Analytically Driven Power Distribution Applications

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Outline

- Overview
- Problem Formulations
- Example Applications
- Remarks
- Discussion

Distribution System Examples

Terrestrial Distribution Systems
[power.ece.drexel.edu]
DOE, NSF, Utilities, Vendors

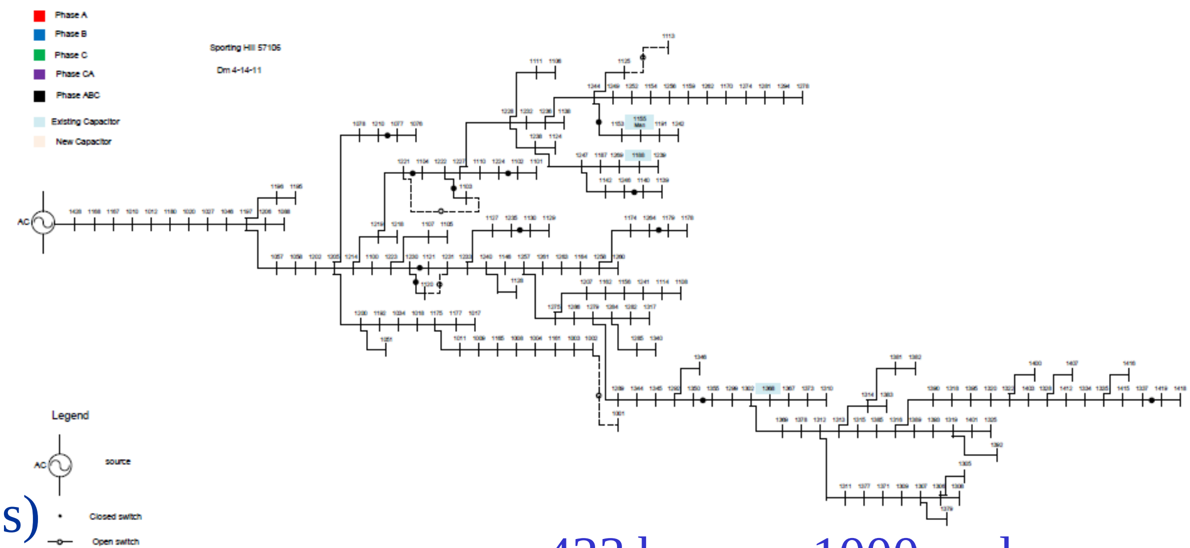
Space Power Systems
[www.nasa.gov]

Shipboard Power Systems
[www.navyleague.org]
ONR

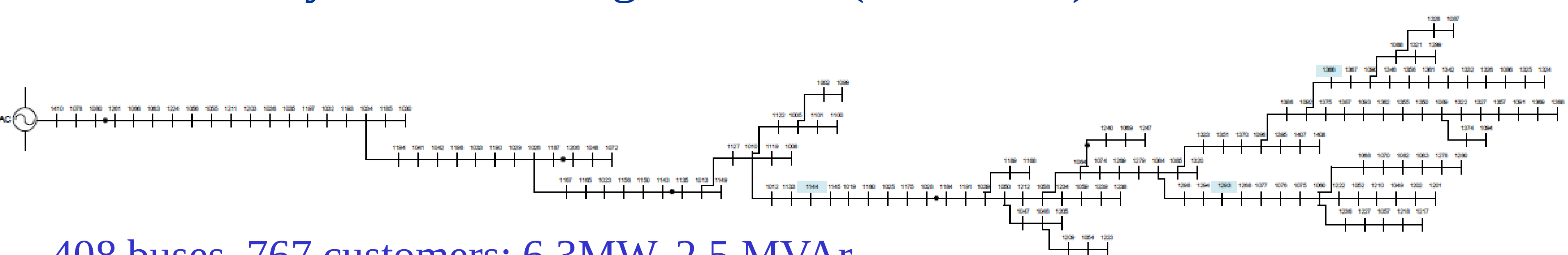
Hybrid Electric Cars/Vehicles
[www.honda.com]
Industry

Terrestrial Distribution Systems

- **Properties:**
  - large systems (10,000+ nodes)
  - normally operated in a radial manner (embedded switches for loops)
  - limited # of real-time measurements
  - uncertainty of loads and generation (stochastic)



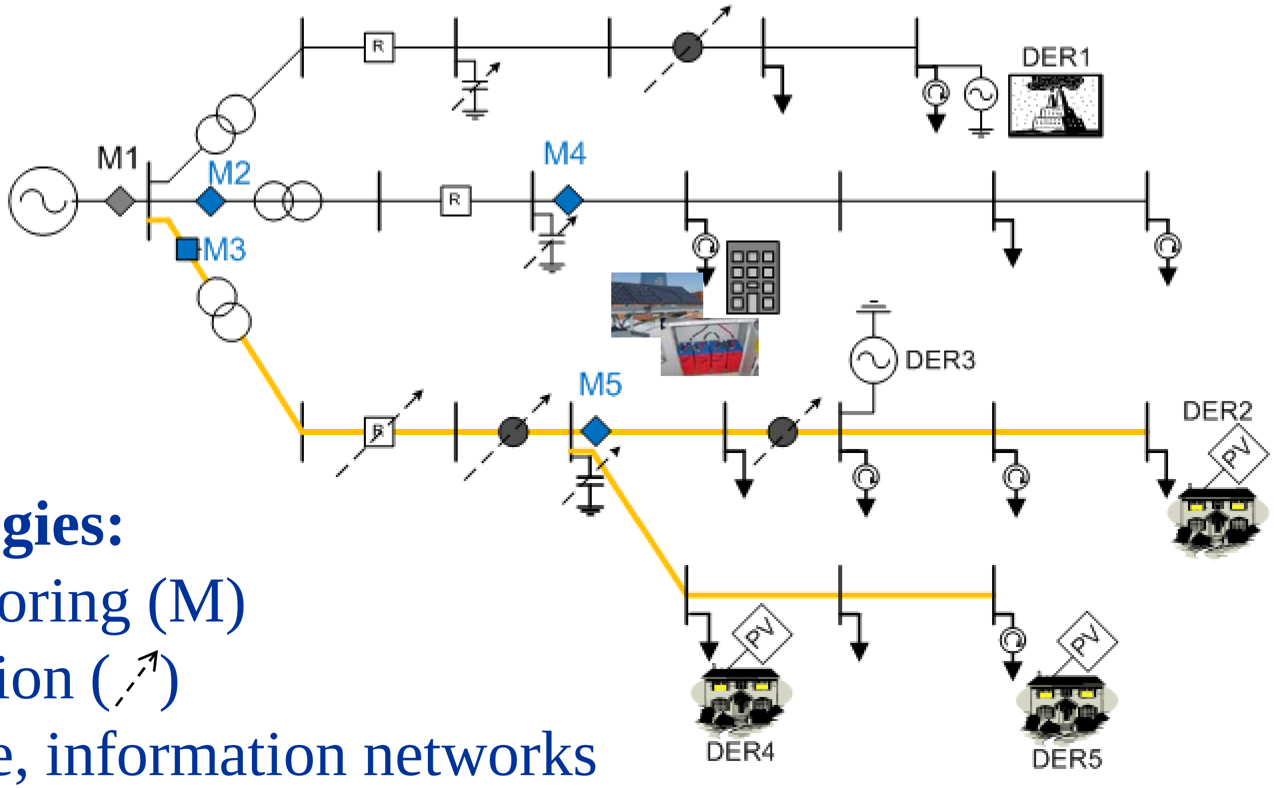
423 buses, ~1000 nodes,
842 customers: 5.6MW, 1.2 MVAr
(only 3 phase buses drawn)



408 buses, 767 customers: 6.3MW, 2.5 MVAr
(only 3 phase buses drawn)

Terrestrial Distribution Systems

- **U.S. Properties:**
  - multi-phase: 2, 3, 4 and 5-wire systems
  - grounded and ungrounded
  - above ground and underground
  - large



- **Enabling technologies:**
  - advanced monitoring (M)
  - control automation (⤢)
  - cost manageable, information networks

Distribution Applications

- Specific Functions of Distribution Automation

- Examples
  - Objective: Improve Reliability
    - Application = Network Reconfiguration/Service Restoration

  - Objective: Improve Efficiency
    - App. = Network Reconfiguration/Load Balancing
    - App. = Voltage/VAR Control (CVR)

  - Objective: Peak Load Management
    - App = Voltage/VAR Control
    - App = Demand Side Management

Outline

- Overview
- Technical Approach
- Example Applications
- Remarks
- Discussion

Technical Approaches

- **Unbalanced component and system analysis tools**

- **Problem Formulations (focus)**
  - planning: optimal placement and replacement/retrofit
    - economically ($) driven
  - operation: control of new technologies
    - customer driven
    - shortened time-windows

- **Solution Algorithms**
  - heuristics
    - Expert system & analytically-based
    - Metaheuristics (intelligent system)
  - mathematical programming (require model/formulation simplifications)

Problem Formulations

- **Examples**
  - Switch Placement & Control for Service Restoration
  - Capacitor Placement & Control for Voltage Spread Reduction

- Optimization (*C*: objectives)
  - *F*: Electrical network constraints (equality)
  - *G*: Operating constraints (inequality)

$$
\begin{aligned}
&\min_{u \in U} C(x, \lambda, u) \\
&s.t. \\
&\qquad F(x, \lambda, u) = 0 \\
&\qquad G(x, \lambda, u) \le 0
\end{aligned}
$$

  - where
    - x: states ($\theta, |V|$); λ: parameters (uncontrollable loads); u: control variables (generation/loads, network device status)
    - U is the search space

Problem Formulation

- Switch Placement

Table: Select Goals Considered for Switch Placement Problems

Consideration	Impact/Metric
Field Limitations	*U*, search space, reduced
Regulatory: e.g. CAIFI	Customer count between switches
SAIFI: Load Restored	Transfer capability of switches
Load Variations (e.g. Cold-Load Pickup)	“ Load curtailment capability

Note:

– analytically determined values are shaded green

– to account for loads, analysis will be necessary

– *U*: gang-operated switches between any two 3P buses

Problem Formulation

- Switch Placement

Table: Select Constraints for Switch Placement Problems

Consideration	Constraint
Voltage Magnitude	$V_k^{p,\min} \leq \left\|V_k^p\right\| \leq V_k^{p,\max}$
Current Magnitudes	$\left\|I_k^p\right\| \leq I_k^{p,\max}$
Power Flows	$\left\|S_k^p\right\| \leq S_k^{p,\max}$
Voltage Rise	$\left\| \left\|V_k^p(u^{exist})\right\| - \left\|V_k^p(u^{new})\right\| \right\| \leq \Delta V_k^{p,\mathrm{rise}}$
Switch Voltage	$\left\|V_i^p\right\| - \left\|V_k^p\right\| \leq \Delta V_{ik}^{p,\max} \quad \forall \text{switches (conn. bus } i \text{ to } k)$

– Note: all analytically determined values

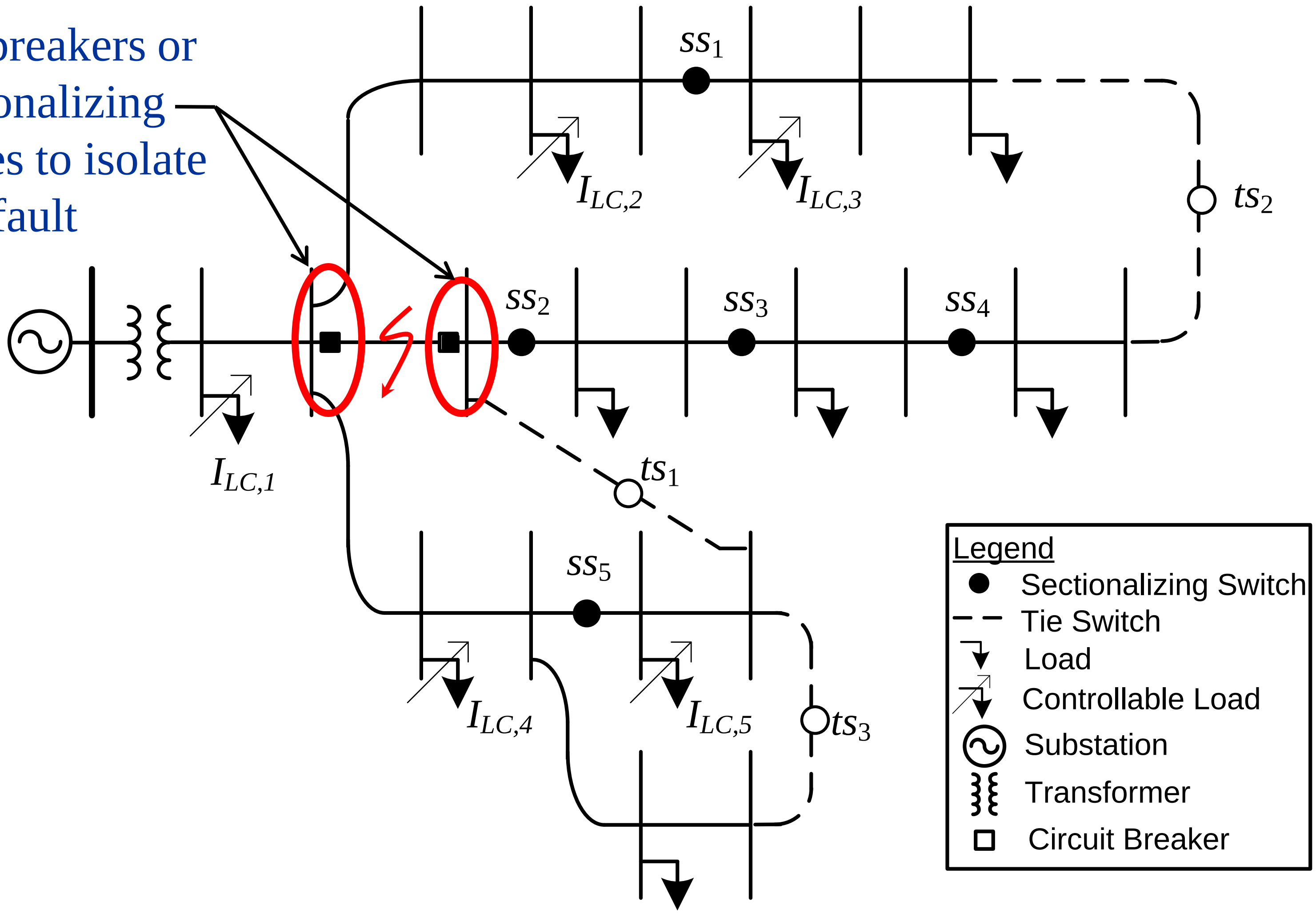
Comments

- Switch Placement
  - if based only on non-analytical indices (e.g. *customer count*) reduces flexibility of operations when considering load variations (e.g. *cold-load pick-up*)
  - transfer capability can be adjusted to account for forecasted load variations

- Switch Control
  - What if the switches are already in place?
    - Analytically based approaches can assist
    - Load control/curtailment may be invoked if available
      e.g. [M. Kleinberg et. al. to appear – TPWRS.2010.2080327]
    - Distributed resources may also be considered
      e.g. [Y. Mao et. al. 2003 - TPWRS]

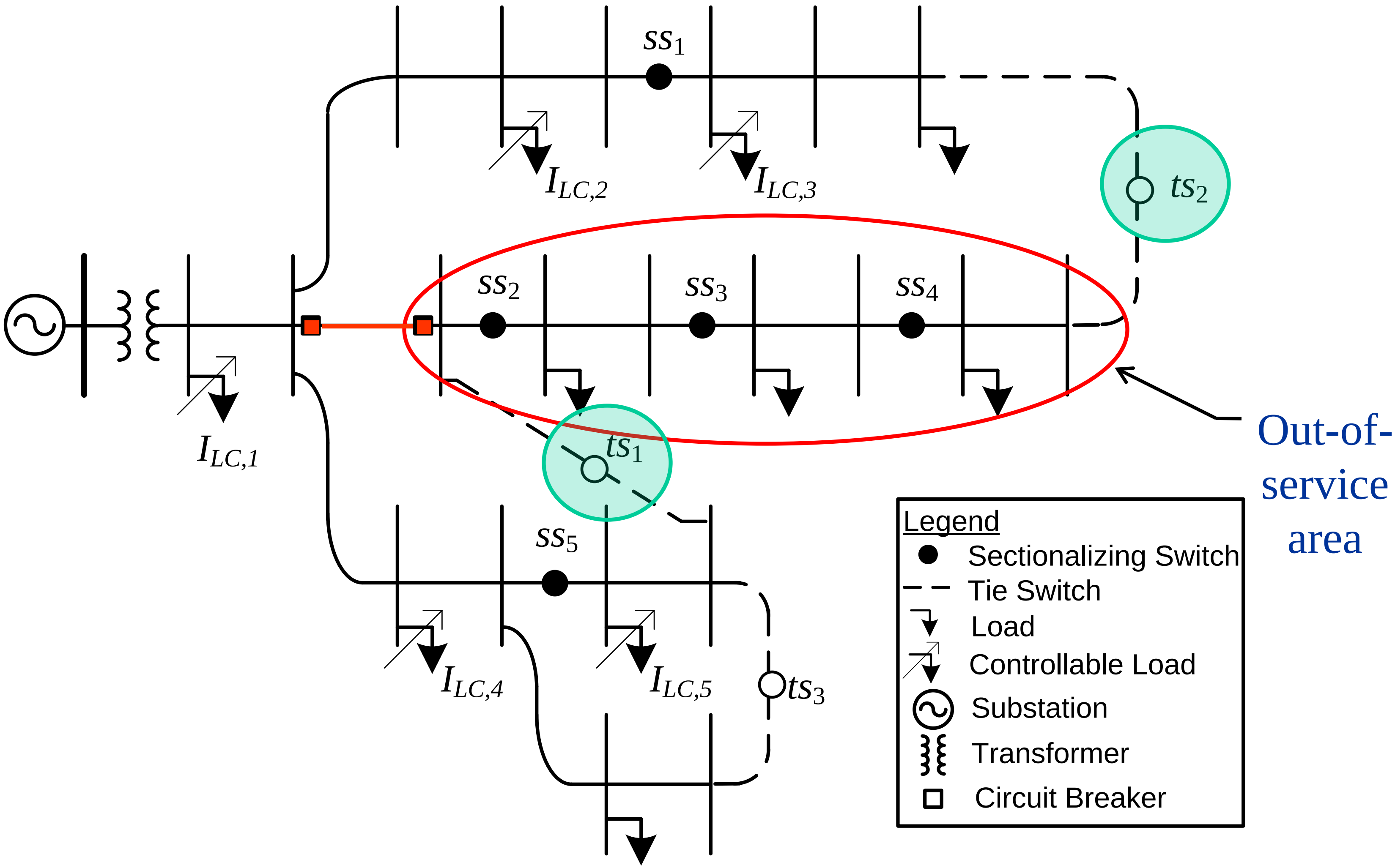
Improving Reliability: Service Restoration with Load Curtailment

Open breakers or sectionalizing switches to isolate fault



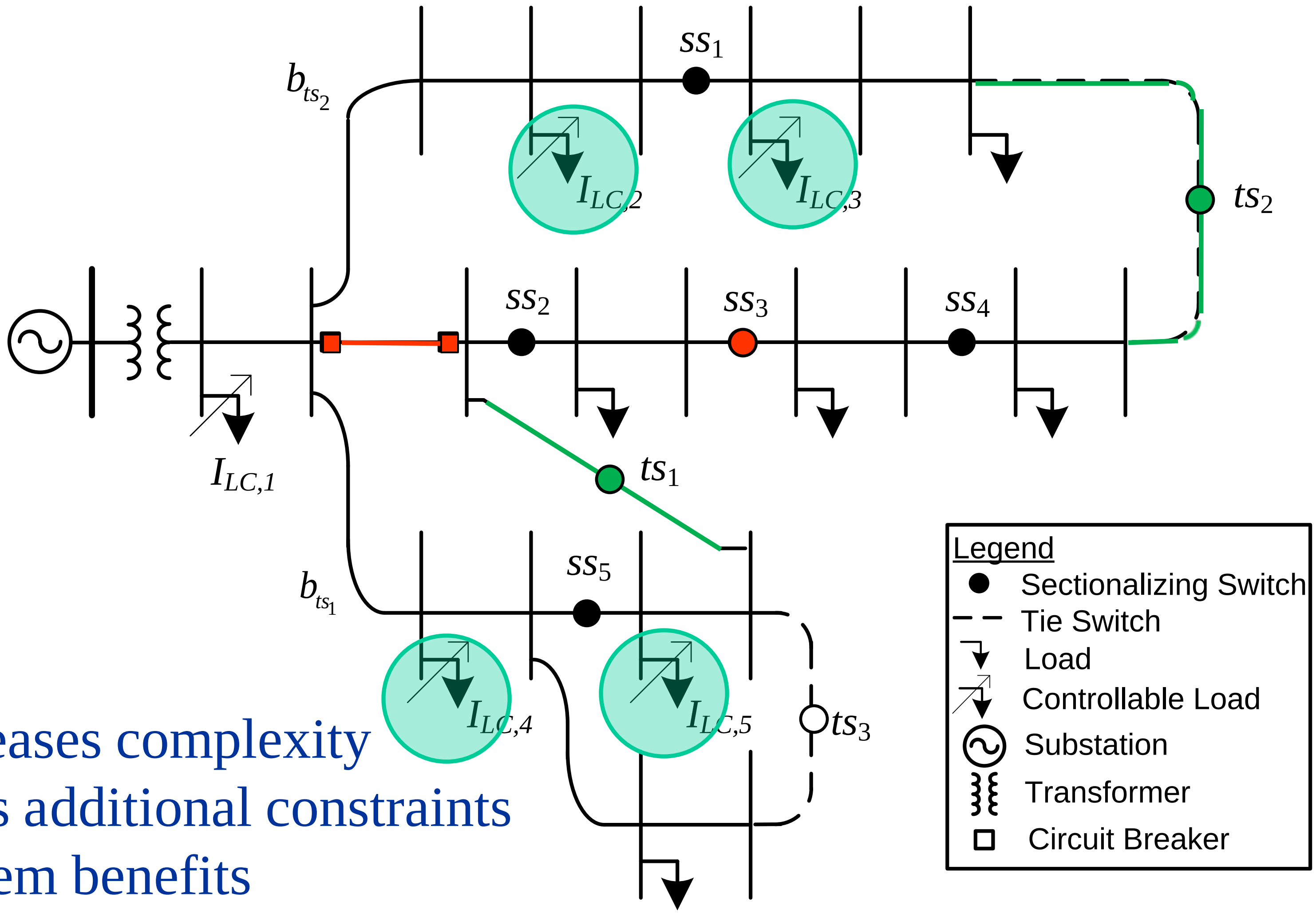
Breakers or sectionalizing switches operated to isolate faulted area

Improving Reliability: Service Restoration with Load Curtailment



Traditional restoration schemes limited by network spare capacity

Improving Reliability: Service Restoration with Load Curtailment



- Increases complexity
- Adds additional constraints
- System benefits

Load curtailment may be used to free-up additional capacity

Problem Formulations

- **Examples**
  - Switch Placement & Control for Service Restoration
  - Capacitor Placement & Control for Voltage Spread Reduction

- Optimization (C: objectives)
  - F: Electrical network constraints (equality)
  - G: Operating constraints (inequality)

$$\min_{u \in U} C(x,\lambda,u)$$
$$s.t.$$
$$F(x,\lambda,u)=0$$
$$G(x,\lambda,u)\leq 0$$

  - where
    - x: states (θ,$|V|$); λ: parameters (uncontrollable loads); u: control variables (generation/loads, network device status)
    - U is the search space

Problem Formulation

- Capacitor Placement

Table: Goals Considered for Capacitor Placement Problems

Consideration	Impact/Metric
In-Field Physical Space	*U*, search space, reduced
Regulatory: Peak Load Reduction	Substation voltage and PQ
System Voltage Spread	Node voltages
System Loss Levels	Branch flows/losses

Note:

– analytically determined values are shaded green

– *U*: all 3P buses, included sizing of existing capacitors

Problem Formulation

- Capacitor Placement

Table: Constraints for Capacitor Placement Problems

Consideration	Constraint
Voltage Magnitude	$V_k^{p,\min} \le \lvert V_k^p \rvert \le V_k^{p,\max}$
Current Magnitudes	$\lvert I_k^p \rvert \le I_k^{p,\max}$
Power Flows	$\lvert S_k^p \rvert \le S_k^{p,\max}$
Voltage Rise	$\lVert V_k^p(u^{exist}) \rvert - \lvert V_k^p(u^{new}) \rVert \le \Delta V_k^{p,\text{rise}}$
Substation Power Factor	$Q_{sub}^{\min} \le \lvert Q_{sub}^{total} \rvert \le Q_{sub}^{\max}$

– Note: all analytically determined values

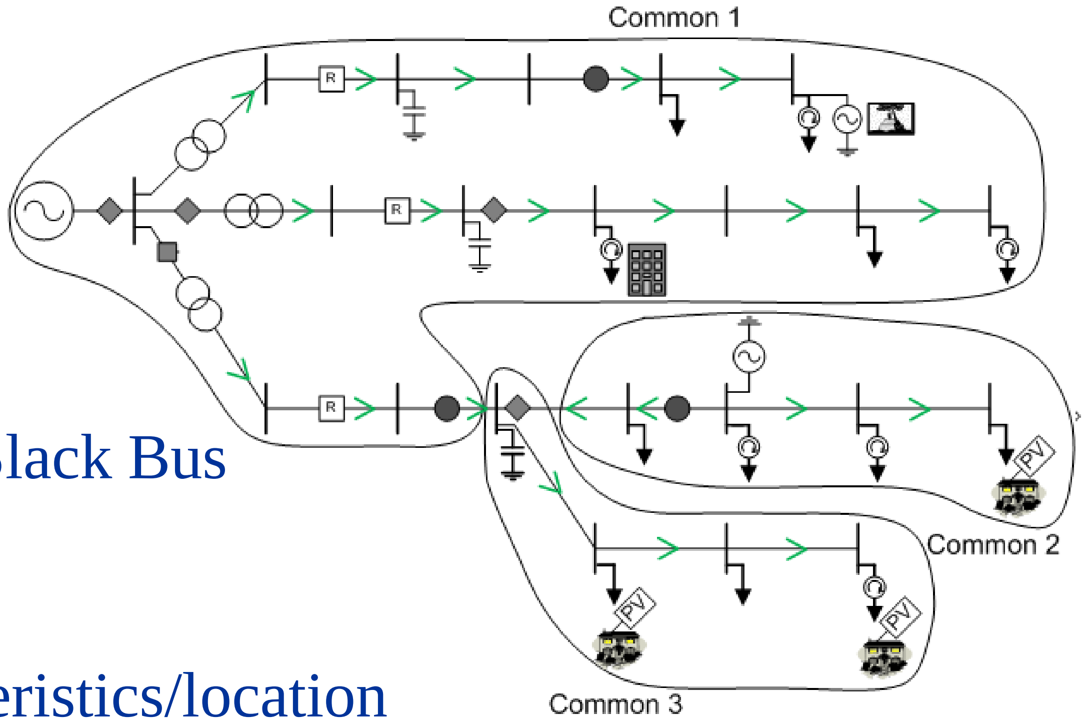
Comments

- Capacitor Placement
  - Priority of objectives should be adjusted wrt load levels.
    - Example to include: peak, 70% loading and low load levels
  - Introducing different levels of analytics yields different results
    - Examples:
      - With power factor constraints and without
      - With system loss considerations and without

- Capacitor Control
  - # of load levels considered will impact operations
  - time windows vary wrt voltage spread vs. loss reduction
  - constraints are also time dependent: e.g. maximum number of switch operations within a 24 hr period.

System Analysis & Control Partitioning

- Practical Field Limitations – reduce the search space
- Operator Preferences
  - controller proximity
- Create directed graphs
- Domain-Based Distributed Slack Bus Models (*P* graphs)
  - attribute load and losses
  - considers network characteristics/location



Energy resource power domains/commons

- Domain-Based Capacitor Placement (Q graphs)
  - considers the location of other capacitors
  - enables “physical spread” of caps

Results – Capacitor Placement

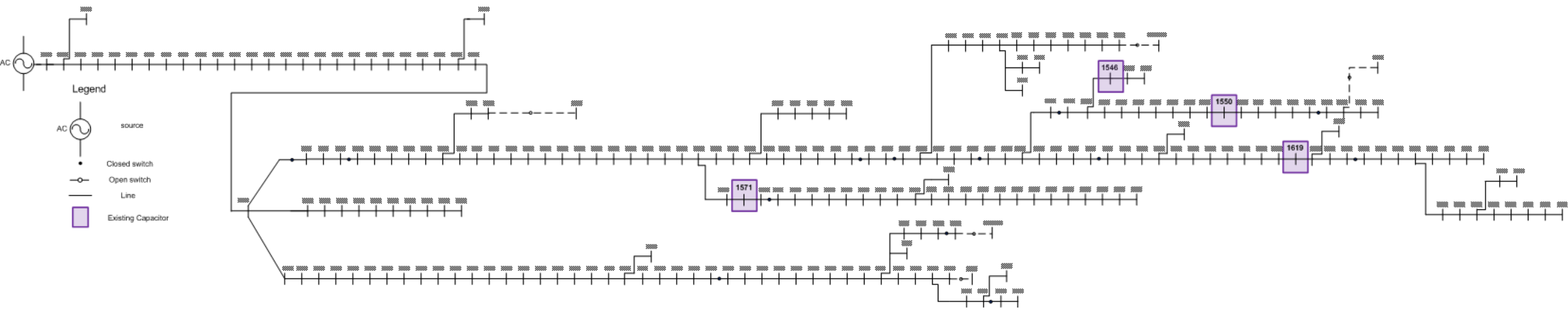


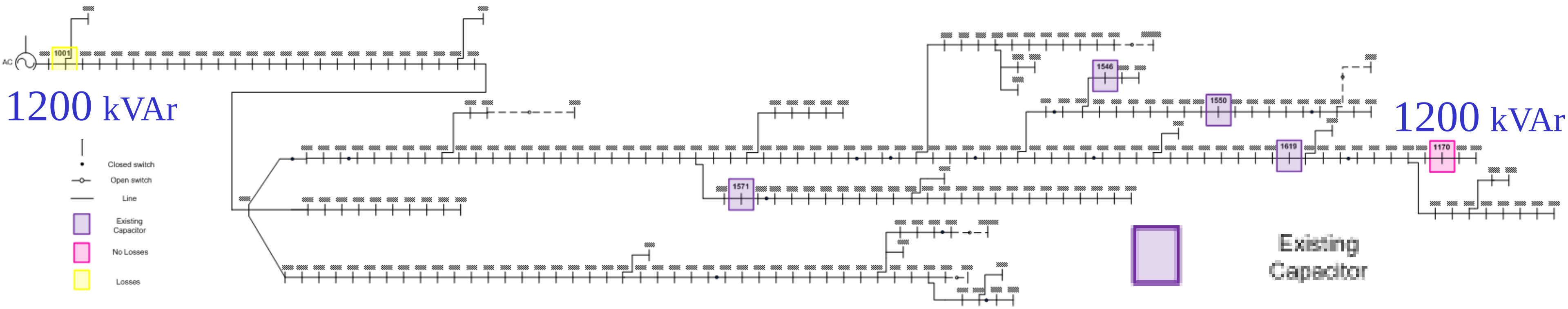
Figure: One-Line Diagram of a 690 bus system

Electrical Component	Count
# of Buses	690
# of Nodes	1082
# of Customers	1864
# of Loads	365
# of 3-Phase Buses	245
3-Phase Capacitors	4

Substation	Quantity
Total P_{Load} (kW)	5553
Total Q_{Load} (kVAr)	1753

Bus Number	Size (kVAr)	Cap Type
1546	900	Automated
1550	600	Automated
1619	900	Automated
1571	600	Manual

Cap Results: Without Q Constraints

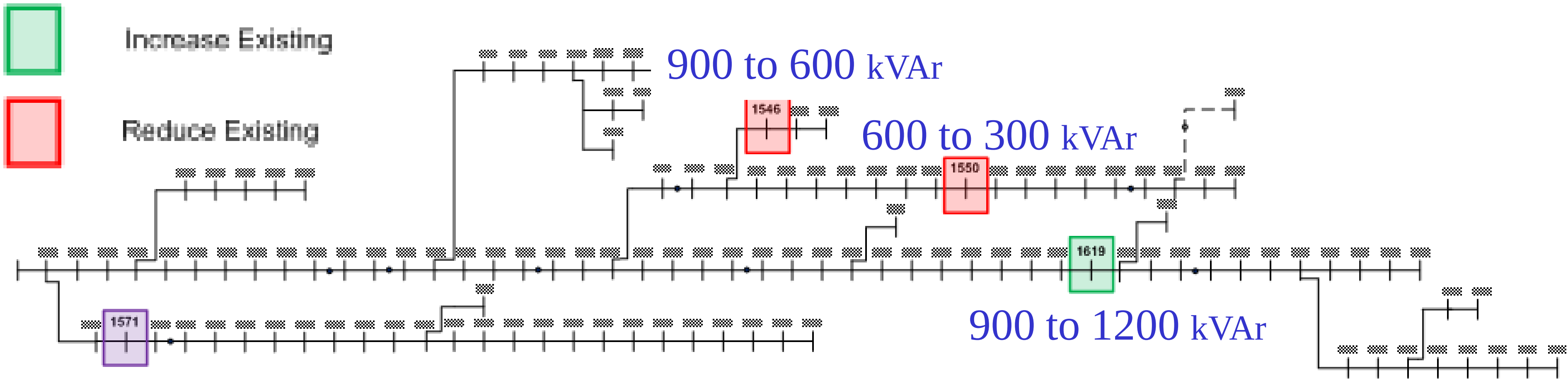


Peak Loading	Base case	No Losses	Losses
|V| spread (p.u.)	0.0317	0.0214	0.0314
Substation Q (kVAr)	-895.83	-2100.33	-2089.77
Substation Power Factor (PF)	0.9879 leading	0.9393 leading	0.9392 leading
Total P_{Loss} (kW)	164.55	199.58	165.129

Selected *u*:
- Different cap placement
- Increased substation Q

Resulting metrics:
- Voltage spread decreased
- P_{loss} increased
- Substation PF decreased

Cap Results: With Q Constraints



Peak Loading	Base case	No Losses	Losses
|V| spread (p.u.)	0.0317	0.0337	0.0337
Substation Q (kVAr)	-895.83	-599.73	-599.73
Substation Power Factor (PF)	0.9879 leading	0.9945 leading	0.9945 leading
Total P_{Loss} (kW)	164.55	160.85	160.85

Selected *u*:
- Identical cap placement
- Reduced substation Q

Metrics:
- Voltage spread increased
- P_{Loss} decreased
- Substation PF increased

Remarks

- Analytically driven applications broaden the scope and scenarios under study.
- Practical considerations should be leveraged to reduce problem size and complexity (as well as facilitate acceptance of results.)
- Each distribution circuit has its own properties/characterisitcs
  - With measurements, this can be quantified; hence, modeled.
- As a result, systematic, repeatable approaches to distribution circuit planning and operation can be realized and used as a guide for engineers.

Remarks

- Remaining Challenges
  - **Access to Power Engineering Education**
    - Relatively few universities with power programs
    - Fewer have formal education in power distribution systems
  - **We do not have a baseline**
    - Economically driven investments require an accepted baseline
  - **Technical challenges**
    - Impacts of large numbers of new components
    - Time and space scaling issues
    - Real-time operation with unsynchronized measurements
    - Large-scale, mixed-integer optimization problems