
Presented by Dr. Xiaokang Xu
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www.pti-us.com
1. Overview of the North American Electricity Transmission Grid
AC Interconnections in North America

- 3 major interconnected systems
  - Eastern
  - Western
  - State of Texas
The North American Over 140 Control Areas

NERC Regions and Control Areas

- WECC
- MAPP
- MAAC
- ECAR
- SERC
- ERCOT
- NPCC
- MAIN

Dynamically Controlled Generation

As of January 1, 2001
HVDC Links and Power Exchanges

- **Vancouver Island**
  - McNeill: 150 MW
  - Miles City: 200 MW
  - Nelson River: 3,800 MW

- **Inter-mountain**
  - Hamil: 100 MW
  - Inter-mountain: 1,920 MW
  - Black-water: 200 MW
  - Eddy County: 200 MW
  - Oklaunton: 200 MW
  - Sidney: 200 MW
  - Square Butte: 500 MW
  - CU: 1,000 MW
  - CU: 1,000 MW
  - Highway: 200 MW

- **James Bay**
  - James Bay: 2,250 MW

- **Eel River**
  - Eel River: 320 MW

- **Madawaska**
  - Madawaska: 350 MW

- **Eel River**
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- **Madawaska**
  - Madawaska: 350 MW

- **Sandy Pond**
  - Sandy Pond: 1,000 MW

- **Chateauguay**
  - Chateauguay: 1,000 MW

- **Highgate**
  - Highgate: 1,000 MW

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- **Chateauguay**
  - Chateauguay: 1,00 Siemens Energy, Inc. Siemens Power Technologies International 5
# U.S. High-Voltage Transmission System

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Miles of Transmission Line</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AC</strong></td>
<td></td>
</tr>
<tr>
<td>230 kV</td>
<td>76,762</td>
</tr>
<tr>
<td>345 kV</td>
<td>49,250</td>
</tr>
<tr>
<td>500 kV</td>
<td>26,038</td>
</tr>
<tr>
<td>765 kV</td>
<td>2,453</td>
</tr>
<tr>
<td><strong>Total AC</strong></td>
<td><strong>154,503</strong></td>
</tr>
<tr>
<td><strong>DC</strong></td>
<td></td>
</tr>
<tr>
<td>250-300 kV</td>
<td>930</td>
</tr>
<tr>
<td>400 kV</td>
<td>852</td>
</tr>
<tr>
<td>450 kV</td>
<td>192</td>
</tr>
<tr>
<td>500 kV</td>
<td>1,333</td>
</tr>
<tr>
<td><strong>Total DC</strong></td>
<td><strong>3,307</strong></td>
</tr>
<tr>
<td><strong>Total AC &amp; DC</strong></td>
<td><strong>157,810</strong></td>
</tr>
</tbody>
</table>
Capacity vs Demand Growth in U.S.
Measure of Reliability

- **Adequacy** - The ability of the electric systems to supply the aggregate electrical demand and energy requirements of their customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.

- **Security** - The ability of the electric systems to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements.

- **Integrity** - The ability of the system to remain interconnected and operation under extreme events.

- **Restorability** - The ability of system speedy recovery or restoration following contingencies.

- **Transfer Capability** - The ability of the system to move power from one region to another.
NERC Regions Responsible for Reliability

NERC REGIONS

Siemens Energy, Inc.
## NERC Planning/Reliability Criteria (www.nerc.com)

<table>
<thead>
<tr>
<th>Category</th>
<th>Contingencies</th>
<th>System Limits or Impacts</th>
<th>Cascading Outages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initiating Event(s) and Contingency Element(s)</td>
<td>System Stable and both Thermal and Voltage Limits within Applicable Rating&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Loss of Demand or Curtailed Firm Transfers</td>
</tr>
<tr>
<td>A</td>
<td>All Facilities in Service</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
| B        | Single Line Ground (SLG) or 3-Phase (3O) Fault, with Normal Clearing:  
1. Generator  
2. Transmission Circuit  
3. Transformer  
Loss of an Element without a Fault.  
Single Pole Block, Normal Clearing<sup>b</sup>:  
4. Single Pole (dc) Line | Yes | No<sup>b</sup> | No |

<sup>a</sup>Applicable Rating is determined by the utility based on system configuration and operational considerations.

<sup>b</sup>Loss of demand and curtailed firm transfers are considered based on the specific contingencies and network conditions at the time of the event.
### NERC Planning/Reliability Criteria (Cont’d)

<table>
<thead>
<tr>
<th>Event(s) resulting in the loss of two or more (multiple) elements</th>
<th>Yes</th>
<th>Planned/Controlled</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SLG Fault, with Normal Clearing</strong>&lt;sup&gt;a&lt;/sup&gt;:</td>
<td>1. Bus Section</td>
<td>Yes</td>
<td>Planned/Controlled&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>2. Breaker (failure or internal Fault)</td>
<td>Yes</td>
<td>Planned/Controlled&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
</tr>
<tr>
<td><strong>SLG or 3Ø Fault, with Normal Clearing</strong>&lt;sup&gt;a&lt;/sup&gt;, Manual System Adjustments, followed by another SLG or 3Ø Fault, with Normal Clearing&lt;sup&gt;a&lt;/sup&gt;:</td>
<td>Yes</td>
<td>Planned/Controlled&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
</tr>
<tr>
<td>3. Category B (B1, B2, B3, or B4) contingency, manual system adjustments, followed by another Category B (B1, B2, B3, or B4) contingency</td>
<td>Yes</td>
<td>Planned/Controlled&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
</tr>
<tr>
<td><strong>Bipolar Block, with Normal Clearing</strong>&lt;sup&gt;a&lt;/sup&gt;:</td>
<td>Yes</td>
<td>Planned/Controlled&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
</tr>
<tr>
<td>4. Bipolar (dc) Line Fault (non 3Ø), with Normal Clearing&lt;sup&gt;a&lt;/sup&gt;:</td>
<td>Yes</td>
<td>Planned/Controlled&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
</tr>
<tr>
<td>5. Any two circuits of a multiple circuit towerline&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Yes</td>
<td>Planned/Controlled&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
</tr>
<tr>
<td><strong>SLG Fault, with Delayed Clearing</strong>&lt;sup&gt;a&lt;/sup&gt; (stuck breaker or protection system failure):</td>
<td>Yes</td>
<td>Planned/Controlled&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
</tr>
<tr>
<td>6. Generator</td>
<td>Yes</td>
<td>Planned/Controlled&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
</tr>
<tr>
<td>7. Transformer</td>
<td>Yes</td>
<td>Planned/Controlled&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
</tr>
<tr>
<td>8. Transmission Circuit</td>
<td>Yes</td>
<td>Planned/Controlled&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
</tr>
<tr>
<td>9. Bus Section</td>
<td>Yes</td>
<td>Planned/Controlled&lt;sup&gt;b&lt;/sup&gt;</td>
<td>No</td>
</tr>
</tbody>
</table>
**NERC Planning/Reliability Criteria (Cont’d)**

<table>
<thead>
<tr>
<th>Extreme event resulting in two or more (multiple) elements removed or Cascading out of service</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>D</strong></td>
</tr>
<tr>
<td>1. Generator</td>
</tr>
<tr>
<td>2. Transmission Circuit</td>
</tr>
<tr>
<td>3. Transformer</td>
</tr>
<tr>
<td>4. Bus Section</td>
</tr>
</tbody>
</table>

| **3Ø Fault, with Normal Clearing** |
| 5. Breaker (failure or internal Fault) |

| **3Ø Fault, with Delayed Clearing** (stuck breaker or protection system failure) |
| 6. Loss of towerline with three or more circuits |
| 7. All transmission lines on a common right-of-way |
| 8. Loss of a substation (one voltage level plus transformers) |
| 9. Loss of a switching station (one voltage level plus transformers) |
| 10. Loss of all generating units at a station |
| 11. Loss of a large Load or major Load center |
| 12. Failure of a fully redundant Special Protection System (or remedial action scheme) to operate when required |
| 13. Operation, partial operation, or misoperation of a fully redundant Special Protection System (or Remedial Action Scheme) in response to an event or abnormal system condition for which it was not intended to operate |
| 14. Impact of severe power swings or oscillations from Disturbances in another Regional Reliability Organization |

Evaluate for risks and consequences:

- May involve substantial loss of customer Demand and generation in a widespread area or areas.
- Portions or all of the interconnected systems may or may not achieve a new, stable operating point.
- Evaluation of these events may require joint studies with neighboring systems.
2. New York State/New York Independent System Operator (NYISO) Grid
1) facilitates open access of the electric transmission system, 2) manages dispatch of generation and congestion, and 3) administers a regional spot market for energy, capacity, and ancillary services. The coordination of these three activities under a centralized operation serves to enhance the stability and reliability of the regional power grid.
The NYISO Geographic Map

- Began operation in December 1, 1999 from NYPP.
Transmission System and Key Interface

New York ISO Transmission System
(230 kV and above)
Statistics and Key Interfaces

Statistics
- 18.9 million people (12+ in New York City)
- Serving the nation’s largest city and most populated metropolitan area
- Supply of 160,000 GWH
- 765, 345, 230, 138 and 115 kV
- 10,755 miles of high voltage transmission
- Over 335 generating units

Key Interfaces
- Total East
- Central East
- Upstate New York (UPNY) - Southeast New York (SENY)
- Upstate New York (UPNY) - Con Edison (CE)
- NYISO-ISO-NE
- NYISO-PJM
The New York Control Area and Interfaces

New York Control Area Transmission System

HQ

OH
A B C D E

Dys. East West Cent Vol. East

Moses South

D - TE W

E - TE W

Total East

Cent. East

Mardy S.

NE

F

F - SUM

UPNY/SENY

UPNY/CE

Mill. South

Y49/50

Li = 99%
Ros = 19%

LIPA

Dunrod South

In-City = 80%
Ros = 38%

PJM

PJM Dum

Siemens Power Technologies International
Utilities or Transmission Owners (TO) in NYS

- Central Hudson Gas & Electric Corporation
- Consolidated Edison Company of New York, Inc.
- Long Island Power Authority
- National Grid, USA
- New York State Electric & Gas Corporation
- Rochester Gas & Electric Corporation
- Power Authority of the State of New York
New York State Power Markets

Buying Power in New York

- Bilateral Contracts outside the NYISO Markets: 50%
- NYISO Day-Ahead Market: 45 - 50%
- NYISO Real-Time Market: <5%
New York State LMP Zones
3. Steady-State Analysis
Power Flow Analysis

- Development of power flow models (base case, various scenarios, stressed transfer case, summer, winter, peak, shoulder, light, etc)

- DC and AC power flow solutions

- Non-divergent power flow solution
Automatic Contingency Analysis

- Contingency Enumeration Approach – Transmission Assessment
- Monte Carlo Simulation – Generation Assessment
Deterministic & Probabilistic Contingency Assessment

- Define: Operating Limits, Monitored Sub-systems, Corrective Actions, Generators for Realignment
- Base Case Power Flow
- Contingency List
- Evaluate Each Contingency
- Classify Results
  - No trouble
  - Local trouble (Overload, Low Voltage, High Voltage, Islanding, Load Shed)
  - System trouble (Voltage Collapse, Cascading Outage)
- Calculate Probabilistic Trouble Indices
## System Problems & Customer Impacts

<table>
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<tr>
<th>Assessment Approach</th>
<th>Criteria</th>
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<tbody>
<tr>
<td>Deterministic</td>
<td>No criteria violation</td>
</tr>
<tr>
<td>Go – no go!</td>
<td></td>
</tr>
<tr>
<td>Probabilistic System Problems</td>
<td>Frequency of system problem &lt; x/year</td>
</tr>
<tr>
<td>Probabilistic – Consumer Impact</td>
<td>Curtailed load or energy MWh &lt; y/year</td>
</tr>
</tbody>
</table>

**Probabilistic Reliability Indices: Frequency, Duration & Severity (LOLE, EUE)**
Probabilistic Contingency Case Study

Deterministic: Line is overloaded for outage of a parallel circuit

Probabilistic: Line is overloaded once a year with average duration of 2.5 hours
Probabilistic Contingency Case Study (Cont’d)

System: Line is overloaded for outage of a parallel circuit

Customer: 25 MW of load is curtailed on outage of a circuit
Voltage Stability Analysis

• Voltage Stability:
  - Small-disturbance voltage stable – voltages near loads being identical or close to pre-disturbance values
  - Voltage stable – voltages near loads approaching post-disturbance equilibrium values

• Voltage Instability:
  - Loss of an equilibrium condition
  - An uncontrolled decay in voltage
  - Ultimately leading to "voltage collapse"

• Voltage Collapse:
  - Sudden and quick drop in voltage some minutes after loss of equilibrium
  - Stalling of induction motors and then dropping out of motors
  - Causing cascading outages
  - Leading to widespread blackout
Analytical Approaches for Voltage Stability Analysis

- Steady-State Voltage Analysis
  - P-V and Q-V Curves
  - Optimal Power Flow (OPF)

- Dynamic Voltage Analysis
  - Long Term Dynamic Simulation
P-V Curve Analysis

- Voltage
- Real Power
- Post-contingency case
- Pre-contingency case
- System load or interface flow
- Margin
Q-V Curve Analysis
Application of Voltage Criteria – Reactive Margin

- Maximum reactive change at most critical bus under worst single contingency plus 5% load increase for Level A:
Required Reactive Margin

- After installing reactive power support:
Application of Voltage Criteria – MW Margin

- 5% for worst single contingency at critical bus for Level A (0.05x500=75 MW):
- Maximum allowable interface flow: 1425 MW
Voltage Stability Case Study
Voltage Stability Case Study (Cont’d)

- Voltage (P.U.)
  - 0.40 0.50 0.60 0.70 0.80 0.90 1.00
  - 0 100 200 300 400 500

- Reactive Power Margin (MVAR)
  - -550 -500 -450 -400 -350 -300 -250 -200 -150 -100 -50 0

- N-1 105% = -125 MVAR
- N-1 100% = -130 MVAR
- N-0 = -500 MVAR
## Voltage Stability Case Study (Cont’d)

<table>
<thead>
<tr>
<th>Contingency</th>
<th>Voltage Bus</th>
<th>Reactive Power Margin (MVAR)</th>
<th>Required Margin (MVAR)</th>
<th>Meeting Voltage Criteria?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N-0 Base Load</td>
<td>N-1 Base Load</td>
<td>N-1 Base Load+5%</td>
</tr>
<tr>
<td>SMOKYHIL-PEAKVIEW 115 kV</td>
<td>DAVIDSON 115 kV</td>
<td>500</td>
<td>130</td>
<td>125</td>
</tr>
<tr>
<td>ARAPAHO-ENGL3TP 115 kV</td>
<td>ENGL3TP 115 kV</td>
<td>530</td>
<td>120</td>
<td>110</td>
</tr>
</tbody>
</table>
Optimal Power Flow

**Typical Applications:**
- Reduce system losses
- Minimize fuel cost
- Voltage instability/collapse analysis
- Shunt compensation requirements
- Series compensation requirements
- Identify load shed strategy to resolve system problems
- Determine maximum power transfer capability
- Must-run generation assessment and congestion management
- Location based marginal cost assessment
Conventional vs. Optimal Power Flow

Conventional Power Flow

- Constraints - power balance equation
- Controls - generator reactive output, transformer taps, phase shifter angles
- Objectives - control local bus voltages
Conventional vs. Optimal Power Flow

Optimal Power Flow

- Objectives are global - e.g., minimize losses in entire system

- Constraints
  - equality, power balance equation
  - inequality, e.g., generator var limits, transformer tap ranges

- Controls - MW dispatch, taps, phase shift angles, shunt capacitor addition, series compensation level, load shed
Example

Single bipolar outage imposes a significant stress on the interconnection

500 kV bipole taken out of service

Weaker lines
### Case Information

<table>
<thead>
<tr>
<th>Buses</th>
<th>Generation Areas Zones Owners Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL PQ&lt;&gt;0, PQ=0, PE/E PE/Q SWING OTHER LOADS PLANTS MACHS USED USED USED TRANS</td>
<td></td>
</tr>
<tr>
<td>10347</td>
<td>5850 2969 1084 411 32 6521 1553 1897 36 200 1 22</td>
</tr>
<tr>
<td>AC Branches</td>
<td>Multi-Section DC Lines Facts</td>
</tr>
<tr>
<td>TOTAL RXB RX RXT RX=0. IN OUT LINES SECTNS 2-TRM N-TRM DEVS</td>
<td></td>
</tr>
<tr>
<td>20217</td>
<td>7666 7254 5223 74 19982 235 0 0 10 0 0</td>
</tr>
</tbody>
</table>

| Generation PQLoad | I LOAD Y LOAD SHUNTS CHARGING LOSSES SWING |
|-------------------|-----------------|-----------------|-----------------|-----------------|
| MW 500548.6 496473.2 | 0.0 | 0.0 | -5206.6 | 0.0 | 9283.1 | 848.6 |
| MVAR 104888.5 176975.0 | 0.0 | 0.0 | -152071.9 | 47949.6 | 127394.2 | -26.5 |

TOTAL MISMATCH = 2463.38 MVA X-----AT BUS-----X SYSTEM X------SWING-----X
MAX. MISMATCH = 641.54 MVA 3469 DC6 JCT4 230 BASE 71219 8BFNP 500
HIGH VOLTAGE = 1.15589 PU 6371 MARATHON 220 100.0
LOW VOLTAGE = 0.84313 PU 52166 XYROFIN 34.5 ADJTHR ACCTAP TAPLIM THRSNWZ 0.0050 1.0000 0.0500 0.000100

X-------SOLV AND MSLV-------X X---NEWTON---X X------TYSL------X BLOW PQ
ACCP ACCQ ACCM TOL ITER ACCN TOL ITER ACCTY TOL ITER UP BRK
1.600 1.600 1.000 0.00010 100 1.00 0.250 100 1.000 0.000010 20 5.0 0.70

PTI INTERACTIVE POWER SYSTEM SIMULATOR--PSS/E THU, MAY 06 1999 10:40
WSAA.5DDVZTY.SAV;WINTER;PK LD 2002;SYSTEM INTACT : WORST
ND=100, MH=500, TC=250, MHOH=200, OHMP=-100, EWTW=-100, BD=-100 MISMATCHES

<table>
<thead>
<tr>
<th>Bus</th>
<th>Name</th>
<th>BSKV</th>
<th>MW</th>
<th>MVAR</th>
<th>MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>3469</td>
<td>DC6</td>
<td>JCT4 230</td>
<td>-582.00</td>
<td>269.90</td>
<td>641.54</td>
</tr>
<tr>
<td>3468</td>
<td>DC5</td>
<td>JCT4 230</td>
<td>-582.00</td>
<td>269.90</td>
<td>641.54</td>
</tr>
<tr>
<td>71644</td>
<td>05GAVIN</td>
<td>765</td>
<td>17.00</td>
<td>0.01</td>
<td>17.00</td>
</tr>
<tr>
<td>71589</td>
<td>02MANSFD</td>
<td>345</td>
<td>15.11</td>
<td>0.01</td>
<td>15.11</td>
</tr>
</tbody>
</table>

Not solved
The Problem at Hand

Two questions need to be addressed:

1. How much var support is needed to overcome the outage and prevent voltage instability/collapse?

2. Without imposing changes in var support, what’s the maximum power that can be transferred across the interface without causing voltage instability?
## OPF Results - 2nd Run (Cont’d)

### Summary Table for Added Shunt (MVar):

<table>
<thead>
<tr>
<th>Bus</th>
<th>Name</th>
<th>Area</th>
<th>Zone</th>
<th>Initial</th>
<th>Final</th>
<th>Change</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Cost</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>709</td>
<td>LANGDON7</td>
<td>115</td>
<td>14</td>
<td>0.000</td>
<td>80.136</td>
<td>-5000.000</td>
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Total: 0.00 152.82

### Voltage check … no violations!

**BUSES WITH VOLTAGE LESS THAN 0.9000:**

<table>
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<tr>
<th>BUS</th>
<th>✗ ✗ ✗</th>
<th>AREA</th>
<th>V(PU)</th>
<th>V(KV)</th>
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* NONE *

---

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Must-Run Generation

- Must-Run Generation
  - Generation required to be on-line for reliability criteria, for meeting load demand in constrained areas, and for voltage and reactive support.
  - dependant on load pockets and transmission constraints or bottlenecks.

- Market Power
  - Merchants seek to install quick generation sources where constraints occur.

- Congestion Management
  - Removing or relieving transmission congestion by corrective actions including must-run generation.
Load Pockets/Local Areas

- Load Center
  - Some local generation
  - Not sufficient transmission capacity to import power (transmission bottlenecks)
Transfer Limit Analysis

- Power Increment
- Sending/Export Area
- Receiving/Import Area
- Interface
Constraints for Transfer Capability (NERC Definition)

**TTC - Total Transfer Capability:** amount of power that can be transferred over the interconnected transmission network (or over a interconnection) in a reliable manner, within all of the pre- and pos-contingency criteria adopted for that particular network.

\[
\text{Total Transfer Capability (TTC)} = \text{Minimum of \{Thermal Limit, Voltage Limit, Stability Limit\}}
\]

![Diagram showing Power Flow, Stability limit, Voltage limit, Thermal limit, and TTC over time.](image)
ATC Calculation Methods

- Linear method
  - Interpolation
  - Distribution factor

- AC power flow

- Dynamic simulation
## Sample Output of AC Transfer Limit Analysis

### AC TRANSFER LIMIT TABLE

<table>
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<th>INTERF</th>
<th>INCR.</th>
<th>LIMITS TRANSF</th>
<th>LIMITING ELEMENTS</th>
<th>CRITERION</th>
<th>DT/DL</th>
<th>DT/DV</th>
<th>CONTINGENCY</th>
<th>DESCRIPTION</th>
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<td>(MW)</td>
<td>From BUS</td>
<td>To BUS</td>
<td>ID</td>
<td>(MW/MVA MW/KV)</td>
<td>From BUS</td>
<td>To BUS</td>
<td>ID</td>
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<tr>
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<td>221 NUKE-B</td>
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<td>V.C.</td>
<td>211 MIDTIE-2</td>
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**Base Case**

---

---
Short Circuit Calculation

**Symmetrical Component Method**

- **Equations**:
  
  \[ V_{c2} = V_{a1} + V_{b2} + V_{c0} \]
  
  \[ V_{a2} = V_{c1} + V_{b2} + V_{a0} \]
  
  \[ V_{b1} = V_{c1} + V_{a2} + V_{b0} \]
  
  \[ V_{a0} = V_{a1} + V_{a2} + V_{a0} \]
  
  \[ V_{b0} = V_{b1} + V_{b2} + V_{b0} \]
  
  \[ V_{c0} = V_{c1} + V_{c2} + V_{c0} \]

- **Diagram**:
  - Three-phase voltage vectors
  - Symmetrical components
  - Notation for voltage components
Modeling and Assumptions

- All generating units, lines and feeders are in service. Synchronous machines (e.g., generators, synchronous condensers, and large motor groups) are modeled using sub-transient saturated reactance ($X_{dv}$). Machine zero-sequence reactance ($X_{0v}$) generally is not required in short-circuit studies.

- Transmission line models include positive- and zero-sequence inductive impedances. Negative-sequence impedance is equal to the positive-sequence impedance and hence not entered separately. Zero-sequence mutual impedances between mutually-coupled line sections, such as those on common rights-of-way, are also included. Positive-sequence mutuals are normally ignored, but can be combined with line impedance in some situations, if needed. Capacitive admittances of lines (line charging), both positive- and zero-sequence, are omitted.
Modeling and Assumptions (Cont’d)

- All transformers are modeled using leakage reactance and load-loss based resistances. Tap ratios for load-tap changing transformers are assumed to be 1:1 (or center tap); phase-angle regulating transformers are assumed on the lowest impedance setting (typically center tap and / or 0-degree shift), and magnetizing branches are omitted. Transformer positive- and negative sequence impedances are identical, and zero-sequence impedances are assumed identical to positive-sequence impedances unless test data indicate otherwise. All windings are modeled with proper winding/grounding connections. 30 degree phase shift in delta-wye connections is considered.

- All fault current-limiting series reactors are in service. Load current-limiting series reactors are represented only if switched permanently into service. Series capacitors are bypassed during close-in faults that exceed the capacitor normal rating (consistent with the series element protection); otherwise, they remain in service.
All loads, shunt capacitors, and shunt reactors are ignored except those shunts used in the representation of three winding transformers. Static VAr Compensators, Static Shunt or Series Compensators (FACTs devices), traditional HVdc converters, and other power-electronic devices are normally omitted, except that any transformers integrating these facilities into a power system are included. Voltage Source Converter HVdc is represented as an equivalent generator source, where appropriate.

All generator internal voltages are set at 1.0 p.u. and no phase displacement due to load.
Types of Faults

- Three Line to Ground
- Double Line to Ground
- Single Line to Ground

All faults are assumed to be a zero-impedance fault with no current limiting effect due to the fault itself.

Fault currents through each interrupting device shall be analyzed for the following fault conditions under all normal system and single contingency system configurations:
  - Bus Fault
  - Close-in Line-end Open Fault
4. Dynamic Simulations
Transient Stability Assessment

- **Modeling Requirements:**
  - Generators – 6th order model (sub-transient)
  - Exciters and governors - IEEE, Manufacturer, etc.
  - Loads – constant power, current and impedance
    - Real power load in NYISO practice:
      1. constant current for Hydro Quebec, New Brunswick, MAAC, and ECAR
      2. constant impedance for New York and New England
      3. 50% constant current and 50% constant impedance for Ontario and Nova Scotia.
    - Reactive load was modeled as constant impedance for all Areas except Hydro Quebec, which uses a 13% constant current and 87% constant impedance model for reactive load.
Transient Stability Assessment (Cont’d)

- HVDC generic and project-oriented models:
  - Generic models permit to simulate HVDC transmission or back-to-back response to changes in the adjacent ac systems, e.g. blocking HVDC in case of ac voltage drop, without taking into account the internal dynamics of the HVDC line and its controls.
  - Project-oriented models allow to simulate an HVDC as an element of the power system, along with the internal dynamics of the line and its controls.

- FACTS models:
  - SVC (standard)
  - TCSC (standard)
  - STATCOM (standard)
  - UPFC (user-defined)
Explicit Numerical Integration

- 15-30 seconds to keep tracking of damping
- 3 phase with normal clearing and single phase to ground with delayed clearing
- extreme disturbances: 3-ph with stuck breaker; loss of an entire substation or plant, loss of all circuits on a tower or the same right-of-way, testing the strength of the grid w.r.t. voltage instability or collapse and rotor angle instability
Long Term Dynamic Simulation

- Slow response and process

![Graph showing voltage over time with events like LINE TRIP, LTCs MOVE, EXCIT'N LIMITING, LOADS SELF-RESTORE (if LTCs HIT LIMITS), CAP BANKS WITH UNDervoltage RELAYS, and UNDervoltage LOAD SHEDDING.](image)
Long Term Dynamic Simulation (Cont’d)

- Additional Modeling Requirements
  - Maximum and minimum excitation limiters
  - On-line tap changers and phase shifters
  - Switched or thyristor-controlled capacitors
  - Self-restoring loads
  - Load dynamics
  - Under-voltage load shedding
  - Relay protections
  - Boiler effects

- Implicit Integration
Long Term Dynamic Simulation (Cont’d)

Complex Load Model

\[ P + jQ \]

\[ T_{ap} \]

\[ R + jX \]

\[ \frac{P_o}{P_o} \]

\[ P_o = \text{Load MW in pu on system base} \]

- Large Motors
- Small Motors
- Discharge Lighting
- Transformer Saturation
- Constant MVA
- Remaining Loads

\[ P = P_{RO} \times V^{K_P} \]

\[ Q = Q_{RO} \times V^2 \]
Long Term Dynamic Simulation (Cont’d)

- On-Line tap Changers

![Diagram of On-Line tap Changers]

- Measuring Element:
  - $t_1 = 0$ for $e = 0$ or $\Delta n \neq 0$
  - $t_1 = t_1 + \Delta t$ otherwise
  - $T_d = T_{d0}$ for first tap
  - $T_d = T_{d1}$ for subsequent taps

- Time Delay Element:
  - $0$ for $t_1 \leq T_d$, $e = \text{arbitrary}$
  - $b = \begin{cases} 
    1 & \text{for } t_1 > T_d, \ e = 1 \\
    -1 & \text{for } t_1 > T_d, \ e = -1 
  \end{cases}$

- Motor Drive Unit and Tap Changer Mechanism:
  - $t_2 = 0$ for $b = 0$
  - $t_2 = t_2 + \Delta t$ for $b \neq 0$
  - $\Delta n = \begin{cases} 
    0 & \text{for } t_2 \leq T_m, \ b = \text{arbitrary} \\
    1 & \text{for } t_2 > T_m, \ b = 1 \\
    -1 & \text{for } t_2 > T_m, \ b = -1 
  \end{cases}$
Long Term Dynamic Simulation (Cont’d)

**Maximum excitation limit**

\[
\begin{align*}
\text{EFD}_{\text{DES}} \times \text{EFD}_{\text{RATED}} + \text{EFD} & \rightarrow (\Sigma) \rightarrow \text{KMX} \rightarrow \text{VOEL to Regulator} \\
\text{EFD}_{\text{DES}} \text{ or } \text{IFD}_{\text{DES}} + \text{EFD or IFD} & \rightarrow (\Sigma) \rightarrow \frac{\text{KMX}}{S} \rightarrow \text{VOEL to Regulator}
\end{align*}
\]
Induction motor modeling (5th order):
- Same level of modeling as generator
- Considering rotor dynamics or sub-transients
- Speed deviation equation
- No angle equation
Self-restoring load
Comparing Load Models
Long Term Dynamic Simulation (Cont’d)

- Under-voltage load shedding:
  - 3 voltage setpoints
  - 3 relay/breaker pickup times
  - 3 fractions of load shed
Long Term Dynamic Simulation Example

![Graph showing voltage and tap ratio over time](image)
Long Term Dynamic Simulation Example (Cont’d)
Long Term Dynamic Simulation Example (Cont’d)
Long Term Dynamic Simulation Example (Cont’d)
Long Term Dynamic Simulation Example (Cont’d)
5. Introduction to Analytical Tools and Software
Power System Simulator for Engineering (PSS®E)

- Most comprehensive and commercial package:
  - Power Flow
  - Optimal Power Flow
  - Transient Stability
  - Fault Analysis
  - Transfer Capability Analysis
  - Automatic Contingency Analysis
  - Long/Extended Term Simulation
  - Small Signal Stability (Eigenvalue and Eigenvector)
PSS®E World User Base

PSS®E is the most capable package for transmission system analysis available today:

- Installed in 130 Countries Including China
- Over 700 customers world wide
- More than 50000 users
- Over 85% market share
- Unquestioned industry leader
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PSS®E Users in Asia

- South Korea
- Singapore
- Malaysia
- Indonesia
- Philippines
- Mongolia
- Laos
- Thailand
- Vietnam
- Others…….
PSS®MUST (Managing and Utilizing System Transmission)

- Extremely fast linear transfer analysis:
  - 1000s time faster than complete AC analysis
  - Graphic Interface & Interactive Analysis, Excel
  - Many features and functions providing complete set of analysis to assess transfer capabilities of the power system
  - AC based contingency and transfer limit analysis
  - PSS/E compatible

- PSS®MUST Applications
  - Super Fast N-1 Transfer Limit Analysis (DC or AC)
  - Transaction Interaction, Impact And Sensitivity Analysis (DC).
  - Premier Tool For New Generators Impact And Siting Studies (DC)
  - Parallel Transfers (DC)
  - Worst Dispatch (DC)
  - Contingency Analysis (AC)
PSS®MUST (Cont’d)
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Thank You!