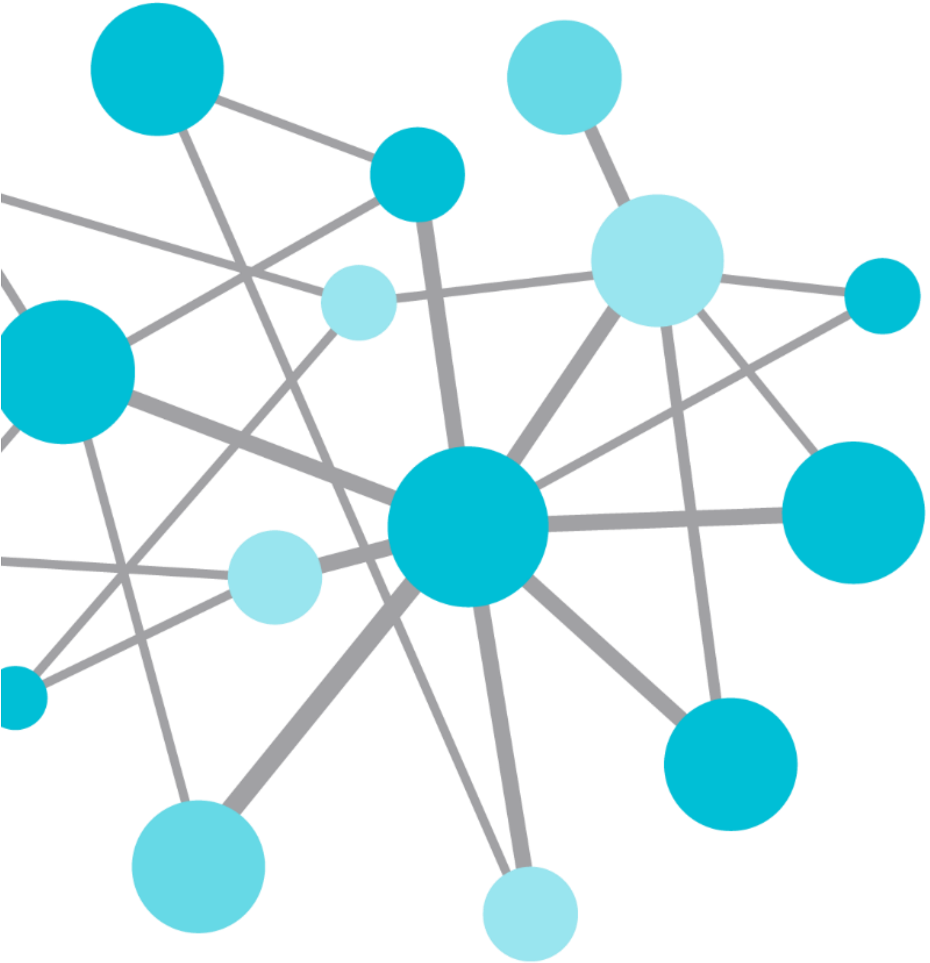


Microgrid

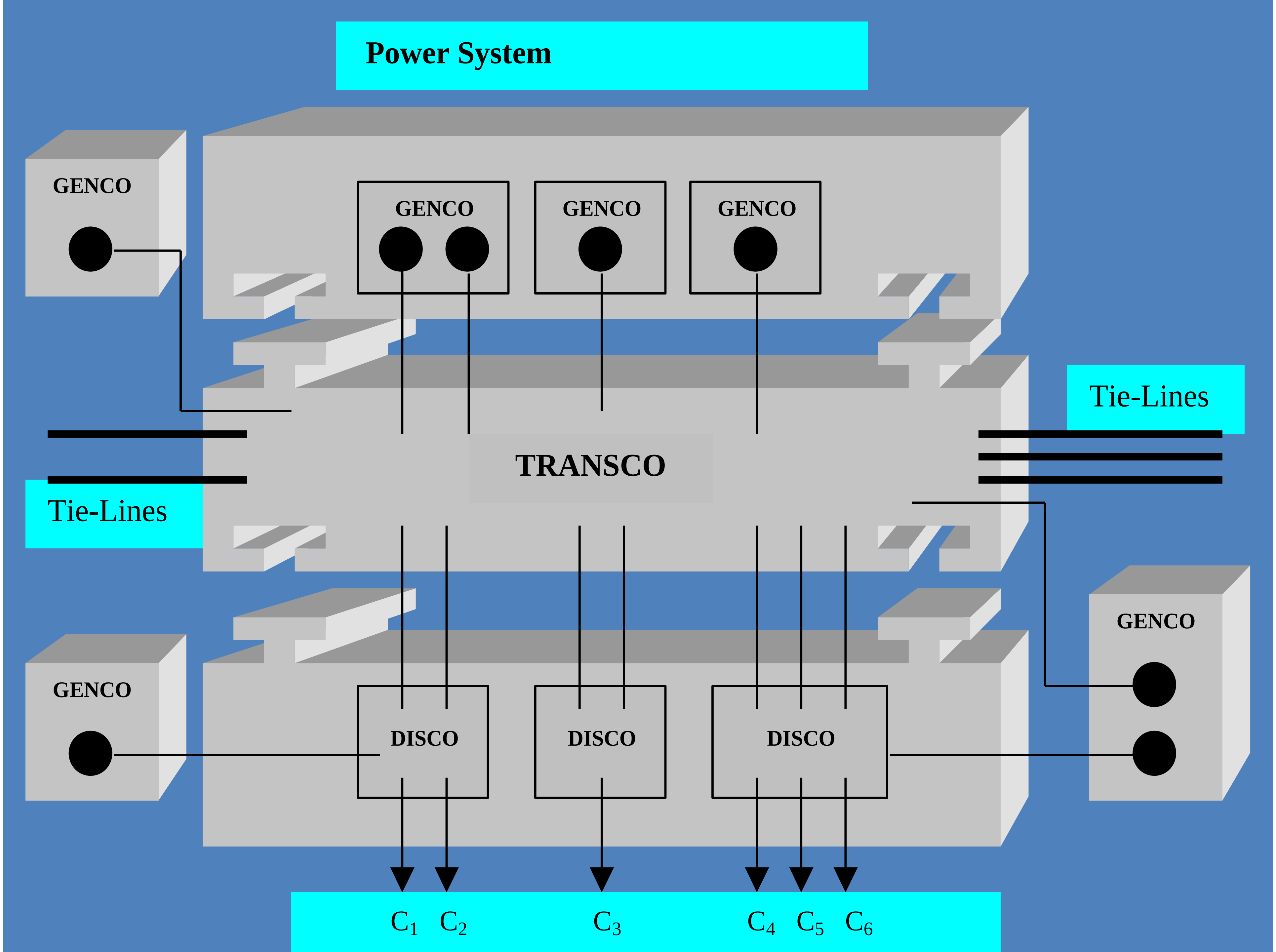
A new hub in energy infrastructure

Presented by Mohammad Shahidehpour - Illinois Institute of Technology

robert w. galvin center for electricity innovation at ILLINOIS INSTITUTE OF TECHNOLOGY

Outline

- Smart Grid Technology
  - Electricity Infrastructure
  - What is Smart Grid
- Microgrids (IIT Perfect Power Project)
  - Components
  - Hierarchical Control, Islanding and Synchronization
  - Optimal Operation of Microgrid
  - Reliability Evaluation
- Perfect Power System
  - Robert W. Galvin Center at IIT

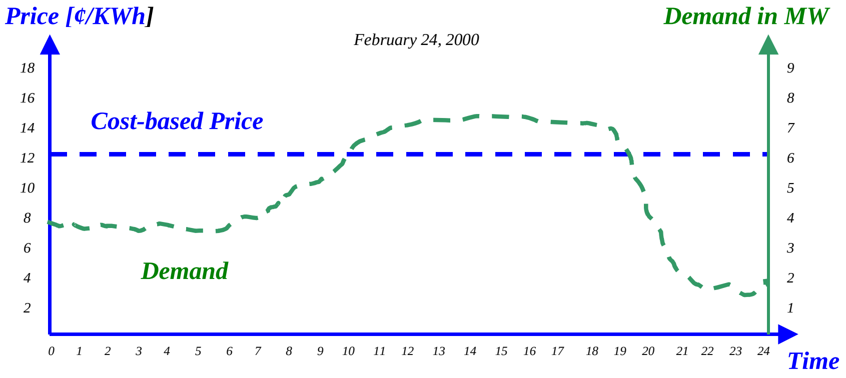

Power System
GENCO
GENCO
GENCO
GENCO
Tie-Lines
TRANSCO
Tie-Lines
GENCO
GENCO
DISCO
DISCO
DISCO
C_1 C_2 C_3 C_4 C_5 C_6

Electricity Infrastructure

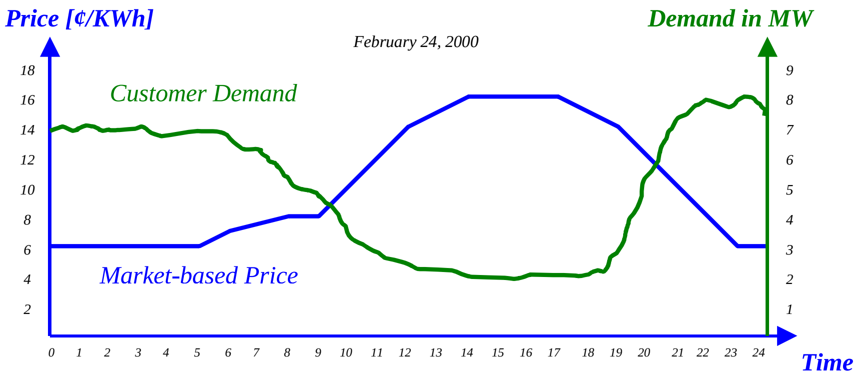
- **Supply Adequacy and Economics**: Applications of renewable energy, storage technologies for enhancing the security, coordination of renewable and storage supplies, carbon footprints
- **Transmission Expansion and Security**: Expansion planning of transmission facilities, coordination of energy infrastructures, superconductors, HVDC, physical and cyber security, wide area measurements, PMUs
- **Smart Grid**: Energy efficiency, price response, peak load reduction, distribution automation, new building technologies, smart metering, sensors, communication and control techniques

What is Smart Grid?

- Smart grid is a response to economic, security, and environmental mandates placed on energy supply and delivery
- Smart grid provides access points that can be identified, much like computer devices, with an IP address on the internet
- Smart grid uses the internet protocol to shuttle information back and forth between the utility and customers
- With two-way communications between consumers and suppliers, both parties can get far more control over the grid consumption, and physical and cyber security



Demand in a Vertically integrated Power Market



Response of a Demand to Price Signals

Introduction to Microgrids

- Microgrid is a system with at least one distributed energy resource (DER) and one demand which can be islanded from the main power distribution system (US DOE).
- Microgrids would address the emergence of a large number of DERs in distribution systems and to ensure secure and optimal operations of potentially islanded power grids.
- Microgrids generate, distribute, and regulate the flow of electricity to local customers, representing a modern small-scale power system with a high degree of flexibility and efficiency in both supply and demand sectors.

Various Size "Islands" on a Distribution System (All Could be Potential Microgrids)

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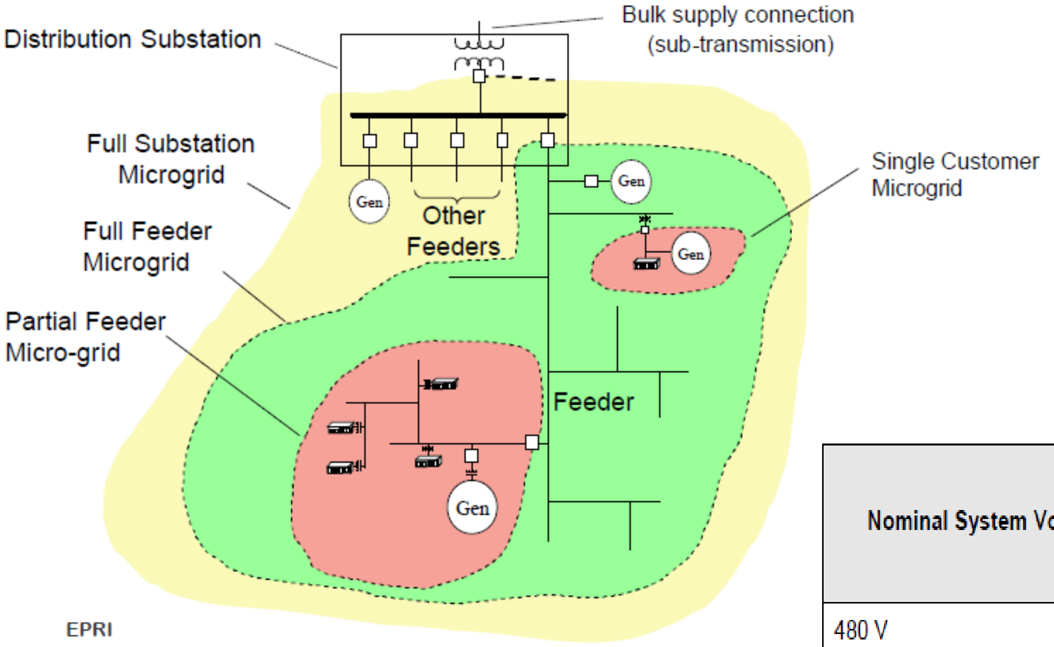


EPRI

Nominal System Voltage	Typical Maximum Loading Limits per Distribution Circuit with Commonly Used Conductors	Approximate Typical Area That Can Be Served per Circuit (km^2) *
480 V	0.1-0.5 MVA	< 0.1
4.8 kV	3-5 MVA	1-10
13.2 kV	7-13 MVA	5-30
25 kV	13-25 MVA	10-60
34.5 kV	18-35 MVA	15-90

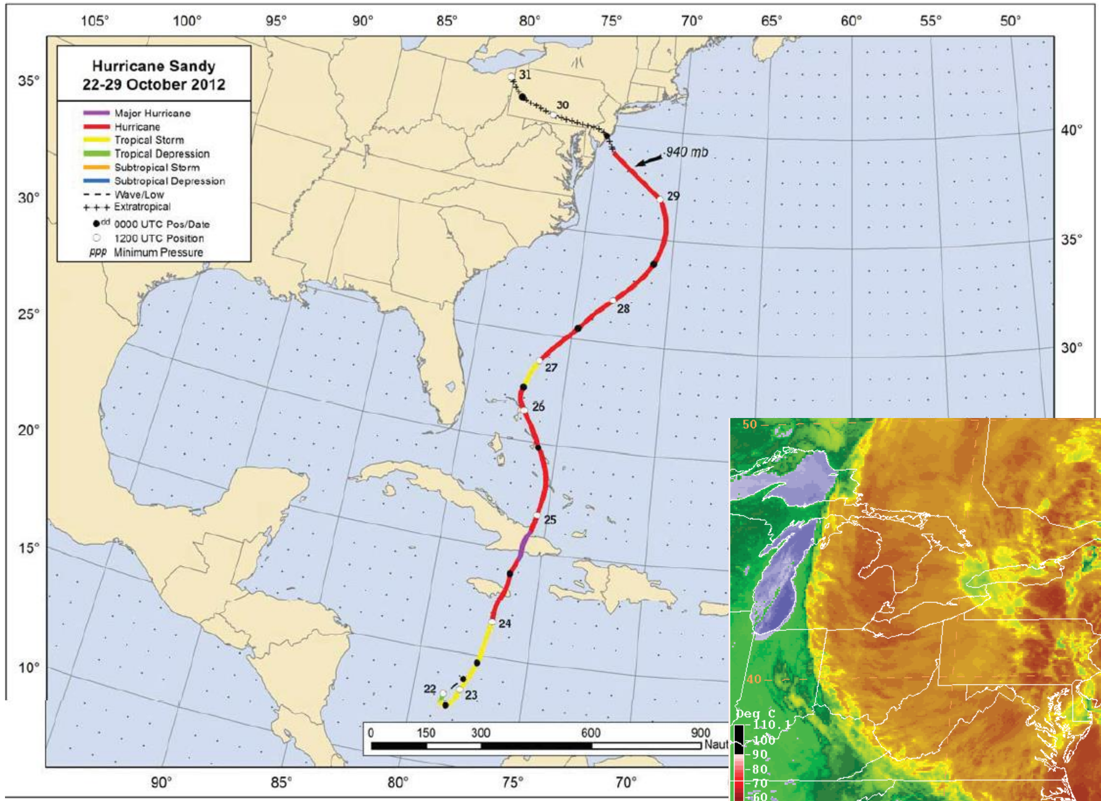
*Service areas are illustrative of those found with load densities ranging from typical rural to typical suburban. Areas served will be less in high-density urban environments.

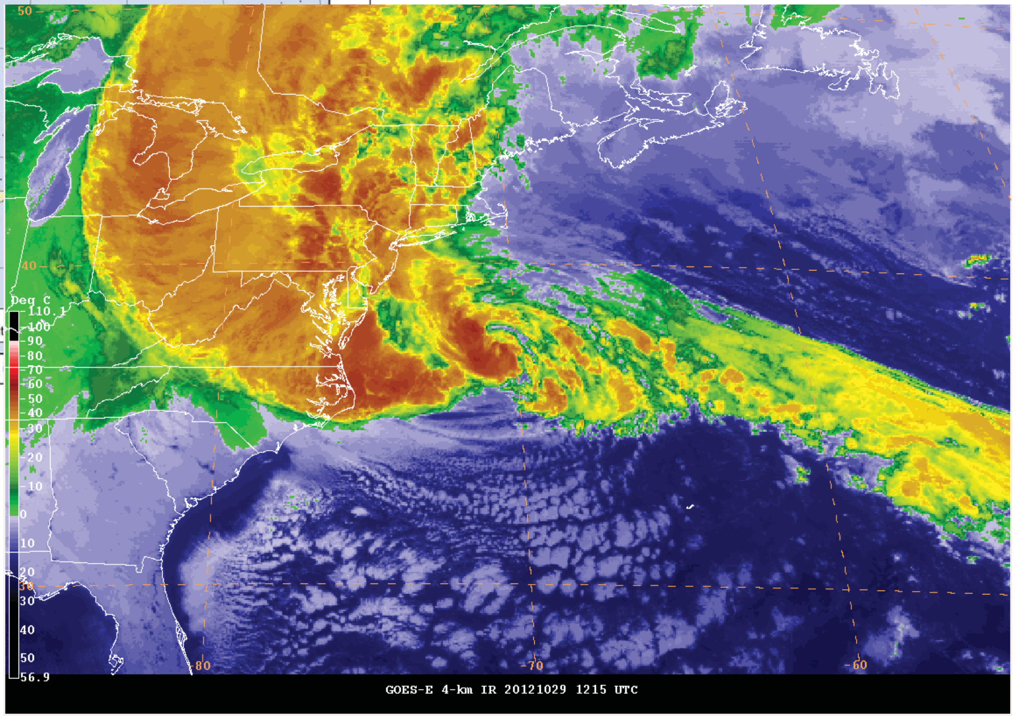
Operation and Control of an Operational Microgrid for Service Restoration

- The short-term reliability algorithm devised at the microgrid master controller would consider seamless islanding and resynchronization and apply emergency demand response and self-healing in case of major outages on either sides of the PCC.

- The economic operation would address the optimal generation scheduling of DER units in grid-connected and island modes and would apply economic demand response for minimizing the operation cost.

Footprint of Hurricane Sandy



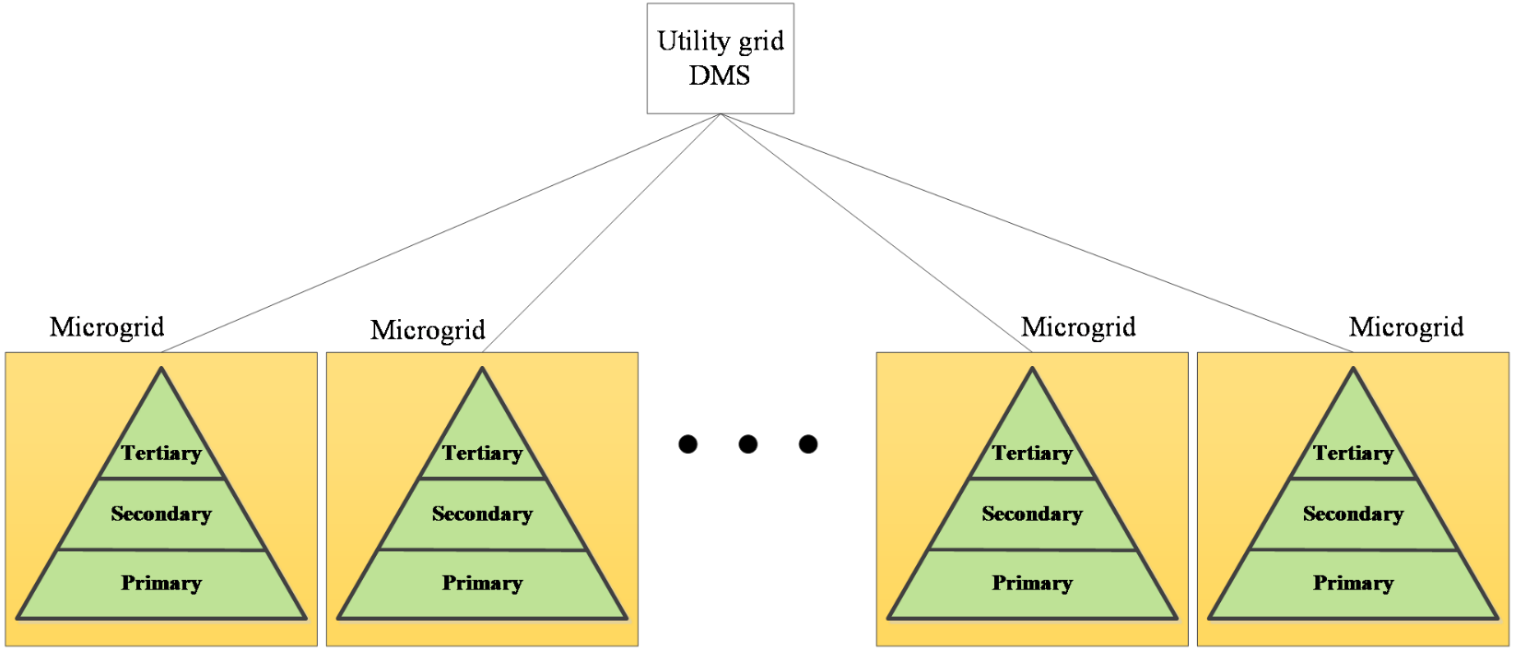


Service Restoration Using Microgrids

- Microgrid can assist distribution system service restoration processes by providing one or more of the following services:
  - Islanding from the grid for the local supply of microgrid loads and reducing the supply provided by the utility grid.
  - Coordinated reduction in microgrid loads by rendering an emergency demand response and curtailing non-critical loads that would minimize the impact of outage on the least number of customers.
  - Increasing the microgrid generation for supplying local loads, and if possible, providing the microgrid surplus generation to the utility grid.

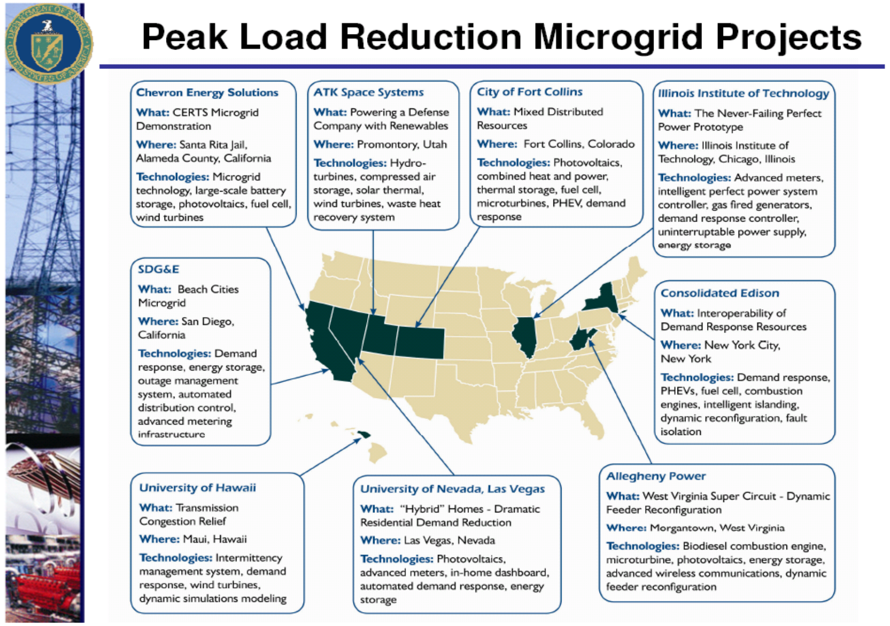
Distribution System Service Restoration Using Microgrids

- A distribution system may consists of a multi-microgrid system comprising several microgrids each equipped with DER units connected through power electronic interfaces and storage devices to provide power balances to a wider area during blackouts.



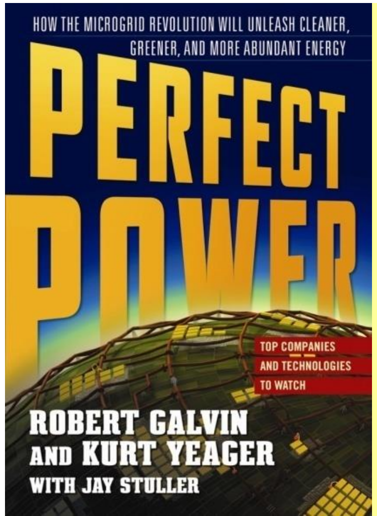
Goals of the DOE RDSI Project

- 50% peak demand reduction
- 20% permanent demand reduction
- Demonstrate the value of Perfect Power
  - Cost avoidance and savings in outage costs
  - Deferral of planned substations
- New products and commercialization
- Replicable to larger cities
- Promotion of energy efficiency in cleaner cities

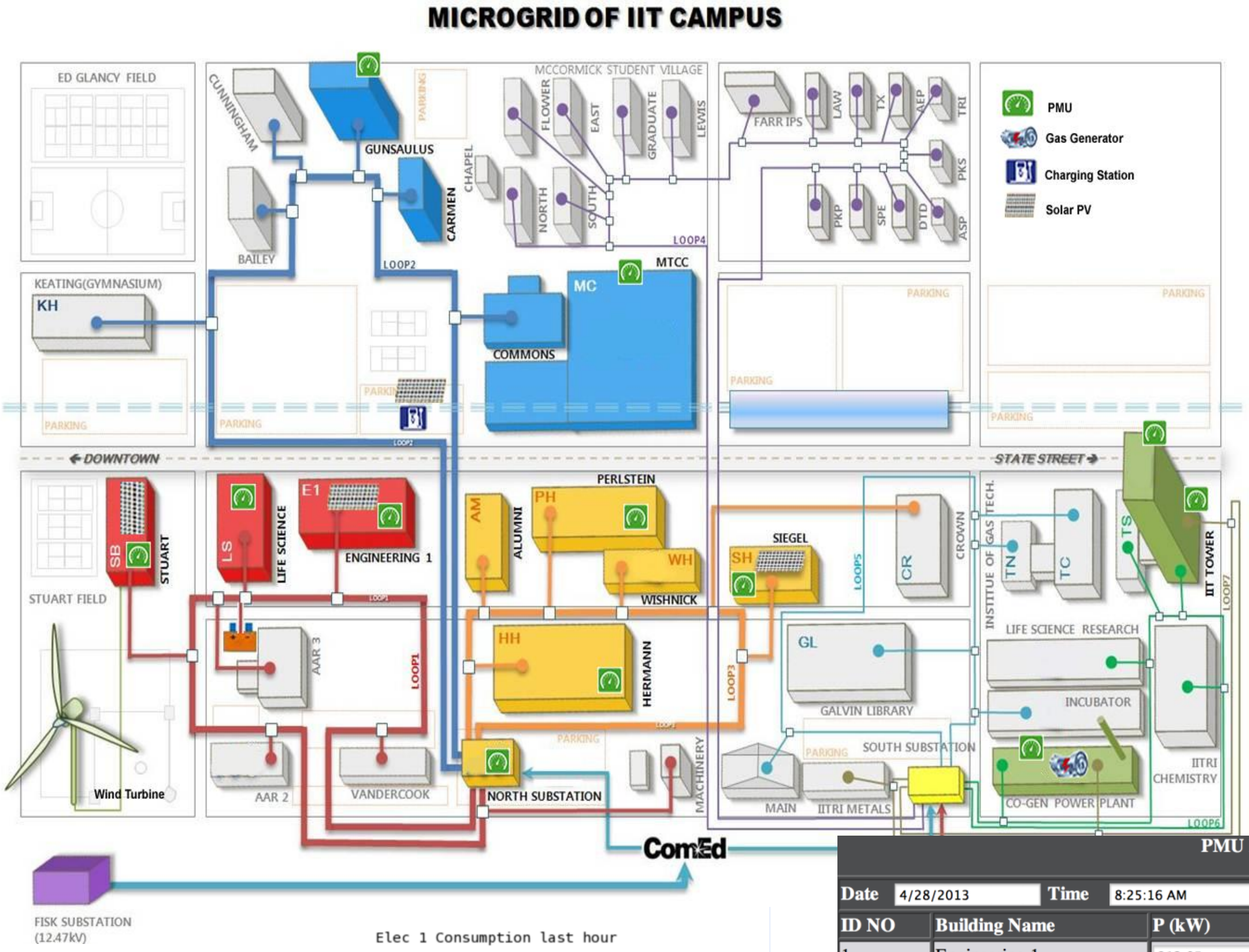


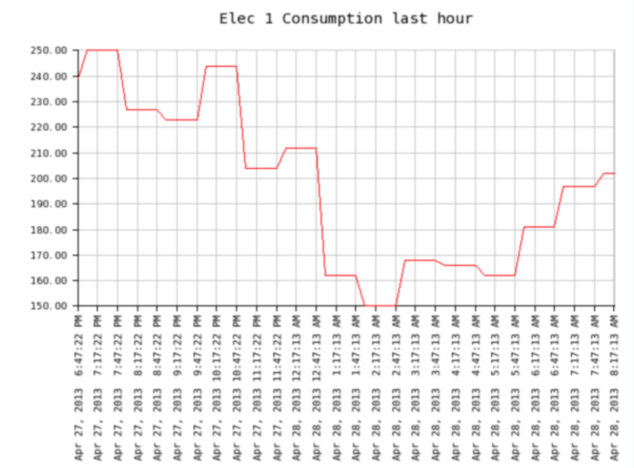
Perfect Power at Illinois Institute of Technology

- Funded by the U.S. Department of Energy
- Located at Illinois Institute of Technology (IIT)
- Involves the entire campus
- Partners: IIT, Exelon, S&C, Schweitzer, Siemens, Schneider, Eaton, GE, Invenergy, Intelligent Generation, ZBB, Viryd, I-GO, Smart Signal, Catch The wind, Veriown, Keri



"The perfect power system will ensure absolute and universal availability of energy in the quantity and quality necessary to meet every consumer's needs. It is a system that never fails the consumer." Bob Galvin

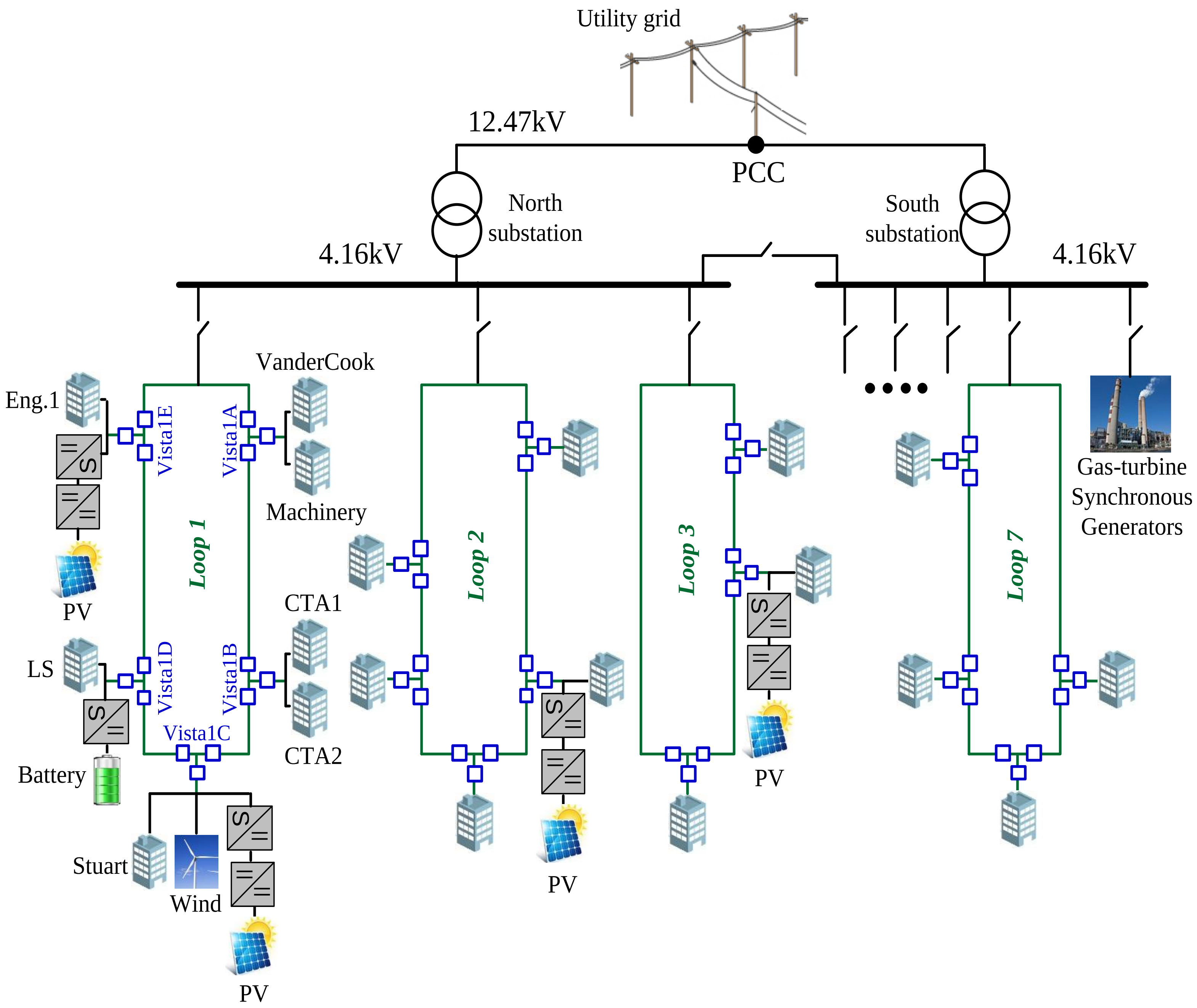




PMU Information

Date 4/28/2013 Time 8:25:16 AM

ID NO	Building Name	P (kW)	Q (kVAr)	Frequency	Power Factor
1	Engineering 1	213.85	321.70	59.9890	0.5536
2	Life Sciences	280.53	312.66	59.9900	0.6678
3	Stuart Building	247.73	102.56	59.9890	0.9239
4	Gunsaulus	41.65	24.83	59.9910	0.8590
5	MTCC	284.18	210.26	59.9910	0.8039
6	Hermann Hall	398.58	11.10	59.9910	0.9996
7	Wishnick Hall	192.28	70.84	59.9900	0.9383
8	Siegel Hall	96.80	161.22	59.9920	0.5148
9	North Substation	3935.93	203.63	59.9910	0.9987
10	IIT Tower	221.17	149.28	59.9910	0.8289
11	IIT Tower (20th Floor)	992.45	-914.62	59.9910	0.7354
12	Power Plant	0.00	0.00	59.9600	0.0000

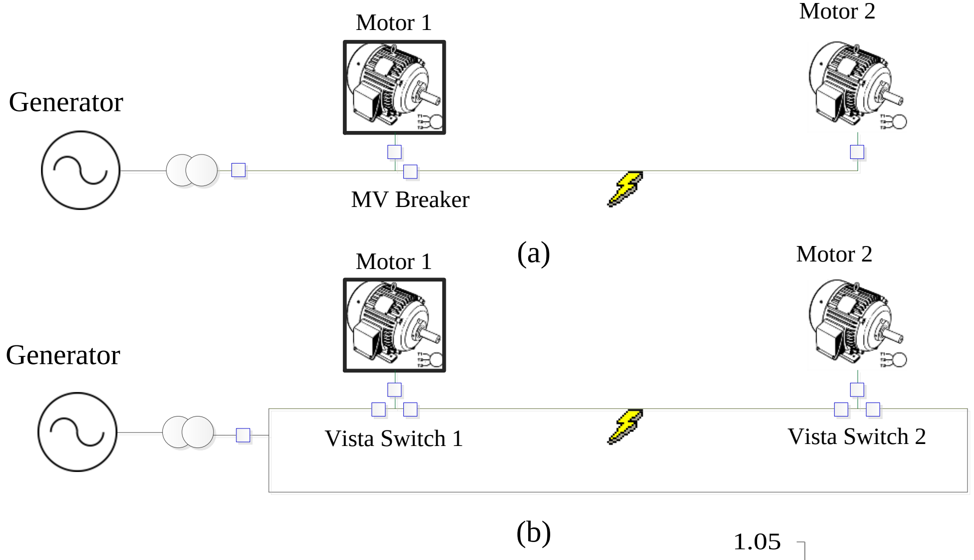


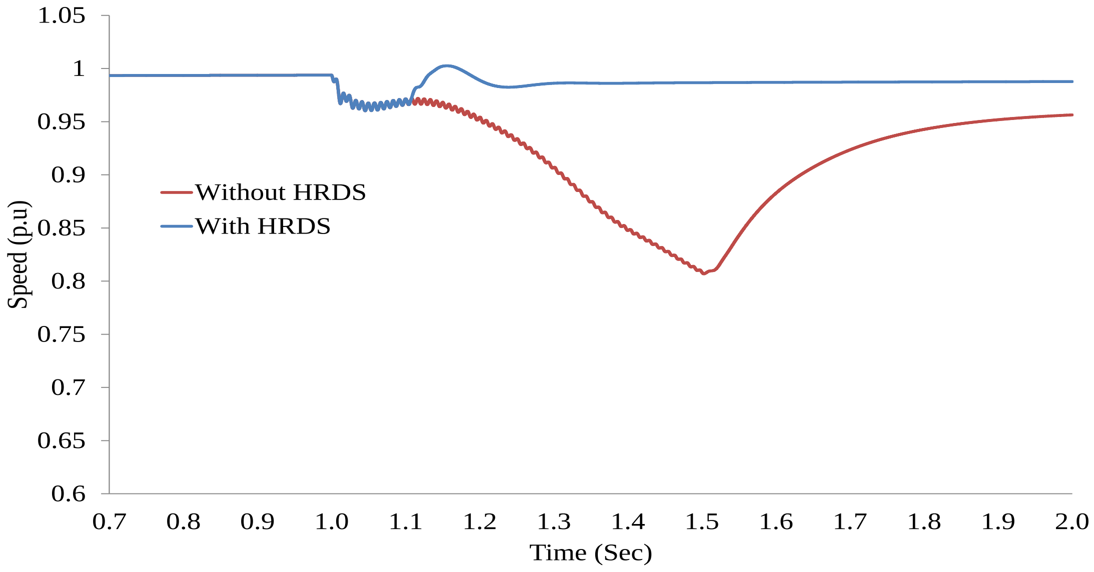
Utility grid
12.47kV
PCC
North substation
South substation
4.16kV
4.16kV
VanderCook
Eng.1
Vista1E
Vista1A
Machinery
Loop 1
PV
CTA1
LS
Vista1D
Vista1B
Vista1C
CTA2
Battery
Stuart
Wind
PV
Loop 2
PV
Loop 3
PV
Loop 7
Gas-turbine Synchronous Generators

High Reliability Distribution System (HRDS)

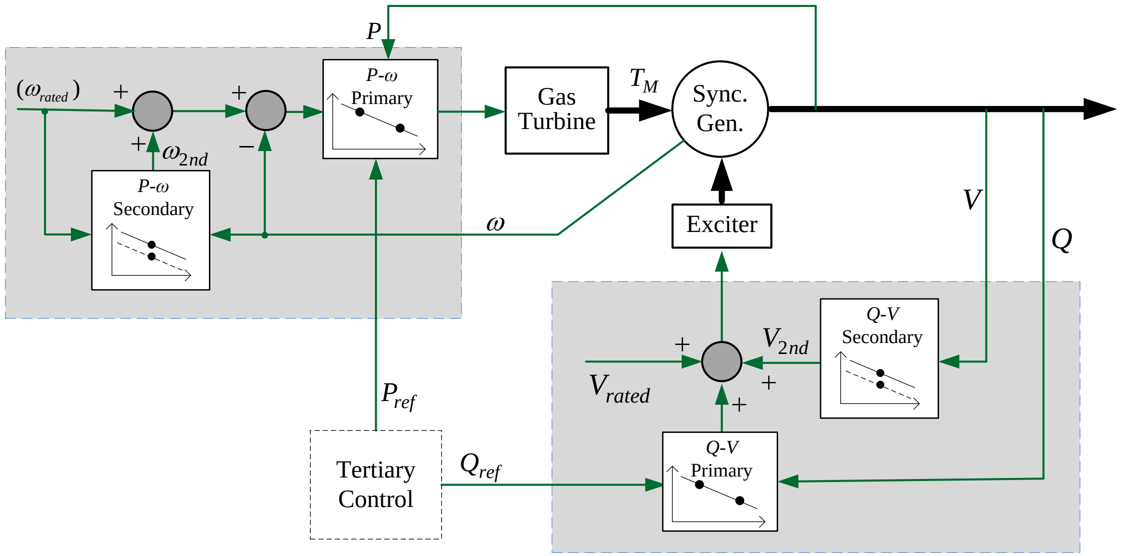
- Implementation of microgrid loops is made possible by the use of automatic switches in HRDS.
- HRDS switches can sense the cable faults and isolate the faulted section with no impact on other sections in a microgrid.
- No HRDS
  - Fault takes 30 cycles to clear.
  - The system is radial. Once the breaker opens, all the loads downstream will be disconnected.
- HRDS
  - Fault takes 6 cycles to clear.
  - The system is loop. Once the breakers open, only the faulted cable is isolated.

HRDS Switches at IIT Microgrid





Power Plant Control at IIT Microgrid



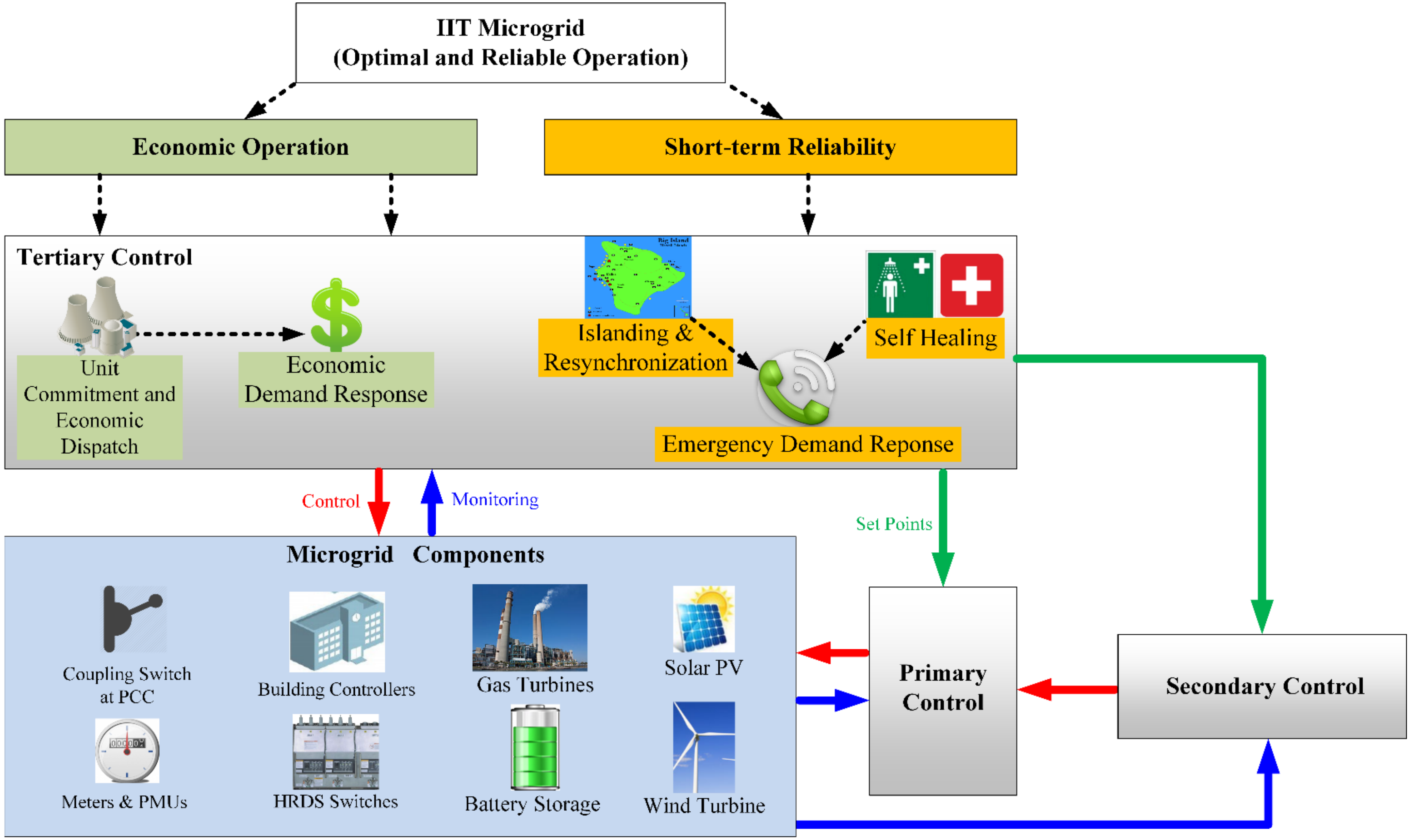
Renewables at IIT Microgrid

Charging Station, Solar Canopy, Flow Battery

Operation and Control of an Operational Microgrid for Service Restoration

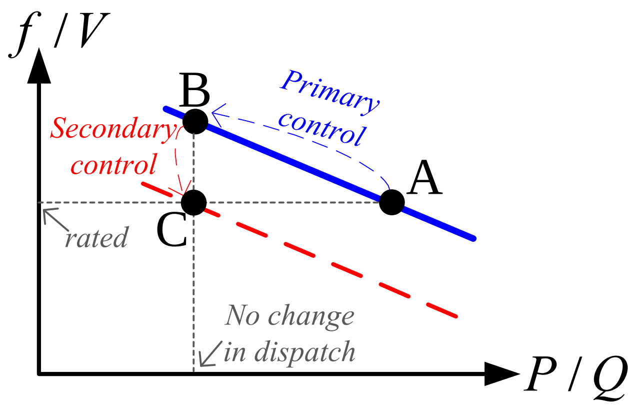
- The three control levels in microgrids include:
  - Primary control which is based on droop characteristics of DER units for sharing the microgrid load.
  - Secondary control performs corrective action to mitigate frequency and voltage errors introduced by droop control.
  - Tertiary control manages the flow between the microgrid and the utility grid and provides the optimal scheduling of DER units and demands in islanded and grid-connected operation of microgrid. Tertiary control would also provide ancillary services to the utility grid including voltage and frequency regulation and restoration services.

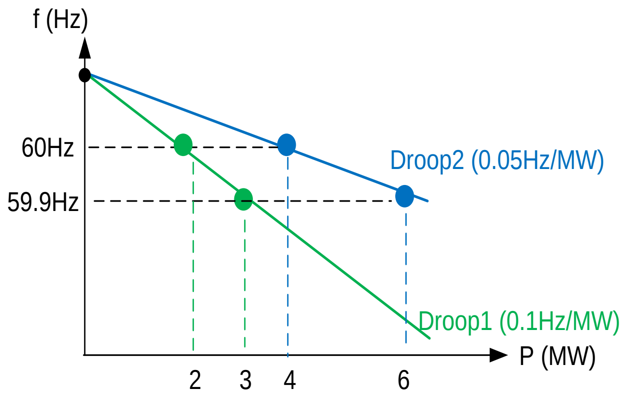
Operation and Control of an Operational Microgrid for Service Restoration

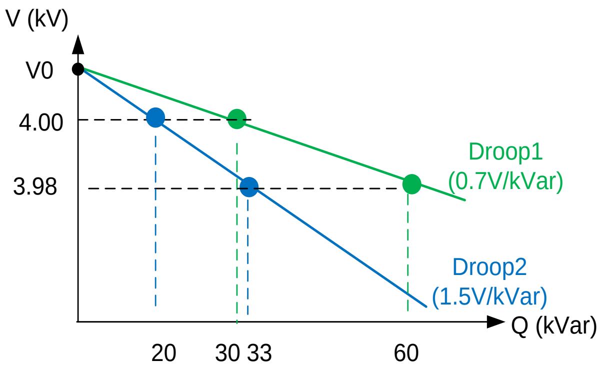


Hierarchical Control of Microgrid

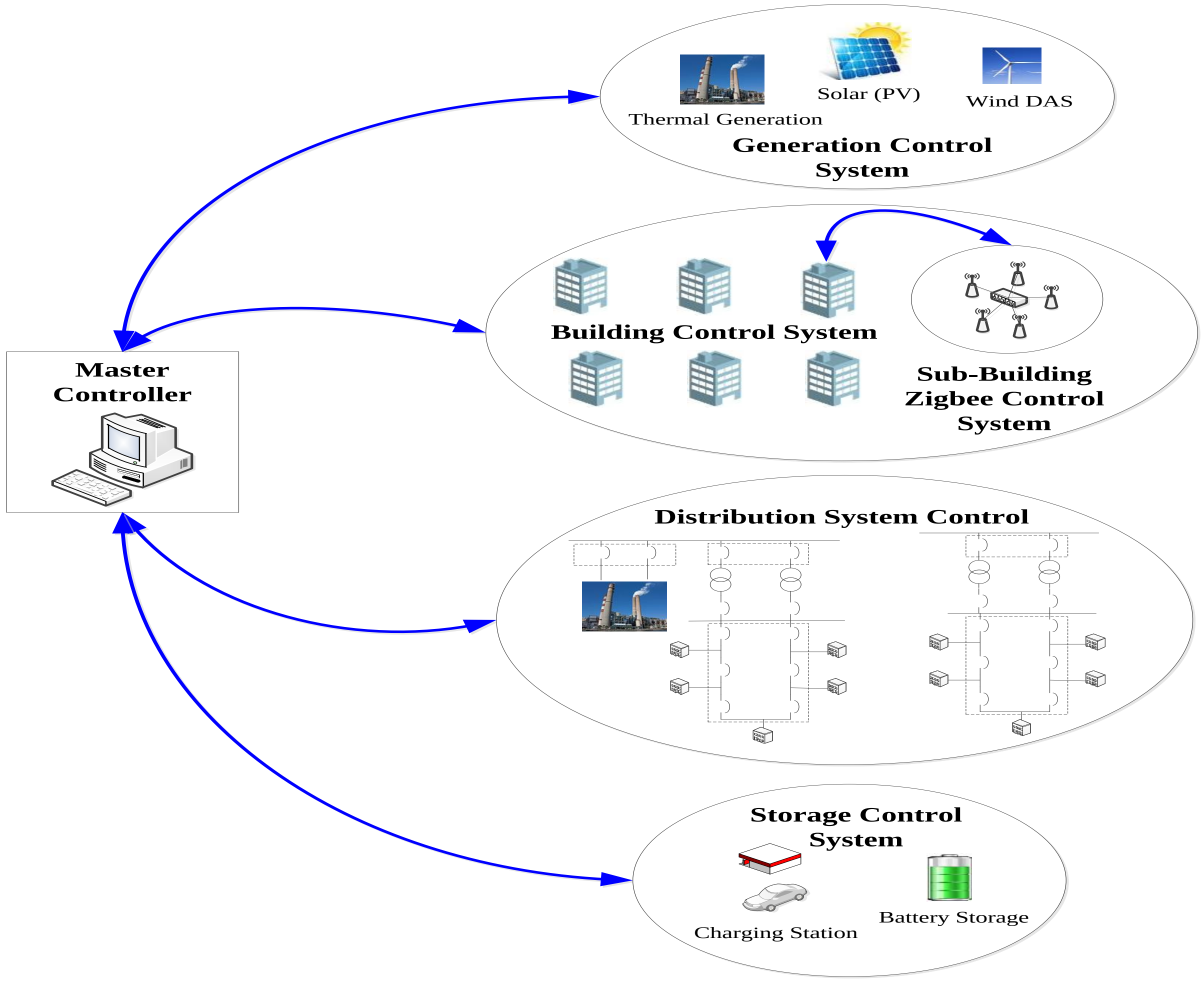
- Primary & Secondary Control







Tertiary Control -- Microgrid Master Controller



Master Controller Formulation

- Master controller is responsible for the economic operation of the microgrid based on signals received from HRDS switches.
- It monitors the status of HRDS switches using the SCADA system.
- It implements a three level hierarchical control (master, building, sub-building)
- It forecasts the real-time price of electricity and optimizes the hourly stochastic unit commitment/dispatch of local generation.
- Forecast errors of day-ahead load and wind speed and random outages of microgrid DG/distribution lines are considered.
- Monte Carlo representation of outages is applied and the Latin Hypercube Sampling (LHS) technique is used to develop a large number of scenarios with equal probabilities.

Master Controller Formulation

$$Min\sum_s p^s \left(\begin{array}{l} \sum_t \sum_i \left(F^s_{c,i}(P^s_{i,t}) + SU^s_{i,t} + SD^s_{i,t} \right) + \\ \rho_t \cdot P^s_{g,t} + VOLL.(\sum_t \sum_b P^{D,s}_{b,t} - P^{d,s}_{b,t}) \end{array} \right)$$

$$\sum_i P^s_{i,t} + P^s_{g,t} + \sum_k P^s_{k,t} \leq P^s_{D,t}$$

$$SU^s_{i,t} \geq CS_i \cdot (I^s_{i,t} - I^s_{i,t-1})$$

$$SD^s_{i,t} \geq CD_i \cdot (I^s_{i,t-1} - I^s_{i,t})$$

$$P^{\min}_i \cdot UX^s_{i,t} \cdot I^s_{i,t} \leq P^s_{i,t} \leq P^{\max}_i \cdot UX^s_{i,t} \cdot I^s_{i,t}$$

$$P^{\min}_g \cdot UX^s_{g,t} \leq P^s_{g,t} \leq P^{\max}_g \cdot UX^s_{g,t}$$

Problem Formulation

$$E_{k,t}^{net,s} = P_{dc,k,t}^{s} - \eta_k \cdot P_{c,k,t}^{s}$$

$$P_{k,t}^{s} = P_{dc,k,t}^{s} - P_{c,k,t}^{s}$$

$$I_{dc,k,t}^{s} + I_{c,k,t}^{s} \leq 1$$

$$I_{c,k,t}^{s} \cdot P_{c,k}^{\min} \leq P_{c,k,t}^{s} \leq I_{c,k,t}^{s} \cdot P_{c,k}^{\max}$$

$$I_{dc,k,t}^{s} \cdot P_{dc,k}^{\min} \leq P_{dc,k,t}^{s} \leq I_{dc,k,t}^{s} \cdot P_{dc,k}^{\max}$$

$$Q_{k}^{\min} \cdot (I_{dc,k,t}^{s} + I_{c,k,t}^{s}) \leq Q_{k,t} \leq Q_{k}^{\max} \cdot (I_{dc,k,t}^{s} + I_{c,k,t}^{s})$$

$$E_{k,t}^{s} = E_{k,t-1}^{s} - E_{k,t}^{net,s}$$

$$E_{k}^{\min} \leq E_{k,t}^{s} \leq E_{k}^{\max}$$

$$E_{k,0} = E_{k,NT}$$

Problem Formulation

$$\sum_{i\in D_j^i} P_{i,t}^{s} + \sum_{g\in D_j^g} P_{g,t}^{s} + \sum_{k\in D_j^k} P_{k,t}^{s} - \sum_{d\in D_j^d} P_{D,t}^{d,s} = P_{j,t}^{inj,s}$$

$$\sum_{i\in D_j^i} Q_{i,t}^{s} + \sum_{g\in D_j^g} Q_{g,t}^{s} + \sum_{k\in D_j^k} Q_{k,t}^{s} - \sum_{d\in D_j^d} Q_{D,t}^{d,s} = Q_{j,t}^{inj,s}$$

$$y_{o,j}^{t,s} = g_{o,j}^{t,s} + jb_{o,j}^{t,s} = \frac{r_{o,j} \cdot U_{o,j}^{t,s}}{r_{o,j}^2 + x_{o,j}^2} - j\frac{x_{o,j} \cdot U_{o,j}^{t,s}}{r_{o,j}^2 + x_{o,j}^2}$$

Problem Formulation

$$P_{j,t}^{inj,s} = (V_{j,t}^{s})^2 \cdot G_{j,j}^{t,s} +$$

$$\sum_{o(j \neq o)}^{NB} V_{j,t}^{s} \cdot V_{o,t}^{s} [G_{j,o}^{t,s} \cos(\theta_{j,t}^{s} - \theta_{o,t}^{s}) + B_{j,o}^{t,s} \sin(\theta_{j,t}^{s} - \theta_{o,t}^{s})]$$

$$P_{j,t}^{inj,s} = (2V_{j,t}^{s} - 1) \cdot G_{j,j}^{t,s} + \sum_{o(j \neq o)}^{NB} G_{j,o}^{t,s} (V_{j,t}^{s} + V_{o,t}^{s} - 1) + B_{j,o}^{t,s} (\theta_{j,t}^{s} - \theta_{o,t}^{s})$$

$$Q_{j,t}^{inj,s} = -(V_{j,t}^{s})^2 \cdot B_{j,i}^{t,s} +$$

$$\sum_{o(j \neq o)}^{NB} V_{j,t}^{s} \cdot V_{o,t}^{s} [G_{j,o}^{t,s} \sin(\theta_{j,t}^{s} - \theta_{o,t}^{s}) - B_{j,o}^{t,s} \cos(\theta_{j,t}^{s} - \theta_{o,t}^{s})]$$

$$Q_{j,t}^{inj,s} = -(2V_{j,t}^{s} - 1) \cdot B_{j,j}^{t,s} + \sum_{o(j \neq o)}^{NB} -B_{j,o}^{t,s} (V_{j,t}^{s} + V_{o,t}^{s} - 1) + G_{j,o}^{t,s} (\theta_{j,t}^{s} - \theta_{o,t}^{s})$$

Problem Formulation

$$PL_{j,o}^{t,s} = (V_{j,t}^{s})^2 \cdot G_{j,j}^{t,s} +$$

$$V_{j,t}^{s} \cdot V_{o,t}^{s}[G_{j,o}^{t,s}\cos(\theta_{j,t}^{s} - \theta_{o,t}^{s}) + B_{j,o}^{t,s}\sin(\theta_{j,t}^{s} - \theta_{o,t}^{s})]$$

$$PL_{j,o}^{t,s} = G_{j,o}^{t,s}(V_{j}^{t,s} - V_{o}^{t,s}) + B_{j,o}^{t,s}(\theta_{j}^{t,s} - \theta_{o}^{t,s})$$

$$QL_{j,o}^{t,s} = -(V_{j,t}^{s})^2 \cdot B_{j,j}^{t,s} +$$

$$V_{j,t}^{s} \cdot V_{o,t}^{s}[G_{j,o}^{t,s}\sin(\theta_{j,t}^{s} - \theta_{o,t}^{s}) - B_{j,o}^{t,s}\cos(\theta_{j,t}^{s} - \theta_{o,t}^{s})]$$

$$QL_{j,o}^{t,s} = B_{j,o}^{t,s}(V_{o}^{t,s} - V_{j}^{t,s}) + G_{j,o}^{t,s}(\theta_{j}^{t,s} - \theta_{o}^{t,s})$$

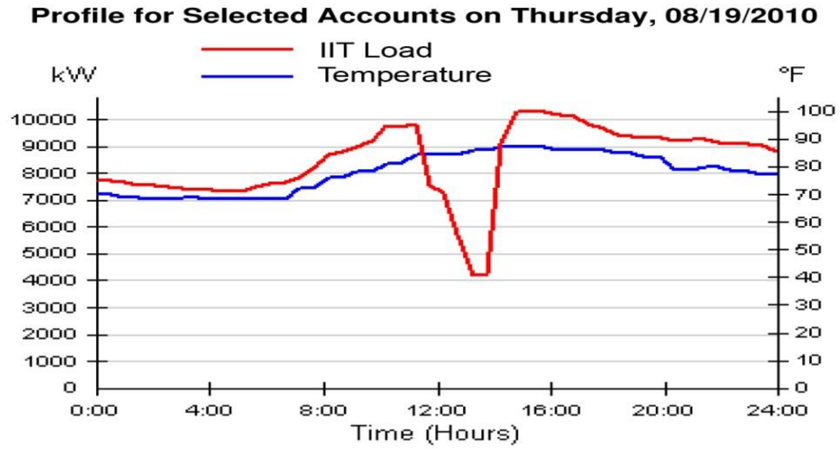
$$(QL_{j,o}^{t,s})^2 + (PL_{j,o}^{t,s})^2 = (SL_{j,o}^{t,s})^2$$

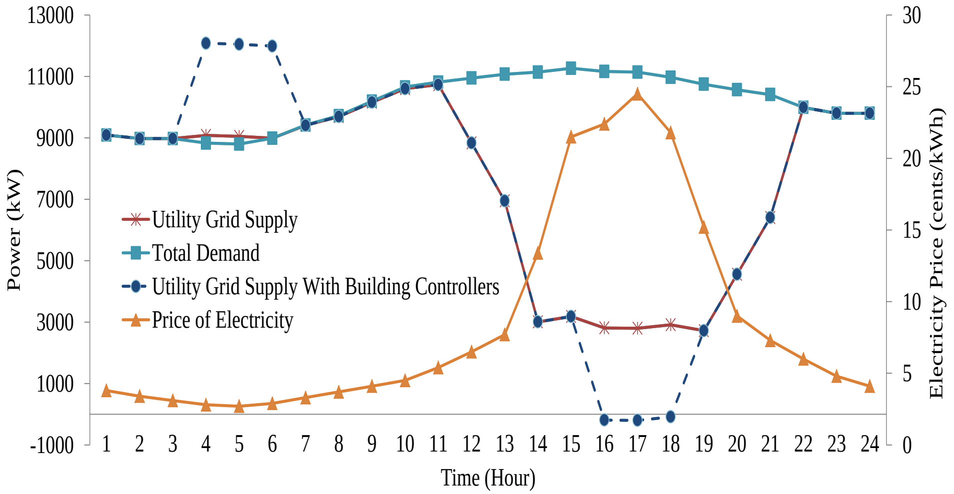
$$SL_{j,o}^{t,s} = PL_{j,o}^{t,s} + \xi_{j,o}^{t,s} \cdot QL_{j,o}^{t,s}$$

$$\left|SL_{j,o}^{t,s}\right| \le SL_{j,o}^{\max}$$

Optimal Operation of Microgrid

Case	No HRDS	HRDS	HRDS + Storage
Exp. SAIDI	1.22	0.18	0.04
Exp. SAIFI	3.29	0.59	0.37
Exp. CAIDI	1.73	0.36	0.04
Exp. CAIFI	2.69	0.68	0.29
Exp. Operation Cost	224,073	146,899	120,038
Exp. Energy not Supplied	1,216.21	251.07	175.10
LOLE	13.153	2.360	1.467





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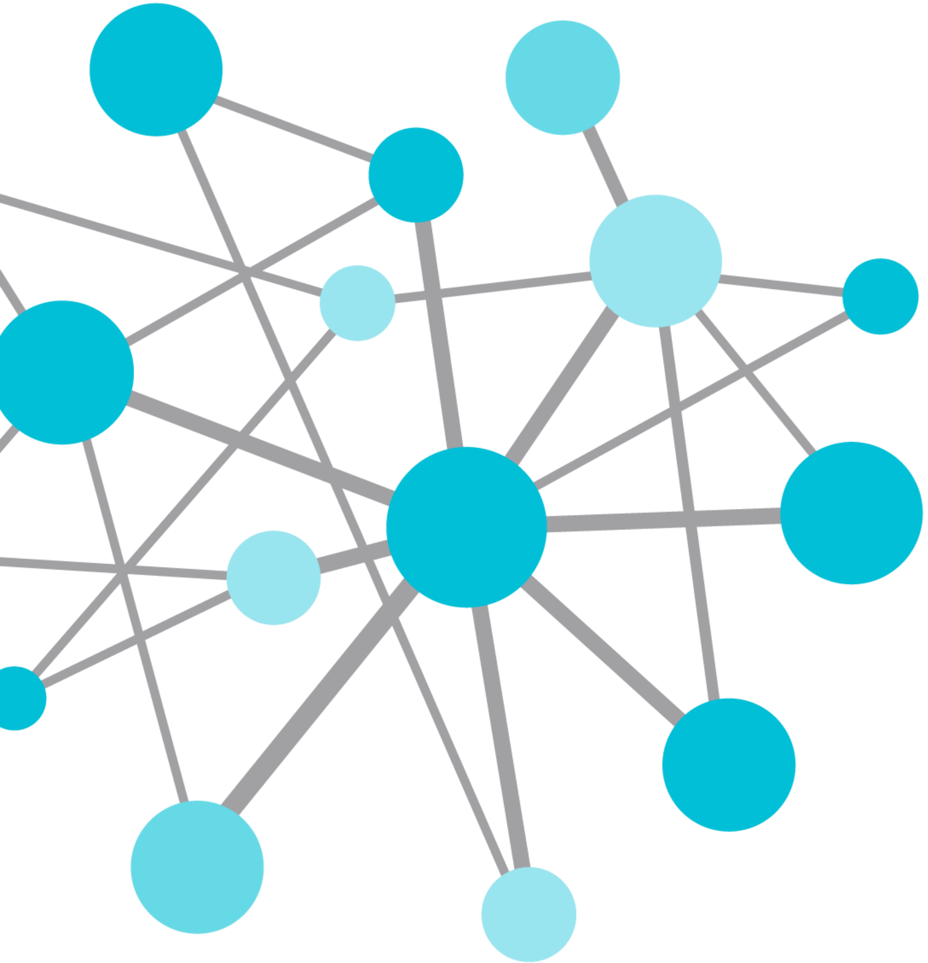

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