearing in the first N contingency rankings (1 is optimal).*

Performance Index

$$\Delta PI = \frac{\tau_k P_k^2}{(1 - B_k \chi_k)^2} + \frac{2\widehat{\theta_k} P_k}{(1 - B_k \chi_k)} - W_k \left(\frac{P_k}{\overline{\overline{P_k}}}\right)^2 \frac{1}{(1 - B_k \chi_k)^2}$$

where:

B_k is the susceptance of circuit k

P_k is the base case real power flow on circuit k

$\overline{P_k}$ is the real power flow limit on circuit k

W_k is the weighting factor of circuit k

$\chi_k = X_{ii} + X_{jj} - 2X_{ij}$ where X_{ij} is the (i,j)th element of the system X matrix

$\tau_k = T_{ii} + T_{jj} - 2T_{ij}$ where X_{ij} is the (i,j)th element of the NxN square matrix T

$\widehat{\theta_k}$ is evaluated using a single additional DC load flow solution

Example Case Results

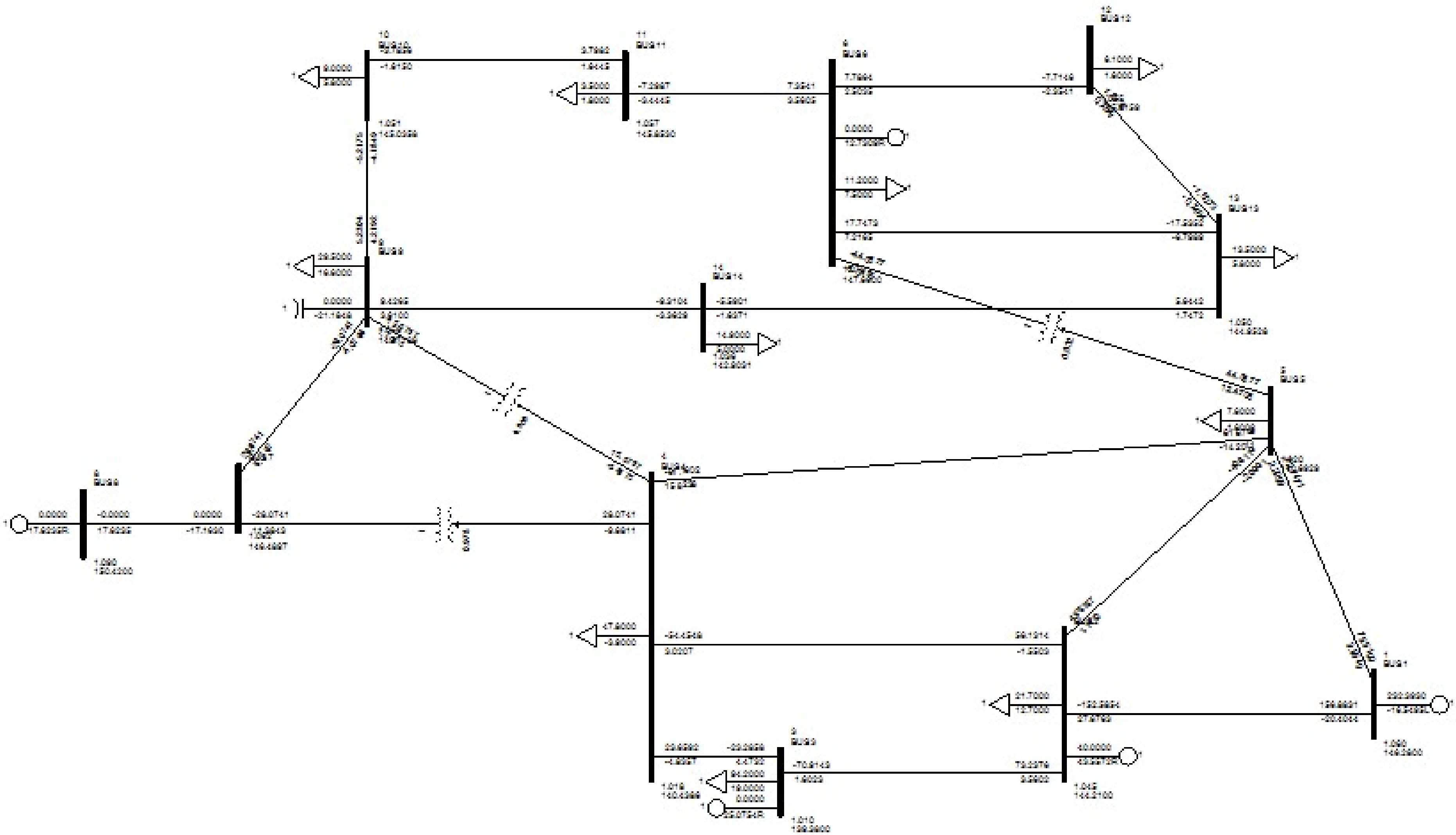
- Case studied was a 239 bus utility system model with 228 possible single contingencies
- Effectiveness profile shows nearly perfect ranking as compared to detailed ranking using DC load flows
- Had capture rate of nearly 1.000
- Masking only occurred for two cases
- Overall, example case showed ranking was much improved over previous method

TEST CASE

IEEE 14 Bus Power Flow Test Case

- Portion of the AEP system from 1962
- Consists of:
  - 14 buses (all 138 kV)
  - 5 generators (including one swing generator)
  - 17 lines (highest loaded line in base case is 158.2045 MVA)
  - 3 transformers (highest loaded in base case is 45.5497 MVA)
  - 11 loads
  - 1 fixed shunt
- Modifications to original test case data:
  - Line and transformer ratings were added manually
  - Line susceptance was added for lines where B=0
  - Transformer magnetizing B was added
- Case data courtesy of *https://www.ee.washington.edu/research/pstca/pf14/pg_tca14bus.htm*

IEEE 14 Bus Power Flow Test Case



Ejebe/Wollenberg Method (PI_{MW})

- Looked at the PI_{MW} method only
- Used PSSE to get output data such as line flow, line limits, and phase angles at surrounding buses from load flow case
- Calculated PI_{MW} and ΔPI_{MW} for each contingency
- Ranked contingencies in order of ΔPI_{MW}

Ejebe/Wollenberg Method (PI_{MW})

```
import psspy
import os

name = 'Bus Data (Xfmr 5-6 OOS).txt'
B = open(name,'w')
B.write('Bus,Vi,Visp,Qi,Qimax'+'\n')
B.close()

#Bus at which the data will be recorded
buses = [1,2,3,4,5,6,7,8,9,10,11,12,13,14]
basekv = 138.0

for bus in buses:

    Vi = psspy.busdat(bus,'PU')
    Visp = psspy.busdat(bus,'BASE')
    Qi = psspy.macdat(bus,'1','Q')
    Qimax = psspy.macdat(bus,'1','QMAX')

    B = open(name,'a')
    B.write(str(bus) + ',' + str(Vi[1]) + ',' + str(Visp[1]/basekv) + ',' + str(Qi[1])+ ',' + str(Qimax[1])+ '\n')
    B.close()


name = 'Branch Data (Xfmr 5-6 OOS).txt'
C = open(name,'w')
C.write('To Bus, From Bus,Pl, Pllim, Phasei, Phasej, Susc'+'\n')
C.close()

#Lines over which the data will be recorded
branches = [[1,2],[1,5],[2,3],[2,4],[2,5],[3,4],[4,5],[6,11],[6,12],[6,13],[7,8],[7,9],[9,10],[9,14],[10,11],[12,13],[13,14]]


x = len(branches)

while x > 0:

    PLine = psspy.brnmsc(branches[x-1][0], branches[x-1][1], '1', 'P')
    PLineLimit = psspy.brndat(branches[x-1][0], branches[x-1][1], '1', 'RATEA')
    Phasei = psspy.busdat(branches[x-1][0],'ANGLE')
    Phasej = psspy.busdat(branches[x-1][1],'ANGLE')
    Susc = psspy.brndat(branches[x-1][0], branches[x-1][1], '1', 'CHARG')

    C = open(name,'a')
    C.write(str(branches[x-1][0]) + ',' + str(branches[x-1][1]) + ',' + str(float(PLine[1])) + ',' + str(float(PLineLimit[1]))+ ',' + str(Phasei[1]) + ',' + str(Phasej[1]) + ',' + str(Susc[1]) + '\n')
    C.close()

    x -= 1
```

Python Script for Collecting Power Flow Data From Load Flow Model

Ejebe/Wollenberg Method (PI_{MW})

	A	B	C	D	E	F	G
1	To Bus	From Bus	PI	PIlim	Phasei	Phasej	Susc
2	13	14	5.380337	30	-0.26377	-0.27993	0.001
3	12	13	1.528291	30	-0.2621	-0.26377	0.001
4	10	11	-3.47393	30	-0.26502	-0.25851	0.001
5	9	14	9.695351	30	-0.26162	-0.27993	0.001
6	9	10	5.537261	15	-0.26162	-0.26502	0.07
7	7	9	28.42481	80	-0.23406	-0.26162	0.001
8	6	13	17.55717	30	-0.24704	-0.26377	0.001
9	6	12	7.696614	30	-0.24704	-0.2621	0.001
10	6	11	7.024922	30	-0.24704	-0.25851	0.001
11	4	5	-61.7659	100	-0.18058	-0.15346	0.05
12	3	4	-23.3785	60	-0.22182	-0.18058	0.0128
13	2	5	41.44781	60	-0.0869	-0.15346	0.0346
14	2	4	56.19562	100	-0.0869	-0.18058	0.034
15	2	3	73.13238	100	-0.0869	-0.22182	0.0438
16	1	5	75.58489	80	0	-0.15346	0.0492
17	1	2	156.7667	250	0	-0.0869	0.0528

	A	B	C	D	E	F	G
1	To Bus	From Bus	PI	PIlim	Phasei	Phasej	Susc
2	4	9	16.34356	50	-0.18058	-0.26162	-0.005
3	4	7	30.21959	50	-0.18058	-0.23406	-0.005
4	5	6	45.65645	50	-0.15346	-0.24704	-0.005

Load Flow Model Output Data (Excel Format)

Ejebe/Wollenberg Method (PI_{MW})

```
%GET INPUT DATA FOR PI FROM LOAD FLOW CASE SOLUTION

%read Excel files containing PSSE load flow data
%future improvement - make generic for other cases
branchfile = 'Branch Data (Base Case Plus Contingencies).xlsx';
[branchdata]=xlsread(branchfile,'BaseCase');
[branchdata_1to2OOS]=xlsread(branchfile,'1-2');
[branchdata_1to5OOS]=xlsread(branchfile,'1-5');
[branchdata_2to3OOS]=xlsread(branchfile,'2-3');
[branchdata_2to4OOS]=xlsread(branchfile,'2-4');
[branchdata_2to5OOS]=xlsread(branchfile,'2-5');
[branchdata_3to4OOS]=xlsread(branchfile,'3-4');
[branchdata_4to5OOS]=xlsread(branchfile,'4-5');
```

Matlab Code to Extract Load Flow Data from Excel Files

Ejebe/Wollenberg Method (PI_{MW})

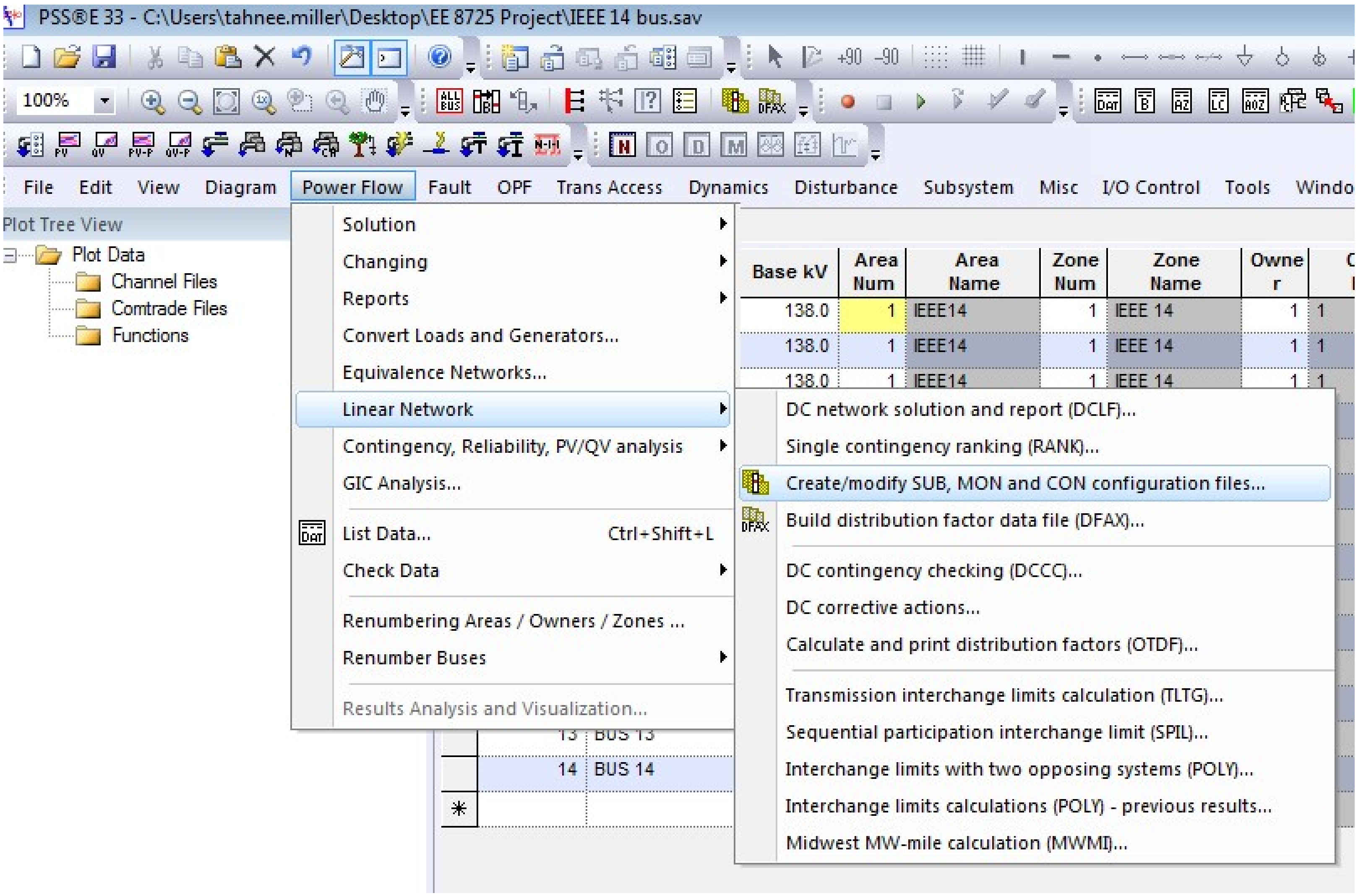
```
%CALCULATE PIMW

print_flag = 1;

%get input data from load flow solution results in Excel
getinputwithcontingencies;

%set exponent and weighting factors to unity
n=1;
W1=1;

%initialize PIMW array to have NL rows and 4 columns
PIMW = zeros(NL,4);

%initialize temporary arrays for summation data storage
PIMWtemp = zeros(1,NL);
deltaPIMWtemp = zeros(1,NL);

%calculate PIMW and deltaPIMW and put into PIMW array along with line IDs
```

Matlab Code to Calculate Performance Index

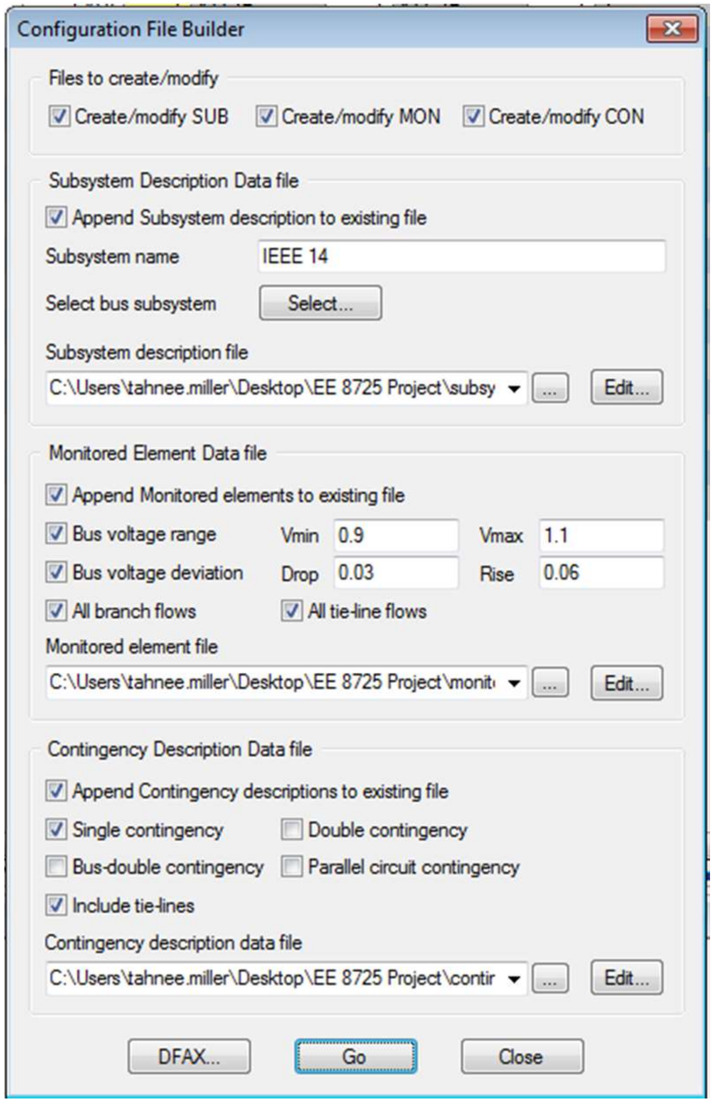
Ejebe/Wollenberg Method (PI_{MW})

Branch			Ejebe/Wollenberg Method Ranking		
From Bus	To Bus	Branch Type	PI_{MW}	ΔPI_{MW}	Ranking
1	2	Line	8.198905	0.014781	1
1	5	Line	3.158477	0.005078	2
2	3	Line	4.848942	0.004928	3
2	4	Line	3.446403	0.003801	4
2	5	Line	2.610697	0.003632	5
3	4	Line	2.551574	0.003496	6
4	5	Line	2.955756	0.003443	7
6	11	Line	2.969232	0.003306	10
6	12	Line	2.818355	0.003303	12
6	13	Line	2.850881	0.003314	8
7	8	Line	Excluded – Swing Generator		
7	9	Line	3.106981	0.003287	16
9	10	Line	2.695153	0.003304	11
9	14	Line	3.14238	0.003306	9
10	11	Line	2.771831	0.003303	14
12	13	Line	2.681364	0.0033	15
13	14	Line	2.630869	0.003303	13
5	6	Transformer	6.472832	0.00325	18
4	7	Transformer	3.022576	0.003243	19
4	9	Transformer	2.929076	0.003282	17

PSSE Activity "RANK"



PSSE Activity "RANK"

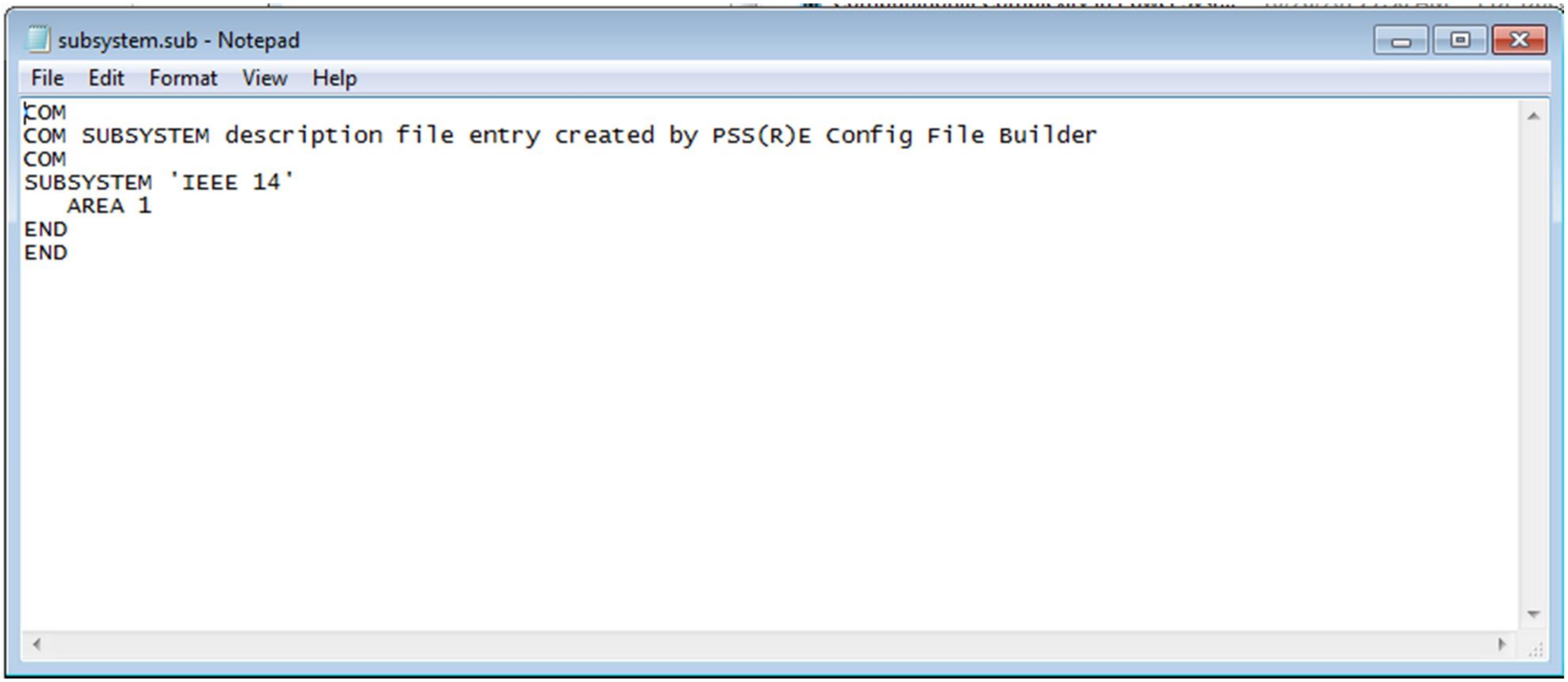


PSSE Activity “RANK”

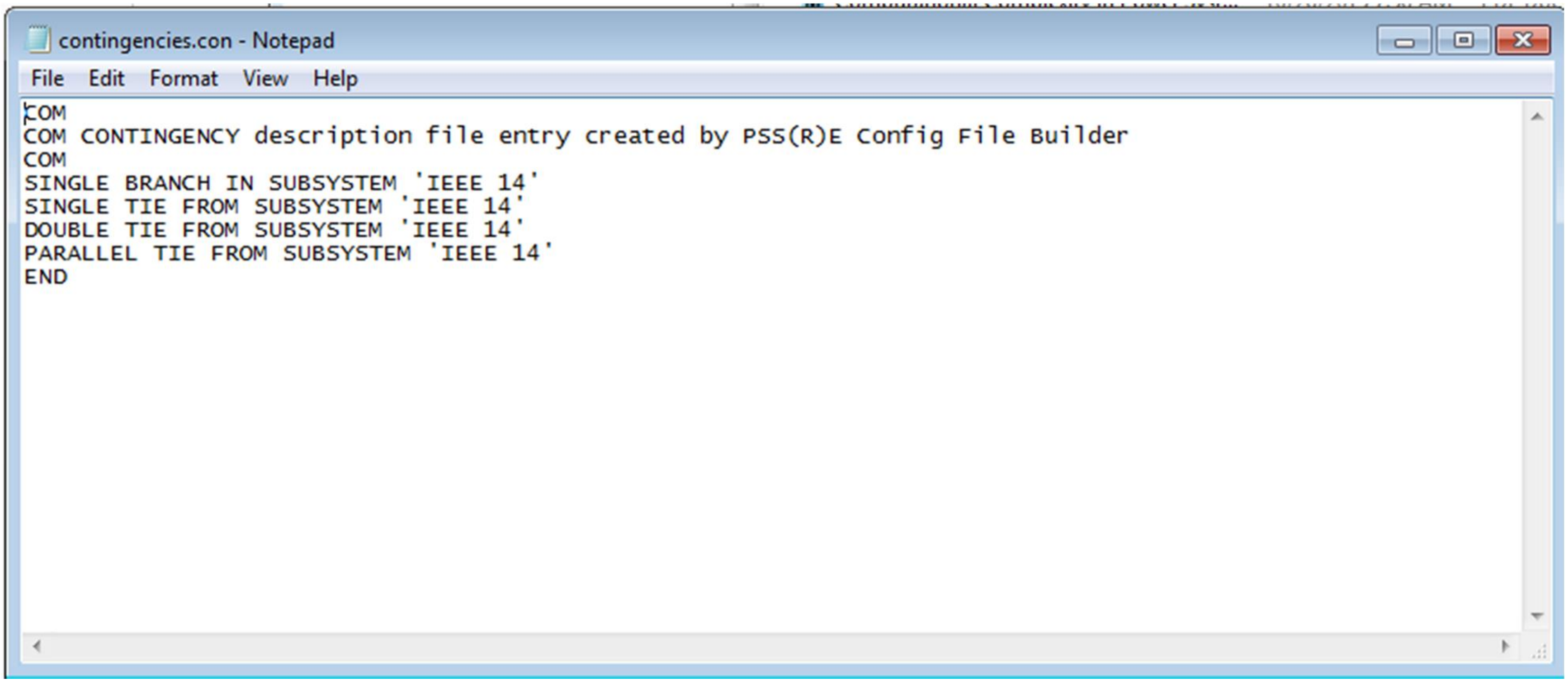
monitor.mon - Notepad

```
COM
COM MONITORED element file entry created by PSS(R)E Config File Builder
COM
MONITOR VOLTAGE RANGE SUBSYSTEM 'IEEE 14' 0.900 1.100
MONITOR VOLTAGE DEVIATION SUBSYSTEM 'IEEE 14' 0.030 0.060
MONITOR BRANCHES IN SUBSYSTEM 'IEEE 14'
MONITOR TIES FROM SUBSYSTEM 'IEEE 14'
END
```

PSSE Activity "RANK"

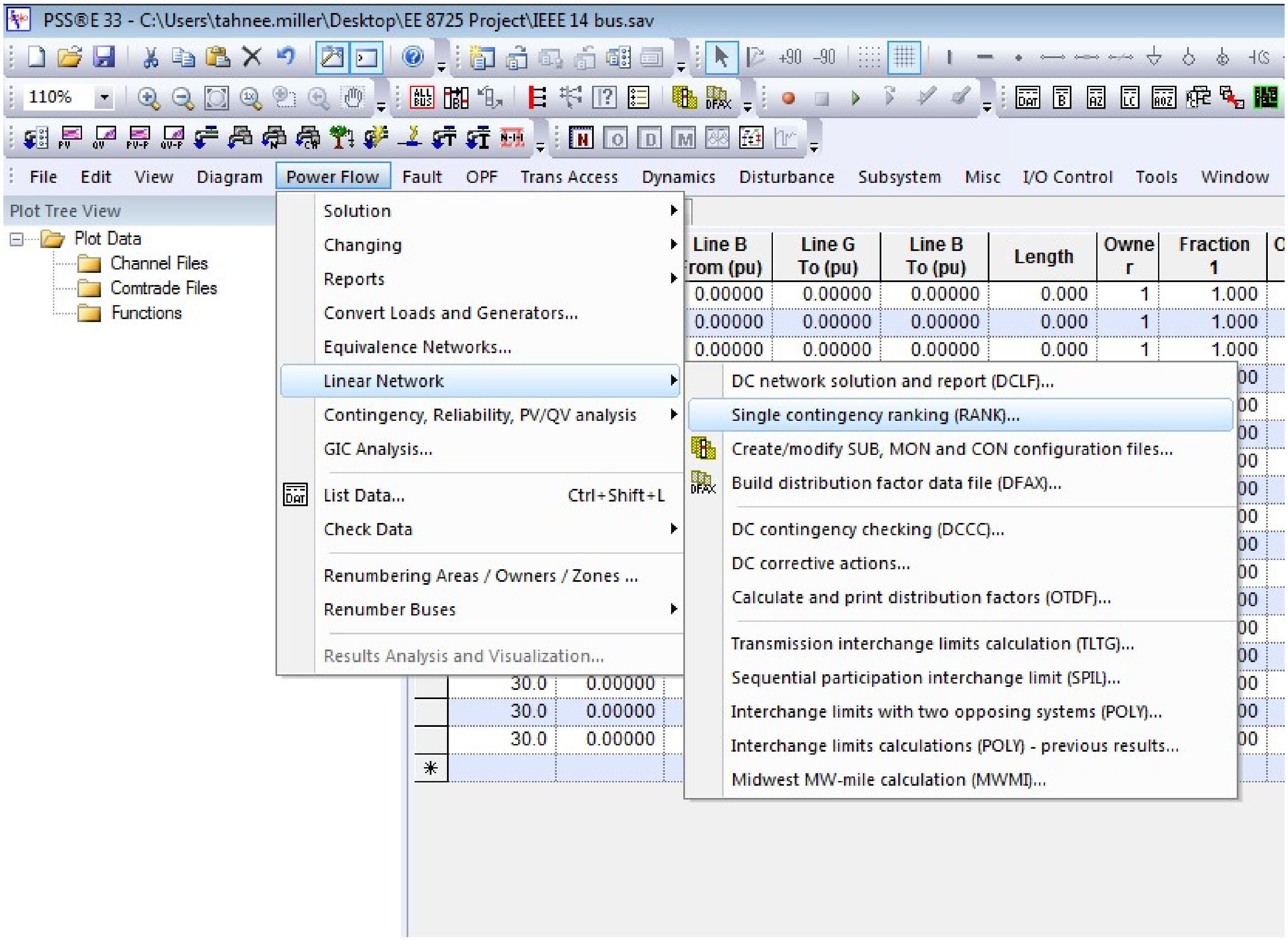


PSSE Activity “RANK”

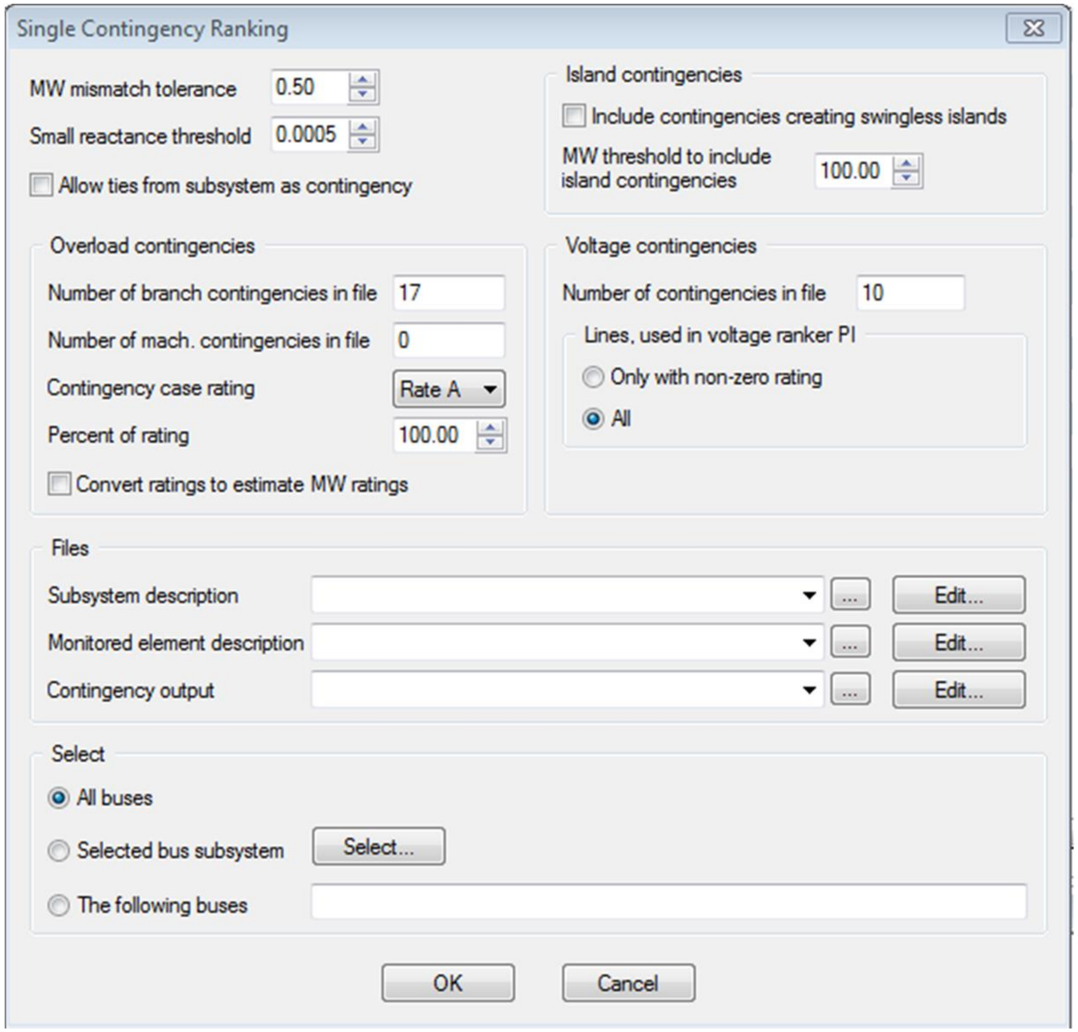



```
COM
COM CONTINGENCY description file entry created by PSS(R)E Config File Builder
COM
SINGLE BRANCH IN SUBSYSTEM 'IEEE 14'
SINGLE TIE FROM SUBSYSTEM 'IEEE 14'
DOUBLE TIE FROM SUBSYSTEM 'IEEE 14'
PARALLEL TIE FROM SUBSYSTEM 'IEEE 14'
END
```

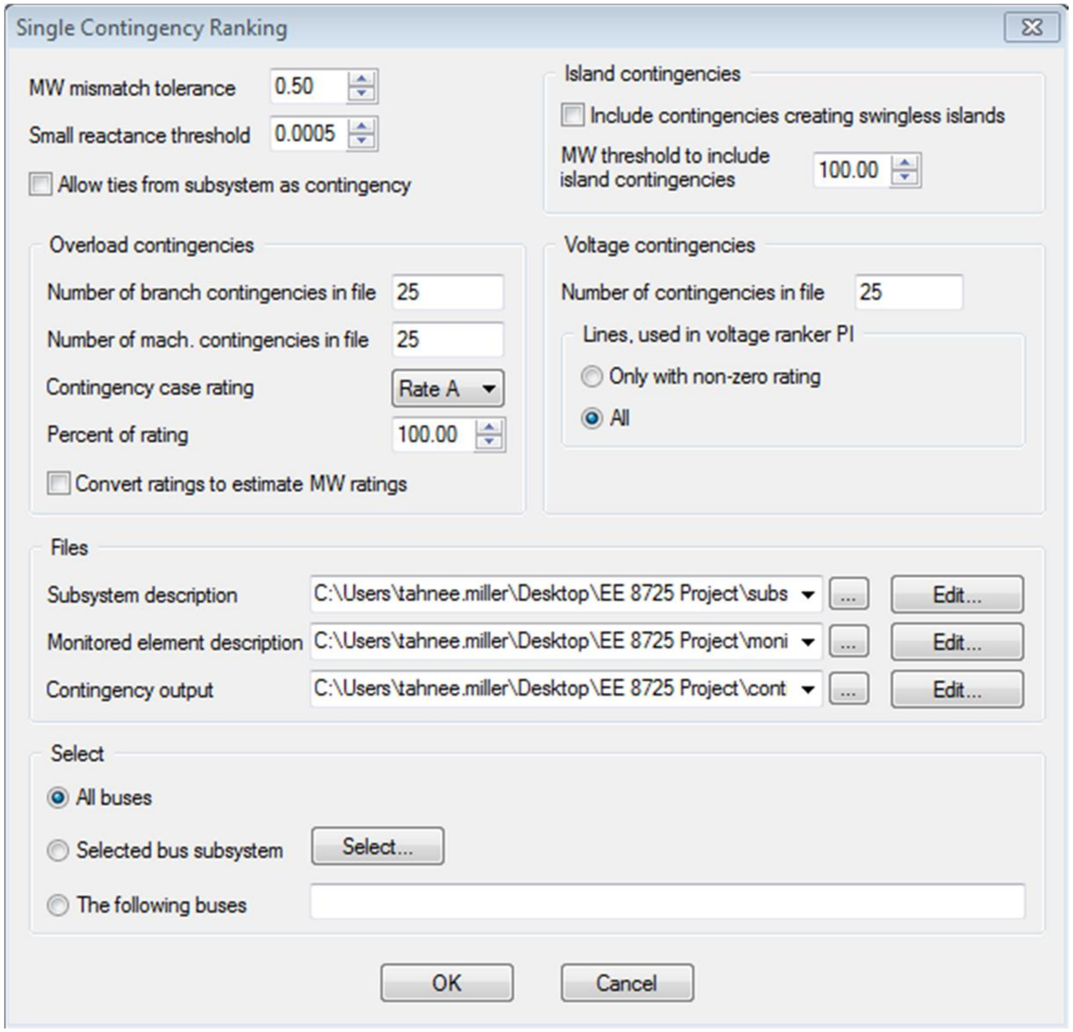
PSSE Activity "RANK"



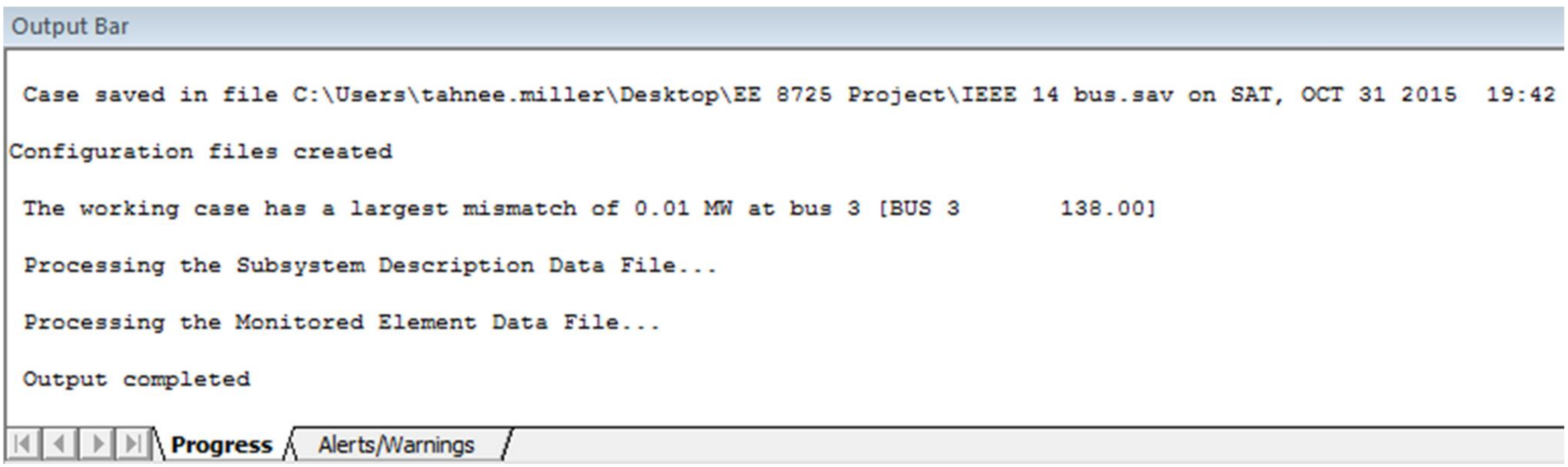
PSSE Activity "RANK"



PSSE Activity "RANK"



PSSE Activity "RANK"



PSSE Activity "RANK"

contingencies.con - Notepad

File Edit Format View Help

```
CONTINGENCY 'OVRLOD 1-2(1)'
OPEN LINE FROM BUS      1 TO BUS      2 CKT 1    / PI=   13.7589 'BUS 1       138.00' TO 'BUS 2       138.00'
END
CONTINGENCY 'OVRLOD 5-6(1)'
OPEN LINE FROM BUS      5 TO BUS      6 CKT 1    / PI=   12.3023 'BUS 5       138.00' TO 'BUS 6       138.00'
END
CONTINGENCY 'OVRLOD 2-3(1)'
OPEN LINE FROM BUS      2 TO BUS      3 CKT 1    / PI=    9.2850 'BUS 2       138.00' TO 'BUS 3       138.00'
END
CONTINGENCY 'OVRLOD 2-4(1)'
OPEN LINE FROM BUS      2 TO BUS      4 CKT 1    / PI=    6.7579 'BUS 2       138.00' TO 'BUS 4       138.00'
END
CONTINGENCY 'OVRLOD 1-5(1)'
OPEN LINE FROM BUS      1 TO BUS      5 CKT 1    / PI=    6.1551 'BUS 1       138.00' TO 'BUS 5       138.00'
END
CONTINGENCY 'OVRLOD 9-14(1)'
OPEN LINE FROM BUS      9 TO BUS     14 CKT 1    / PI=    6.1447 'BUS 9       138.00' TO 'BUS 14      138.00'
END
CONTINGENCY 'OVRLOD 4-7(1)'
OPEN LINE FROM BUS      4 TO BUS      7 CKT 1    / PI=    5.9301 'BUS 4       138.00' TO 'BUS 7       138.00'
END
CONTINGENCY 'OVRLOD 7-9(1)'
OPEN LINE FROM BUS      7 TO BUS      9 CKT 1    / PI=    5.9301 'BUS 7       138.00' TO 'BUS 9       138.00'
END
CONTINGENCY 'OVRLOD 6-11(1)'
OPEN LINE FROM BUS      6 TO BUS     11 CKT 1    / PI=    5.8128 'BUS 6       138.00' TO 'BUS 11      138.00'
END
CONTINGENCY 'OVRLOD 4-9(1)'
OPEN LINE FROM BUS      4 TO BUS      9 CKT 1    / PI=    5.7339 'BUS 4       138.00' TO 'BUS 9       138.00'
END
CONTINGENCY 'OVRLOD 6-13(1)'
OPEN LINE FROM BUS      6 TO BUS     13 CKT 1    / PI=    5.5211 'BUS 6       138.00' TO 'BUS 13      138.00'
END
CONTINGENCY 'OVRLOD 6-12(1)'
OPEN LINE FROM BUS      6 TO BUS     12 CKT 1    / PI=    5.5094 'BUS 6       138.00' TO 'BUS 12      138.00'
END
CONTINGENCY 'OVRLOD 4-5(1)'
OPEN LINE FROM BUS      4 TO BUS      5 CKT 1    / PI=    5.4191 'BUS 4       138.00' TO 'BUS 5       138.00'
END
CONTINGENCY 'OVRLOD 10-11(1)'
OPEN LINE FROM BUS     10 TO BUS     11 CKT 1    / PI=    5.4146 'BUS 10      138.00' TO 'BUS 11      138.00'
END
CONTINGENCY 'OVRLOD 12-13(1)'
OPEN LINE FROM BUS     12 TO BUS     13 CKT 1    / PI=    5.2586 'BUS 12      138.00' TO 'BUS 13      138.00'
END
CONTINGENCY 'OVRLOD 9-10(1)'
OPEN LINE FROM BUS      9 TO BUS     10 CKT 1    / PI=    5.2448 'BUS 9       138.00' TO 'BUS 10      138.00'
END
CONTINGENCY 'OVRLOD 13-14(1)'
OPEN LINE FROM BUS     13 TO BUS     14 CKT 1    / PI=    5.1523 'BUS 13      138.00' TO 'BUS 14      138.00'
END
CONTINGENCY 'OVRLOD 2-5(1)'
OPEN LINE FROM BUS      2 TO BUS      5 CKT 1    / PI=    5.1020 'BUS 2       138.00' TO 'BUS 5       138.00'
END
CONTINGENCY 'OVRLOD 3-4(1)'
OPEN LINE FROM BUS      3 TO BUS      4 CKT 1    / PI=    4.9723 'BUS 3       138.00' TO 'BUS 4       138.00'
END


END
```

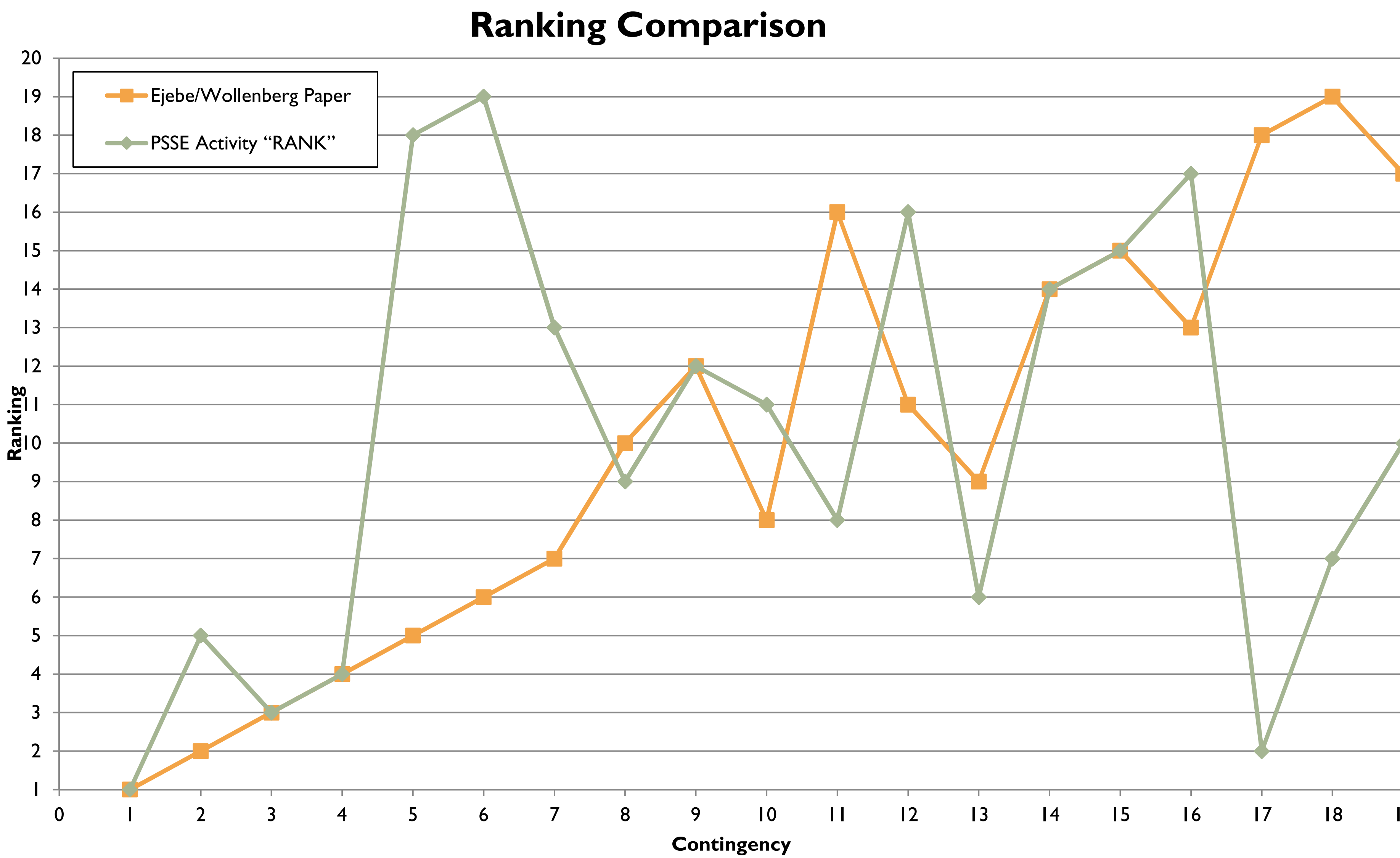
PSSE Activity "RANK"

Branch			Contingency File Output	
From Bus	To Bus	Branch Type	PI	Ranking
1	2	Line	13.7589	1
1	5	Line	6.1551	5
2	3	Line	9.2850	3
2	4	Line	6.7579	4
2	5	Line	5.1020	18
3	4	Line	4.9723	19
4	5	Line	5.4191	13
6	11	Line	5.8128	9
6	12	Line	5.5094	12
6	13	Line	5.5211	11
7	8	Line	Excluded – Swing Generator	
7	9	Line	5.9301	8
9	10	Line	5.2448	16
9	14	Line	6.1447	6
10	11	Line	5.4146	14
12	13	Line	5.2586	15
13	14	Line	5.1523	17
5	6	Transformer	12.3023	2
4	7	Transformer	5.9301	7
4	9	Transformer	5.7339	10

Method Comparison

Branch				Ranking	
Contingency	From Bus	To Bus	Branch Type	Ejebe/Wollenberg Paper (PI_{MW})	PSSE Activity "RANK"
1	1	2	Line	1	1
2	1	5	Line	2	5
3	2	3	Line	3	3
4	2	4	Line	4	4
5	2	5	Line	5	18
6	3	4	Line	6	19
7	4	5	Line	7	13
8	6	11	Line	10	9
9	6	12	Line	12	12
10	6	13	Line	8	11
-	7	8	Line	Excluded – Swing Generator	
11	7	9	Line	16	8
12	9	10	Line	11	16
13	9	14	Line	9	6
14	10	11	Line	14	14
15	12	13	Line	15	15
16	13	14	Line	13	17
17	5	6	Transformer	18	2
18	4	7	Transformer	19	7
19	4	9	Transformer	17	10

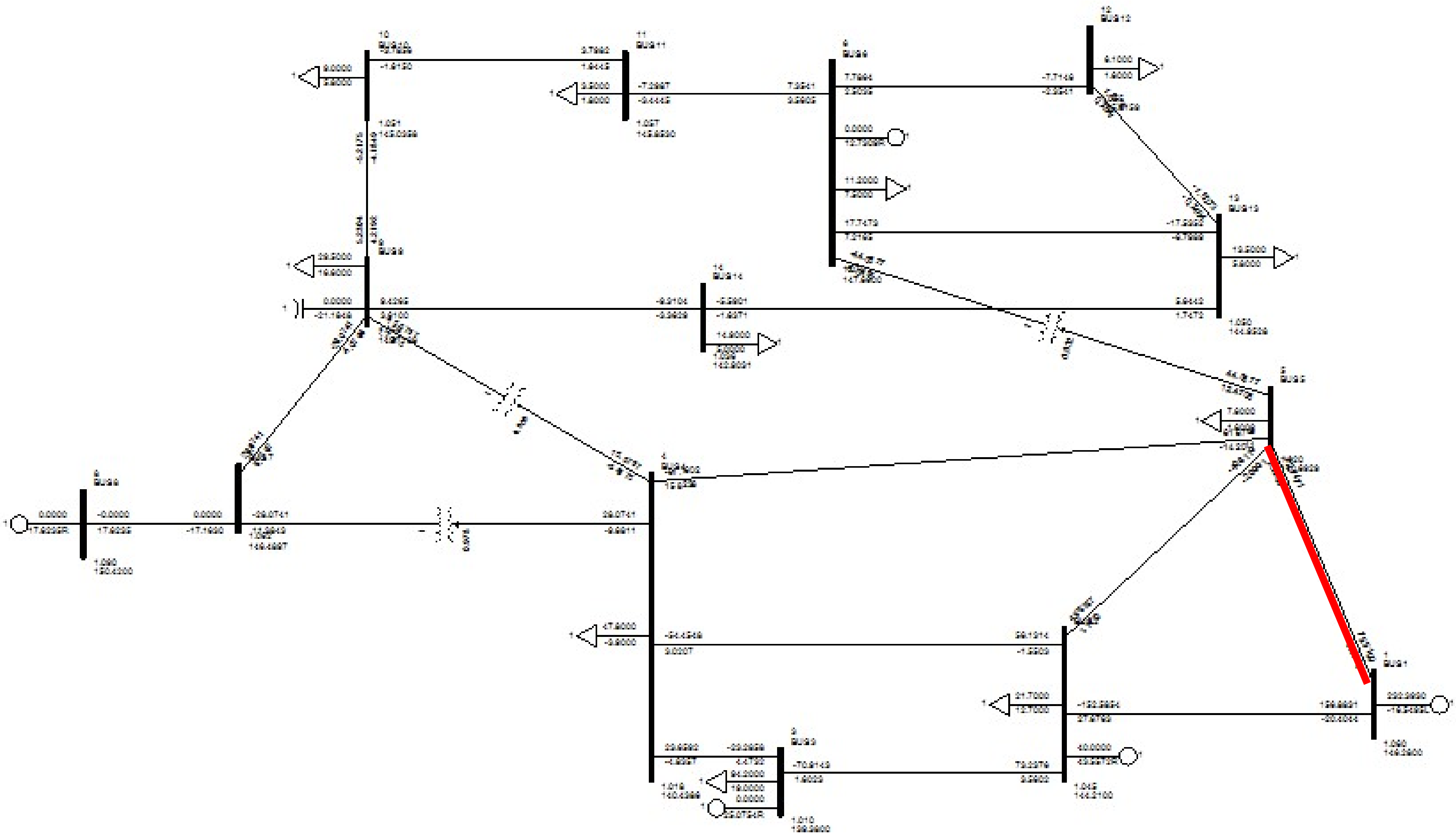
Method Comparison



Method Comparison

- Rankings were quite different between the two methods
- Issues due to manually set line overloads
  - Purposely set contingency #2 (line 1 to 5 OOS) to have a rating very close to the actual line flow during normal operation.
    - Ejebe/Wollenberg method: #2
    - RANK method: #5
  - Saw masking using Ejebe/Wollenberg method because performance index values were very similar.

Method Comparison



CONCLUSIONS

Summary

- Methods gave very different results in test case
- Research is extensive for test cases comparing contingency selection methods
  - First Order (Ejebe/Wollenberg method using Tellegen's theorem)
  - Second Order (Mikolinnas/Wollenberg method using Taylor expansion)
  - Detailed DC load flow
  - Detailed AC load flow
- Mikolinnas/Wollenberg (RANK) method seems to be most widely used to minimize calculation time and get accurate results