Transmission Planning
An Introduction
Transmission Planning

• Primary Purpose of Transmission Planning - to determine the lowest possible cost, transmission and substation additions which render the transmission network to be able to supply the loads and facilitate wholesale power marketing with a given criteria

• Issues & Factors in A Transmission Planning Study
  • Planning Period
  • Load Forecast and transmission usage projection
  • Generation Resources (Location, Type, etc.)
  • Discrete Transmission Capacities
  • Different Alternatives
  • End Effects
  • Economy of Scale
  • Economic and Financial Constraints
  • R-O-W Limitations
  • New and Emerging Technology
  • Various Uncertainties and Risks
  • Service Reliability and Cost Considerations
Transmission Planning Section

• Forecasts and consideration of uncertainties:
  • Load forecasting
  • Forecasts of generation patterns and other factors that may influence transmission needs

• Postulation of reinforcement alternatives

• Analysis and reliability testing of reinforcement alternatives
  • Load flow studies for flow, voltage, and transmission loss evaluations
  • Contingency load flow analysis for alternatives to meet reliability criteria
  • Stability analysis to verify that alternatives meet reliability criteria.
  • Short circuit tests to verify that existing or new breakers will be able to interrupt faults within their ratings.
  • Other studies including voltage sag studies.
  • Alternative methods

• Prioritization and tentative timing of transmission reinforcements
WHAT IS A WELL PLANNED SYSTEM

- ADEQUACY -- Normal and Contingency
- BALANCE -- Size & Strength
  - Provide Proper Economic Signals to the Competitive Market Place
- MAINTAINANCE -- Effective, Efficient, Suitable & Flexible
- SAFETY & PROTECTION
- RECOVERY -- Restoration
Planning Methodology

- Develop Base Cases
- Define Generation Scenarios
- Develop Horizon Year Alternatives
- Test with Planning Criteria
- Technical Evaluation of Alternatives
- Costing & Market response of Alternatives
- Selection of Preferred Alternatives
- Detailed Analysis of Preferred Alternative - MADM

Alternate Plant Site
Revision
Transmission Plan Development – Tech Studies

- Horizon Year Base Case
- Design for Thermal Capacity – Transfer Limits, etc.
- Transmission Additions
- Design for Voltage/Reactive Criteria
- Reactive Compensation/Controls
- Test with Steady-State Criteria
- Design for Stability
- Test with Dynamic Criteria
- Stability Measures
- Transmission Alternative

Decoupled Thermal & Voltage Planning

Expansion Planning

Failed Cases
Decoupled Thermal & Voltage Studies

- Skeleton Network
- Future Generation
- Future Load

Base Case

- Available ROW
- Line Designs
- Available Voltage Control Equipment

Evaluate Thermal Capacity Requirements

- Transmission Reinforcements

Evaluate Voltage Control Requirements

- Capacitor/reactor Additions; e.g. SVC, etc.

Contingency Analysis

- Stability Evaluation
Simplified Flow Chart for Contingency Analysis

Define: Operating Limits

Adjust solution steps for Divergence

Evaluate Each Contingency

Classify Results

Local Problems
- Overload
- Low Voltage
- High Voltage
- Islanding
- Load Shed

System Problems
- Voltage Collapse
- Cascading Outage

Eliminate Troubles Using Optimization

Calculate Probabilistic Indices

Input:
- Outage Statistics

Input:
- Customer Or Load Interruption Costs

Calculate Cost of Load Curtailment

No Problem

Contingency List

Input:
- Specified Contingencies
- Ranking Type
- Sub-system for automatic Contingency Testing
- Contingency Levels

Remedial Schemes:
- Islanding
- Trip sequences
- Generation Re-dispatch
- Load Shedding

Normal Condition, Solved Power Flow

Calculate Cost of Load Curtailment

Evaluate Each Contingency

Evaluate Each Contingency

Evaluate Each Contingency
Approaches to Transmission Planning

- Alternatives Approach
- Optimization Methods
- Horizon Year & Staging
- Scenario Method
- Ranking Options / Decision Functions
- Trade-Off / Risk Analysis
Steps in Alternatives Approach

1. Identify Basic Alternatives
2. Engineer Alternatives to Functional Equivalency (Screening)
3. Select Prime Alternatives
4. Optimize Prime Alternatives
5. Select Final Plan
Steps in Optimization Approach

• The two items specific to optimization procedure are:
  - Determination of effective alternatives which are technically feasible,
  - The optimization process and selection of the "optimum" plan.

• Techniques of optimization procedures commonly used:
  - Gradient techniques
  - Linear programming
  - Integer programming
  - Dynamic programming
  - Branch and bound algorithms
Horizon Year & Staging Approach

• A lowest cost transmission plan for the horizon year (20th year in a 20 year planning study) is developed (Note that if necessary and proper, an optimization method may be applied to this horizon year plan).

• Once an optimized horizon year plan is available, several transmission staging plans may be developed for the planning period:
  • The staging intervals may be different from one stage to the next.
  • Staging at every 5 years is usually considered appropriate.
  • In a high growth system, staging at say 3 or annual plans may be required.

• Keeps in focus the long-term needs of the system in proper perspective

• Once the staging plans are complete, the present worth or other types of analysis may be performed for different horizon year and corresponding staging year plans (the selection of the most suitable plan among the low cost plans may be accomplished, via the alternative approach).
**Scenario Approach to Address Uncertainties**

**Uncertainties:**
- Competitions,
- Load Growth (power and energy),
- IPPs
- Fuel and Hydro Resources,
- Construction,
- Environmental Issues,
- New Technology,
- Capital and Financial Factors,
- Institutional and Government Regulations.

**In Concept, it involves:**
- develop alternate scenario,
- analyze each scenario,
- select the best plan(s).

(The scenarios may be based on a set of likely possibilities or selected on the basis of reasonable extremes)

This master transmission plan may be in the form of

1. a robust plan or
2. one of the scenario plans, but with a strategy to cope with the undesirable events.
Multiple Objective Evaluation Approach

• Some of the multiple attenuates, depends upon particular project, location and situations, include - Net present value, Right-of-Way and terrain, Environmental impact (EMF), habitat, urban and rural life impacts, etc., Reliability, Financing, Operation flexibility, Dependence on outside sources, construction feasibility.

• To evaluate, use either of the two different approaches, ranking and decision functions:

single objective function = a * COST + b * Reliability Index + C * R-O-W + ......

or

RANKING OF SYSTEM EXPANSION ALTERNATIVES

<table>
<thead>
<tr>
<th>System Expansion Alternative</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Smallest net present worth (NPV)</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>2. Least environmental impact</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3. Least interference with operations</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>4. Least impact on neighbors</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>5. Highest transmission strength</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>6. Most favorable financing requirements</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>
Trade off and Risk Analysis Approach

• Trade-off analysis assumes that consideration of more than one single scaler criterion is necessary for determining an optimum plan (That is, any time a plan has to be optimized with additional considerations beyond NPV criterion, conflicts may arise and reasonable compromises are necessary. With the use of trade off method, planners are able to consider a wide variety of options in an organized manner. The method permits the planner to eliminate unacceptable or inferior plans, based on multiple objectives and focus on a small set of plans (referred to as decision set) which represents reasonable compromises).

• A trade-off risk analysis essentially has four steps:
  • Perform trade-off risk analysis for each future and find a global decision set.
  • Measure the robustness of each plan in the global decision set.
  • If no plan is completely robust, measure exposure.
  • Develop hedges (new options) to protect against adverse futures.
Typical System Performance Testing

START

MORE ALTERNATIVES

SIMPLIFIED POWER FLOW STUDIES

⇓

AC POWER FLOW STUDIES

⇓

STABILITY STUDIES

⇓

SPECIAL TRANSIENT PROBLEMS

⇓

SHORT CIRCUIT STUDIES

⇓

LINE DESIGN STUDIES

⇓

RELAY COORDINATION

LESS DETAIL

FEWER ALTERNATIVES

SATISFACTORY ALTERNATIVE(S)

MORE DETAIL
Four Hierarchies in Reliability Analysis

1. DETERMINISTIC
   - Contingency Analysis
     - Problems Number & Degree

2. PROBABILISTIC – SYSTEM PROBLEMS
   - Outage Statistics
     - Probabilistic Indices for Problems

3. PROBABILISTIC – LOAD CURTAILMENT, TL, etc.
   - Operator Actions
     - Probabilistic Indices for Delivery Points

4. COST EFFECTIVENESS
   - Value, Cost, Utilization Factor, Price
     - Economic Measure
## DETERMINISTIC CRITERIA

- **“UMBRELLA APPROACH”** – Normal Conditions

- **N-1**, Probable contingencies or most frequent contingencies (repair time is not a concern)

- **N-2**, Possible and less likely with low probability

- **N-3**, Extreme contingencies (including S/S failure) or Possible but least likely with very low probability contingencies - resolution dependent on affected elements; severity of problems

### Consequence of the Criteria to the Industry

- MAY BE COSTLIER

- DIFFICULT TO JUSTIFY IN OPEN MARKET
I. Normal conditions - the state of the transmission system:

- All circuit in-service,
- Any load level,
- No conductor loaded above 100 percent of normal rating,
- No equipment loaded above 100 percent of normal rating,
- Voltage in the transmission system in the range of 97 to 105 percent of 69, 138, and 345 kV.
II. Probable stress conditions - any of the single point failures

- Loss of any transmission tower and all the circuits on that tower,
- An internal fault on any circuit breaker,
- A fault on any substation in the system,
- Loss of any generating unit,
- Failure of any other single component in the system.

For the full range of possible load levels, generation schedules, sales and purchases to other utilities, and assuming proper operation of system protection devices, the transmission system will be tested to insure:

- Voltage throughout the system remain within the range of 93 to 105 percent of 69 kV, 138 kV, or 345 kV,
- No conductor loading shall exceed 110 percent of normal rating,
- No equipment loading shall exceed 110 percent of normal rating,
- A system cascade and blackout will not occur.
III. Brief Outage Conditions - as contingencies that occur due to correct, or incorrect, system protection device operation and are in addition to any Probable Stress Condition

- For these conditions the transmission system will be tested to insure:
  - No conductor loading shall exceed 140 percent of normal rating,
  - No equipment loading shall exceed 140 percent of normal rating,
  - Voltage throughout the system shall remain within the range of 93 to 105 percent of 69, 138 or 345 kV.
IV. Extreme Disturbances - potential of resulting in an uncontrolled breakup of the system / excessively long outage of service

- Loss of all lines emanating from a generating station, switching station, or substation,
- Loss of all circuits on a common right-of-way,
- Any Probable Stress Condition in addition to another transmission component out-of-service for an extended period of time,
- Any other credible contingency which might lead to a system collapse.
## Summary of Deterministic Reliability Test

<table>
<thead>
<tr>
<th>Basic Reliability Tests</th>
<th>Test Conditions</th>
<th>Analysis</th>
<th>Acceptable System Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal Steady State(^1) Conditions</td>
<td>Steady State Load Flow</td>
<td>System within normal loading and voltage limits</td>
</tr>
<tr>
<td></td>
<td>Single Contingencies</td>
<td>Steady State Load Flow</td>
<td>System within emergency loading and voltage limits immediately after outage and within normal limits after system adjustments</td>
</tr>
<tr>
<td></td>
<td>Double Contingencies</td>
<td>Steady State Load Flow</td>
<td>System within emergency loading and voltage limits after system adjustments</td>
</tr>
<tr>
<td></td>
<td>Dynamic Contingencies(^2)</td>
<td>Steady State Analysis</td>
<td>No voltage collapse or overload cascading</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dynamic Analysis</td>
<td>Transiently and dynamically stable</td>
</tr>
<tr>
<td>Supplementary Test to Assess System Reliability</td>
<td>Extreme Contingencies</td>
<td>Steady State and Dynamic Analyses</td>
<td>Avoidance of widespread load interruptions, uncontrolled cascading, system blackouts</td>
</tr>
</tbody>
</table>

\(^1\) Steady State Load Flow

\(^2\) Steady State and Dynamic Analyses
## Comparison of Contingency Testing: No Emergency Limit Violations

<table>
<thead>
<tr>
<th>Contingency</th>
<th>Precontingency Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(System Adjusted after Outage)</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
</tr>
<tr>
<td>Loss of Load</td>
<td>W</td>
</tr>
<tr>
<td>One Transformer</td>
<td>CPNSW</td>
</tr>
<tr>
<td>One Line</td>
<td>CPNSW</td>
</tr>
<tr>
<td>One Generator Unit*</td>
<td>CPNSW</td>
</tr>
<tr>
<td>Common Tower Line*</td>
<td>PNS</td>
</tr>
</tbody>
</table>

**Legend:**  NPCC(N), MAPP(P), MACC(C), SPP(S), WSCC(W)
Contingency Testing - Dynamic Simulations Must Remain Stable without Load Shedding or Generator Dropping Comparison of Criteria

<table>
<thead>
<tr>
<th>Element Faulted</th>
<th>Normal</th>
<th>One Out</th>
<th>Line</th>
<th>One Transformer Out</th>
<th>One Generator Unit Out*</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-PHASE FAULT NORMAL CLEARING</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transformer</td>
<td>C P N S W</td>
<td>P N S W</td>
<td>P N S</td>
<td>P N S W</td>
<td></td>
</tr>
<tr>
<td>Line</td>
<td>C P N S W</td>
<td>P N S</td>
<td>P N S</td>
<td>C P N S W</td>
<td></td>
</tr>
<tr>
<td>Bus Section</td>
<td>C P N S</td>
<td>P N S</td>
<td>P N S</td>
<td>P N S</td>
<td></td>
</tr>
<tr>
<td>Special Double</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Ckt Line</td>
<td>C P N S</td>
<td>P N S</td>
<td>P N S</td>
<td>P N S</td>
<td></td>
</tr>
<tr>
<td>SINGLE LINE-TO-GROUND DELAYED CLEARING</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transformer</td>
<td>C P N S W</td>
<td>P N S</td>
<td>P N S</td>
<td>P N S</td>
<td></td>
</tr>
<tr>
<td>Line</td>
<td>C P N S W</td>
<td>P N S</td>
<td>C P N S</td>
<td>C P N S</td>
<td></td>
</tr>
<tr>
<td>Bus Section</td>
<td>C P N S</td>
<td>P N S</td>
<td>P N S</td>
<td>P N S</td>
<td></td>
</tr>
<tr>
<td>Double Ckt Line</td>
<td>CP</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>SINGLE LINE-TO-GROUND NORMAL CLEARING</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circuit Breaker</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>Transformer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Line</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Bus Section</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double Ckt Line</td>
<td>N S</td>
<td>N S</td>
<td>N S</td>
<td>N S</td>
<td></td>
</tr>
</tbody>
</table>
PROBABILISTIC INDICES

- FREQUENCY OF OVERLOAD, LOW VOLTAGE, VOLTAGE COLLAPSE, LOAD CURTAILED etc. (events/year)

- AVERAGE DURATION (Hours)

- PROBABILITY

- UNSERVED ENERGY (EUE or ENS)
Modeling and Index Calculations

- There is no absolute level of reliability requirement but,
- Can provide a superior measure of relative strength of different options
- Required Inputs - System data in terms of network topology, configuration, and component Failure rates and Repair times
MOST COMMON COMPONENT RELIABILITY PARAMETERS

- Permanent Short Circuit Failure Rate — events per year
- Temporary Short Circuit Failure Rate — events per year
- Open Circuit Failure Rate
- Mean Time To Repair — hours
- Mean Time To Switch — hours
- Scheduled Maintenance Frequency - number/yr
- Mean Time To Maintain — hours
BASIC RELATIONSHIP

probability of outage

\[ probability = \frac{frequency \times duration}{8760} \]

*frequency is in number of outages per year*
*duration is in hours*

Expectation = Sum\((prob_i \times Value)\)
## Reliability Index Calculations

<table>
<thead>
<tr>
<th>Outage Scenario</th>
<th>Load &gt;85%</th>
<th>Load &gt;90%</th>
<th>Load &gt;95%</th>
<th>Load &gt;100%</th>
<th>Load &gt;105%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>1277.838</td>
<td>764.277</td>
<td>415.163</td>
<td>195.450</td>
<td>84.920</td>
</tr>
<tr>
<td>Underground Line</td>
<td>288.096</td>
<td>172.311</td>
<td>93.601</td>
<td>44.065</td>
<td>19.146</td>
</tr>
<tr>
<td>Overhead Line</td>
<td>68.687</td>
<td>41.082</td>
<td>22.316</td>
<td>10.506</td>
<td>4.565</td>
</tr>
<tr>
<td>Transformer</td>
<td>56.120</td>
<td>33.565</td>
<td>18.233</td>
<td>8.584</td>
<td>3.729</td>
</tr>
<tr>
<td>Generator &amp; Generator</td>
<td>148.868</td>
<td>89.038</td>
<td>48.366</td>
<td>22.770</td>
<td>9.893</td>
</tr>
<tr>
<td>Generator + Underground Line</td>
<td>33.563</td>
<td>20.074</td>
<td>10.904</td>
<td>5.134</td>
<td>2.230</td>
</tr>
<tr>
<td>Generator + Generator + Generator</td>
<td>17.343</td>
<td>10.373</td>
<td>5.635</td>
<td>2.653</td>
<td>1.153</td>
</tr>
<tr>
<td>Generator + Overhead Line</td>
<td>8.002</td>
<td>4.786</td>
<td>2.600</td>
<td>1.224</td>
<td>0.532</td>
</tr>
<tr>
<td>Generator + Transformer</td>
<td>6.538</td>
<td>3.910</td>
<td>2.124</td>
<td>1.000</td>
<td>0.434</td>
</tr>
<tr>
<td>Underground Line + Underground Line</td>
<td>7.567</td>
<td>4.526</td>
<td>2.458</td>
<td>1.157</td>
<td>0.503</td>
</tr>
<tr>
<td>Underground Line + Overhead Line</td>
<td>1.804</td>
<td>1.079</td>
<td>0.586</td>
<td>0.276</td>
<td>0.120</td>
</tr>
<tr>
<td>Underground Line + Transformer</td>
<td>1.474</td>
<td>0.882</td>
<td>0.479</td>
<td>0.225</td>
<td>0.098</td>
</tr>
<tr>
<td>Overhead Line + Overhead Line</td>
<td>0.430</td>
<td>0.257</td>
<td>0.140</td>
<td>0.066</td>
<td>0.029</td>
</tr>
<tr>
<td>Overhead Line + Transformer</td>
<td>0.351</td>
<td>0.210</td>
<td>0.114</td>
<td>0.054</td>
<td>0.023</td>
</tr>
<tr>
<td>Transformer + Transformer</td>
<td>0.287</td>
<td>0.172</td>
<td>0.093</td>
<td>0.044</td>
<td>0.019</td>
</tr>
</tbody>
</table>
PROBABILISTIC - INDICES

UNACCEPTABLE EVENTS

FREQUENCY (OCC/YR)
DURATION (HRS)
SEVERITY

SYSTEM PROBLEMS
SYSTEM STATE
LOAD CURTAILED
LOLP – A Typical Reliability Measure for A Power System

- Consider three independent generating units of 100 MW each, whose outages are independent.

- Calculate the probability of each state given that each unit has an operating probability of 0.8 and failure probability of 0.2. The generating units have to supply a load of 200 MW.

- Calculate the Expected Unserved Energy (EUE) and the Loss of Load Probability (LOLP) for one year.
## LOLP

<table>
<thead>
<tr>
<th>Number of units out:</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity loss (MW)</td>
<td>0</td>
<td>100</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>Unserved Demand (MW)</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>State Probability</td>
<td>$0.8^3 = 0.51$</td>
<td>$(3)(0.2)(0.8^2) = 0.384$</td>
<td>$(3)(0.8)(0.2^2) = 0.096$</td>
<td>$0.2^3 = 0.008$</td>
</tr>
<tr>
<td>LOLP</td>
<td>0</td>
<td>0</td>
<td>0.096</td>
<td>0.008</td>
</tr>
<tr>
<td>EUE (MWh)</td>
<td>0</td>
<td>0</td>
<td>84,096</td>
<td>14,016</td>
</tr>
</tbody>
</table>

where

$$\text{LOLP} = P\{\text{Unserved Demand} > 0\} = 0.104 \text{ day/yr}$$

$$\text{EUE} = (\text{Probability})(\text{Unserved Demand})(\text{Time period}) = 98,112 \text{ MWh}.$$  

This risk model assumes a constant demand of 200 MW. The long-run probability of residing each state can be determined by using a Markov probabilistic model or the binomial method. In this example, the binomial method was used.
Market Based Planning/Evaluations

Scenario Definition, Likelihood of scenarios, Database and system model development – IPP location and time, Old unit retirement, Load growth, Power wheelings, etc.

System Reinforcement Options

Chronological Market Simulations

Reliability Constraints

Probabilistic Reliability Assessment, with Remedial Actions

Economic Benefits

Reliability Measure Calculations

System Risk, Reliability Cost, and Expected LMPs

Probabilistic Multi-Attribute Decision Making

The Transmission Alternative

Next Year?