AUTOMATIC CONTINGENCY SELECTION

Ejebe/Wollenberg

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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.
- An adaptive contingency processor can be set up by performing sequential contingency tests starting with the most severe and stopping when the severity drops below a certain threshold.
- Numerical examples on several test cases are provided.

Presentation Summary

- Introduction to Methodology
- System Performance Indices
  - System Performance Index for Voltage Analysis
  - System Performance Index for Power Flow Analysis
  - Other Contingency Ranking Methods
- Creating Ordered Contingency Lists
- Numerical Examples
- Stopping Criteria for the Adaptive Contingency Processor
- Conclusions

INTRODUCTION TO METHODOLOGY

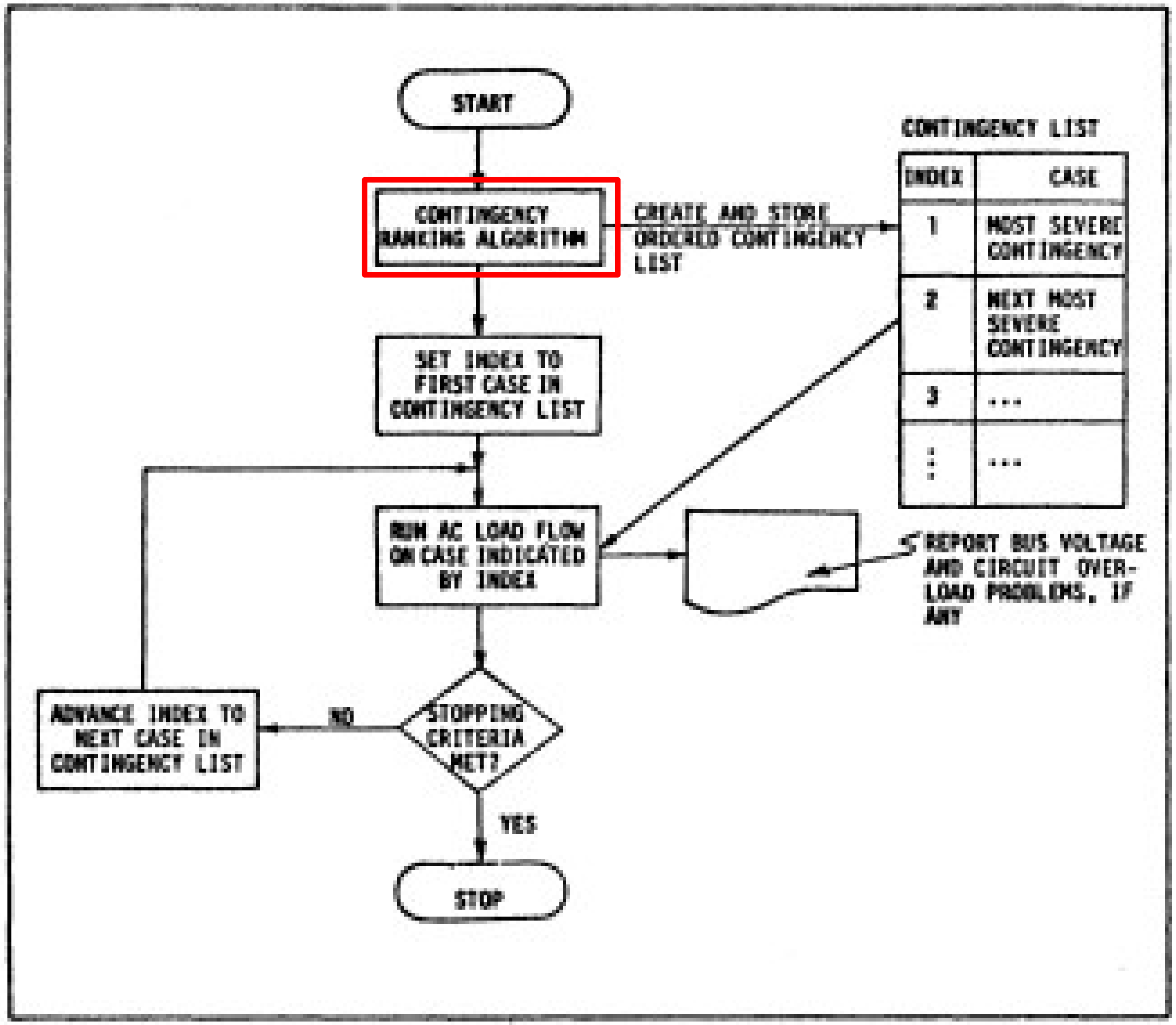
Traditional Approach

- Simulate outages to determine impact on bus voltages and power flow using fast computational techniques
- Time-consuming and costly
- Contingencies often selected based on planner's experience
- In real time, contingency testing is up to operator
  - System is constantly changing so impact is different than what may have been determined to be "worst case" by planners

Proposed Solution

- Purpose is to be able to rank contingencies by severity
- Method uses Tellegen's theorem to order the outages
- Non-linear AC load flow equations are used to evaluate contingencies based on voltage quality
- Simplified DC load flow model is used to evaluate contingencies based on power flow
- Method DOES NOT indicates if the contingency will cause problems, just ranks them in order of severity
- Result is a list of contingencies from "worst" to "best"
  - You can then run detailed analysis starting at top of list until you reach a case that does not cause system issues

Adaptive Contingency Processor



SYSTEM PERFORMANCE INDICES

Background

- Traditional approach is to model outage, perform load flow calculations, and check for:
  1. Bus voltages outside of normal limits
  2. Branch power flows outside of normal operating limits
- Proposed method uses these two sets of limits to develop system performance indices reflecting the contingency severity
  - Limits are treated as soft constraints to rank contingencies

1. Index for Voltage Analysis

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

where:

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

$\left|V_i^{sp}\right|$ 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

I. 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

Other Contingency Ranking Methods

1. Distribution factor method
   - Very fast, but not very accurate
   - Can be used to prescreen contingencies for AC load flow
   - Does not provide voltage prediction

- Ranking based on assumption that the loss of a heavily loaded line would likely result in overloads on other lines
  2. Ranking in order of most heavily loaded to least
  3. Ranking in order of absolute magnitudes of line flows
  - Both methods were considered, but were determined to not provide proper contingency selection

CREATING ORDERED CONTINGENCY LISTS

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

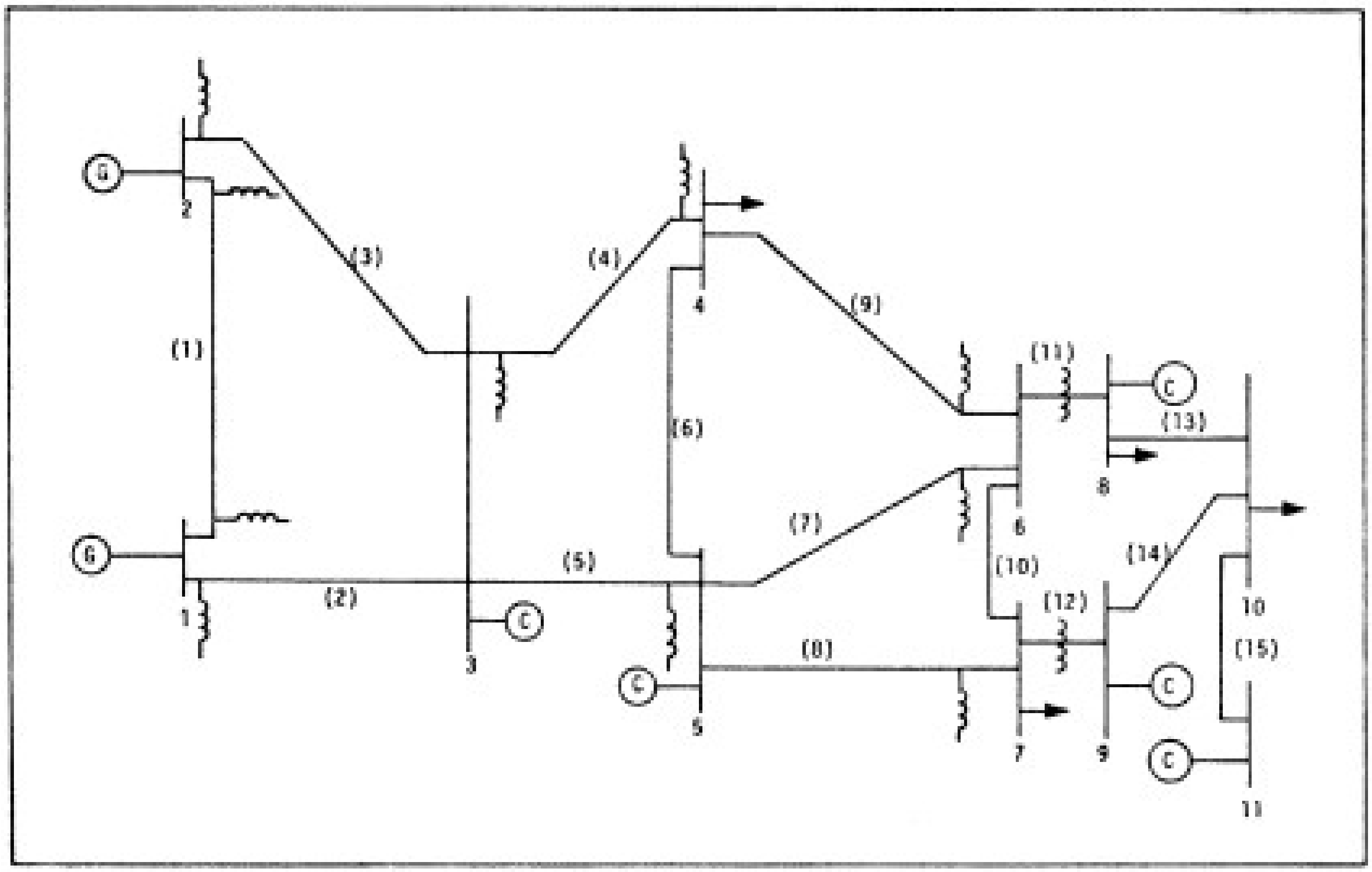
Tellegen's Theorem

- All three options give sensitivities in terms of incremental change in performance index to an incremental change in line admittance or generator output
  - The full effect would be found my multiplying the derivative by the full line admittance using Tellegen's Theorem
- Tellegen's Theorem: allows rapid computation of gradient vectors which contain the performance index derivatives
- Resulting normalized numbers represent the ΔPI for each contingency
  - Misorderings may occur due to the linear approximation
  - Non-perfect ranking is ok because the stopping criteria will cover that

NUMERICAL EXAMPLES

Test System #1 – 11-Bus System

- EHV backbone of the ITAIPU transmission system
- Scheme designed for use in Brazil over lone 800 kV lines



Test System #1 – 11-Bus System

- System has synchronous generators and reactors
- Has had previous indications of reliability issues
- Chosen to be a test case for the voltage performance index PI_V with line outages only (Option 1)
  - ΔV_i^{Lim} was set to 0.075 pu (±7.5% voltage threshold)

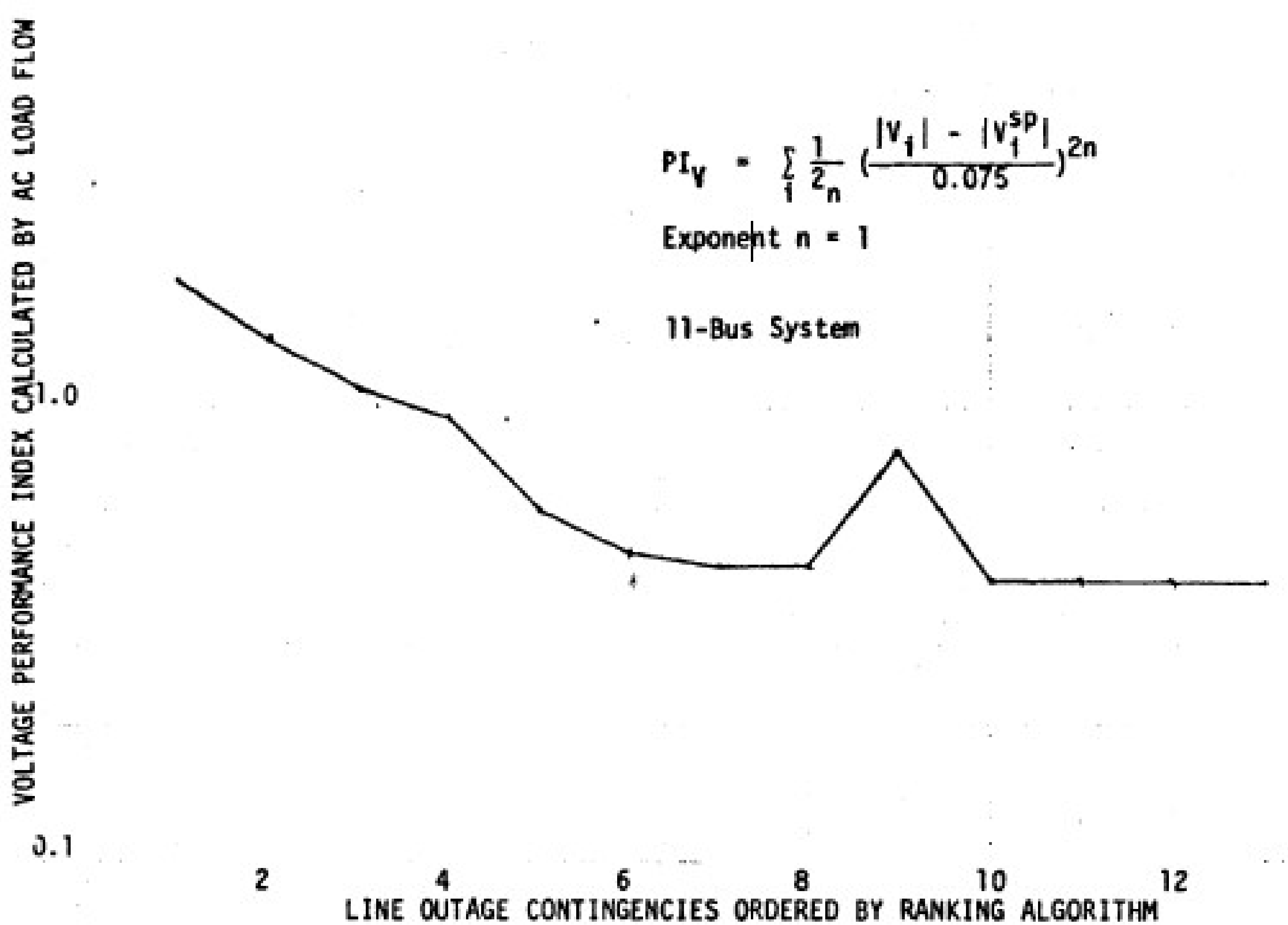
Test System #1 – 11-Bus System

Comparison of AC Load Flow and Contingency Ranking Algorithm for the Voltage Index on 11-Bus System

Line Outage Ranking by AC Load Flow			Line Outage Ranking by Contingency Selector	
Ordered Line Numbers	Voltage Performance Index PI_V	Worst % of Out-of-Limit Voltage	Ordered Line Numbers	Normalized Sensitivity (ΔPI)
7	1.9697	1.24	7	0.2676
8	1.4341	0.97	8	0.2475
9	1.127	0.93	9	0.1784
5	0.9878	0.78	5	0.1445
4	0.8073	0.72	6	0.0659
6	0.6182	0.64	12	0.0364
12	0.4861	0.67	11	0.0322
11	0.4797	0.64	10	0.0314
10	0.4654	0.67	4	0.0236
3	0.4374	0.60	15	0.0022
2	0.4310	0.60	13	0.0002
13	0.4273	0.61	1	-0.2504E-5
15	0.4271	0.60	2	-0.1295E-4
14	0.4252	0.60	3	-0.2171E-4
1	0.4198	0.59	14	-0.2101E-4

Test System #1 – 11-Bus System

Effectiveness Profile of Voltage Performance Index for 11-Bus System



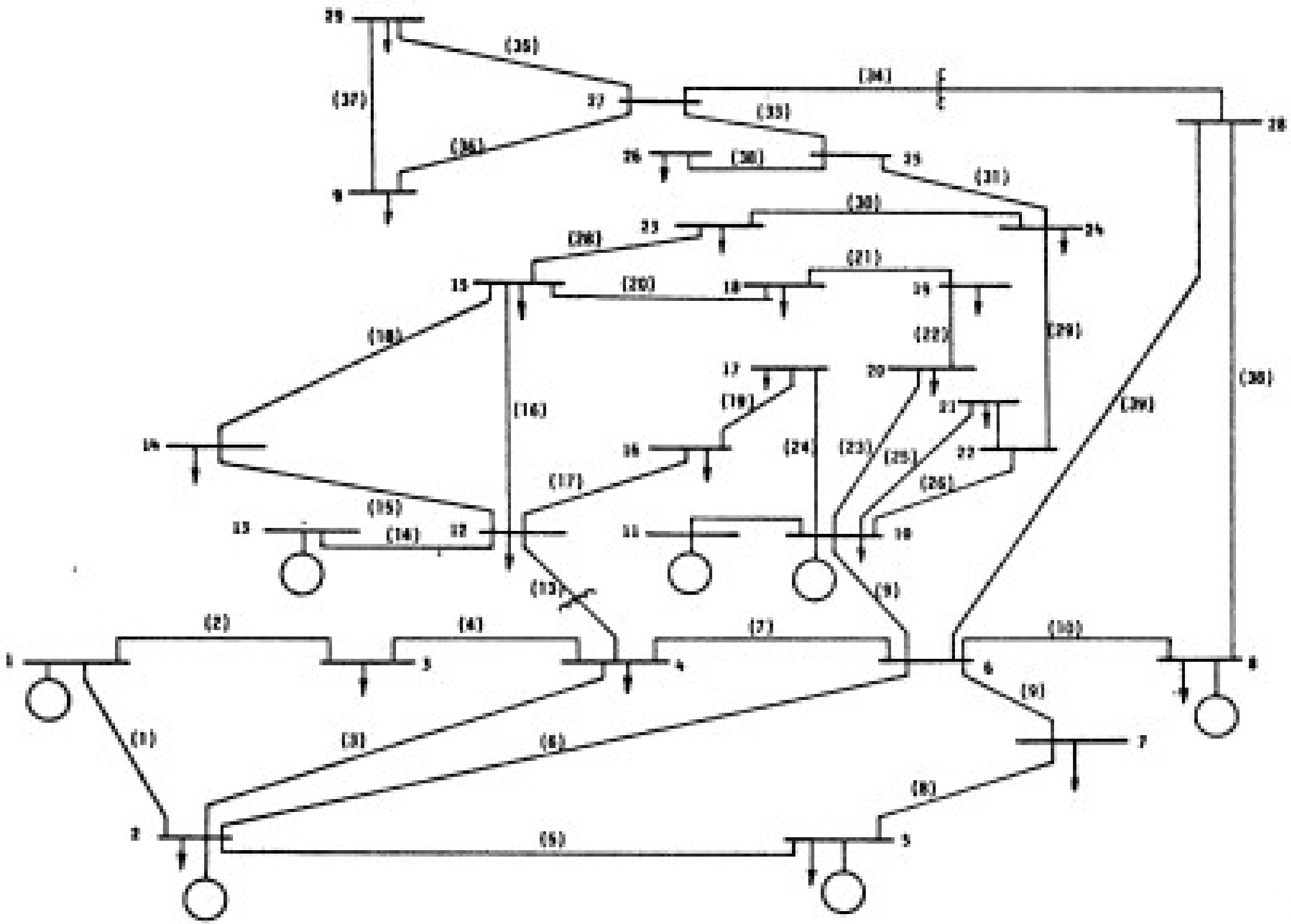
Test System #1 – 11-Bus System

Comparison of Voltages and Voltage Indices for Worst Three Outages on 11-Bus System

Bus	Base Case Voltages	Line 7 Outage	Line 8 Outage	Line 9 Outage
1	0.9950	0.9950	0.9950	0.9950
2	1.0000	1.0000	1.0000	1.0000
3	0.9807	0.9693	0.9875	0.9810
4	0.9900	0.9346	0.9547	0.9398
5	0.9517	0.9021	0.9938	0.9669
6	0.9469	0.9354	0.9295	0.9380
7	0.9443	0.9199	0.9392	0.9291
8	0.9700	0.9700	0.9655	0.9700
9	0.9657	0.9665	0.9700	0.9700
10	0.9778	0.9782	0.9782	0.9792
11	0.9900	0.9900	0.9900	0.9900
	Voltage Index	1.9697	1.4341	1.1270

Test System #2 – 29-Bus System

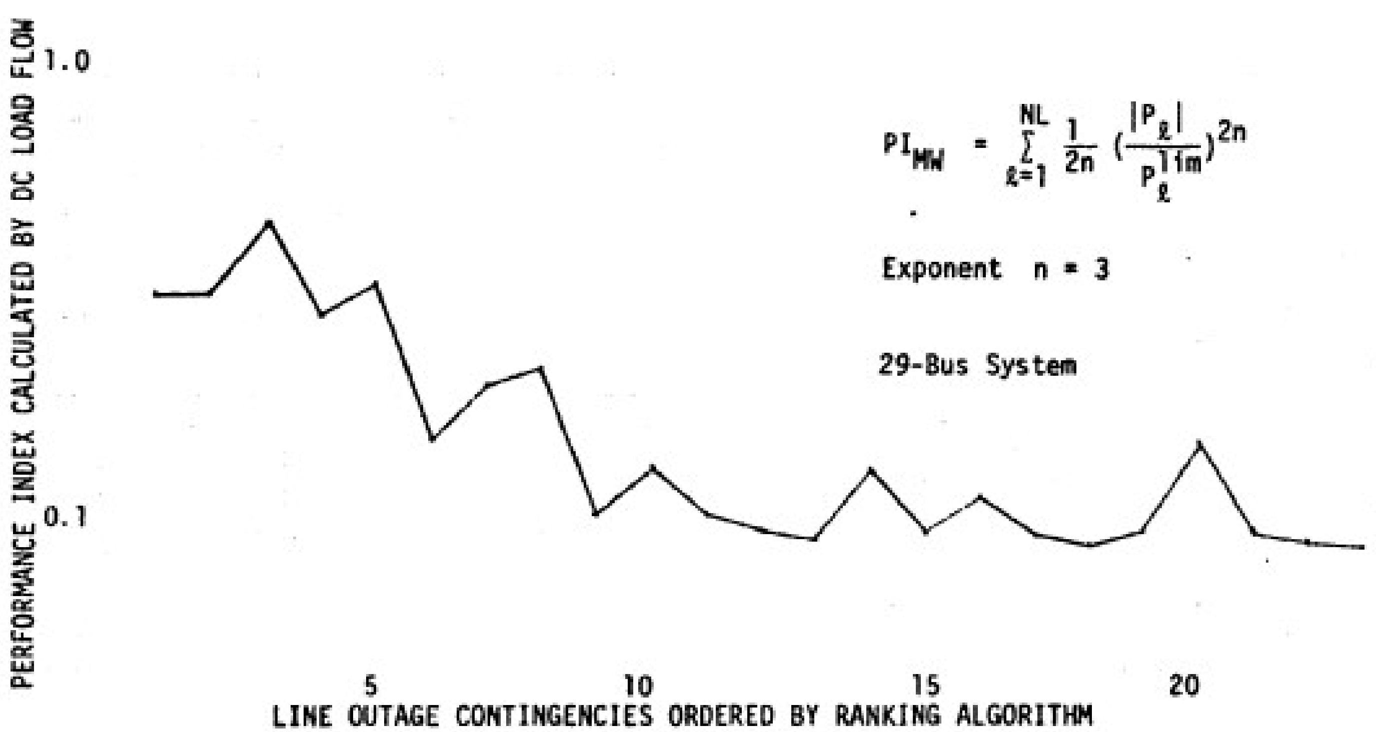
- A modified version of the IEEE 30-bus system as shown below



Test System #2 – 29-Bus System

- Chosen as a test case for PI_{VQ} (Option 1) with line outages and PI_{MW} with line outages (Option 2)

Effectiveness Profile for Real Power Performance Index for 29-Bus System



Test System #3 – 10-Bus CIGRE System

- System has seven generating plants
- Chosen as a test case for PI_{VQ} (Option 1) with generator outages and PI_{MW} with generator outages (Option 3)

Contingency Selection Rankings on 10-Bus CIGRE System

Ranking for Voltage Analysis

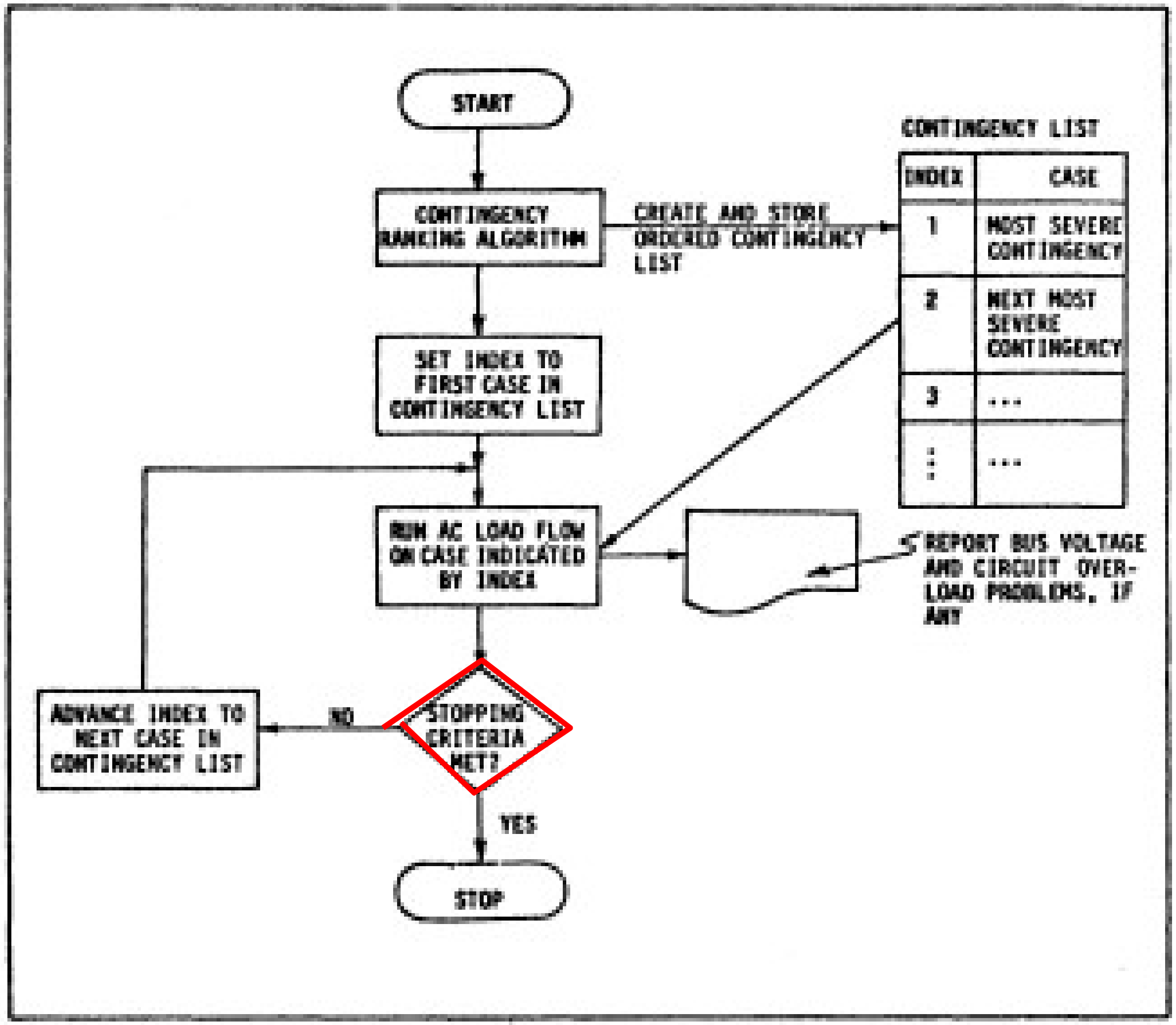
AC Load Flow		Contingency Selection		
Ordered Generator Numbers	Voltage Performance Index PI_V	Ordered Generator Numbers	Normalized Sensitivity (ΔPI)	Worst Bus Voltage
3	0.9543	3	0.4832	0.818
5	0.9215	5	0.1849	0.834
6	0.6912	6	0.1383	0.886
7	0.3136	4	0.1165	0.965
4	0.3010	2	0.0065	0.970
2	0.1373	7	-0.3059	0.983
1	Swing bus generator excluded from voltage ranking			

Ranking for Line Overloads

DC Load Flow		Contingency Selection	
Ordered Generator Numbers	Voltage Performance Index PI_{MW}	Ordered Generator Numbers	Normalized Sensitivity (ΔPI_{MW})
3	1.6932	3	0.4699
7	0.7985	4	0.1683
4	0.6589	6	0.1442
6	0.6157	7	0.1418
5	0.4818	5	0.0386
1	0.3188	1	-0.3328
2	0.1935	2	-0.9597

STOPPING CRITERIA FOR ADAPTIVE CONTINGENCY PROCESSOR

Advanced Contingency Processor



Stopping Criteria

- Simplest option would be to stop as soon as a case showed an out-of-limit condition
  - This would work for some cases, but not others
- A better option is to do the load flows and stop once there were no out-of-limit conditions X times in a row
  - X would be determined by experience
- Another option is to just run N number of cases, regardless of if there are out-of-limit conditions are not
  - N would be determined by experience, but typically between 1 and 20
- One referenced program ran N primary outages and X secondary outages, combining the second two options above

CONCLUSIONS

Summary

- Algorithm presented increases the effectiveness of existing contingency analysis techniques
  - Provides an ordered list of contingencies to identify those which are likely to cause the most sever system issues
  - Process creates a list of primary contingencies and then lists for secondary contingencies
  - Will enable system operators to identify weaknesses more quickly
- Ranking algorithm is not perfect, and requires user input for the stopping criteria
- Process has been applied to single outage contingency cases
  - Further work anticipated for multiple outages