ENGINEERING

Long-term Planning of Generation, Transmission and Distribution Assets

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Outline of today’s presentation

- Introduction
- Planning for a sustainable energy system—a top-down approach
  - Sustainable generation, delivery and utilization
  - Cyber-enabled system
- Planning approaches
  - Experience with distribution system expansion planning
  - Bulk power system expansion
  - Return of integrated system planning
- Summary of research and other experience
- Concluding remarks

Mitra: education and experience

- Education
  - Ph.D. in Electrical Engineering, 1997, Texas A&M University, College Station, TX
  - B.Tech.(Hons.) in Electrical Engineering, 1989, Indian Institute of Technology, Kharagpur, India
- Experience
  - Nine years in academia
    - Assoc. Prof., Michigan State University, 2008-present
    - Assoc. Prof., New Mexico State University, 2003-08
    - Asst. Prof., North Dakota State University, 2000-03
  - Five years in industry and consulting

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Research projects—past and ongoing

- Autonomous control of microgrids (NSF Collaborative, 2007-10)
- Protection of microgrids and smart distribution systems
- CAREER Award on microgrid architecture (NSF, 2002-07)
- Resource optimization in microgrids (SNL, 2005-07)
- Identification of modes of catastrophic failures of power systems
- Advanced transformer modeling (BPA, 2002-03)
- Distributed generation in demand management (OTP, 2001-03)
- Role of Induction Motors in Stability (OTP, 2001-02)
- Dynamic Rating of Transmission Components (OTP, 2001-02)

Other contributions

- Fundamental contributions to reliability analysis
  - A direct method for determination of failure frequency indices using state space decomposition
  - Method of pruning and simulation
  - State space decomposition with linearized flow representation
- Experimental and hardware development
  - Three-phase transformer modeling (BPA sponsored)
  - Synchronization hardware for off-the-shelf standby generators (US Patent 7,180,210)

Educational experience

- Nine years in academia
  - Taught 15 different lecture and laboratory courses
  - Advised 17 graduate students—6 current, 11 graduated
  - Mentoring 1 post-doctoral research associate
- Short Courses
  - Power system reliability
  - Power system fundamentals
  - Life extension of substations
- IEEE Tutorial
  - Electric delivery system reliability tutorial offered at three IEEE conferences earned TC recognition award
- IPU courses for regulators and policy makers

Service and outreach activities

- Student activities
  - Chair of IEEE-PES Student Meetings SC 2007-08
  - In six years (2003-08) as SC officer, I helped organize eight Student Programs, with a total participation of over 770 students (20% women, 15% minorities)
  - Eight poster contests with over 360 participants
- Other IEEE activities
  - Current chair of Reliability, Risk and Probability Applications SC
  - Participation in standards development
  - Involvement in several committees, SCs, WGs and TFs
- University service: served on numerous committees

Other leadership activities

- Associate Director, Electric Utility Management Program, NM State University, 2003-08
  - Industry liaison
  - Educational fund-raising
- Conferences organized
  - TCPC for Power System Analysis, Computing and Economics committee at IEEE-PES General Meeting 2009
  - Chair, North American Power Symposium 2007
  - Co-Chair, Distributed and Renewable Energy Symposium 2003
- Conference sessions organized/chaired
  - Organized and chaired/co-chaired two panel sessions
  - Chaired eight technical paper sessions

Contribution to technology roadmaps

- NSF-NIST National Workshop on Research Directions for Future Cyber-Physical Energy Systems, Baltimore, MD, June 3-4, 2009.
- “Smart Grids” breakout session facilitator at Great Lakes Alliance for Sustainable Energy Research Workshop, Chicago, IL, May 26, 2009.
- NSF Workshop on the Future Power Engineering Workforce, Washington, DC, November 29-30, 2007.
- Workshop on Power System Security, sponsored by Indian Ministry of Power, Kharagpur, India, January 13-14, 2006.
- NSF-EPRI Workshop on Understanding and Preventing Cascading Failures, Denver, CO, October 27-28, 2005.
- DOE Workshop on National Electric Delivery Technologies Roadmap, Washington, DC, July 8-9, 2003.
- NSF/EPRI/DOE Workshop on Future Research Directions for Complex Interactive Electric Networks, Washington, DC, November 16-17, 2000.

Energy in the 21st century and beyond

- The 20th century has seen significant advances in energy generation, delivery and utilization, but has also produced tremendous impact on the environment and natural resources.
- Significant changes must be made to how we generate, deliver and use energy so as to
  - establish sustainable utilization, and
  - restore environmental balance.
- Education must occur at all levels:
  - researchers;
  - workforce;
  - consumers.

Need to recompose energy portfolio

- Decrease fossil fuel consumption
  - 85% of today's energy supply comes from fossil fuels
  - Transportation and electric generation need to move away from fossil fuels
  - Fossil fuels are the predominant contributors to environmental pollution (COx, SOx, NOx, particulates)
  - Will also lead to energy independence
- Increase renewable generation
  - 7% of today's energy supply comes from renewable sources (hydroelectric, geothermal, wind, solar, biomass)
  - Renewable generation must increase significantly but responsibly
- Increase nuclear generation suitably
  - 8% of today's energy supply comes from nuclear power
  - Nuclear generation must increase so that there is adequate supply from steady sources

Planning for sustainable generation

- Technological enablers
  - Solar generation technologies (photovoltaic and solar thermal)
  - Wind generation and integration
  - Other generation technologies: geothermal, biomass/biofuels, tidal, kinetic, wave, ocean thermal
  - Storage technologies
- Old technology, new role: nuclear power
- Need for holistic analyses
  - Life-cycle and cost-benefit, including decommissioning
  - Environmental impact during manufacture, during useful life and after decommissioning

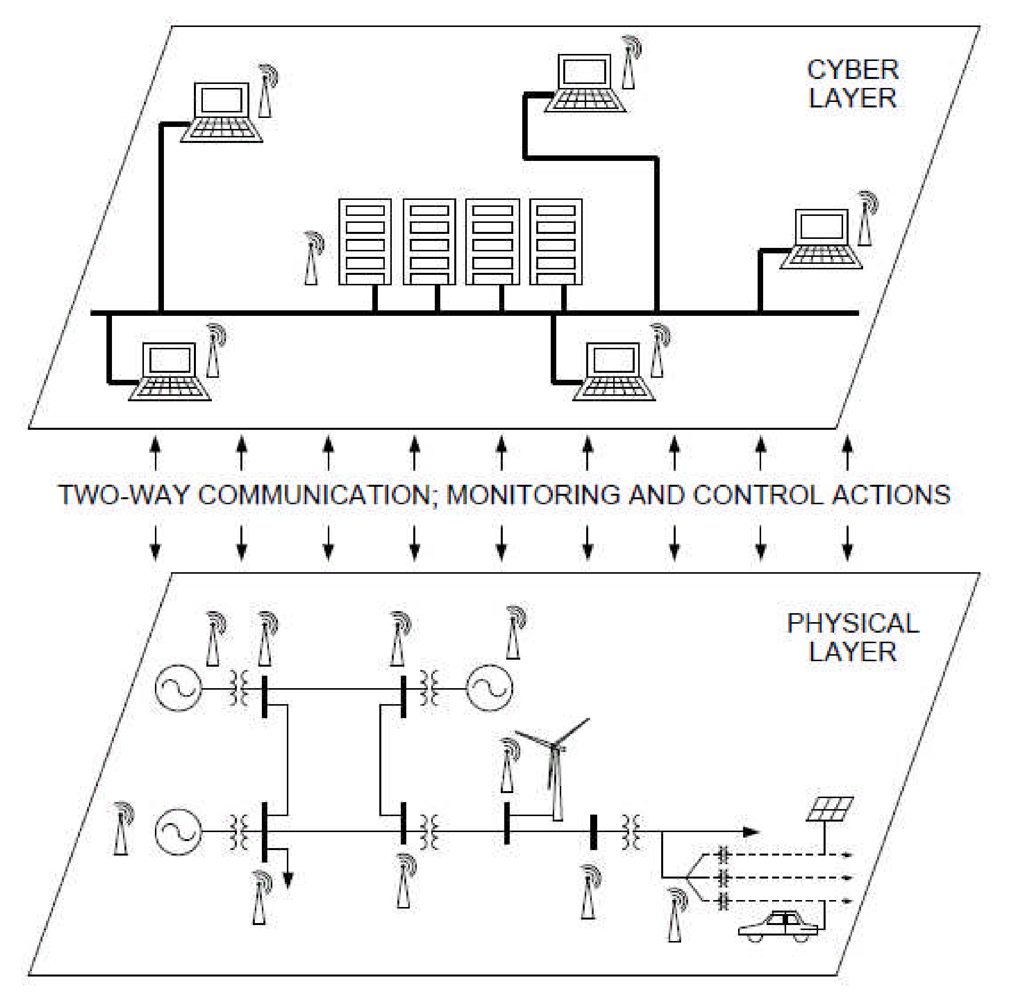
Sustainable and secure delivery

- Technological enablers
  - "Smart" transmission grids: synchrophasors, wide-area measurement and control, FACTS, dynamic rating, data management optimization
  - "Smart" distribution systems: smart meters and communication, distribution automation, microgrids, V2G interface
  - Advanced stability, control, security, protection, optimization
  - Market design and operation
- Re-emergence of integrated resource planning
  - Transmission additions and upgrades have become increasingly expensive and time consuming
  - Transmission expansion should not be decoupled from generation

Sustainable utilization

- Technological enablers
  - Energy efficient buildings with thermal storage
  - “Smart” homes and “smart” appliances
  - Demand response and load management programs
  - Energy efficient transportation: hybrid and electric vehicles
  - Storage and direct conversion technologies
- Growing need for conservation
- Demand profiles will change significantly
  - Composition of load is changing
  - Load factor is likely to change too

The “smart” or cyber-enabled system



Benefits:

- Enables active participation by consumers
- Optimizes asset utilization and efficient operation
- Anticipates and responds to system disturbances
- Accommodates all generation and storage options
- Provides power quality for the digital economy
- Enables new products, services and markets

Challenges:

- Data management
- Interoperability
- Cybersecurity

Grid resilience

- Transient and dynamic stability
- Reliability (service continuity)
- Security (resistance to disruption, from both inadvertent and malicious causes)
- Strategic and tactical countermeasures
  - Systemic vulnerabilities will have to be addressed through appropriate integrated resource planning
  - Tactical responses will have to be programmed into the “cyber” layer
  - Distributed energy resources (DER) will have a role as a backup system

Experience with distribution system expansion planning: Microgrid architecture

- Grand challenge:

  Transformation of today’s distribution systems into the *modern*, *reliable*, *secure*, *robust*, *autonomous*, *self-organizing*, *self-healing*, *intelligent* power delivery systems of *tomorrow*.

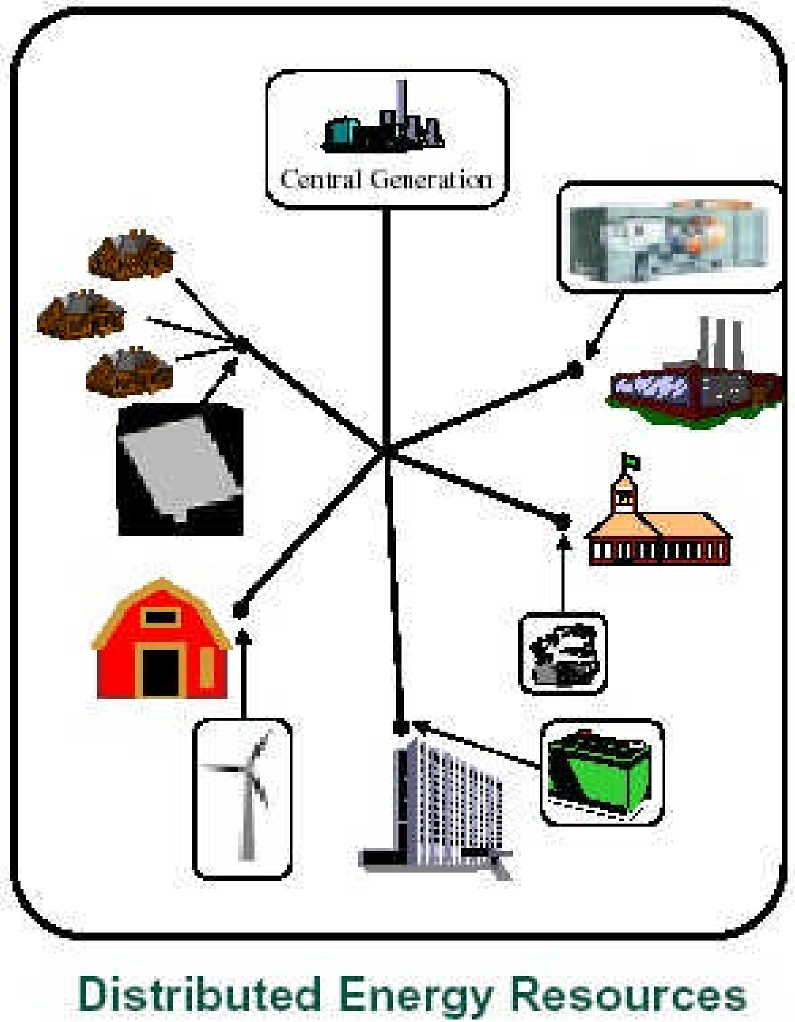
- Based on DoE’s *National Electric Delivery Technologies Roadmap*

What are Microgrids?

‘Under this vision, integrated clusters of small (<200kW) DERs provide firm power with a guaranteed level of power quality through operation in either grid-connected or island modes.’

(U. S. Department of Energy, “Transmission Reliability Multi-Year Program Plan FY2001–2005,” July 2001.)

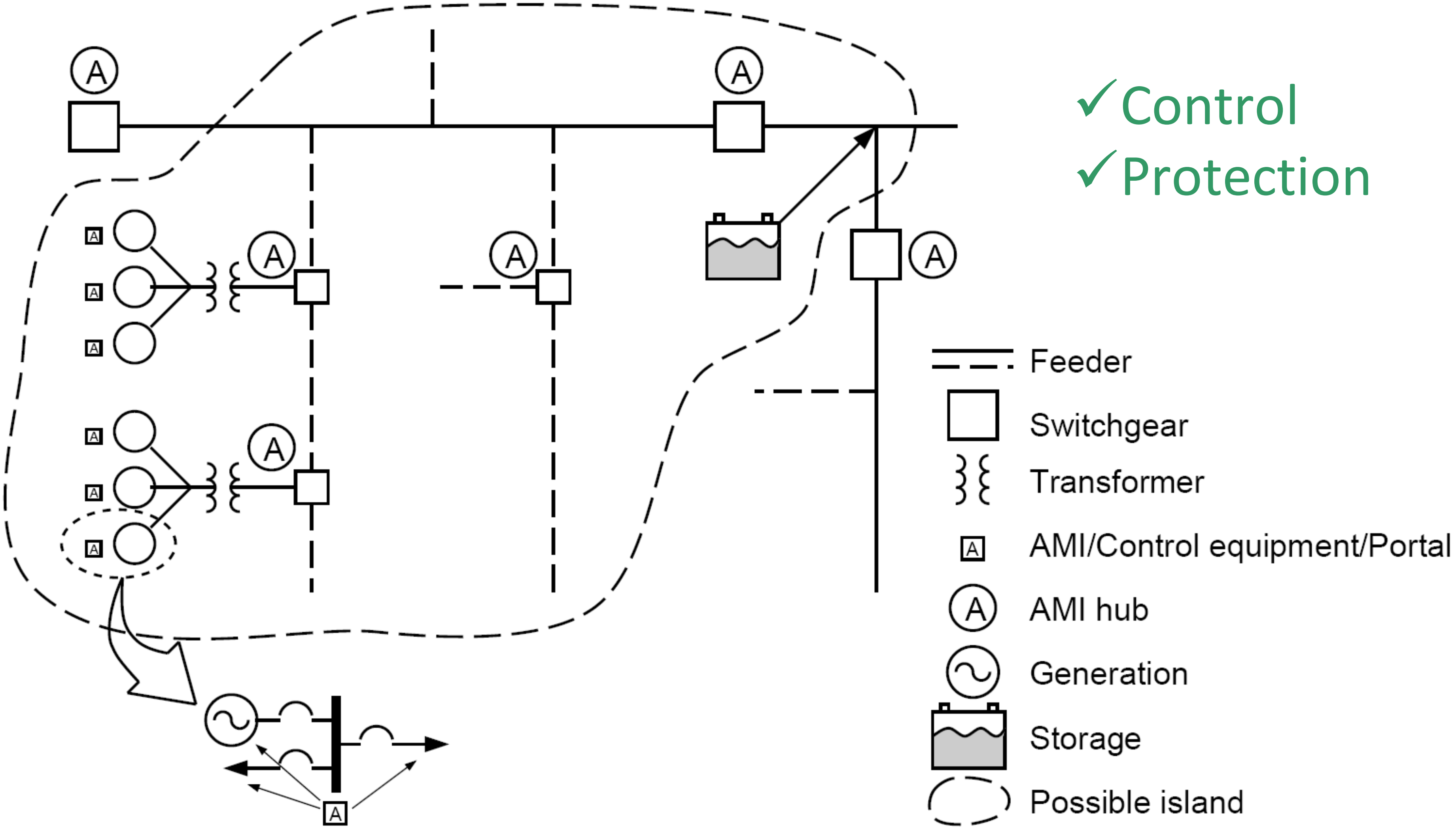
Distributed energy resources



(U. S. Department of Energy, “Transmission Reliability Multi-Year Program Plan FY2001–2005,” July 2001.)

- Generating Devices
  - Windmills
  - PV and solar thermal
  - Microturbines
  - Fuel cells
  - Biomass and biofuels
  - Geothermal power
  - Tidal and ocean thermal
  - Reciprocating engines
- Storage Devices
  - Batteries
  - Ultracapacitors
  - SMES
  - Flywheels
- Combined heat and power
- Interruptible loads

Autonomous microgrid



- ✓Control
- ✓Protection

Two layers of microgrid architecture

- Reliability-centered optimal expansion strategies
  - Optimal network expansion
  - Optimal resource deployment
  - Integrated expansion problem
  - Supported by NSF and SNL
- Control and protection
  - Multi-agent systems (MAS) for autonomous control
  - Communication-assisted protection
  - Optimized distributed sensing strategies
  - Supported by NSF

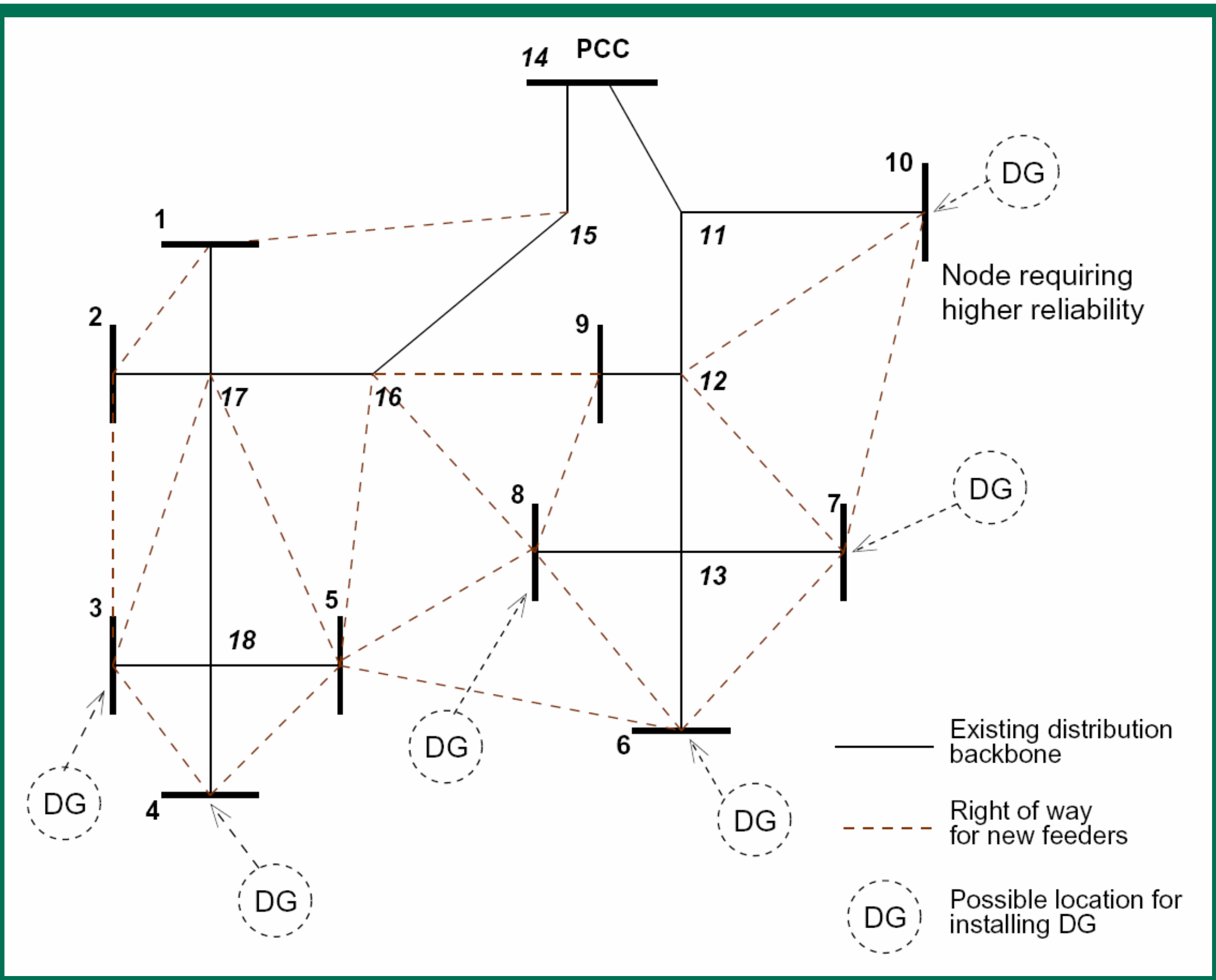
Reliability-centered optimal system expansion: motivation

- Reliability (service continuity) and security (resistance to disruption) are major concerns driving microgrid development
- Reliability-differentiated services will be offered in the future
- It makes sense to use reliability as a criterion in planning for system expansion

Reliability-driven expansion

- Given:
  - A distribution system with an anticipated load growth
  - DG installation options: sizes of DG (distributed generation) clusters, possible locations, deployment costs
  - Network augmentation options: rights of way, cost of installing new feeders
- Determine:
  - Least cost deployment and network expansion
- Subject to:
  - System-wide and locational reliability guarantees (*EIR* or *Availability*)

Study system (for augmentation)



System data

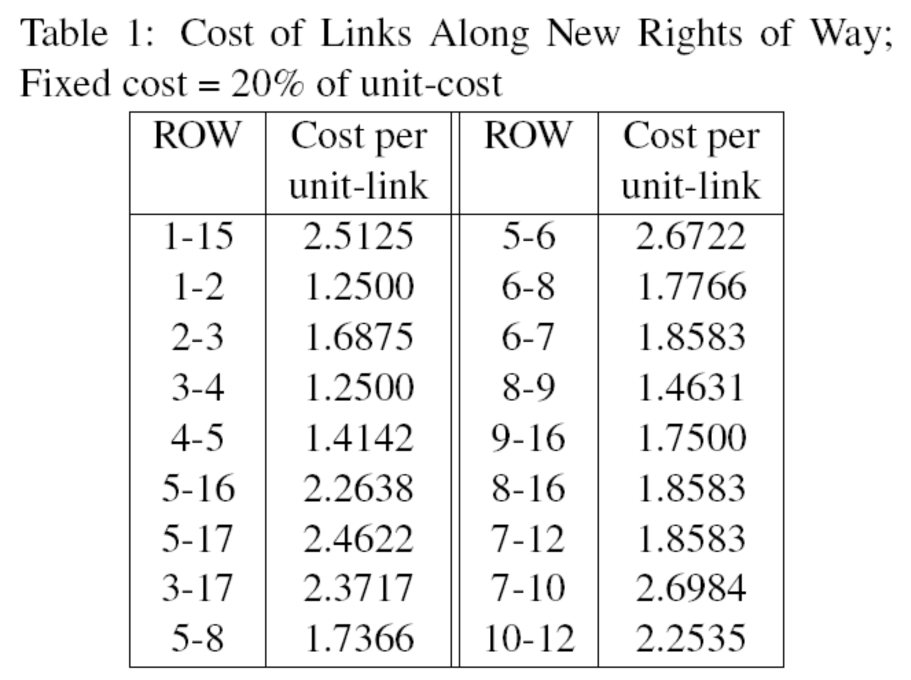


Table 1: Cost of Links Along New Rights of Way; Fixed cost = 20% of unit-cost

ROW	Cost per unit-link	ROW	Cost per unit-link
1-15	2.5125	5-6	2.6722
1-2	1.2500	6-8	1.7766
2-3	1.6875	6-7	1.8583
3-4	1.2500	8-9	1.4631
4-5	1.4142	9-16	1.7500
5-16	2.2638	8-16	1.8583
5-17	2.4622	7-12	1.8583
3-17	2.3717	7-10	2.6984
5-8	1.7366	10-12	2.2535

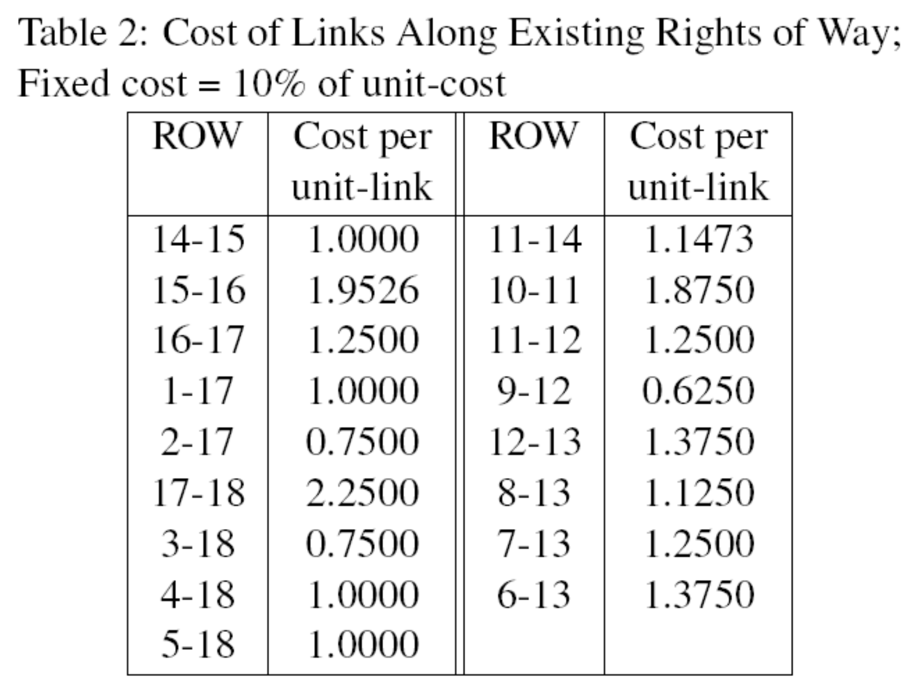


Table 2: Cost of Links Along Existing Rights of Way; Fixed cost = 10% of unit-cost

ROW	Cost per unit-link	ROW	Cost per unit-link
14-15	1.0000	11-14	1.1473
15-16	1.9526	10-11	1.8750
16-17	1.2500	11-12	1.2500
1-17	1.0000	9-12	0.6250
2-17	0.7500	12-13	1.3750
17-18	2.2500	8-13	1.1250
3-18	0.7500	7-13	1.2500
4-18	1.0000	6-13	1.3750
5-18	1.0000		

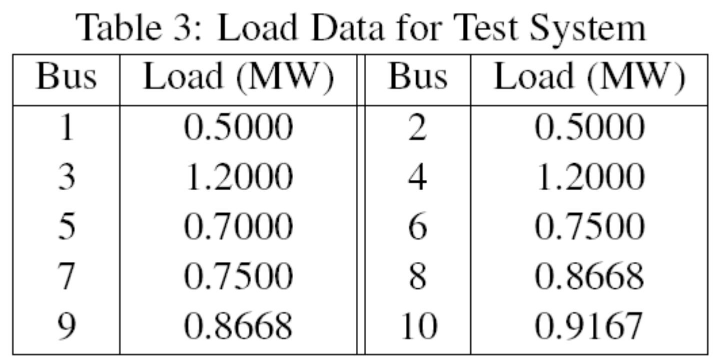


Table 3: Load Data for Test System

Bus	Load (MW)	Bus	Load (MW)
1	0.5000	2	0.5000
3	1.2000	4	1.2000
5	0.7000	6	0.7500
7	0.7500	8	0.8668
9	0.8668	10	0.9167

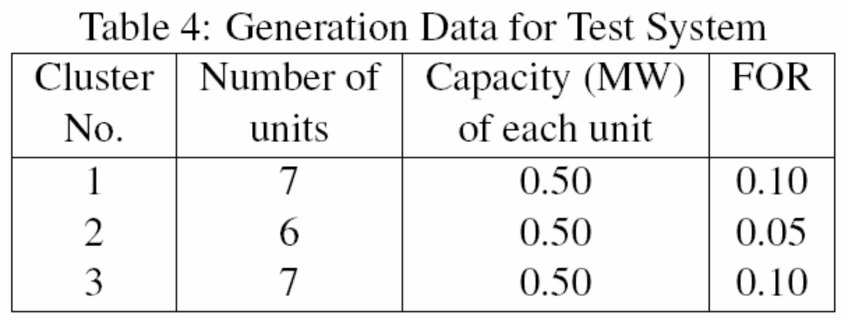


Table 4: Generation Data for Test System

Cluster No.	Number of units	Capacity (MW) of each unit	FOR
1	7	0.50	0.10
2	6	0.50	0.05
3	7	0.50	0.10

Modeling challenges

Simultaneously include in the optimization framework the dependencies between line characteristics and performance

- Dependencies in characteristics:
  - ⇨ between capacity and impedance
  - ⇨ between impedance and length
  - ⇨ between length and cost
  - ⇨ between capacity and cost
- Dependencies in operation:
  - ⇨ KVL and KCL

Solution approach

Accommodation of dependencies in characteristics:

Unit link concept

Accommodation of KVL and KCL:

Linear approximation of power dispatch

Unit link concept

A *unit-link* connecting a given pair of buses is a line of

- fixed capacity
- fixed cost per unit length
- fixed impedance per unit length
- length corresponding to the right of way between the buses

Unit-links between different bus pairs will have different lengths, impedances and costs, but same capacity.

A *link* between a given pair of buses can consist of one or more (an integral number of) unit-links connected in parallel between that bus pair. The cost of a link is equal to the total cost of the unit links that constitute the link plus a fixed cost for installing the link along the corresponding right of way.

Linear flow representation (Dispatch module)

$$\text{Loss of Load} = \text{Min} \sum_{i=1}^{N_b} C_i$$

subject to:

$$\begin{aligned}
\hat{B}\theta + G + C &= D \\
G &\leq G^{max} \\
C &\leq D \\
b\hat{A}\theta &\leq F_f^{max} \\
-b\hat{A}\theta &\leq F_r^{max} \\
G, C &\geq 0 \\
\theta & \quad \text{unrestricted}
\end{aligned}$$

Solution strategy 1: Particle Swarm Optimization

PSO imitates the behavior of a flock of birds (swarm of particles) in search of food (objective function).

Velocity vector:

$$\begin{aligned} v[\cdot] \leftarrow \quad & v[\cdot] + \text{rand}() \times c_1 \times (pbestx[\cdot] - presentx[\cdot]) \\ & + \text{rand}() \times c_2 \times (pbestx[gbest] - presentx[\cdot]) \end{aligned}$$

Position vector:

$$presentx[\cdot] \leftarrow presentx[\cdot] + v[\cdot]$$

Comments:

- Collective intelligence of swarm helps identify objective
- Parameters need to be tweaked to achieve good performance (speed and convergence)

PSO implementation: modeling

- Search space is (N_G+N_T)-dimensional; each point in this space corresponds to a configuration for system augmentation
- Search for a point in this space that minimizes expansion cost $(J=J_G+J_T)$ subject to system-wide and locational reliability criteria

Reliability corresponding to a particle

- The existing system is augmented by the coordinates of the particle
- The augmented system is evaluated using a contingency selection procedure
  - ⇨ All first order transmission and first and second order generation contingencies are considered
  - ⇨ For each contingency the dispatch module is solved and system and locational indices are determined
  - ⇨ Each overall system or locational index is determined from the weighted sum

$$R_j = \sum_{i=1}^{N_{\text{cont}}} P_i R_{ji}$$

PSO implementation: constraints

- Particles assume positions with non-negative coordinates
- Penalty for violating reliability stipulations: problem is modified to

$$\text{Min} \quad J = J_G + J_T + \sum_{i=1}^{N_C} \phi_i \left(x_2 | x_1 \right)$$

where

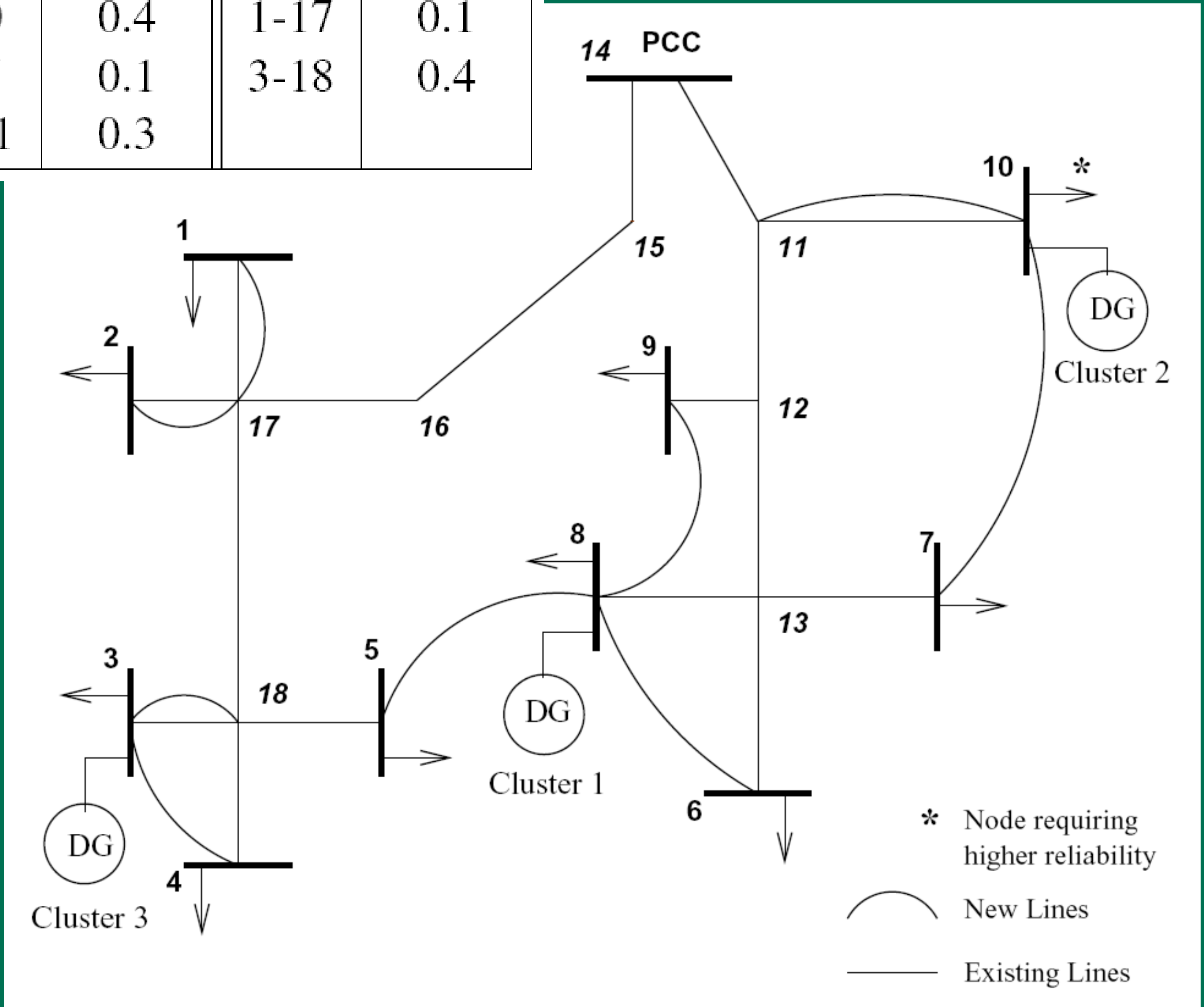
$$\begin{aligned} \phi_i \left(x_2 | x_1 \right) &= k_i \times \left(\frac{R_{0i} - R_{2i}}{R_{1i} - R_{2i}} \right) \times \left| J_1 - J_2 \right| && \text{if } i\text{th criterion is violated} \\ &= 0 && \text{otherwise} \end{aligned}$$

Solution steps

1. Build search space, initialize particles in feasible region
2. For each particle, determine reliability indices and expansion cost
3. Using cost as objective (or “fitness”) function (lower cost implies better fitness), determine the particle velocity vectors
4. Using the particle velocity vectors, update the particle position vectors
5. Repeat steps 2 through 4 until the cost function converges (standard error less than tolerance)
6. Augment system by coordinates of solution point (group best at convergence)

Result: augmented system

Line	Cap (MW)	Line	Cap (MW)
3-4	0.7	5-8	0.6
6-8	0.5	8-9	0.5
7-10	0.4	1-17	0.1
2-17	0.1	3-18	0.4
10-11	0.3		



Solution strategy 2: Dynamic Programming

Consider generator locations to be fixed; then

Objective function is network expansion cost, subject to system-wide and locational reliability criteria:

$$\text{Min} \quad J = \sum_{i=1}^{N_T} J_{0i} + J_i x_i$$

subject to:

$$\begin{aligned} EIR_{sys} &\geq EIR_{sys}^{min} \\ A_{sys} &\geq A_{sys}^{min} \\ EIR_k &\geq EIR_k^{min} \\ A_k &\geq A_k^{min} \end{aligned}$$

Inclusion of generators described later

Solution method using DP

- Solved in a stage-wise manner using Dynamic Programming (DP).
  - In each stage the network is incremented by one *unit-link.*
  - DP stage: represents the number of *unit-links* utilized
  - DP state: reliability vector
  - DP decision: the *unit-link* to be added at each stage
- Reliability vector for each unit link addition is determined using contingency evaluation method

  As done for each particle, described before

Challenges with DP method

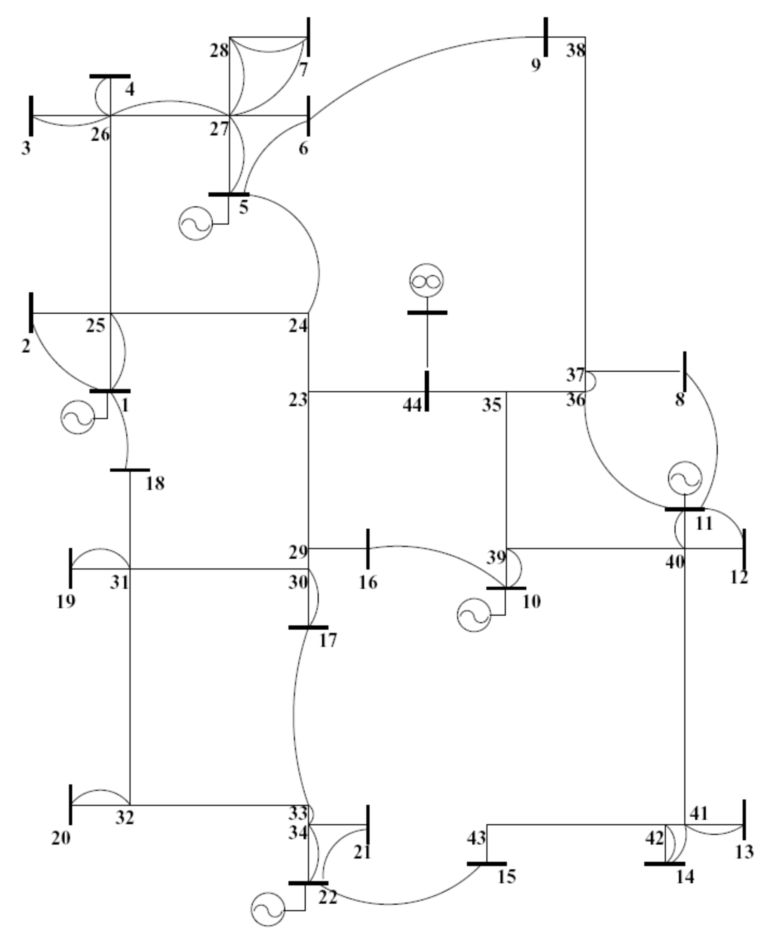
Overwhelming computational complexity

- At each stage, all configurations with same reliability were examined and only lowest cost configuration was retained, all others were discarded
- Algorithm was parallelized and distributed over a 128-node Beowulf cluster
- Solved in two phases because of parallelization

Comparison of PSO and DP

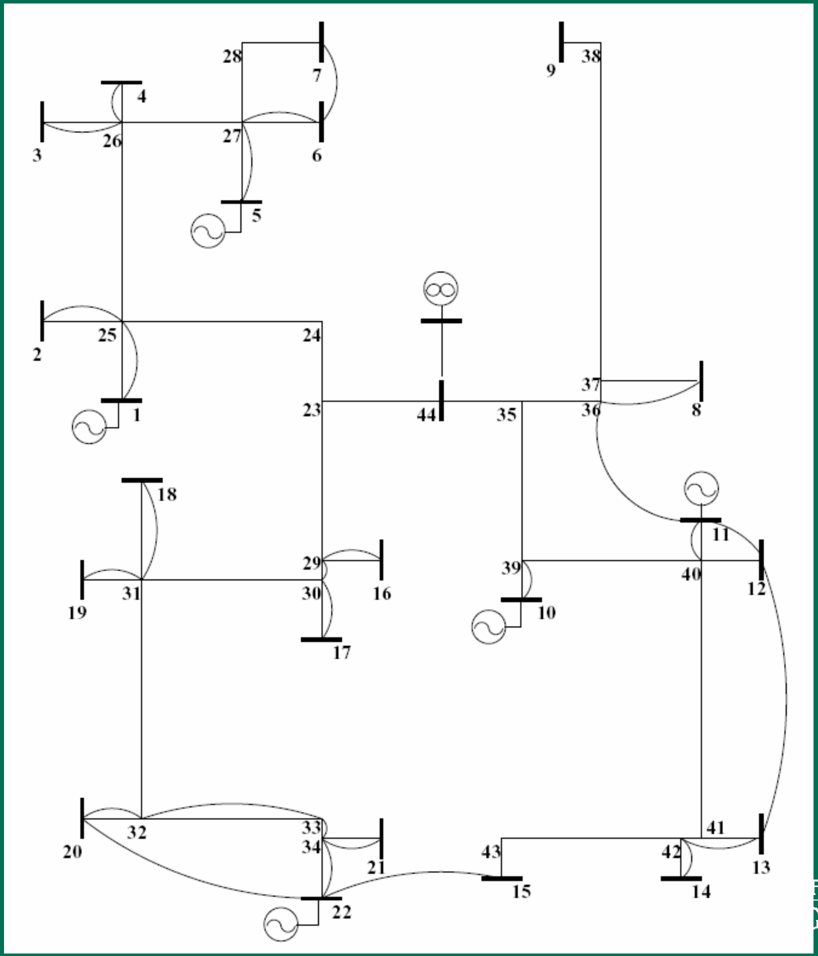
PSO Solution

Min augmentation cost: 486



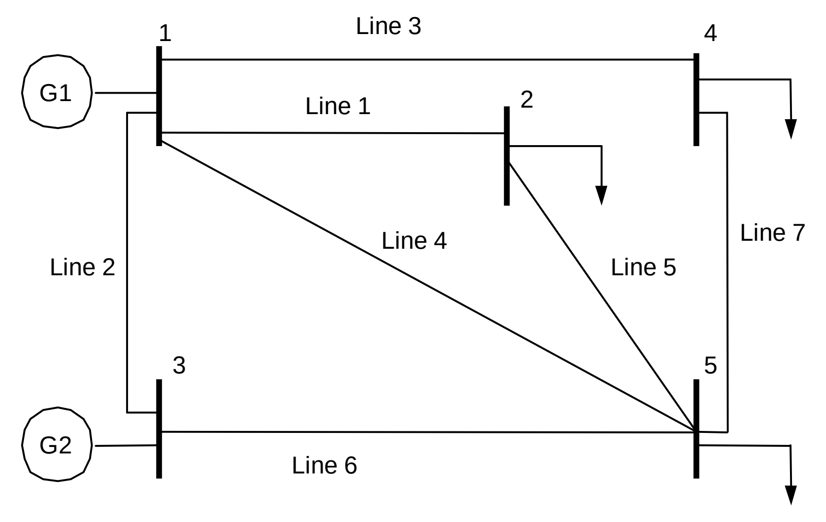
DP Solution

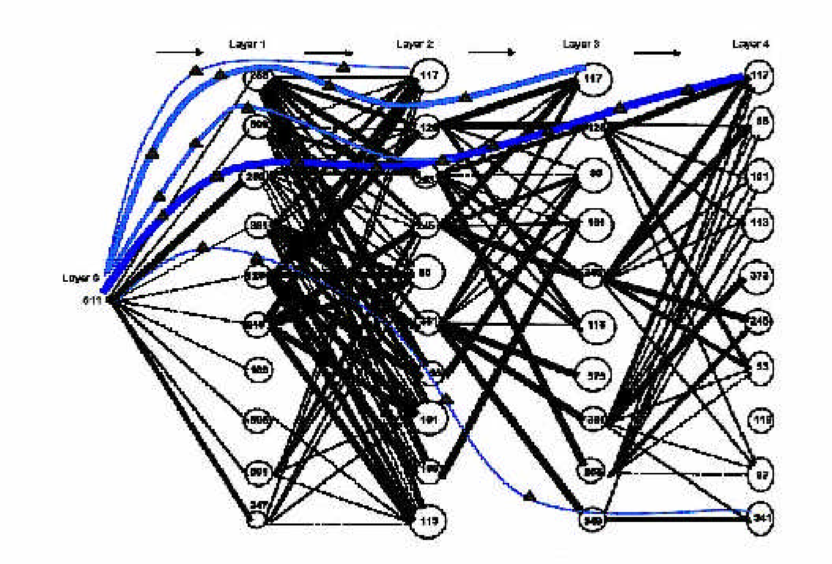
Min augmentation cost: 460



Grid security research

- Problem statement: Identify likely event sequences that lead to catastrophic failures
- Challenges:
  - Model system dependencies
  - Identify most likely even sequences
- Approach: layered genetic algorithm





Return of integrated resource planning

- Tomorrow's sustainable, resilient system can be accomplished by thoughtful and responsible integrated resource planning
- Expansion planning methods described before can be adapted to bulk system with suitable modifications
  - Select most resilient solution from multiple optima
  - Include determination of appropriate resource mix
  - Include ac flow and appropriate load models
  - High performance computing will play a key role

Concluding remarks

- Creative approaches will be critical to the development of planning tools for the complex energy system of the future
- Multiple, and sometimes conflicting, objectives will contribute to the complexity
- Presence of variable resources will require geospatial modeling and weather data/forecasts