Module 7-4
N-Area Reliability Program (NARP)

Chanan Singh
Associated Power Analysts
College Station, Texas

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N-Area Reliability Program

- A Monte Carlo Simulation Program, originally developed for studying the ERCOT system
- Reliability evaluation within context of interconnected power system for purposes of:
  - Generation capacity planning
  - Interconnection capacity planning
- System components modeled
  - Generating units in each area
  - Equivalent transmission links between areas
  - Hourly load in areas

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Basic Features and Capabilities

Transmission Network

Generating Units

Loads

Area Interchanges

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Transmission Network

- Up to 15 areas
- Up to 60 transmission links between areas
- One bus in each area, no explicit modeling of area interior transmission networks – such modeling reflected in the calculation of equivalent transmission model
- Transmission flows modeled using DC load flow
- Transmission links modeled as 6-state channels characterized by capacities, admittances, and probabilities
- Transmission link state capacities can be specified as function of direction of power flow
- Transmission link state capacities can be specified as function of statuses of key generating units
- Constraints on sum of transmission flows around areas can be specified

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Generating Units

- Up to 600 generating units
- Generating units modeled as two or three-state units, capacities and probabilities specified for each state
- Capacities can be varied seasonally, up to four seasons per year
- Unit planned outages modeled deterministically, up to two planned outages per year
- Planned outage schedules can be pre-specified or determined automatically, or combination

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Loads

- Annual hourly load cycle for each area used to create per unit load cycle for each area
- Specified peak loads for each area used to create study load cycles
- Load forecast uncertainty
  - Normally distributed load forecast uncertainty about nominal loads
  - Specified standard deviation in percent of nominal for each area
  - Area load forecast errors perfectly correlated

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Area Interchanges

- Firm MW contracts between areas, can be changed daily
- Jointly-owned or out-of-area generating units modeled
- Emergency interchanges
  - No-loss sharing
  - Loss sharing

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General Program Logic

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Simulation steps – proceed hour by hour

1. Each hour draw status of each generator and transmission link
2. For each area find:
   - Available capacity of all units in area
   - Available capacity of units owned by area
3. Update native load for each area
4. Determine scheduled transfers between areas reflecting net of:
   - Firm transfers
   - Transfers reflecting entitlements in jointly-owned/ out-of-area units

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5. Margin in each area is (available capacity of all units in area) – native load. If margins in all areas positive, return to step (1) and advance clock, otherwise continue.
6. If only one area has negative margin, see if necessary capacity assistance available from directly connected areas. If yes, return to step (1) and advance clock. If no, continue.
7. Compute flows using DC load flow module and injections associated with net scheduled interchanges and desired emergency transfers. If feasible solution is found, return to step (1) advance clock, otherwise continue.

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8. Employ linear programming model to find feasible load flow or to minimize load loss considering selected mode of emergency assistance. If no load loss, return to step (1) and advance clock, otherwise continue.
9. Gather load loss statistics; then return to step (1) and advance clock.
10. Continue simulation process until specified number of years replicated or convergence criterion satisfied.

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Reliability Indices and Measures

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- Indices for each area and for pool
  - LOLE: Expected number of daily peak load loss events per year
  - HLOLE: Expected number of hourly load loss events per year
  - EUE: Expected unserved energy per year, MWH
  - XLOL: Expected magnitude of a load loss event, MW

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- Indices separated into “generation constrained” and “transmission constrained” categories as aid to analysis
- Probability distributions
  - Number of daily peak load loss events per year
  - Number of hours of load loss per year
  - Unserved energy per year
- Flows in all transmission links whenever a transmission constraint in encountered can be output

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Statistical Convergence

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- Monte Carlo simulation creates artificial history. How many years of artificial history (replications) are required to estimate the reliability indices of interest with satisfactory accuracy?
- The measure of statistical convergence used in NARP is the standard deviation of the chosen reliability index. This standard deviation is computed as follows.

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- Let

  I_i = value of reliability index obtained from simulation data for year i

  N = number of years of simulated data available

- Then,

$$\bar{I} = \sum_{i=1}^{N} I_i \Big/ N$$

  $\bar{I}$ = estimate of the expected value of index

- Also,

$$S_I = \sqrt{S^2 / N}$$

  S_I = standard deviation of $\bar{I}$

- Where:

$$S^2 = \sum_{i=1}^{N} \left(I_i - \bar{I}\right)^2 \Big/ N$$

  S^2 = variance of I

- Here

  S^2 is measure of year-to-year variation in

  S_I is measure of uncertainty in ,the expected value of

- Note
  - S^2 is characteristic of system being studied
  - Large for systems with large year-to-year variation in reliability
  - Small for systems with small year-to-year variation in reliability
  - S_I varies as $\sqrt{S^2}$ and $1/\sqrt{N}$

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- NARP convergence criteria:
  - Standard deviation of specified reliability index less than specified value, or
  - Maximum number of simulated years

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Generating Unit Model

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Modeling of generating unit FOR

- Two-state Model
  - Unit Fully Available
    - Capacity = Rated
    - Probability = 1 – FOR
  - Unit Totally Unavailable
    - Capacity = 0
    - Probability = FOR
- Three-state Model
  - Unit Fully Available
    - Capacity = Rated
    - Probability = 1 – FOR – DFOR
  - Unit Totally Unavailable
    - Capacity = 0
    - Probability = FOR
  - Unit Derated
    - Capacity = Expected Derated
    - Probability = DFOR

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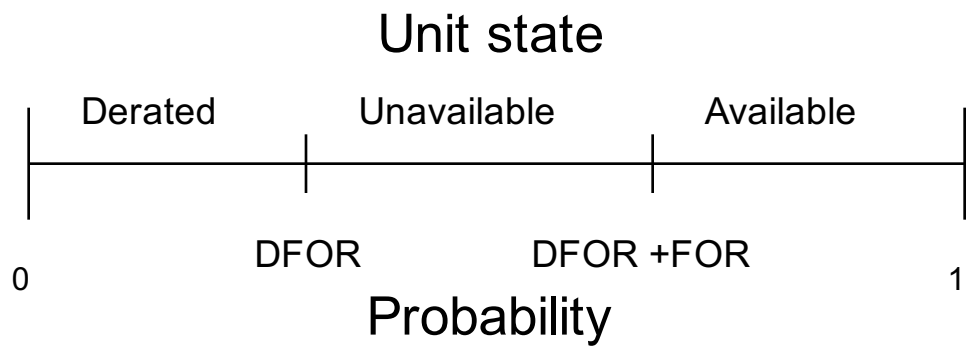
Simulation Procedure

1. Draw random number N from uniform distribution of range 0-1.
2. Determine state of unit using N
   - Unit fully available
     if N ≥ FOR + DFOR
   - Unit totally unavailable
     if FOR + DFOR > N ≥ DFOR
   - Unit derated
     if N < DFOR

This can be visualized pictorially as follows:



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Generator Planned Outages

- Generator planned outages can be scheduled manually or automatically or in combination
- Up to two planned outages per year
- Outage duration is integer number of weeks
- Data for automatic scheduling:
  - Plant within which unit installed
  - Unit planned outage duration in weeks
  - Periods within which planned outages forbidden
- General procedure if to levelize reserve while enforcing constraints
  - No outages in forbidden periods
  - Only one unit in a plant out at a time

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Method outline

- Compute "effective" capacity of each unit as follows:

EC_i = effective capacity of unit I

$$= C_i - M \cdot \log R_i$$

$$R_i = 1 - FOR_i\left(1 - e^{C_i/M}\right)$$

M = slope of capacity outage probability graph with capacity on y-axis (linear-scale) and probability on x-axis (log-scale)

FOR_i = forced outage rate of unit I

C_i = capacity of unit i

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Then proceed as follows:

1. Compute product of effective capacity and outage duration for each unit and sum these products for each plant
2. Rank plants based on product sums, largest first. Rank units within each plant based on rated capacity x duration, largest first.
3. Schedule units sequentially using plant priority within plant. Scheduling process minimizes sum of weekly peal load and effective capacity on planned outage while observing constraints.

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Transmission Link Model

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- Transmission links between areas are modeled as six-state lines with each stage characterized by a probability, and admittance, and capacities in the forward and backward flow directions. The forward direction of flow in a link is arbitrarily chosen.
- Transmission link states are chosen in the simulation process in a manner similar to that used for generating units. The procedure is to draw a uniformly distributed random number using the dedicated random number generator provided for each transmission link. The random number is then used to select a state according to the state probability distribution specified in input data.
- The NARP program also provides for transmission link capacities to be modified as a function of the status of specified key generating units. This feature permits some recognition of the influence of internal transmission limitations on area transfer capabilities

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Modeling

- Six-state lines with each stage characterized by
  - A probability
  - An admittance
  - Capacities in the forward and backward flow directions.
- The forward direction of flow in a link is arbitrarily chosen.

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State Selection

- Similar to that used for generating units.
- Draw a uniformly distributed random number using the dedicated random number generator provided for each transmission link.
- The random number is then used to select a state according to the state probability distribution specified in input data.

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Additional Features

- Transmission link capacities can be modified as a function of the status of specified key generating units.
- This feature permits some recognition of the influence of internal transmission limitations on area transfer capabilities

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Transmission Network Model

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Objective

- To determine whether the loads at the various nodes can be satisfied by the available generation without the flows through tie lines exceeding their capabilities and the algebraic sum of flows at any node exceeding a specified value.
- If the loads cannot be satisfied, then this module determines the load loss at each node. This module has two policies for sharing the available capacity amongst various areas.

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No-Load-Loss Sharing

- An area will provide emergency assistance to other areas only to the extent of its surplus capacity.
- The first obligation is the area's own load.
- An area will, however, help other areas only after its own demand has been met.

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Load-Loss Sharing

- The areas share the loss of load.
- The objective here is to minimize pool load loss.
- The areas, therefore, help each other even at the expense of losing their own load to achieve this objective.

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Procedure

1. Net scheduled transfers are determined by algebraically adding transfers due to firm contracts and jointly owned units
2. Net scheduled transfers are input to the network flow module to determine feasible transfers and line flows.
3. If load in each area can be satisfied by the capacity in each area together with the feasible scheduled transfers determined in step (2), no further computation is necessary.

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Procedure (cont.)

4. For loss sharing policy:
   - Network flow module is called by setting net injection at each node equal to capacity – load

   For no loss sharing policy:
   - Feasible scheduled transfers are subtracted from net injections.
   - Line constraints and sum of flow constraints modified by flows calculated in step (2).
   - Network flow module is called to determine loss of load.

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Network Flow Calculations

The overall procedure consists of the following steps.

1. Assign injections at all nodes and perform a DC load flow.
2. Check the constraints. If the line flows are within the line capabilities, then exit; otherwise go to step (3).
3. Perform optimization procedure.

The DC load flow takes much less time than the optimization procedure. Therefore, step (1) is an attempt to find a feasible solution without performing the optimization

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DC Load Flow

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Underlying Assumptions

The network flow calculations in the transmission module are made using DC load flow.

- Only real power is considered.
- Voltage at each bus is assumed fixed at 1 per unit.
- Resistance of transmission lines is ignored.

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The DC load flow or linearized power flow model is usually expressed by the following equation.

$$B\Theta = I \qquad (1)$$

Where matrix B is such that

b_{ij} = ij th element of B

= -(the susceptance between nodes i and j),

b_{ii} = sum of the susceptances connected to node I, if i = j.

Θ = node voltage angle vector

I = bus injection vector

Therefore,

$$\Theta = ZI \qquad (2)$$

Where

Z = B^{-1} , is the bus impedance matrix

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Once Θ has been determined, the line flows can be determined by equation (3).

f_{ij} = flow from node i to j

$$f_{ij} = \left(\Theta_i - \Theta_j\right) r_{ij} \qquad (3)$$

where

r_{ij} = susceptance between nodes i and j

It should be noted that if there is a change in the status of a line, matrix can be readily modified using techniques described in literature. This avoids the inversion of B for every flow calculation.

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Optimization Procedure

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Linear programming optimization

- If the DC load flow after the assignment of injections does not give a feasible solution, then the program enters the optimization phase.
- The optimization procedure is based on linear programming (revised simplex method) and it assigns positive margins or curtails negative margin/load so as to minimize the loss of load for the pool.

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- Minimization is performed under the following constraints.
  1. For no-loss sharing, the load curtailment at a node is less than or equal to the negative injection at the node. For loss sharing, the curtailment can be up to the actual load at the node.
  2. Flows in the tie lines are within their capabilities.
  3. The sum of flows at any node is less than the specified value.

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Mathematical Formulation

- The problem can be formulated as:

$$\text{Loss of Load} = \text{Min} \sum_k c_k$$

Subject to (4)

$$B\Theta + g + c = d$$

$$g \le g^{\max}$$

$$c \le d$$

$$f \le f^{f}$$

$$-f \le f^{r}$$

$$s \le s^{\max}$$

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Where

d = vector of net negative injections for no-loss sharing and actual loads for loss sharing

g = vector of net positive injections for no load-loss sharing and actual generation plus scheduled transfers for load-loss sharing

c = vector of negative injections curtailments for no loss sharing and load curtailments for load loss sharing

c_k = k th element of C

$g^{\max}$ = vector of max available net positive injection for no-loss sharing and max generation for loss sharing

s = vector of sum of flows at nodes

$s^{\max}$ = max possible values for S

f^f f^r = indicate max flow capabilities in the forward and reverse directions of tie lines

f and s are related to Θ and the tie line susceptance by equation (3).

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MODELING HYDRO GENERATION ETC

- Program has a mechanism to shut down or derate a give unit on a given day.
- This mechanism can be exercised using logic reflecting the appropriate reason
- Hydro could be modeled by unit-derating to reflect energy unavailability or load modification or a combination.

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HVDC Modeling

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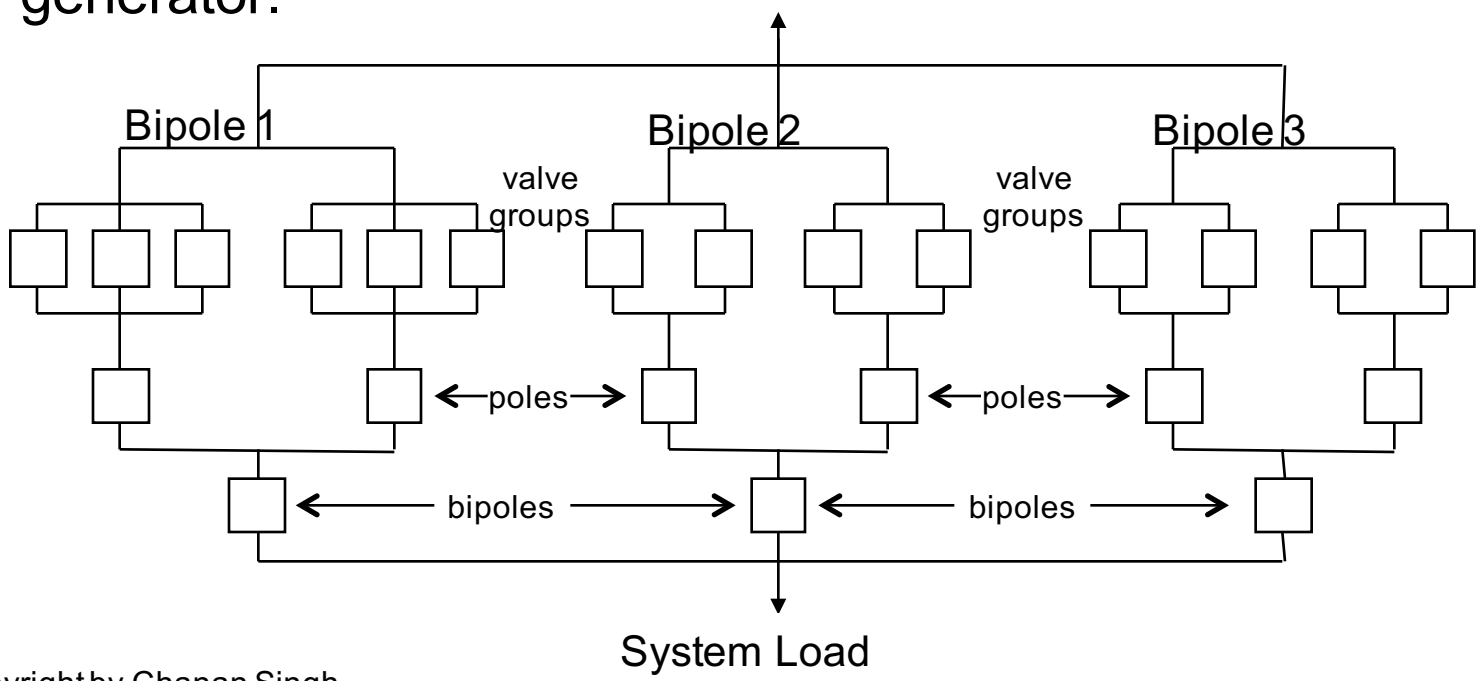
Bipole Example

- Total capacity = 2000 MW.
- Program combines this information to produce capacity outage probability table of an equivalent generator.

Item	Capacity	FOR
Each valve group	500 MW	0.0289000
Each pole	1000 MW	0.0084050
Bipole	2000 MW	0.0006475



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NARP – some differences with MARS

- Transmission modeling:NARP uses DC load flow whereas MARS uses transportation network model
- Loss sharing policy: NARP can use either NLLS(No load loss sharing) or LLS(Load loss sharing) whereas MARS uses NLLS
- NARP explicitly models Out of Area Units/Jointly owned units
- NARP can output line loading information for capacity constrained events
- One version of NARP can also model unit start ups and shut downs – not normally done in planning programs

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A note on admittances

- Incremental load flow studies provide the power distribution factors
- These factures are used to derive the relative admittances using a separate program

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CAPABILITIES OF APA

- Extensive experience in reliability analysis – specializes in reliability studies
- Developed single area program GRIP used by many utilities
- Developed multi-area program NARP to specifications of ERCOT
- Developed large sections of MARS for GE
- NARP has been used to perform studies for ERCOT.
- A modified version of NARP was also used for TXU and Sandia National Labs to study the impact of deregulation on multi-area reliability

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continued

- Being the program's author, Dr. Singh can modify the program for specific applications.

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