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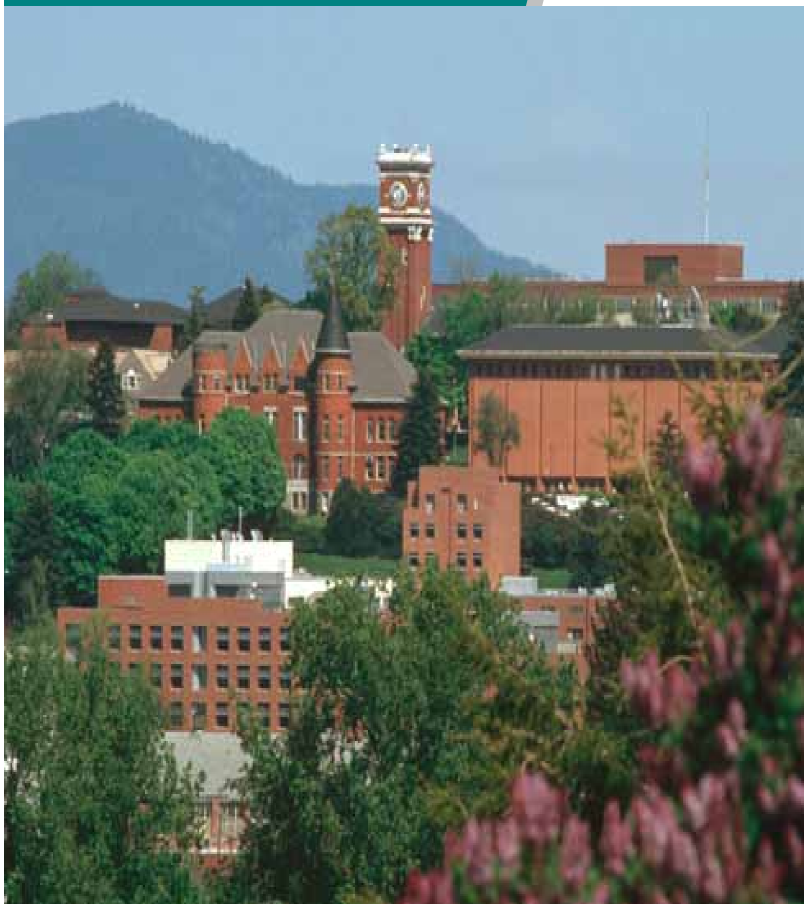

Distributed Generation Expansion: Analysis, Directions, Modeling, and Formulation

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Importance of Distribution Systems

- Reliability under competition
  - Concern: Problems with transmission reliability and security
  - Reality: Most outages will still be from distribution
- System complexity
  - Concern: Large scale of transmission and generation
  - Reality: Distribution systems far more complex
- Benefits of competition
  - Concern: Prices in energy market
  - Reality: Customer interface is distribution and determines value of market

First Some Competing Visions EPRI - IntelliGrid

A new electric power delivery infrastructure that integrates advances in communications, computing and electronics to meet the energy needs of the future

- **Example components**
  - **Power Electronics-based Power Flow Controllers**
  - **Infrastructure Quality and Reliability**
  - **Forecasting tools**
  - **Advanced Sensors**
  - **Utility Communications - State of the art and trends of communications in utilities systems**

More Competing Visions
DOE - GridWise

GridWise ***denotes the operating principle of a modernized electric infrastructure framework where open but secure system architecture, communication techniques, and associated standards are used throughout the electric grid to provide value and choices to electricity consumers.***

GridWise ***is an entirely new way to think about how we generate, distribute and use energy. Using advanced communications and up-to-date information technology, GridWise will improve coordination between supply and demand, and enable a smarter, more efficient, secure and reliable electric power system.***

Some Competing Visions
Tomsovic – "Genius" grid

Apparently the Grid is currently pretty stupid so sure, all of the above.

But beyond these big visions we still need to formulate some technical problems that can be analyzed and solved.

Distribution System Operations and Planning

- **Extremely complex**
- **Typical substation**
  - **4-6 feeders**
- **Typical feeder**

$\Rightarrow$

- **3000 customers**
- **6 reclosers, interrupters**
- **75 fuses**
- **50 miles of circuit**
- **500 line sections**
- **5 capacitors**
- **5 voltage boosters**
- **400 distribution transformers**
- **Disconnect switches**
- **Splicers and elbows**
- **Lightning arresters**
- **Metering equipment**

Traditional Problems of Importance

- Planning/design
  - Feeder routing
  - Capacitor placement
  - Switch location
  - Protective device type and location
  - Maintenance scheduling
  - Substation siting
- Operations
  - Restoration
  - Adaptive relaying
  - Loss minimization
  - Load balancing
  - DSM
  - Trouble call analysis
  - New services

⟹ **All of these are greatly impacted by DG; problems mostly "utility-centric"**

Directions for Distribution System Problems

- **Increased importance of optimal designs**
- **Limited availability of experienced engineers**
- **Importance of distribution systems for overall system performance**

Many problems solvable

Overview

Some problem applications

- Protection design
- Diagnostics and maintenance
- Restoration
- Expansion planning
- Load following
- Performance/efficiency
  - Voltage control for efficiency

➔ Impact of DG on these areas - new computational approaches/concerns

Example: Distribution Protection Design

- Protective devices
  - Circuit Breaker
  - Line Recloser
  - Interrupter
  - Sectionalizer
  - Fuse

Basic Objectives of Protective Devices

- **Prevent or minimize damage to equipment by clearing an abnormal condition.**
- **Prevent hazards to the public by removing a faulted circuit from the network.**
- **Improve service reliability by removing a small section of the circuit for a given fault and automatically restoring a momentarily faulted section.**

Current Protection Design Practice

- **Utility guidelines (rules-of-thumb)**
- **Engineer experience**
- **Analyze reliability for several possible designs**

$\Longrightarrow$ **But optimal solutions are tractable**

Some Reliability Indices

- **Customer oriented, *SAIFI* index**

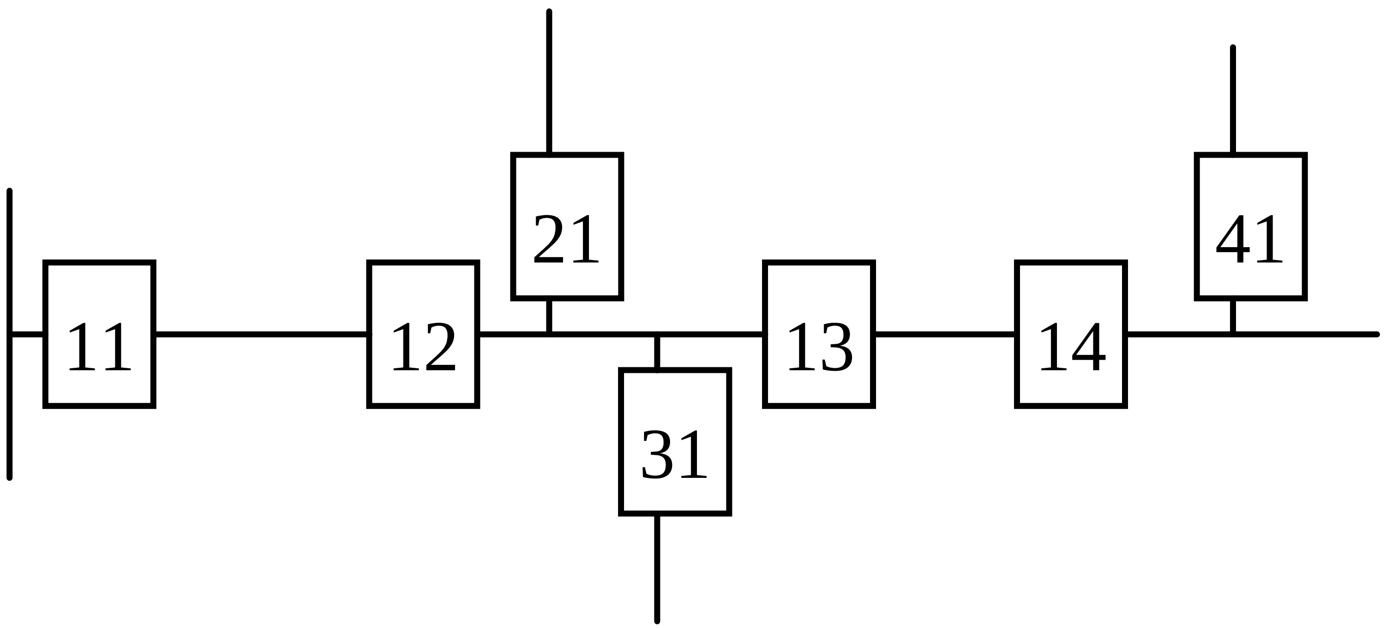
$$SAIFI = \frac{\sum \lambda_i N_i}{N_T}$$

- **Load oriented, *ASIFI* index**

$$ASIFI = \frac{\sum \lambda_i L_i}{L_T}$$

Locating Protective Devices

- **Optimize reliability and satisfy constraints**



Binary Programming Formulation

- **Categorize branches, *SAIFI* from main laterals**

$$\sum_{i=1}^{q_n}\left(\lambda_{qi}+\gamma_{qi}\right)\sum_{j=i}^{q_n}N_{qj}-\sum_{i=1}^{q_n}\gamma_{qi}x_{qi2}\sum_{j=i}^{q_n}N_{qj}+$$

$$\sum_{i=2}^{q_n}\lambda_{qi}\sum_{j=1}^{i-1}N_{qj}\prod_{k=j+1}^{i}x_{qk1}x_{qk2}+\sum_{i=2}^{q_n}\gamma_{qi}\sum_{j=1}^{i-1}\left(1-x_{qj2}\right)\sum_{k=j}^{q_n}N_{qk}\prod_{l=j+1}^{i}x_{ql1}x_{ql2}$$

- **Non-linear objective but can be transformed into linear function of binary variables**

Binary Programming Formulation

- **Constraints**
  - **Coordination**
  - **No reclosers downstream from a fuse**
  - **Certain laterals must be fused**
  - **Limited number of protective devices**

Multi Objectives in Optimization

- **Minimize SAIFI index**
- **Minimize ASIFI index**
- **Fuse saving schemes must not overly impact momentary outages**

Impact of Distributed Generation

- Coordination much more difficult
- Utility guidelines (rules-of-thumb) and engineer experience not particularly useful
- Protection design (optimal or just functional) for reliability depends on DG location, which is probably outside of utility control
- Numerous issues associated with microGrids or location dependent reliability

➔ But optimal solutions are probably tractable, if expensive

Example: Distribution System Condition Monitoring and Maintenance

- Approximate information in diagnosis
  - Methods are approximate and require experience to apply
  - Data is imprecise and noisy
  - Interpretation of observations depends on history
  - Is measurement taken after beginning of fault and before major fault occurs?
  - Definitive identification of a fault requires removal from service

Example: Condition Monitoring and Maintenance (cont.)

- **Reliability calculation concerns**
  - **Probability distributions unknown**
  - **Manage imprecise relationships independently**
  - **Accumulate diverse information (e.g.,bounds on probability)**
  - **Robust with respect to missing information**
  - **Failure rates generally low**

Example: Condition Monitoring and Maintenance (cont.)

- Maintenance for reliability
  - Use approximate probabilities
  - Estimate affect of maintenance procedures
  - Optimize maintenance decisions
- Distribution systems
  - Tree trimming
  - Circuit breakers, reclosers, interrupters
  - Sectionalizers, capacitors, voltage regulators
  - Fuses, elbows, splices (replacement)

Relationship of Protection to Maintenance

- **Protection determines failure area**

$$SAIFI = \frac{\sum_{q=1}^{\rho} \tilde{A}_q}{N_T}$$

$$\tilde{A}_q = \left(\tilde{\lambda}_{q1} + \sum_{l=2}^{L} \tilde{\lambda}_{ql} \sum_{k=1}^{K_l} \delta_{lk} x_{qlk} \right) \tilde{N}_q$$

Optimization Problem

- **Binary programming to optimize estimated failure rates**
- **Decision variable is type and component for maintenance**
- **Constraints include resources, crew availability, etc.**

Impact of Distributed Generation

- Condition/reliability of DG units may be completely unknown
- Utility guidelines (rules-of-thumb) and engineer experience not particularly useful

➔ Solutions from a utility point-of-view probably not tractable, too many unknowns – rely on supplier guidelines

Another Example: Restoration

- Restore customers following a fault
  - Feeder thermal limits
  - Transformer thermal limits
  - Three phase balance
  - Voltage profile
  - Protection limits
- Objectives
  - Minimize switching actions
  - Minimize losses
  - Minimize unserved energy

Impact of Distributed Generation

- **Ability of DG units to pick up load or run in isolation may be limited but in general should be able to help**
- **Potentially significant help with cold load pick up**
- **May be able to minimize amount of needed load shifting among feeders**

→ Solutions from a utility point-of-view tractable and beneficial assuming some control over DG units

Another Example: Expansion Planning

- Most effective to plan for the substations and feeders simultaneously
- Single criterion

Economical Objective:

Determine the most economical multistage expansion profile such that for every stage:

- every demand center is served
- every element is operating within it's capability
- Satisfactory voltage provided at every demand center
- all expenditure is within budget

General Formulation

$$Min\ C = \sum_{t=1}^{T} \left\{ \sum_{S \in Stations} Cf_{S,t} + \sum_{S \in Stations} Cv_{S,t} + \sum_{F \in feeders} Cf_{F,t} + \sum_{F \in feeders} Cv_{F,t} \right\} \quad (1)$$

$$Subject\ to: \sum X_{ij,t} - \sum X_{jk,t} = P_{j,t} \quad \forall\ j \in \text{Load Centers}, ij \text{ and } jk \in \text{Feeders} \quad (2)$$

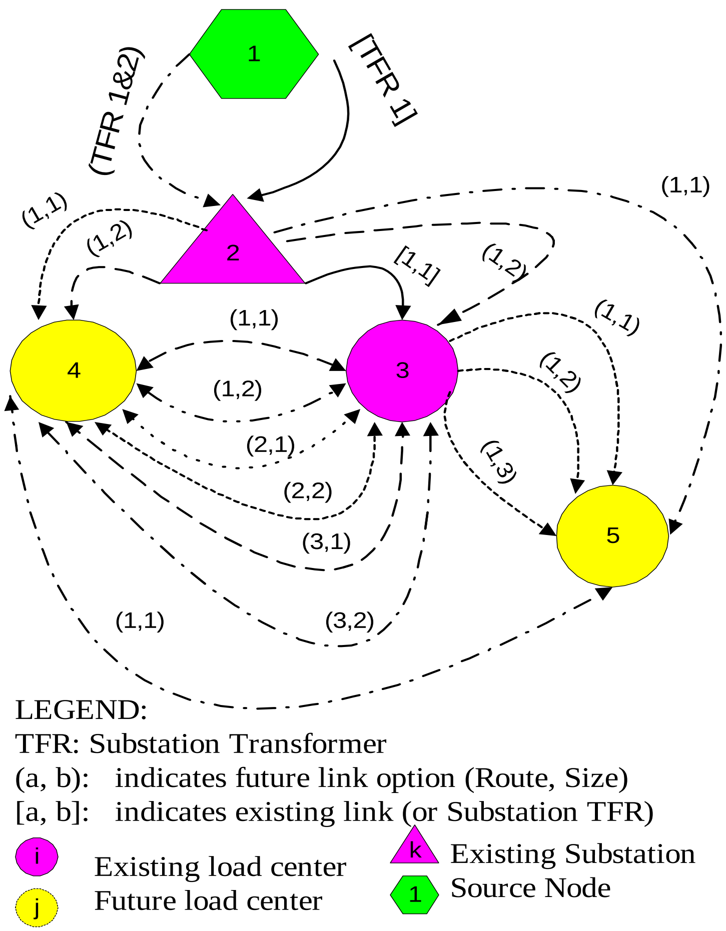
$$V^{Min} \leq V_{j,t} \leq V^{Max} \quad \forall\ j \in \text{Load Centers} \quad (3)$$

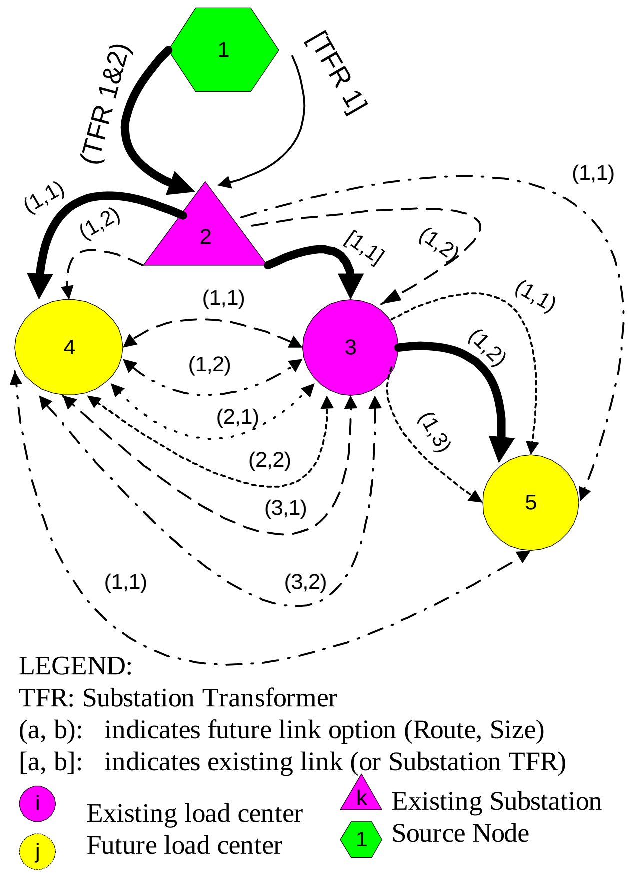
$$S_{i,t} \leq S_i^{Max} \quad \forall i \in \text{Stations} \quad (4a)$$

$$X_{ij,t} \leq X_{ij,t}^{Max} \quad \forall\ ij \in \text{Feeder Links} \quad (4b)$$

$$\sum_{S \in Stations} Cf_{S,t} + \sum_{S \in Stations} Cv_{S,t} + \sum_{F \in Feeders} Cf_{F,t} + \sum_{F \in Feeders} Cv_{F,t} \leq B_t, \quad \forall\ t = 1,2,\ldots,T \quad (5)$$

Test Case Results





Extensions, Upgrades, and Optimal Load Assignment

- **Upgrades**
  - **Crucial in distribution planning, generally not considered**
  - **Usually much more economical**
  - **Re-conductor, Underground Temp facilities**
  - **Can upgrade, but not degrade**
- **Optimal Load Assignments**
  - **Can also be done at Planning stage**
  - **Can provide valuable input to the DM**
  - **My be used for local area design**

Impact of Distributed Generation

- Greatly increase the uncertainties in design

➔ Solutions from a utility point-of-view probably not fully tractable, too many unknowns

➔ But potential for huge cost savings by limiting amount of needed capacity

Distribution System Operations

Traditionally not much one can do - propose similar structure to system operations

- **Normal operations**
  - **AGC/Load following controls**
  - **Voltage controls**
- **Security**
  - **In radial system all contingencies lead to outages but some worse than others**
  - **If islanding allowed, then must operate within capacity limits to survive contingency**

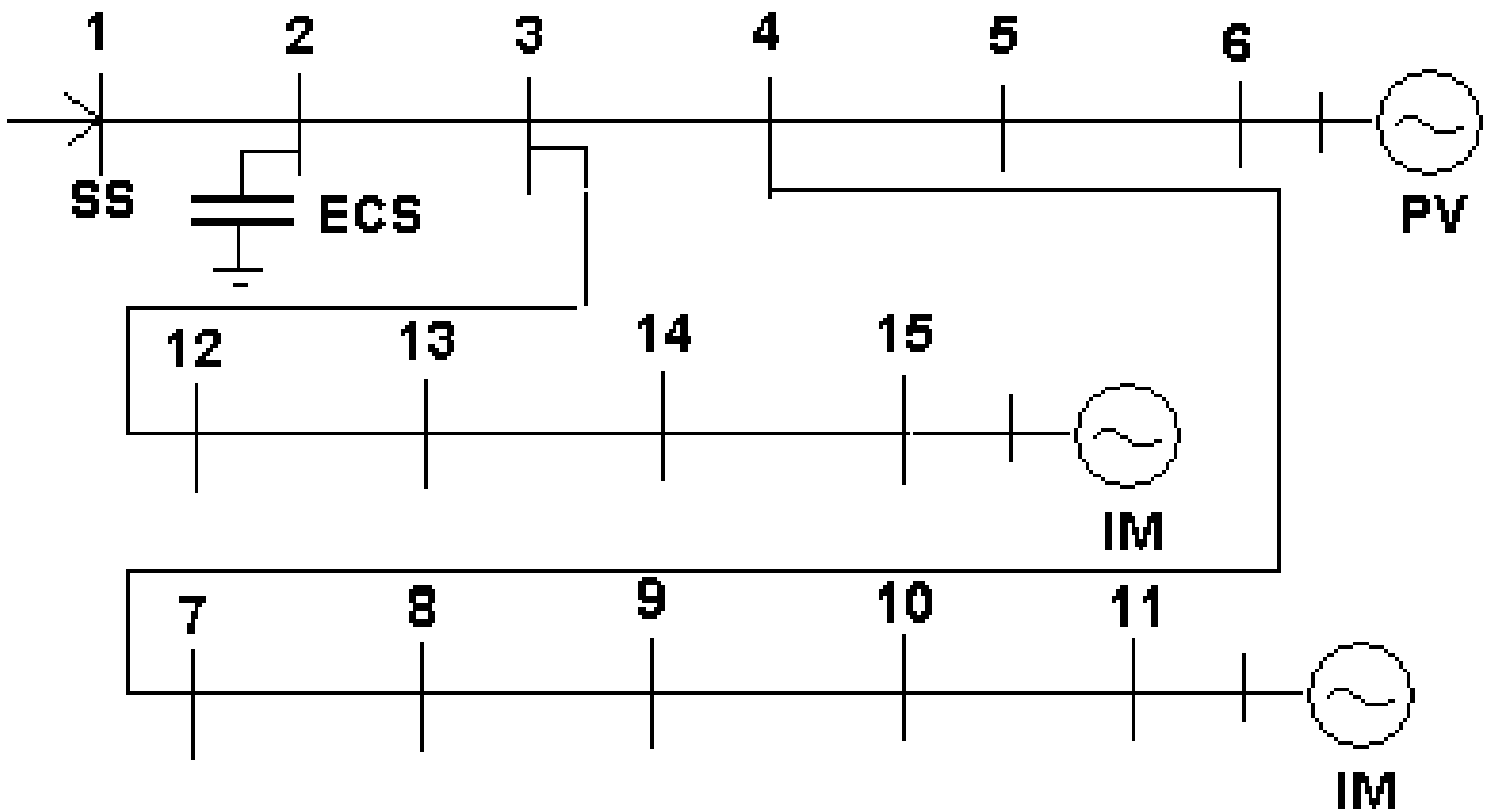
Control Approach for Load Following Service

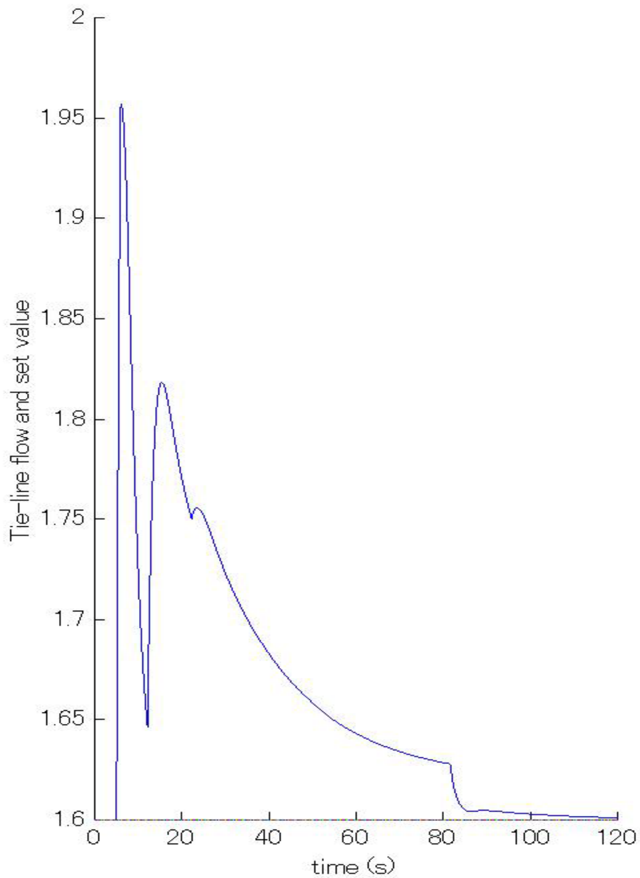
- **Flow from substation acts similar to tie line**
- **Frequency fluctuations minimally impacted by distribution system**
- **During disturbance control law is simply**

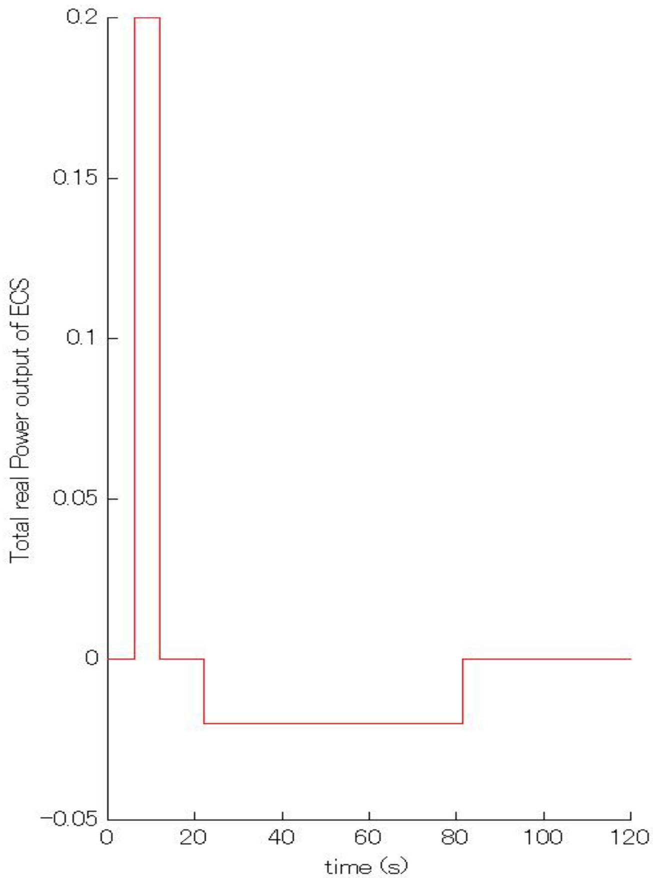
$$P_{\text{out}} = P_{\text{tie}} - P_{\text{set}}$$

- **After disturbance recharge/discharge ECS to set value**

Example System 1 with DER
(Modified Kumamoto City)




Tie-line flow and set value
2
1.95
1.9
1.85
1.8
1.75
1.7
1.65
1.6
0
20
40
60
80
100
120
time (s)


Total real Power output of ECS
0.2
0.15
0.1
0.05
0
−0.05
0
20
40
60
80
100
120
time (s)

Voltage Control for Efficiency OR Conservation Voltage Reduction

- Loads increase consumption with increasing voltage
- But too low voltages also increase current flow and stress equipment

➔Ideal is maintain flat voltage along feeder but existing controls inadequate to achieve this

- Efficiency savings on the order of 5-10%
  - Note in Washington State, conservation counts towards renewable energy credits

➔DG can also help on voltage profiles but so can a number of technologies

Energy Scavenging and Micro-sources

- **Palm-sized fuel cells that cost only a few cents apiece**
- **Batteries charged by body heat**
- **Pacemakers powered by sugar**
- **Vibration based power generation for cell phones**
- **Millimeter sized internal combustion engine (MEMS technology)**
- **"Shake" charged flashlights**
- **Wind generation from rippling of flag**

➔ Research Question: Can these be scaled up and scheduled to provide energy to a new grid that is a dynamic fluctuation of on and off-grid components? A true switching network similar to the internet.

Alternative Infrastructures

- **Prepaid energy cards (common in many developing countries)**
- **Load scheduling as predominant mode of electric energy consumption (far more extensive than simply load leveling)**
- **Selective reliability (may be particularly relevant for developing countries)**
- **Etc.**

Concluding Comments

- As researchers we should be thinking of wholly new applications – not just incremental improvements in existing problem areas
- Technology developments are leading to the possibility of industry/problems driven by innovation instead of regulation
- In any conceivable future scenario (technical, political, economic, environmental), research on the bulk generation and delivery of electric energy will be central to success

Discussion