Comprehensive Power System Reliability Assessment

A. P. Meliopoulos (GIT), D. Taylor (GIT), Fang Yang (GRA),
George Stefopoulos (GRA), Chanan Singh (TAMU)

Outline

- **Objectives of Reliability Assessment**
- **Basic Observations**
- **Selective Enumeration Approach**
- **Important Advancements**
  - Single Phase Quadratized Power Flow
  - Advanced Modeling Methods
  - Advanced Contingency Simulation Methods
  - Contingency Selection via Multiple Performance Indices
  - Remedial Actions
- **Reliability Index Computations (Markov Models)**

Reliability Assessment: Objectives

Identify Events that Will Results in Abnormal Conditions (Low Voltage, Congestion, etc.). Quantify the Frequency and Duration of Such Problems

Identify Sequence of Events/Outages That Will Result in Local Service Interruptions. Quantify the Number of Affected Customers, Lost Revenues, Frequency and Duration.

Identify Sequence of Events/Outages That Will Result in Wide Spread Service Interruptions/Blackouts. Quantify the Risk of Such Events.

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Basic Observations

Reliability Assessment Problems

Generation System Reliability
Bulk System Reliability
Distribution System Reliability
"Active" Distribution System Reliability

Approaches

Monte Carlo Simulation
(Impractical for large systems)
Selective Enumeration
(Viable for large systems)

Bulk System Reliability (NP Complete)
Cumulative Probability and Number of States
300 units (FOR=0.05), 2000 circuits (FOR=0.001)

m	0	1	2	3	4	5	6
$\Pr[N_G \le m]$	2.0753e-7	3.4843e-6	2.9268e-5	1.6406e-4	6.9083e-4	0.0023	0.0065
$\Pr[N_L \le m]$	0.1352	0.4059	0.6767	0.8572	0.9474	0.9835	0.9955

m	0	1	2	3	4	5	6
$\#[N_G \le m]$	1	301	45,151	4.5e6	3.35e8	1.99e10	9.827e11
$\#[N_L \le m]$	1	2,001	2.0e6	1.3e9	6.66e11	2.66e14	8.85e16

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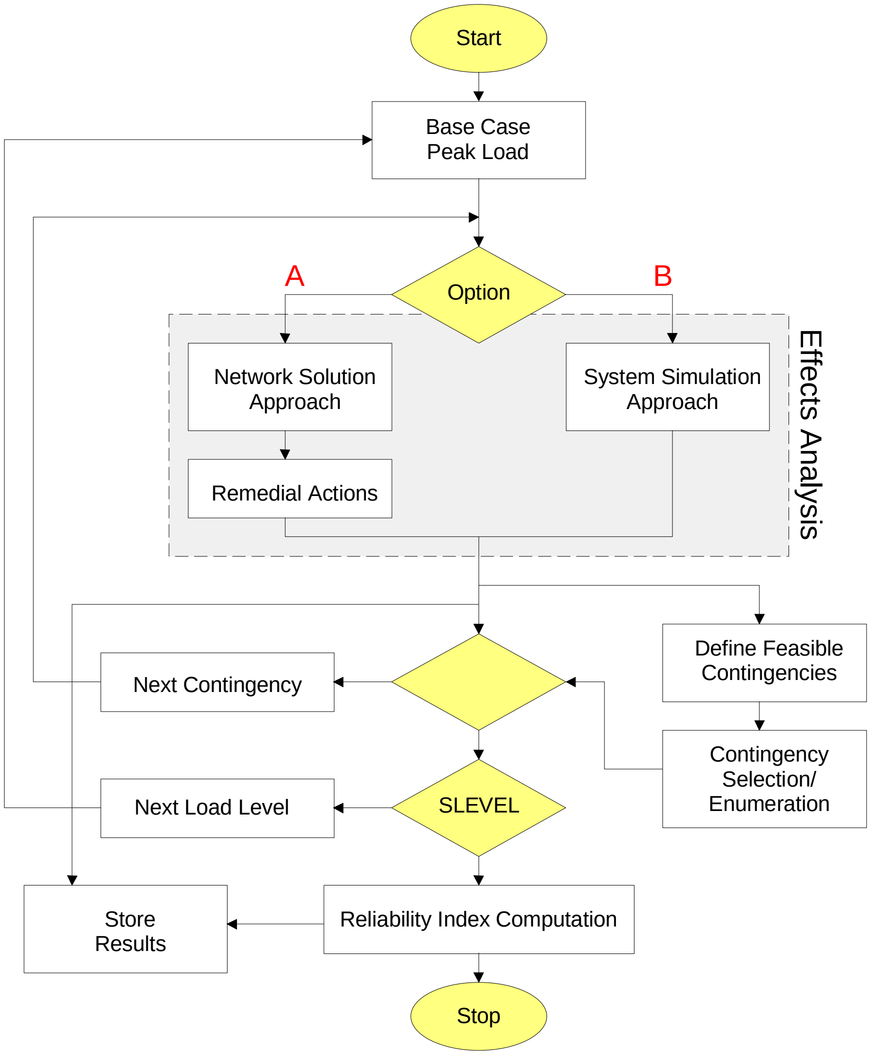
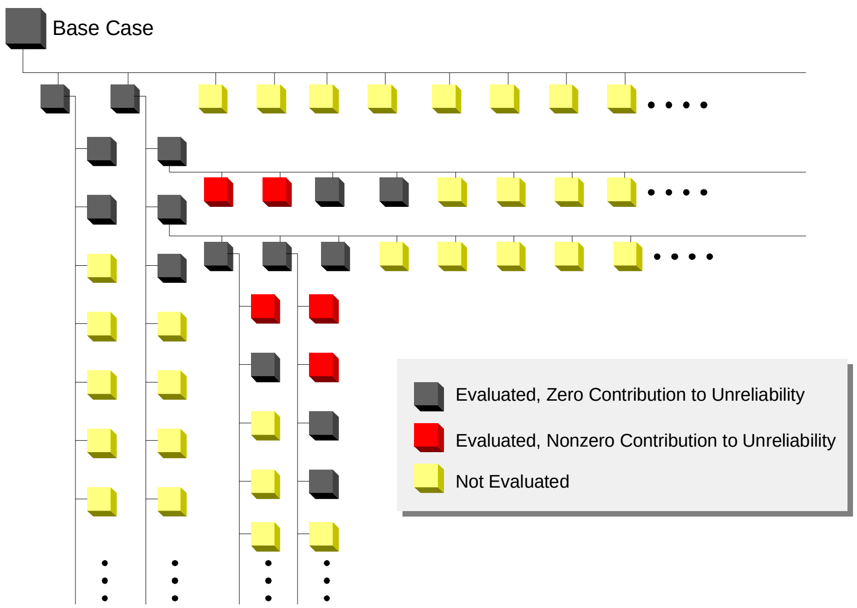
Reliability Assessment: Overall Computational Algorithm

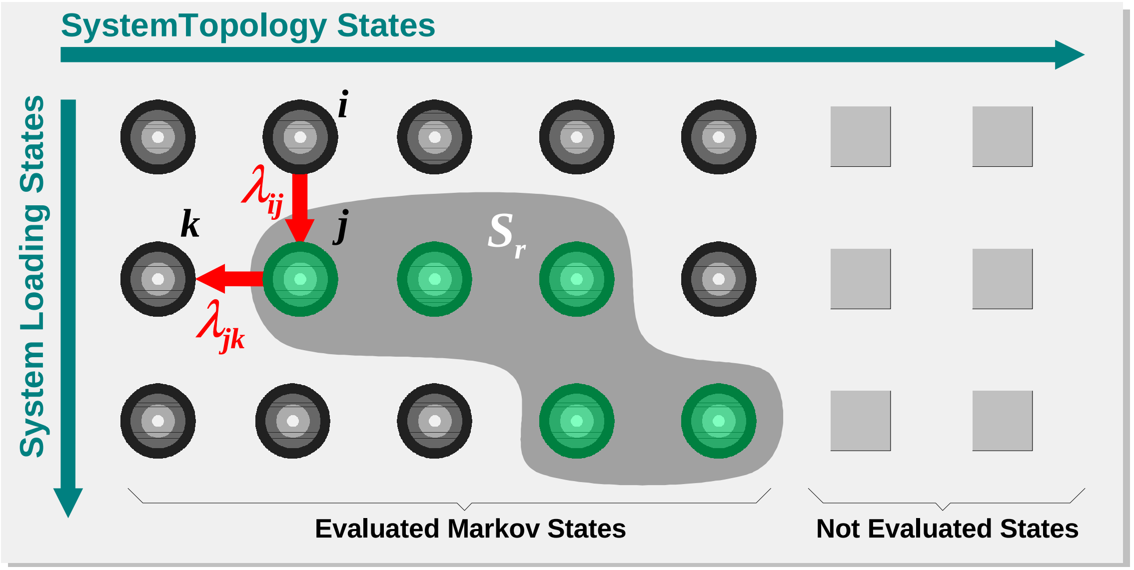
Algorithm



Wind-Chime Scheme



Reliability Indices



S_r: *Event* (*Voltage*, *LOL*, *etc.*)

Probability Index

$$\Pr[S_r] = \sum_{j \in S_r} p_j$$

Frequency Index

$$f = \sum_{j \in S_r} p_j \sum_{j \in S_r, k \notin S_r} \lambda_{jk}$$

Duration Index

$$T = \frac{\Pr[S_r]}{f}$$

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System Reliability Indices

A. Probability Indices
   1. Service Failure Probability
   2. Unsupplied Energy Probability
B. Expectation Indices
   1. Service Failure Occurrences
   2. Service Failure Duration
   3. Expected Unsupplied Energy
   4. Unserviced Customer Hours
   5. Customer Interruptions
C. Bulk System Reliability Indices
   1. Bulk Power Interruption Index
   2. Bulk Power Energy Curtailment Index
   3. Bulk Power Supply Average Curtailment Per Disturbance
D. Customer Interruption Indices
   1. System Average Interruption Frequency Index
   2. System Average Interruption Duration index
   3. Customer Average Interruption Duration Index
   4. Average Service Availability Index
   5. Average Number of Customers Per Interruption

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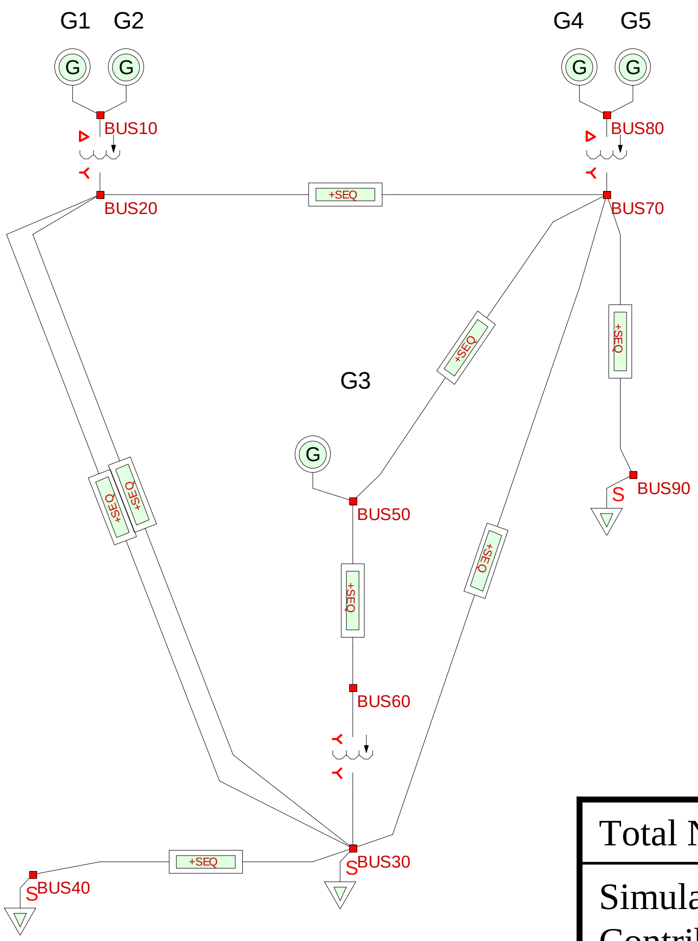
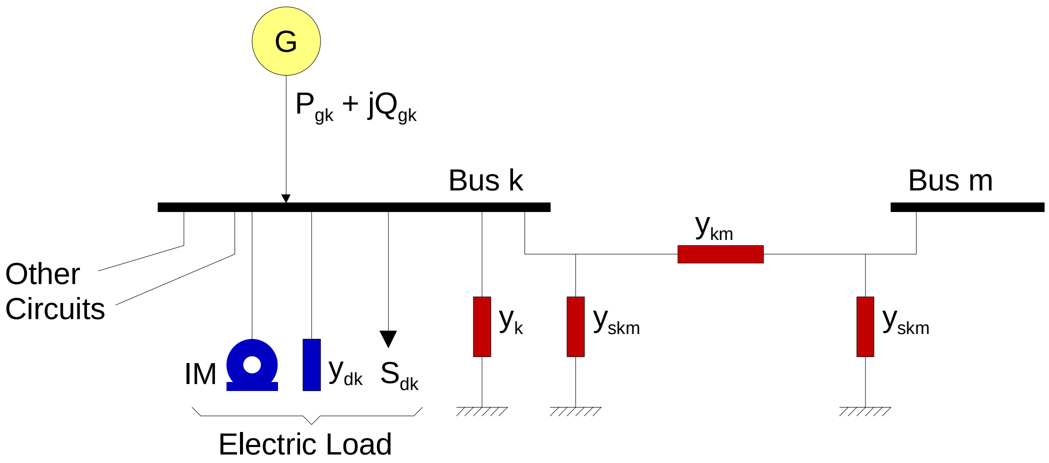
Example Results: Selective Enumeration



	Upper Bound	Lower Bound
Service Failure Probability	0.0614	0.0314
Service Failure Frequency	76.2 (per year)	16.6 (per year)
Service Failure Duration	102.2 (hrs/year)	16.5 (hrs/year)

Total Number of Considered Contingencies	1,136
Simulated Contingencies with Nonzero Contribution (probability of system failure)	30
Simulated Contingencies with Zero Contribution (probability of system failure)	22
Contingencies Screened as Noncritical	1,084

Single Phase Quadratized Power Flow



Formulation

Kirchoff's Current Law

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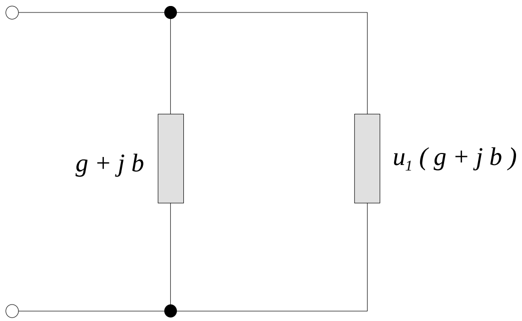
Mostly Linear Equations

NonLinear Component Example: Constant Power Load



$$\tilde{I}_{dk} = (g + jb)\tilde{V}_k + u_1(g + jb)\tilde{V}_k$$

$$0 = gu_2 + gu_1u_2 - P_{dk}$$

$$0 = u_2 - V_k^2$$

SPQPF: Algorithm

Component Model

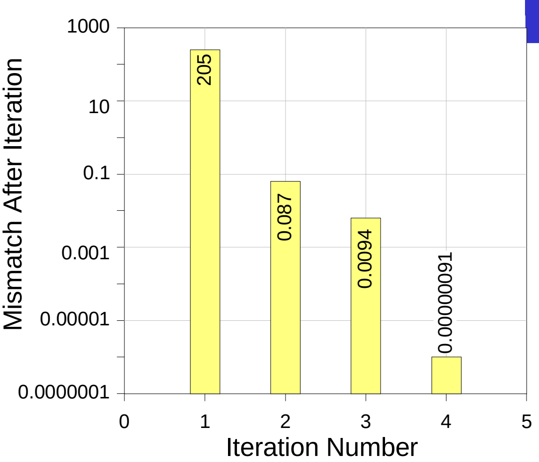
$$\begin{bmatrix} i^k \\ 0 \end{bmatrix} = Y^k x^k + \begin{bmatrix} {x^k}^T F_1^k x^k \\ {x^k}^T F_2^k x \\ \end{bmatrix} - b^k$$

Connectivity Constraints

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = Yx + \begin{bmatrix} x^T F_1 x \\ x^T F_2 x \\ \end{bmatrix} - b$$

Newton's Method

x(t)



Electric Load Models

Load Types

Constant Impedance

Constant Power

Induction Motors

Comments

Captures Correct System Response

Load Control

Firm Load

Critical Load

Interruptible Load

Comments

Provide Capability To Assess Impact Of Customer Incentives/Load Control Programs

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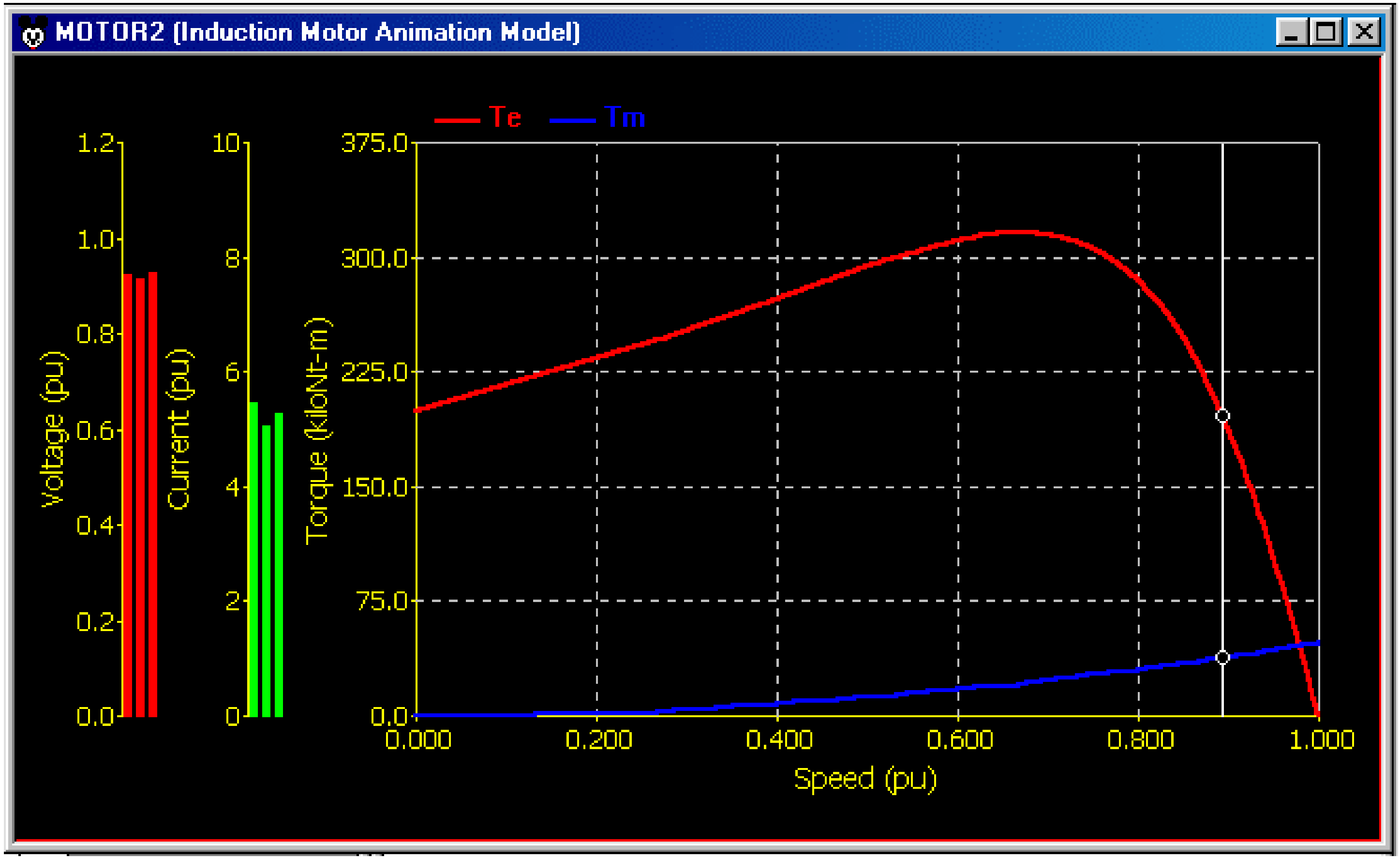
Induction Motors Characteristics



Comment

Reactive Power Absorption VERY Sensitive to Motor Speed

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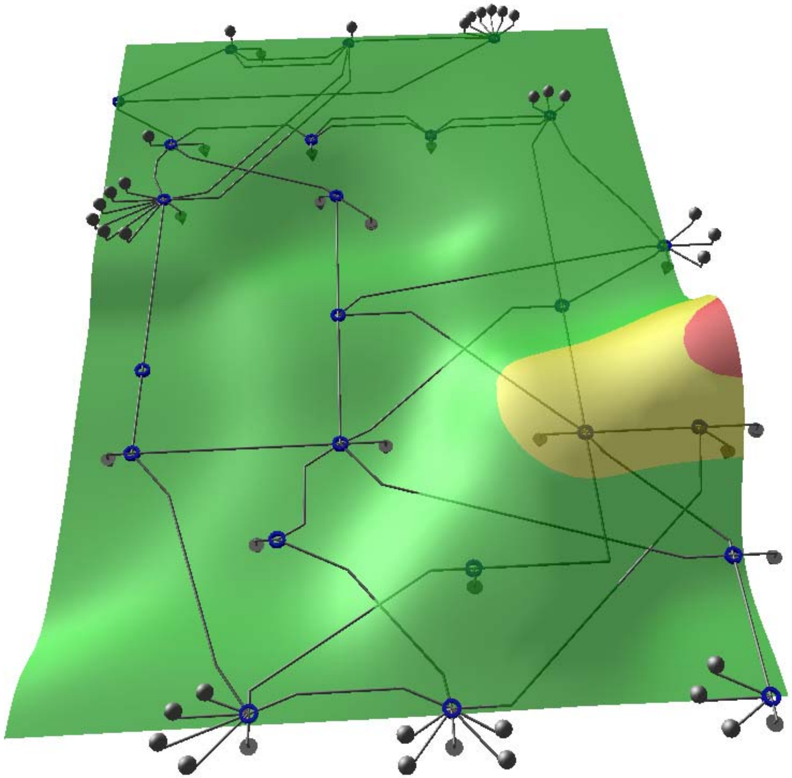
Contingency Simulation: Effects of Load Model

Steady State Operating Conditions

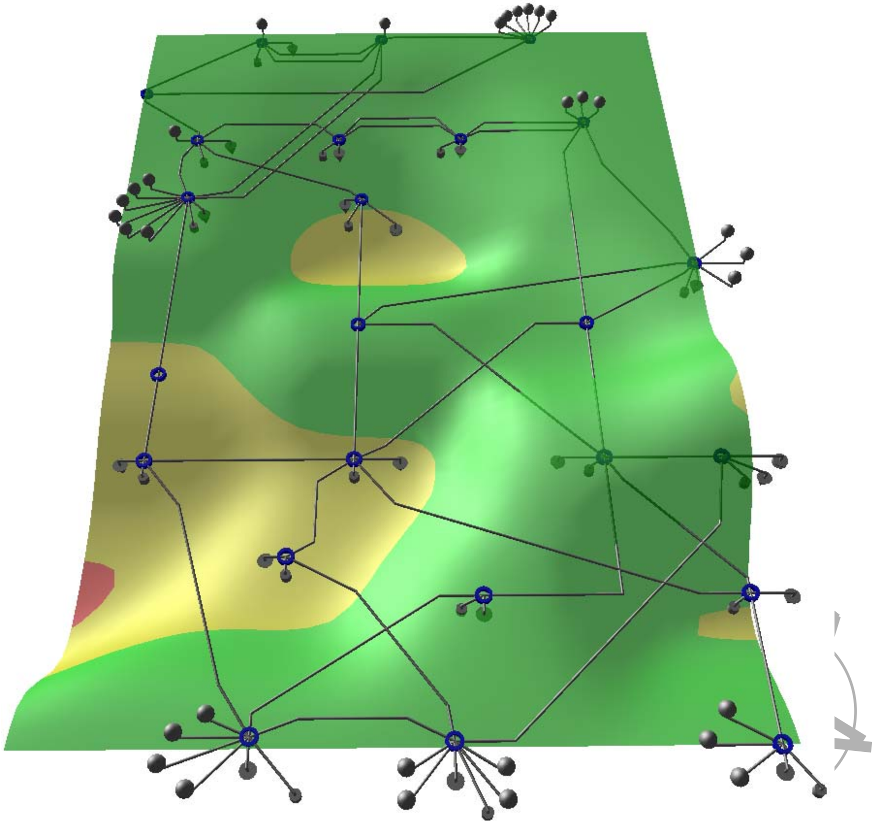
Constant Power Load

Vmax=1.105, Vmin=0.955



50% Induction Motors

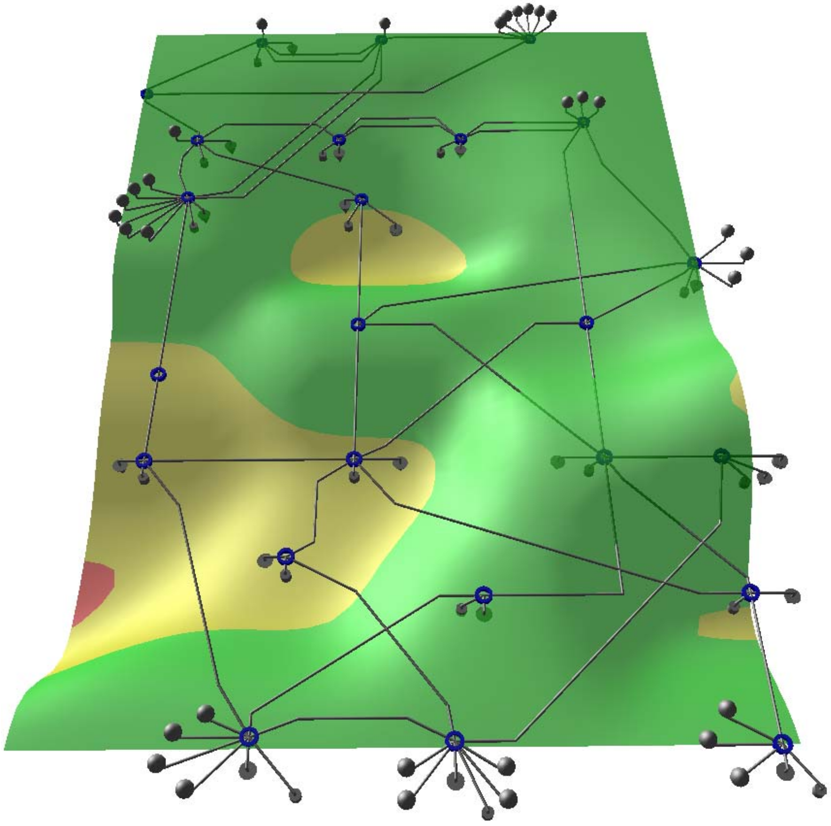
Vmax=1.046, Vmin=0.908



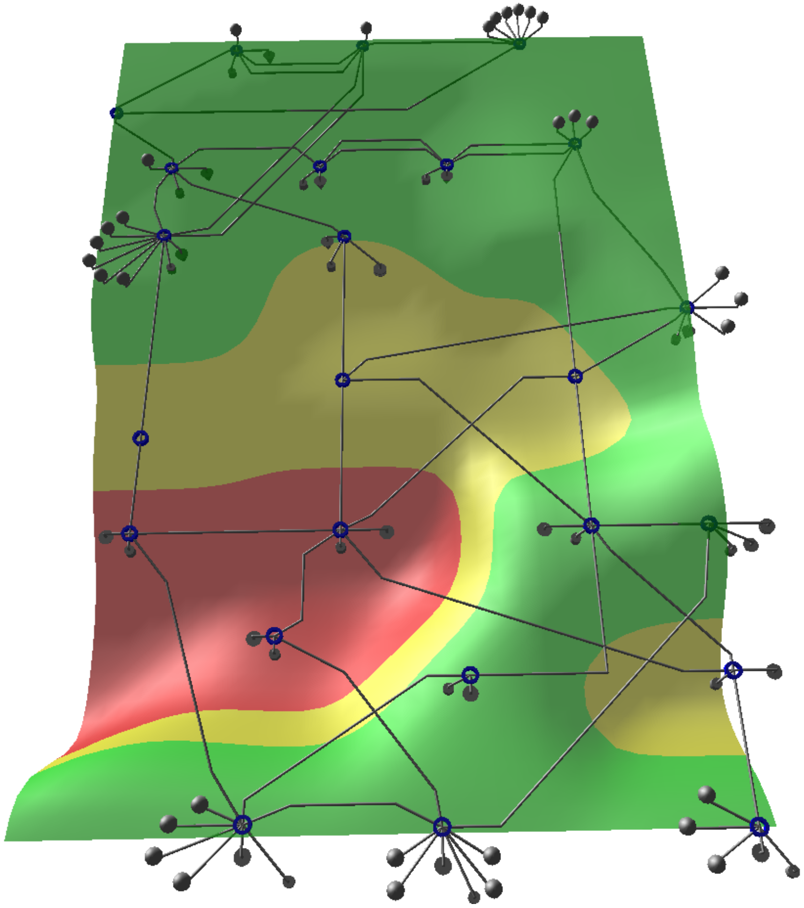
Contingency Simulation: Effects of Load Dynamics

Conditions Immediately After Fault Clearing

50% Induction Motors
Vmax=1.046, Vmin=0.908



50% Induction Motors
2% SlowDown During Fault
Vmax=1.01, Vmin=0.82



Multiple Performance Indices

Circuit-Loading Index

$$J_C = \sum_{km} W_{km} \left(\frac{\left|\tilde{I}_{km}\right|}{\bar{I}_{km}} \right)^{2n}$$

$\bar{I}_{km}$ Thermal limit of the transmission line km

$$\left|\tilde{I}_{km}\right| = \sqrt{\mathrm{Re}\left(\tilde{I}_{km}\right)^2 + \mathrm{Im}\left(\tilde{I}_{km}\right)^2}$$

$$\mathrm{Re}\left(\tilde{I}_{km}\right) = g_{km}(V_{kr} - V_{mr}) - b_{km}(V_{ki} - V_{mi}) - b_{kms}V_{ki}$$

$$\mathrm{Im}\left(\tilde{I}_{km}\right) = g_{km}(V_{ki} - V_{mi}) + b_{km}(V_{kr} - V_{mr}) + b_{kms}V_{kr}$$

Voltage Security Index

$$J_v = \sum_j W_j \left(\frac{V_j - V_{j,ave}}{V_{j,step}} \right)^{2n}$$

Reactive Power Generation Index

$$J_q = \sum_j W_j \left(\frac{Q_{gj} - Q_{gj,ave}}{Q_{gj,step}} \right)^{2n}$$

$$Q_{gj} = \sum_{m \in K(j)} Q_{jm}$$

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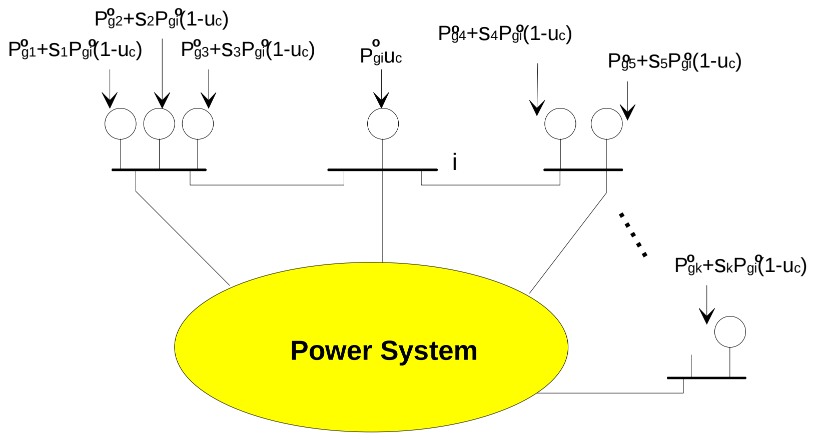
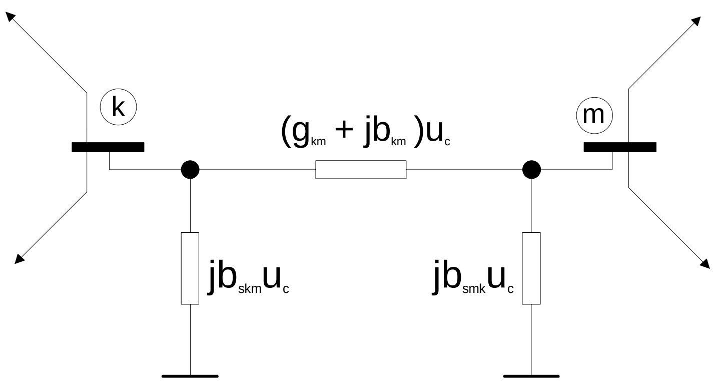
Reliability Assessment: Outage Model

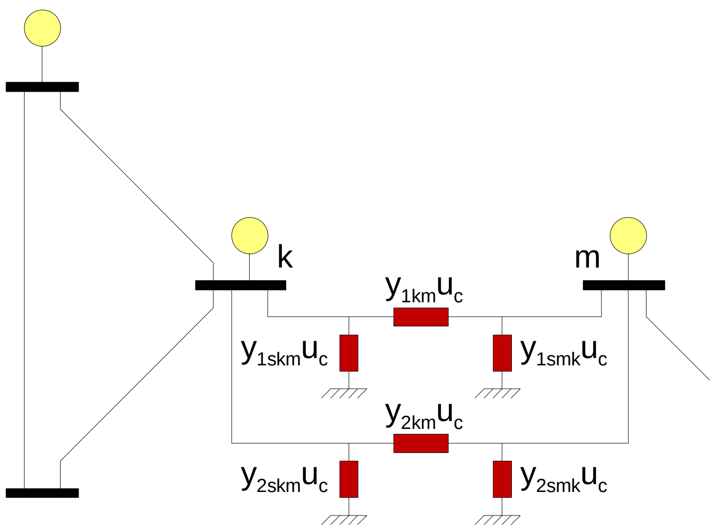
Independent Outages

Precise Modeling with the Introduction of
Outage Control Variable, u

Common Mode Outages







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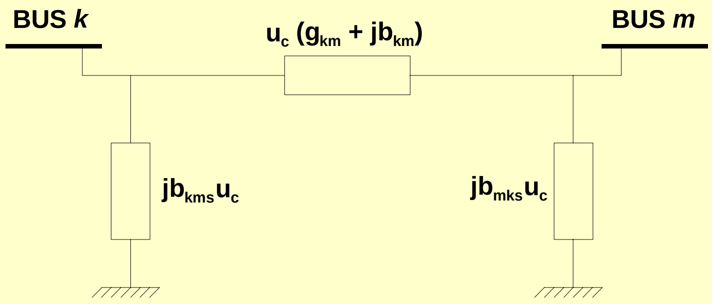
Contingency Selection – SPQPF Model

Performance Index – Current Based

More Realistic Ranking

$$J_C = \sum_{km} W_{km} \left(\frac{\left| \tilde{I}_{km} \right|}{\bar{I}_{km}} \right)^{2n}$$



$$u_c = \begin{cases} 1.0, & \text{if the component is in operation} \\ 0.0, & \text{if the component is outaged} \end{cases}$$

$$\tilde{I}_{km} = jb_{kms} u_c \tilde{V}_k + (g_{km} u_c + jb_{km} u_c)(\tilde{V}_k - \tilde{V}_m)$$

$$\hat{x}^T = \left(\frac{\partial J_C}{\partial x} \right) \left[\frac{\partial G}{\partial x} \right]^{-1}$$

Computational Efficiency

$$\left[\frac{\partial G}{\partial u_c} \right] = \begin{bmatrix} 0 \\ \vdots \\ \mathrm{Re}(\tilde{I}_{km}) \\ \mathrm{Im}(\tilde{I}_{km}) \\ 0 \\ \vdots \\ \mathrm{Re}(\tilde{I}_{mk}) \\ \mathrm{Im}(\tilde{I}_{mk}) \\ 0 \\ \vdots \end{bmatrix}$$

$$\frac{\partial J_C}{\partial u_c} = 2nW_{km} \left(\frac{\left| \tilde{I}_{km} \right|}{\bar{I}_{km}} \right)^{2n}$$

$$\frac{dJ_C}{du_c} = \frac{\partial J_C}{\partial u_c} - \hat{x}^T \left[\frac{\partial G}{\partial u_c} \right]$$

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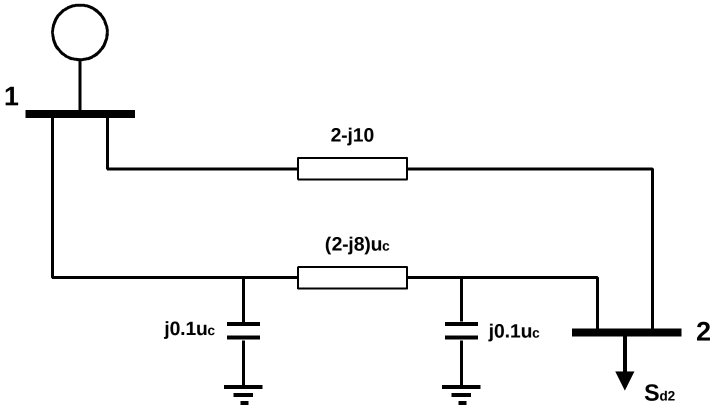

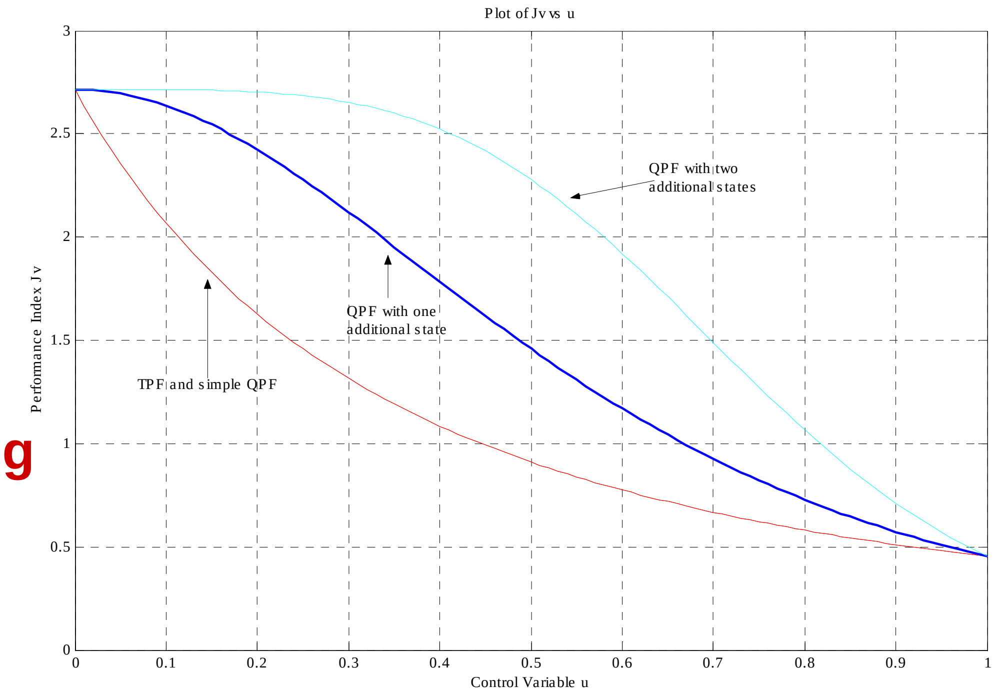

Performance Index Based Ranking

$$\frac{dJ}{du_c} = \frac{\partial J}{\partial u_c} - \hat{x}^T \frac{\partial g(x,u)}{\partial u_c}$$

Traditional Power Flow

$$J = \left(\frac{V_2 - 1.0}{0.05} \right)^2$$

$$\vec{g}(\vec{x},u_c) = \begin{bmatrix} \vec{g}_1(\vec{x},u_c) \\ \vec{g}_2(\vec{x},u_c) \end{bmatrix} = \begin{bmatrix} 4V_2^2 - 2V_2\cos\delta_2 + 10V_2\sin\delta_2 - 2V_2u_c\cos\delta_2 + 8V_2u_c\sin\delta_2 + 3 \\ (7.9u_c + 10)V_2^2 - 2V_2\sin\delta_2 - 10V_2\cos\delta_2 - 2V_2u_c\sin\delta_2 - 8V_2u_c\cos\delta_2 + 1.5 \end{bmatrix}$$

Quadratized Power Flow

$$J = z_1$$

$$\vec{g}(\vec{x},u_c) = \begin{bmatrix} \vec{g}_1(\vec{x},u_c) \\ \vec{g}_2(\vec{x},u_c) \\ \vec{g}_3(\vec{x},u_c) \\ \vec{g}_4(\vec{x},u_c) \\ \vec{g}_5(\vec{x},u_c) \\ \vec{g}_6(\vec{x},u_c) \end{bmatrix} = \begin{bmatrix} 5V_{2r} + 2V_{2r}u_c + 3V_{2r}u_1 + 11.5V_{2i} + 7.9V_{2i}u_c + 1.5V_{2i}u_1 - 2u_c - 2 \\ -11.5V_{2r} - 7.9V_{2r}u_c - 1.5V_{2r}u_1 + 5V_{2i} + 2V_{2i}u_c + 3V_{2i}u_1 + 8u_c + 10 \\ u_2 + u_1u_2 - 1 \\ V_{2r}^2 + V_{2i}^2 - u_2 \\ z_1 - z_2^2 \\ V_{2r}^2 + V_{2i}^2 - (0.05z_2 + 1)^2 \end{bmatrix}$$

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Contingency Selection – SPQPF Model

Sun Wook Kang and A. P. Meliopoulos, "Contingency Selection via Quadratized Power Flow Sensitivity Analysis", accepted for presentation and publication in the Proceedings of the IEEE/PES Summer Meeting, July 2002

Test System Result of Ranking for the circuit loading index

Contingency	Index Before Contingency	After Contingency					
		Index After Contingency		Linearized Index (TPF)		QPF Index	
		Value	Change	Value	Change	Value	Change
u_{c12}	0.30392	0.30395	0.00003	0.30394	0.00002	0.30394	0.00002
u_{c13}	0.3039	5.6357	5.3318	0.1917	-0.1122	0.5403	0.2364
u_{c14}	0.3039	4.9665	4.6626	0.4910	0.1871	0.9684	0.6645
u_{c24}	0.3039	2.7788	2.4749	0.3046	0.0007	0.3284	0.0245
u_{c34}	0.3039	0.2921	-0.0118	0.2977	-0.0062	0.2994	-0.0045

Contingency	Ranking				
	u_{c12}	u_{c13}	u_{c14}	u_{c24}	u_{c34}
Original Index	4	1	2	3	Improved
Linearized Index (Pbase)	2	improved	1	Improved	Improved
Linearized Index (TPF)	3	improved	1	2	Improved
Linearized Index (QPF)	4	2	1	3	Improved

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Remedial Actions

Control Options (u)

Shunt Capacitor Switching
Shunt Reactor Switching
Phase Shifter Adjustment
MVAR Generation
Generation Bus Voltage
Transformer Taps
FACTS Controls
Load Transfer
MW Generation
Area Interchange
Interruptible Load
Firm Load
Critical Load

Formulation

$$Min \quad f(x,u) = \mu \sum_{i \in free} |u_i| + \sum_{j \in nonfree} c_j(u_j)$$

$$subject\ to: \quad G(x,u) = 0$$

$$h(x,u) \leq 0$$

$$u_{\min} \leq u \leq u_{\max}$$

Special OPF
Linearization via Co-State
LP Solution
Very Fast

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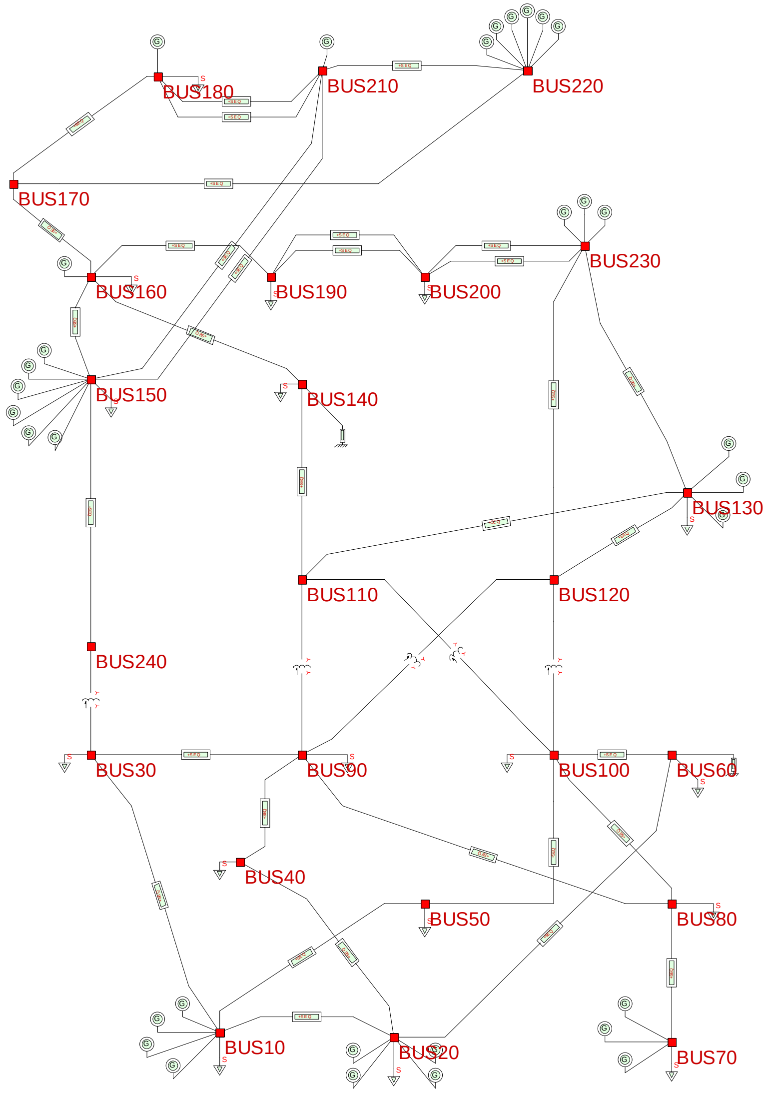
Example Results: Effects of Load Model



Constant Power Load
Single Contingencies

Probability of
Voltage Problems: 0.031

50% Induction Motors
Single Contingencies

Probability of
Voltage Problems: 0.082

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Future Direction

Complete Prototype Program (Dec 2003)

Apply Method to a Realistic System

Apply Methodology to Identify System Vulnerabilities

(Risk Assessment,
Sequence of Events that May Lead to Voltage Collapse,
Sequence of Events that may Lead to Blackout, etc.)

Extent Methodology to Probabilistic Congestion Management

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