Integration of Smart Grid Enabling Technologies Within Power Distribution Systems

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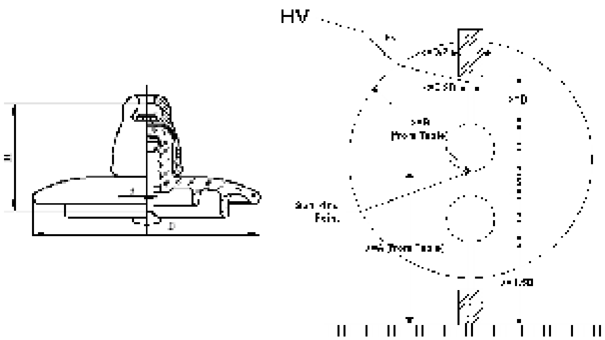
Outline

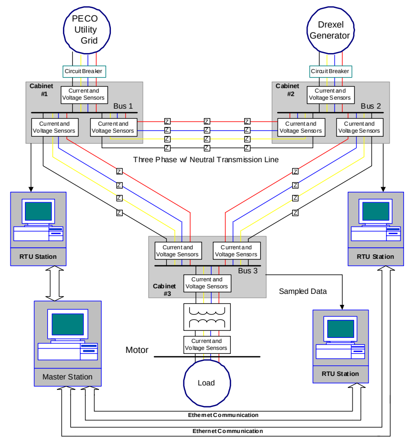
- Overview
- Challenges
  - Societal Issues
  - Technical Problems
- How should we approach these problems?
- Remarks & Discussion

Overview

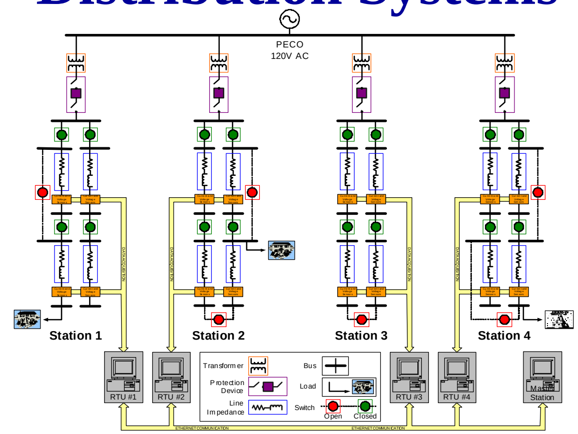
High Voltage



Transmission Systems



Distribution Systems



Interconnected systems have different:

- power and voltage levels
- structures
- measurement systems & fidelity

→ All systems must be studied carefully

Distribution System Examples

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

Space Power Systems
[www.nasa.gov]

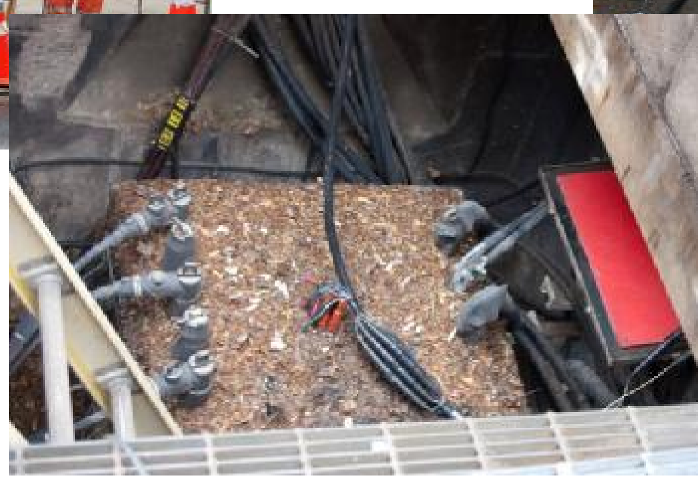
Shipboard Power Systems
[www.navyleague.org]
ONR

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

What are they?

- **Electric Power Distribution Systems: Terrestrial**
  - substations (< 115kV)
  - distribution network within cities/towns
  - secondary transformers/service lines (<500V)
  - meters up to the customer wall



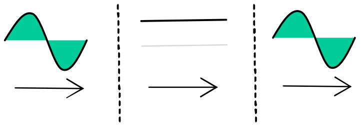


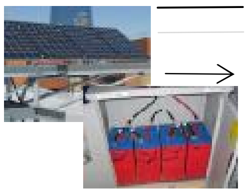

What are they?

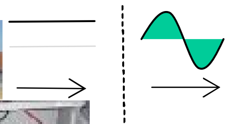
- **U.S. Properties:**
  - – above-ground and underground
  - – grounded and ungrounded

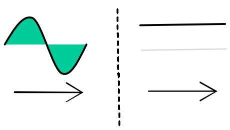
    (multi-phase: 2, 3, 4 and 5-wire systems)
  - – interconnections
  - power electronic devices:
    - – source & motor interconnections
    - – network switches for reconfiguration

AC DC AC



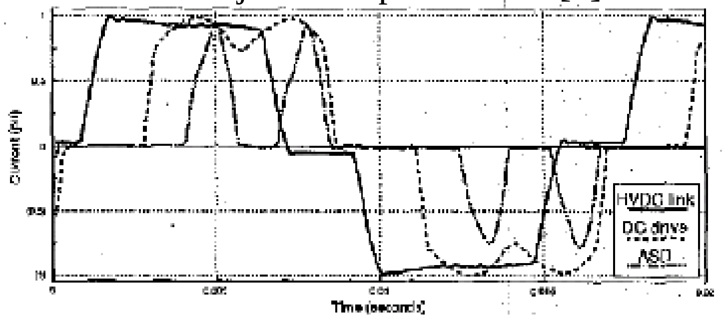






- Network
- Loads:
  - – AC motors (air cond.)
  - – electronics
  - – DC motors: elevators

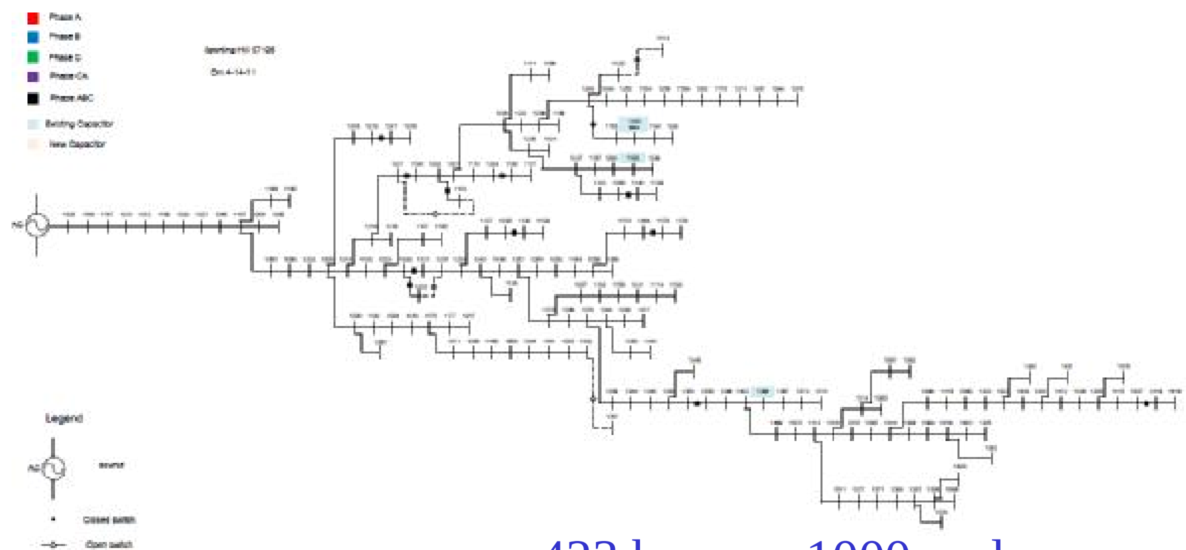
AC current of HVDC links, 6-pulse dc drives, and adjustable speed drives [1]



[1] Task Force on Harmonics Modeling and Simulation, "Modeling and simulation of the propagation of harmonics in electric power network," IEEE Trans. on Power Delivery, vol. 11, no. 1, pp. 452-465, Jan. 1996

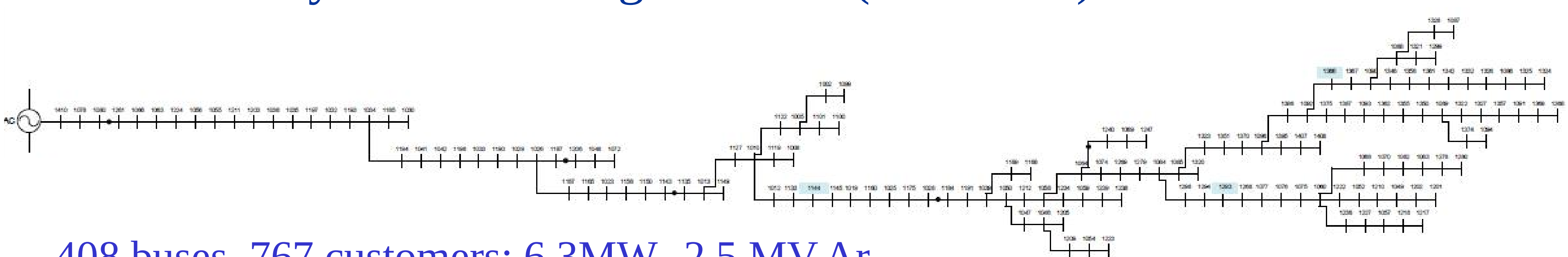
What are they?

- **Properties:**
  - large systems
    (10,000+ nodes)
  - normally operated in a radial manner
    (embed switches for loops)



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

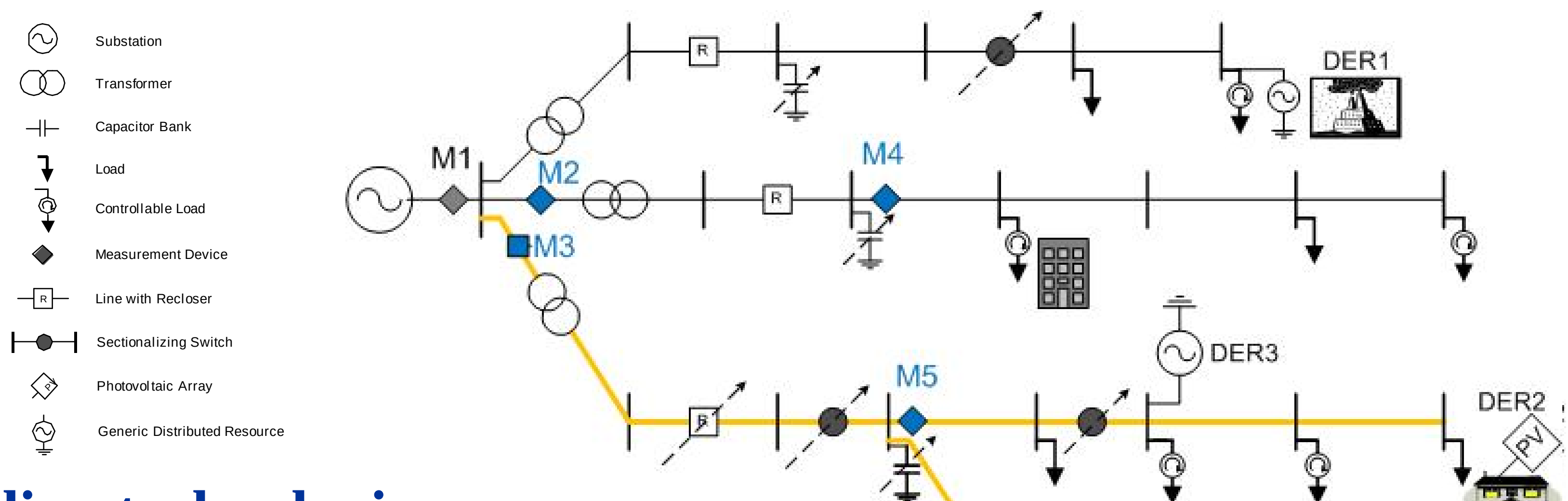
  - limited # of real-time measurements
  - uncertainty of loads and generation (stochastic)

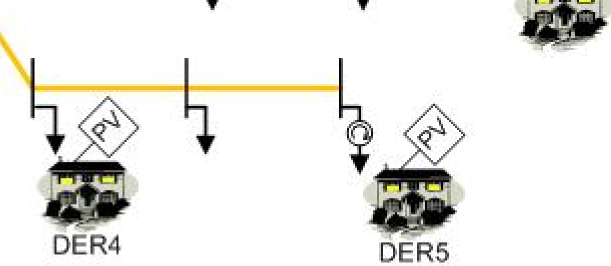


408 buses, 767 customers: 6.3MW, 2.5 MV Ar
(only 3 phase buses drawn)

What is emerging?

- **Government (US states) programs:**
  - to encourage or mandate the growth of renewable energy
  - *Distributed* Energy Resources (DER):
    - solar, wind, biomass, microturbines, ice storage, etc.
    - load control





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

What is “Smart Grid”?

- Expected/Desired Impacts:
  – high penetration of DER
  – Distribution Automation for
    - improved reliability
      – reconfiguration
    - improved efficiency
      – voltage control

- Overview
- Challenges
  - Societal
  - Technical
- How should we approach these problems?
- Remarks & Discussion

Societal Challenges (US)

- **Energy Policy -** no clear energy policy, historically
- **Acceptance of Technology**
  - Load control: customer compliance not just $ based
- **Access to Technology & Timing**
  - Potentially & unintentionally penalizes night shift workers, the economically stressed & elderly à handled via regulation
- **Access to Power Engineering Education**
  - Relatively few universities with power programs
  - Even fewer have formal education in power distribution systems

Technical Problems

- **We do not always have a baseline**
- **Integration:** What are the *system* impacts of large numbers of new components?
  - 2007: Denmark – high penetration of alternative energy sources into passive network causing network operation and stability problems
- **Fundamentals:**
  - Time and space scaling issues
  - Mathematical foundations to subsequent models
- **Optimization & Optimal Control:**
  - Large-scale, mixed-integer, non-linear optimization problems
  - Real-time operation with unsynchronized measurements

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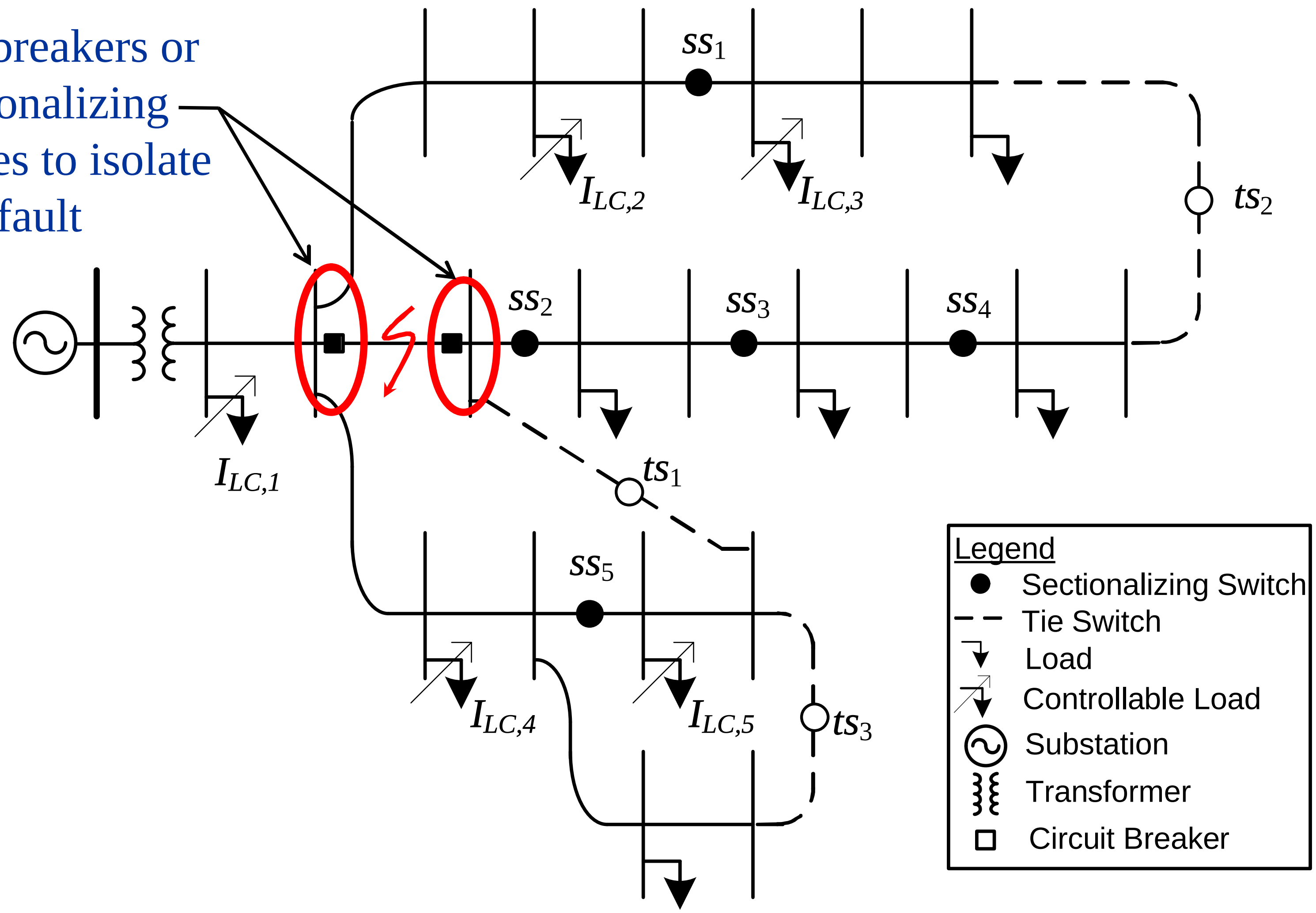
Technical Approach

- **Unbalanced system analysis tools**
  - integrate *arbitrary numbers* of advanced components
  - expand traditional system parameters
  - static and dynamic estimation
  - physically distribute simulations

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

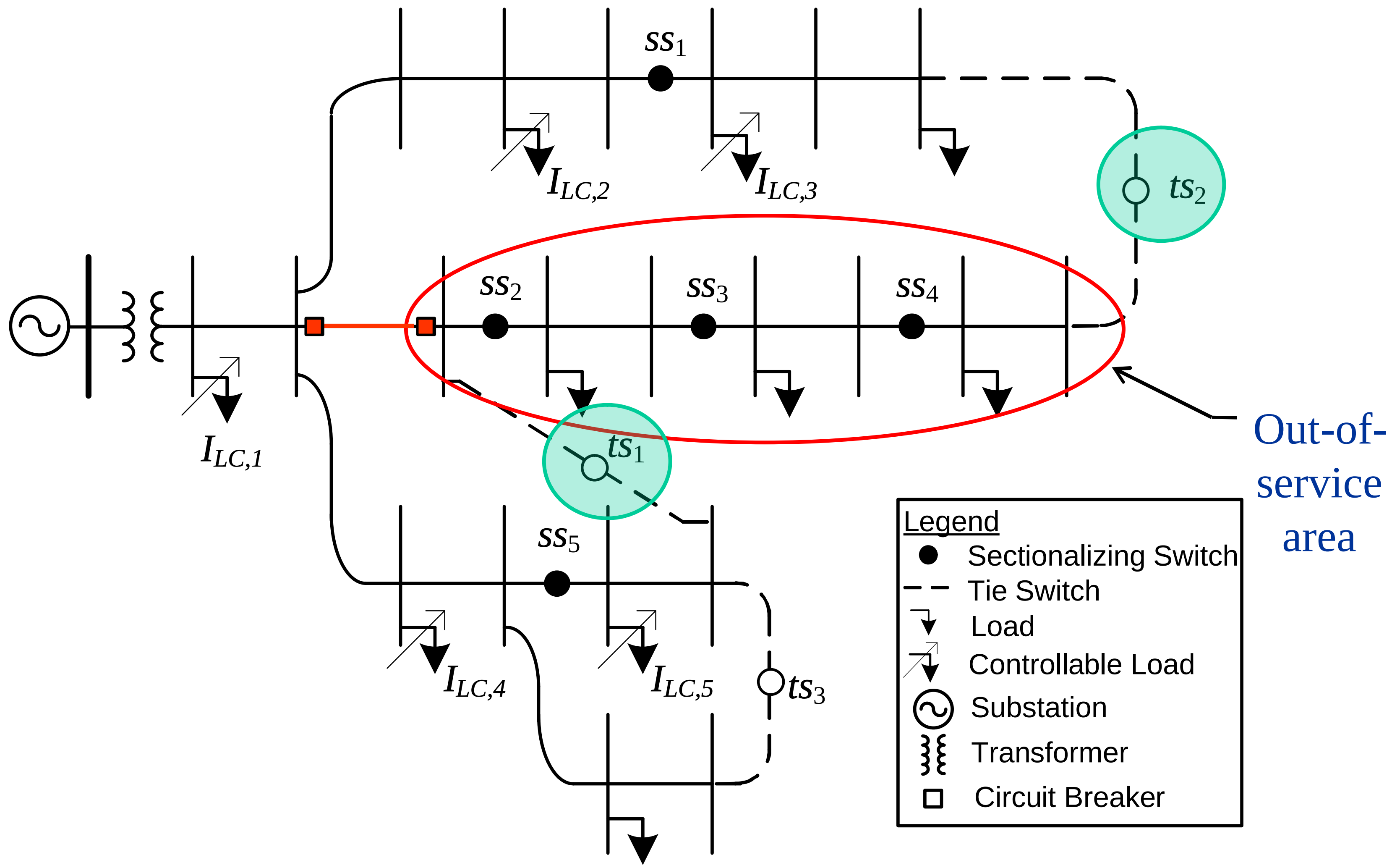
Improving Reliability: Service Restoration with Load Curtailment

Open breakers or sectionalizing switches to isolate fault



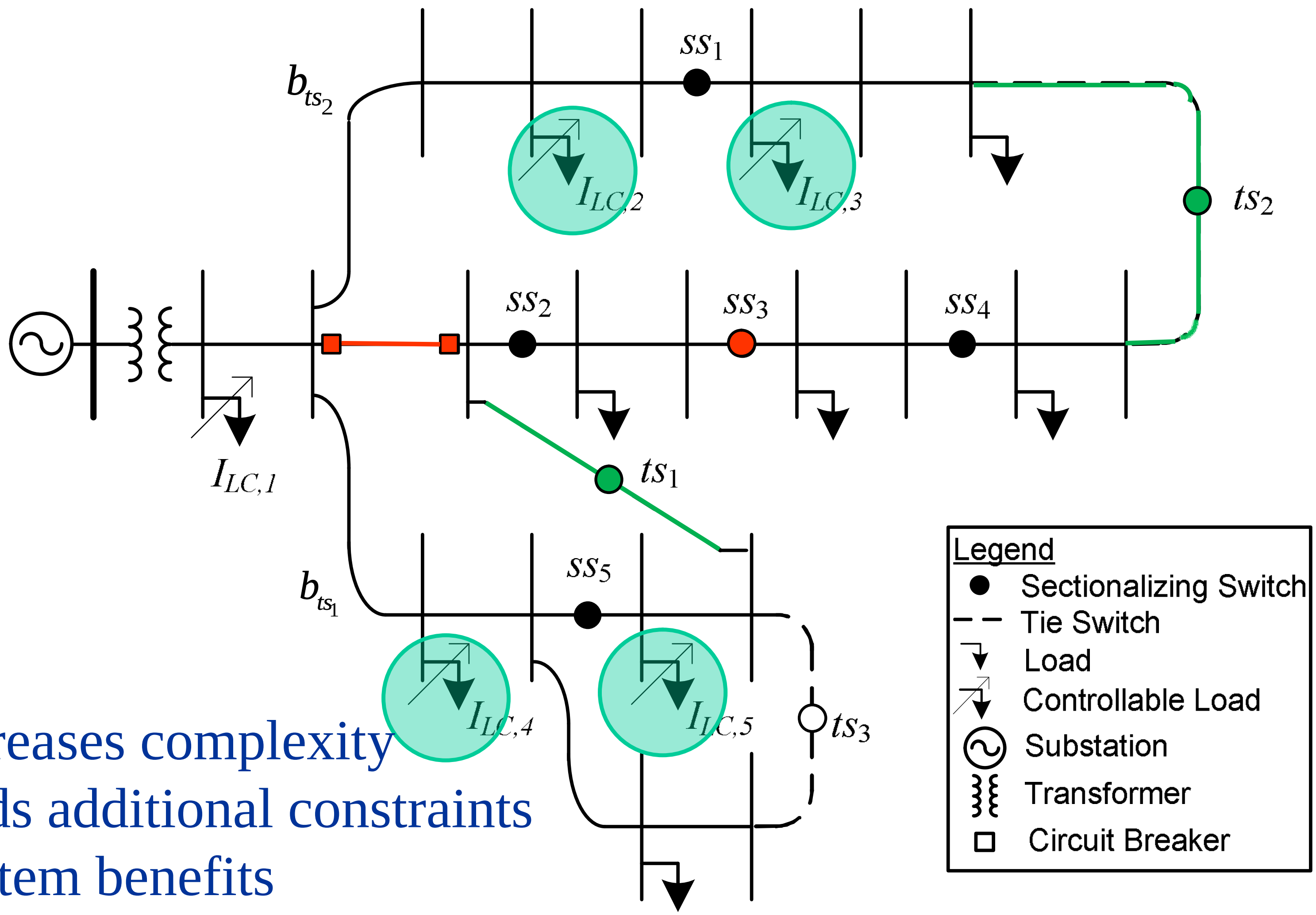
Breakers or sectionalizing switches operated to isolate faulted area

Improving Reliability: Service Restoration with Load Curtailment



Traditional restoration schemes limited by network spare capacity

Improving Reliability: Service Restoration with Load Curtailment

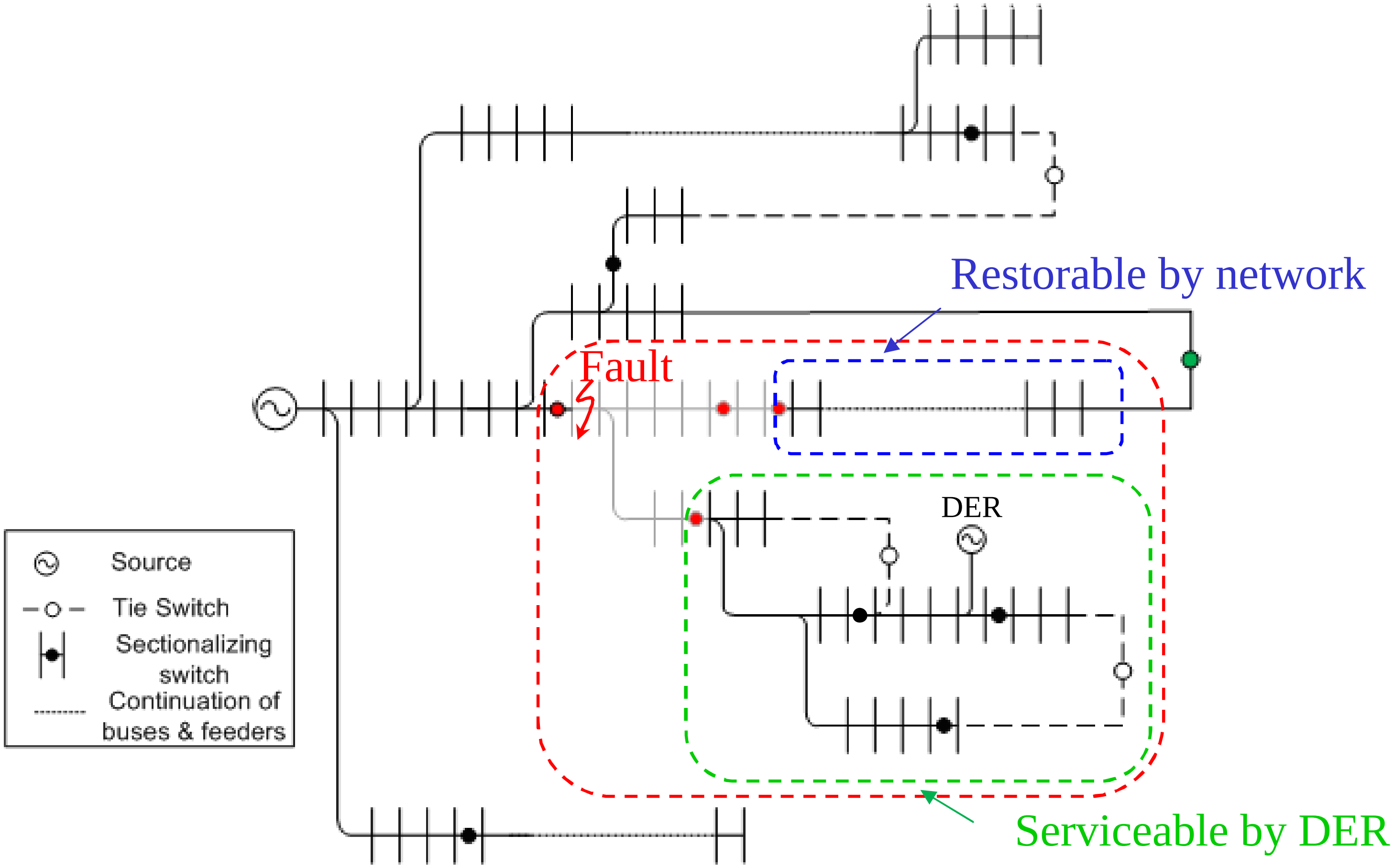


- Increases complexity
- Adds additional constraints
- System benefits

Load curtailment may be used to free-up additional capacity

Improving Reliability: Switch Placement for Microgrids

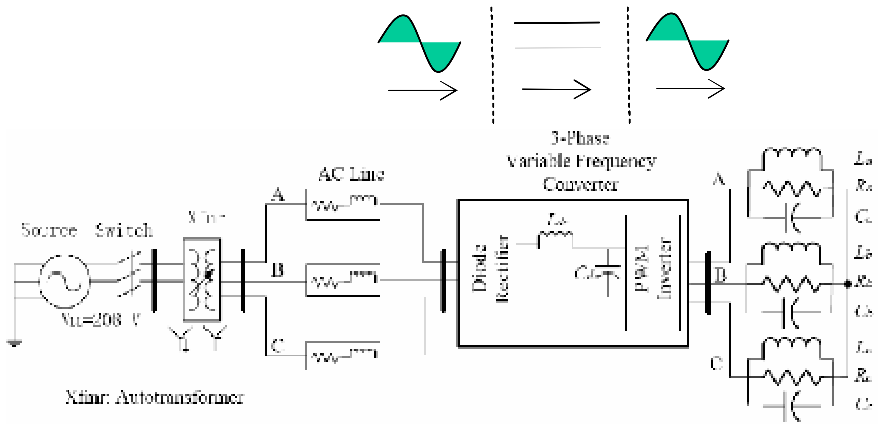
- Concept to Reality:
  - “DER should reduce power outages”
  - engineers currently working on expanding interconnection standards



Improve system reliability by switch placement and network reconfiguration

(Y. Mao & KM)

AC/DC System Modeling & Analysis



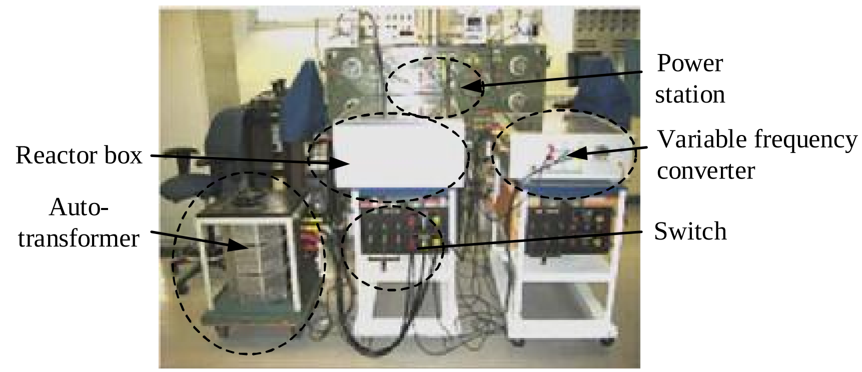


Figure: A generic ac/dc system setup with a 3-phase variable frequency converter(X. Yang & KM)

- **Unified AC/DC Equations**

AC →

$$
\left[\begin{array}{ccc|cc|cc}
Y_{sub} & Y_{sub,ac} & 0 & 0 & 0 & 0 & 0 \\
Y_{sub,ac} & Y_{ac} & Y_{ac,Conv} & 0 & 0 & 0 & 0 \\
0 & Y_{ac,Conv} & Y_{Conv} & 0 & 0 & B_{Conv,ac} & 0 \\
\hline
0 & 0 & 0 & G_{dc} & G_{dc,Conv} & 0 & 0 \\
0 & 0 & 0 & G_{dc,Conv} & G_{Conv} & 0 & B_{Conv,dc} \\
\hline
0 & 0 & C_{Conv,1} & 0 & C_{Conv,2} & D_{Conv,1} & D_{Conv,2} \\
0 & 0 & C_{Conv,3} & 0 & C_{Conv,4} & D_{Conv,3} & D_{Conv,4}
\end{array}\right]
\left[\begin{array}{c}
V_{sub} \\ V_{ac} \\ V_{Conv} \\ \hline V_{dc} \\ V_{Conv,dc} \\ \hline I^{3\_\Delta}_{Conv} \\ I^{3\_\Delta}_{Conv,dc}
\end{array}\right]
=
\left[\begin{array}{c}
I_{sub,L}(V_{sub}) \\ I_{ac,L}(V_{ac}) \\ I_{Conv,L}(V_{Conv}) \\ \hline I_{dc,L}(V_{dc}) \\ I_{Conv,L_{dc}}(V_{Conv,dc}) \\ \hline F_{Conv} \\ F_{Conv,dc}
\end{array}\right]
$$

← DC

Conversion ↗

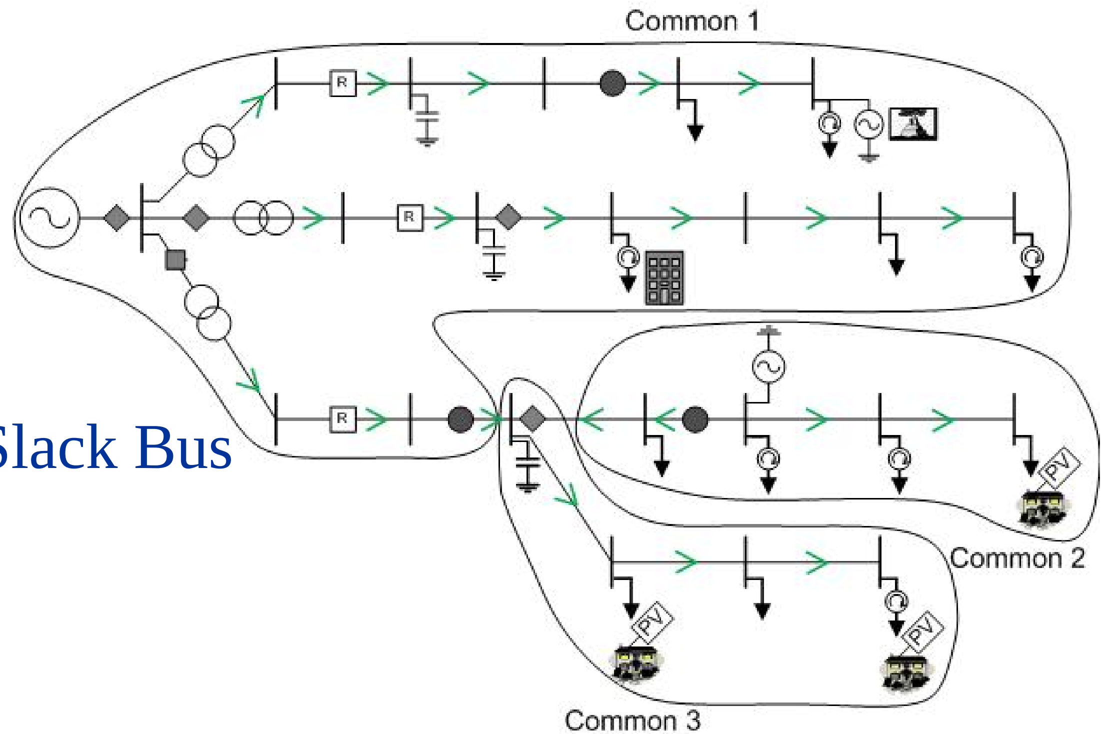
Distributed Analysis & Control Partitioning

- Models: non-linear algebraic equations

$$g(x, y, u) = 0$$

- Create directed graphs
- Domain-Based Distributed Slack Bus Models
  - attribute load and losses
  - considers network characteristics/location
  - significant $ impact

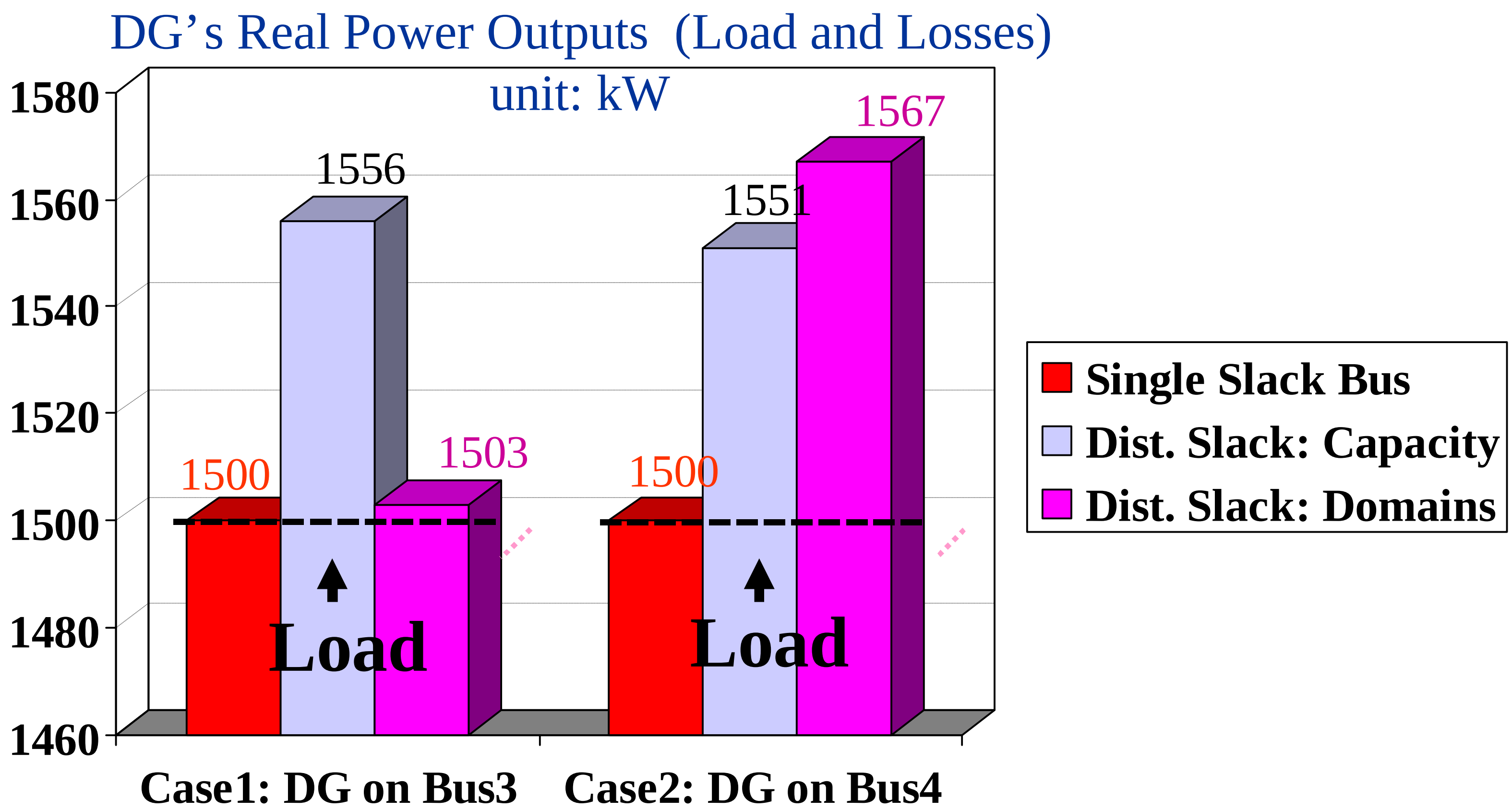
    (on both suppliers and distribution company)



Energy resource power domains/commons

Distributed Generator Output

- Traditional Models vs. Domain-Based Distributed Slack Bus Models
  - between 3.7 to 4.5% difference



Distribution System Considerations

Common Considerations:

- Decisions based on 5% differences in load
- Often 5% or lower (2-3%) max imbalance tolerance at the substation
- Capacity planning still must consider consumption (w/o DER)
- Assumption:
  - Diversified load
    - This changes with Smart Appliances & time-of-use rates (real-time pricing)
    - Start-up currents (2-4 times higher than steady-state) à new constraints

Remarks

- Mandated installation of mixed energy sources will significantly impact the distribution system and subsequently, the power system/grid as a whole
- Distributed intelligence can be effectively utilized to solve large-scale problems
- Fundamental changes in the operating and planning are imminent and expected for the foreseeable future

Acknowledgements:

- M. Kleinberg, Y. Mao, S. Tong, X. Yang (grad & former grads)
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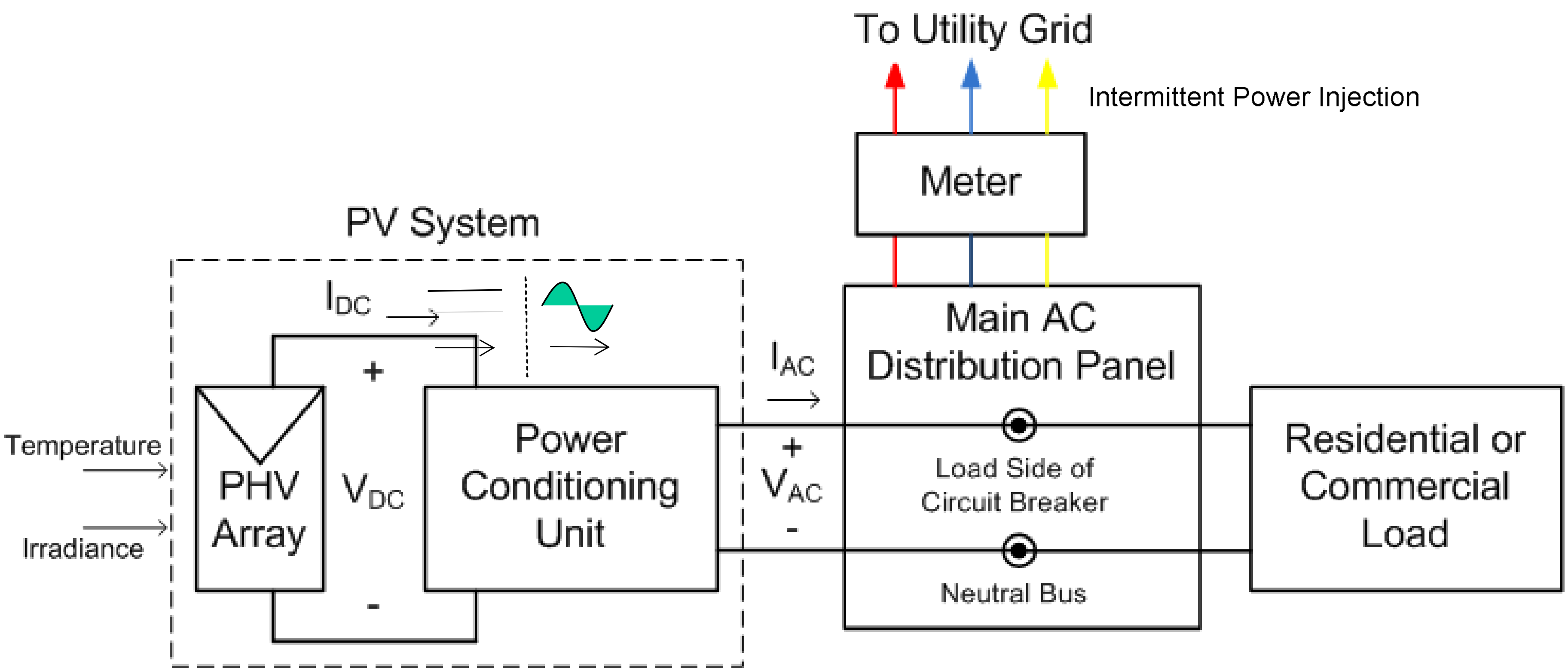
- US Office of Naval Research
- US National Science Foundation

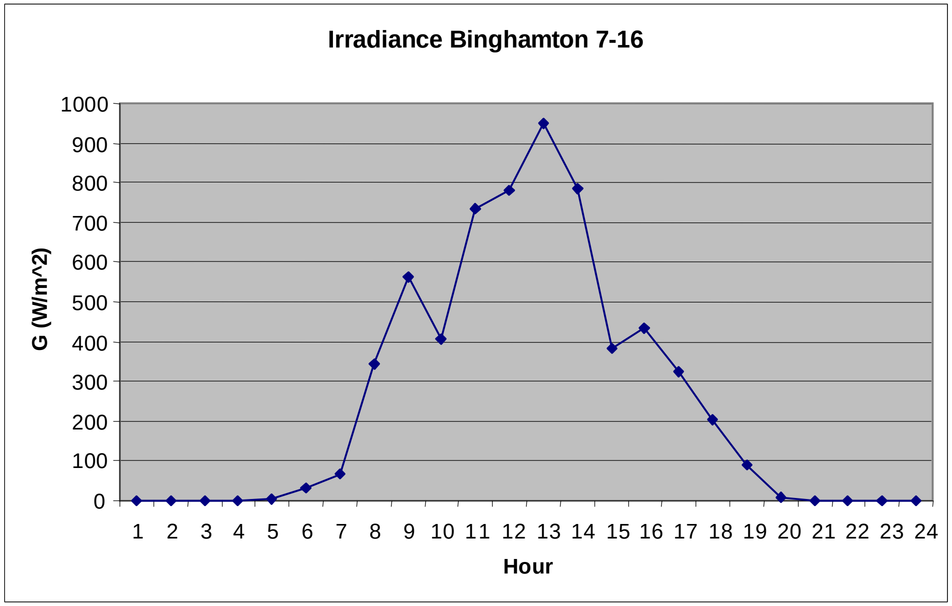
Distributed Energy Resources: e.g. PV (PhotoV oltaics)

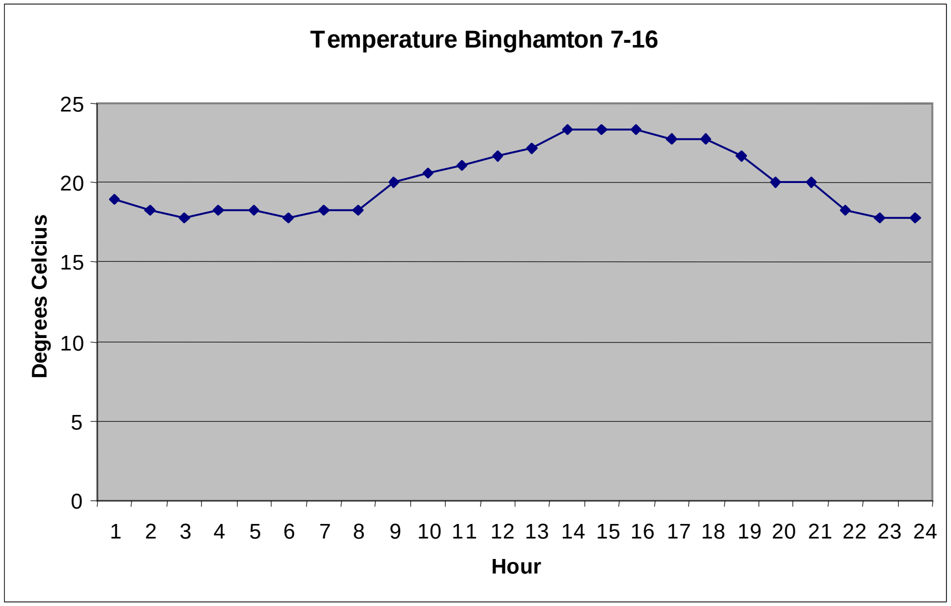


Typical connection scheme for residential (1Φ) or commercial (1Φ – 3Φ) PV: highly distributed (<10kW), less so (<2MW)

Challenge: significant # of PV Generators do not have associated storage

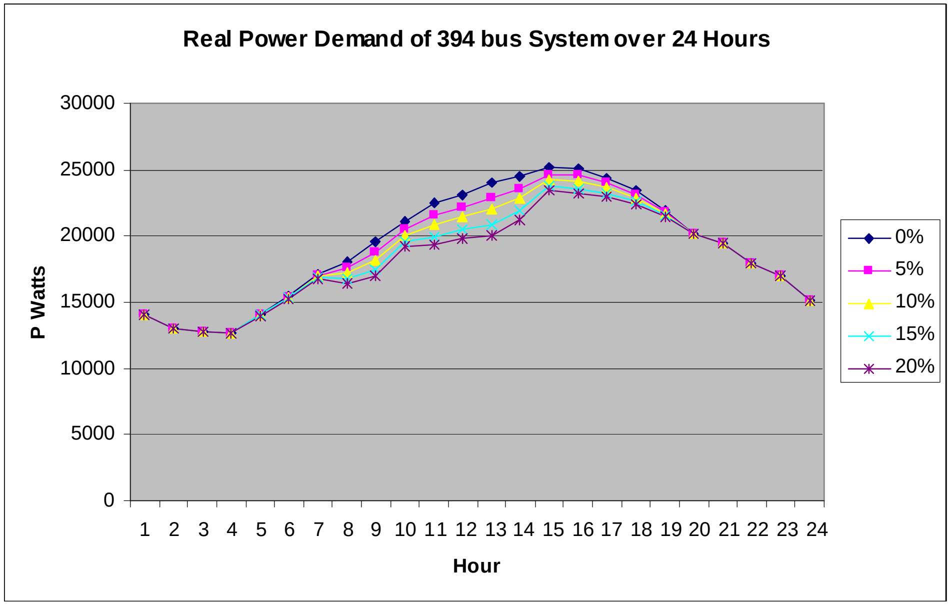
Example: 394 bus system, New York





Properties:

- 394 buses (1108 nodes)
- 199 loads: 28.2MW, 14.9 MVAr
- 65 randomized locations



Simulated Results

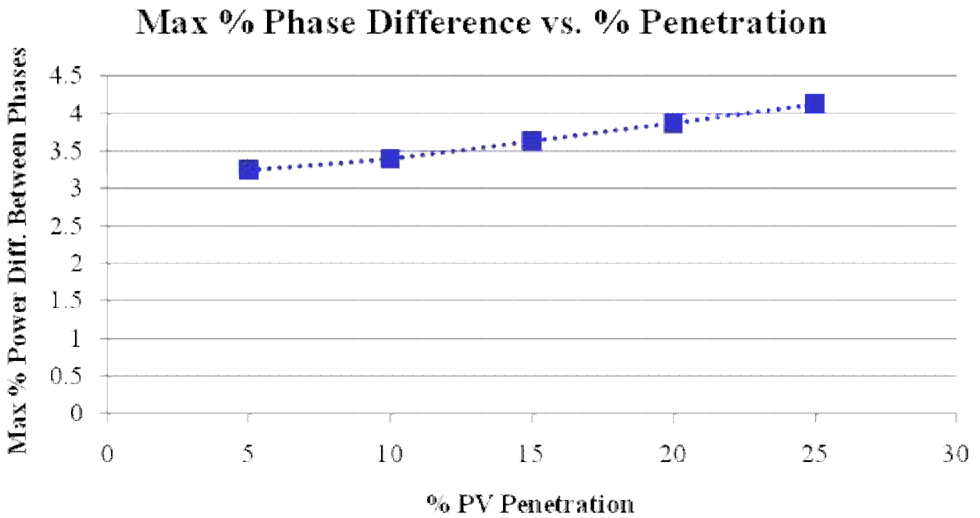


Figure: Max % difference between phases of the substation power output
Randomized PV locations (500 trials),
65 (out of 107) Balanced Installations

Remarks:

- Balanced PHV generators can increase system imbalance
- Most placements will not be balanced
- Customer decisions on PV generator locations