Distributed Grid Intelligence in the FREEDM System

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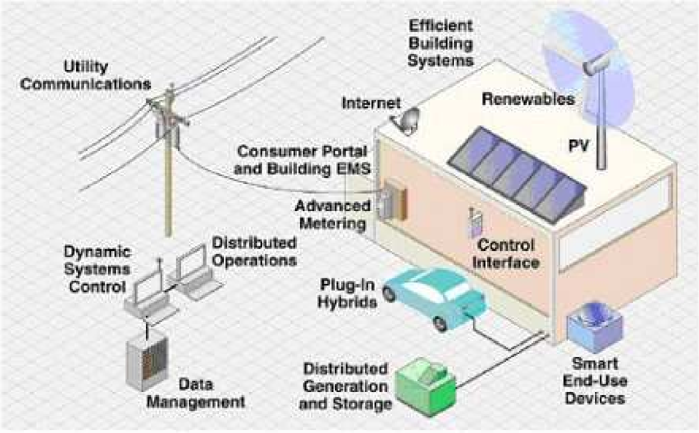
Outline

- DGI System Overview – Dr. McMillin
- CoDES – Dr. Chow
- Volt-Var – Dr. Baran

Cyber-Enabled Smart Distribution

- **Smart Grid**
  - **Automated Meter Reading (AMR)**
  - **Demand Side Management**
- **Centralized Supervisory Control And Data Acquisition (SCADA)**
- **Electric Utility Control**



Source: Electric Power Research Institute

Scalability, fault management, security and privacy

Source, Monitor Mapboard Systems

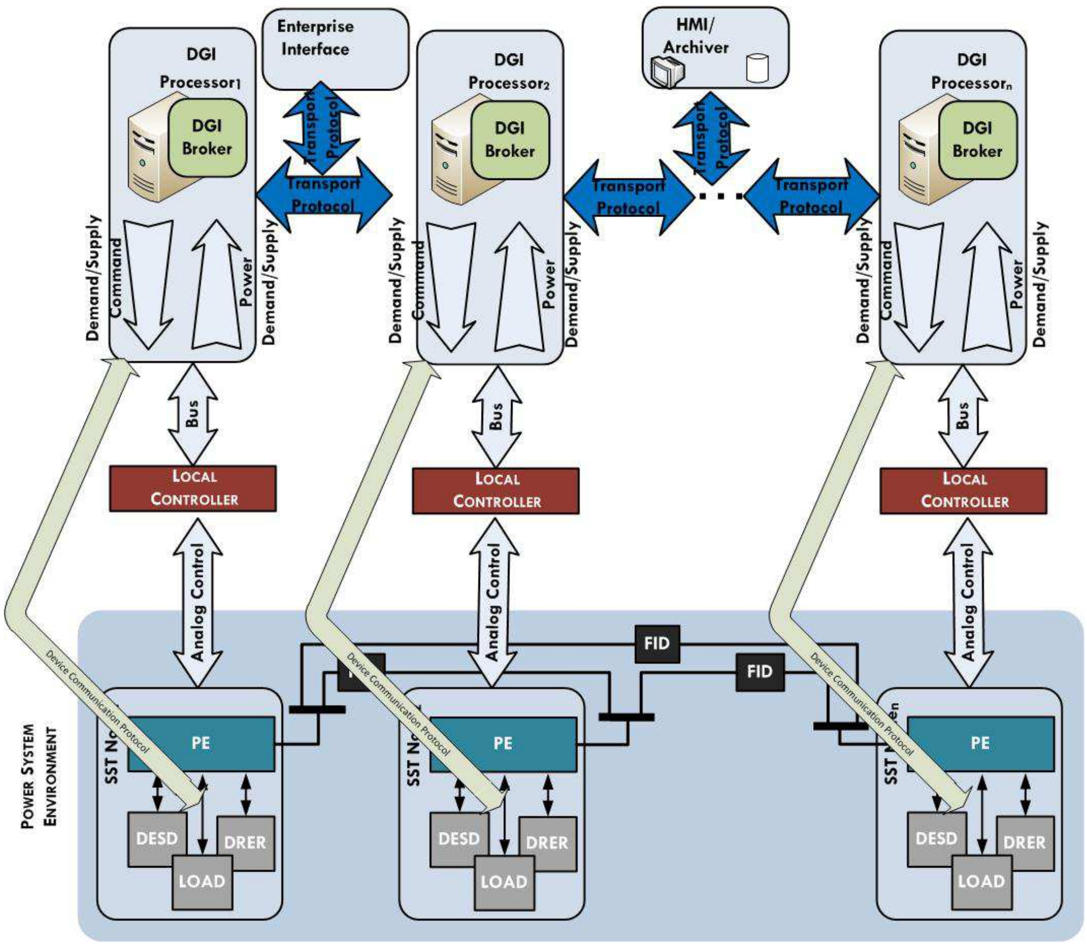
- **Smart Grid Version 1**

How much farther can we take this idea?

The FREEDM (Future Renewable Electric Energy Delivery and Management) Concept

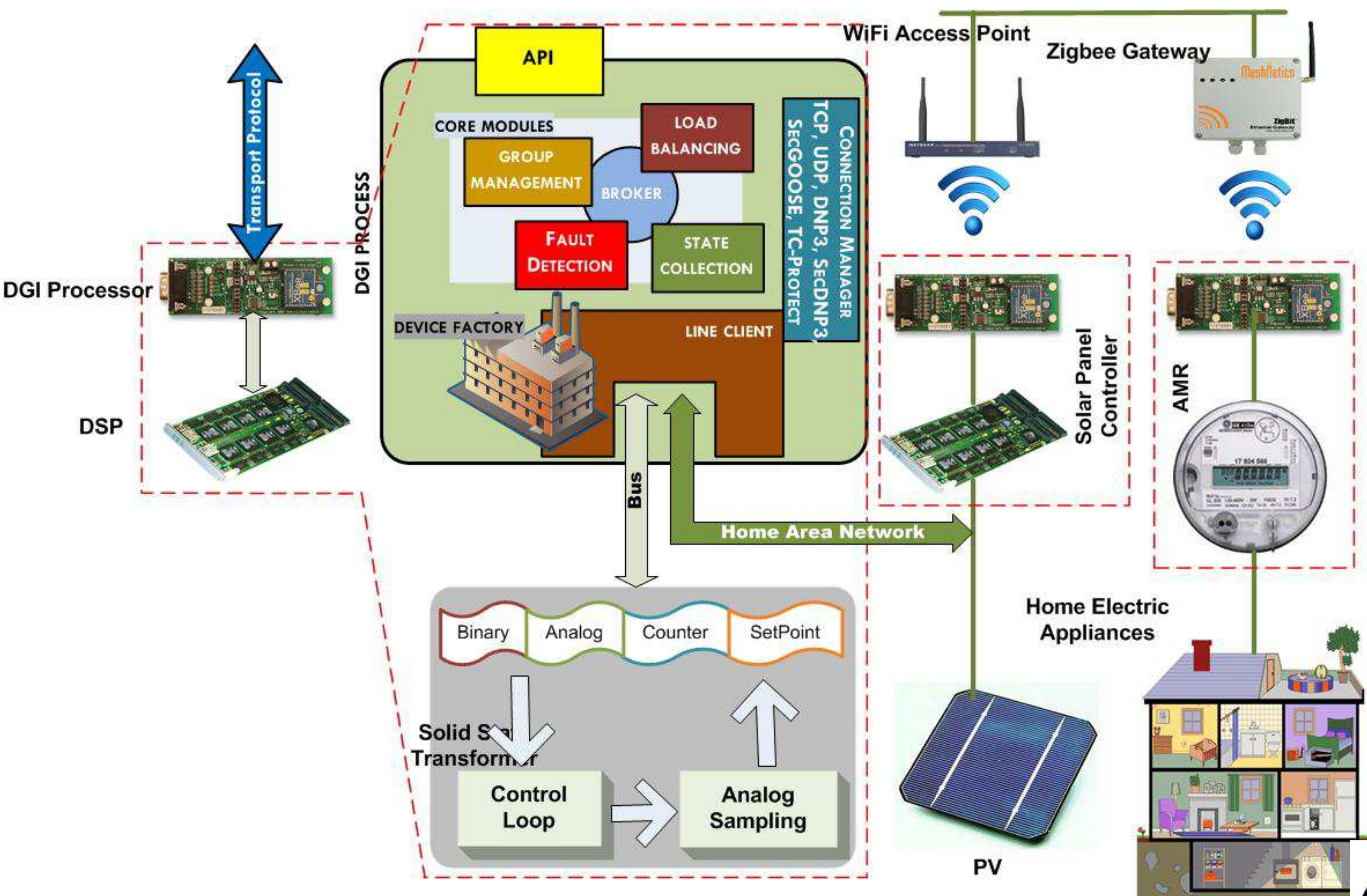
- Distributed Grid Intelligence (DGI)
  - People share energy resources
  - Neighborhood or industrial level
  - Where is the centralized controller?
  - Peer-to-peer

DGI Architecture

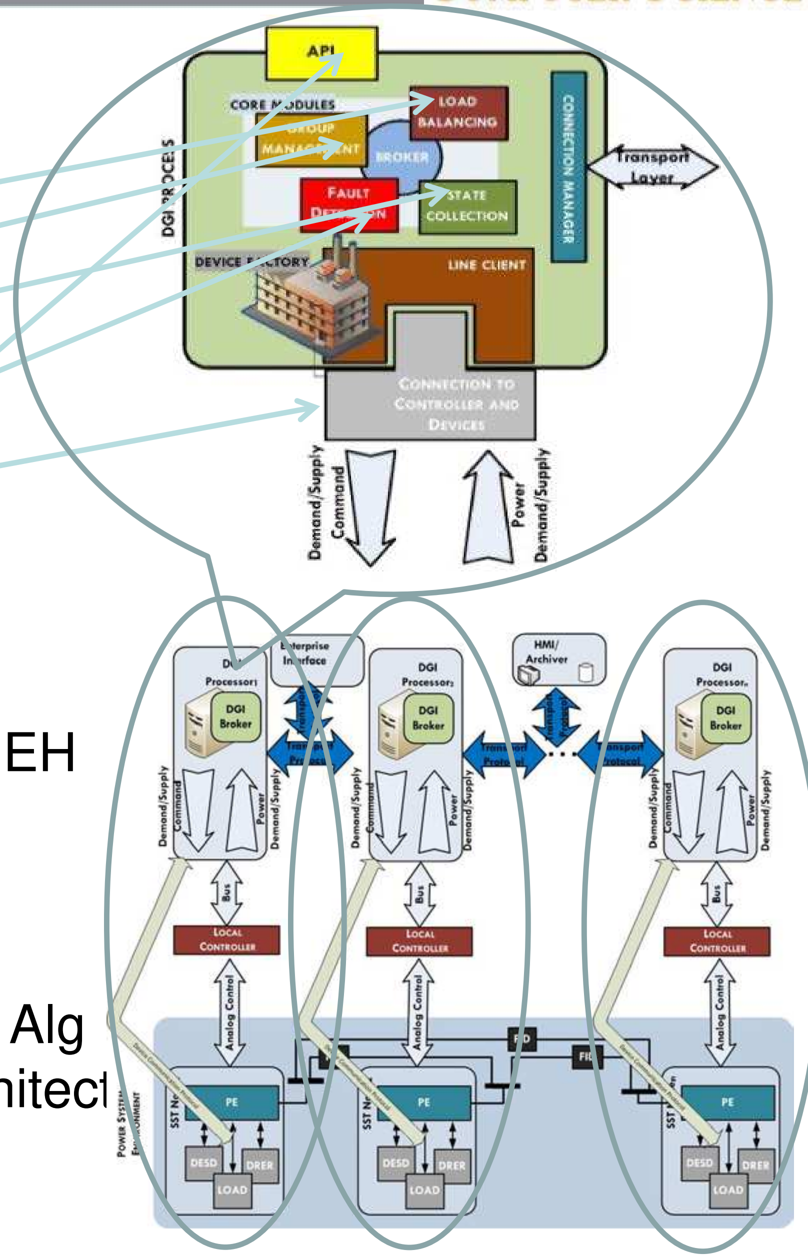


- •Local Computation on embedded computers
- •Transport Protocol i.e. TCP/IP
- •Device/Power Electronics Communication Protocol
- •System State Management
- •Fault Interrupters
- •Reconfigurable

Home Environment

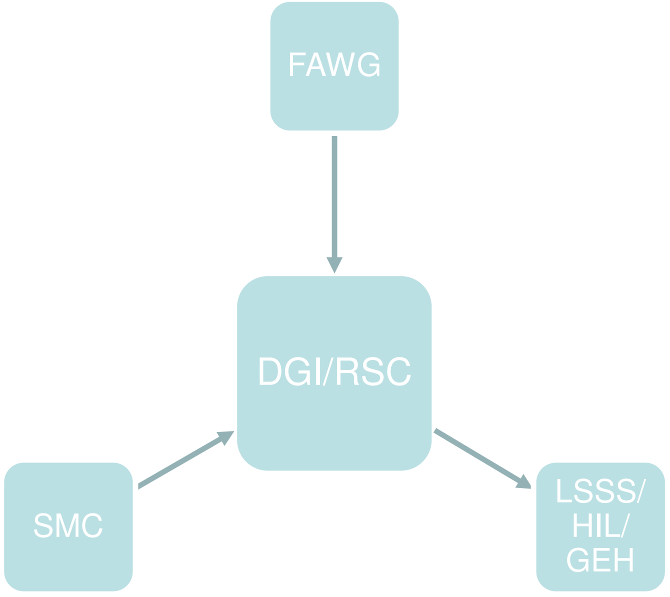


- DGI/RSC Provides FREEDM's Operating System Services
  - Power/Energy Balance (Y1)
  - Group Management (Y2)
  - State Collection (Y3-4)
  - Fault Detection & Invariants (Y5-6)
  - Plug and Play (Y5,8)
  - MQTT Integration with DGI (Y8)
  - DGI Algorithms (Y5-Y10)
- Current status
  - Integrated in HIL, Implemented in GEH
  - Replaced Interfaces with 3rd party
  - Real Time
- Limitations
  - Limited Set of Secure Management Alg
  - Lack of Center-Wide Invariants/Architect
  - Partial Integration with FID



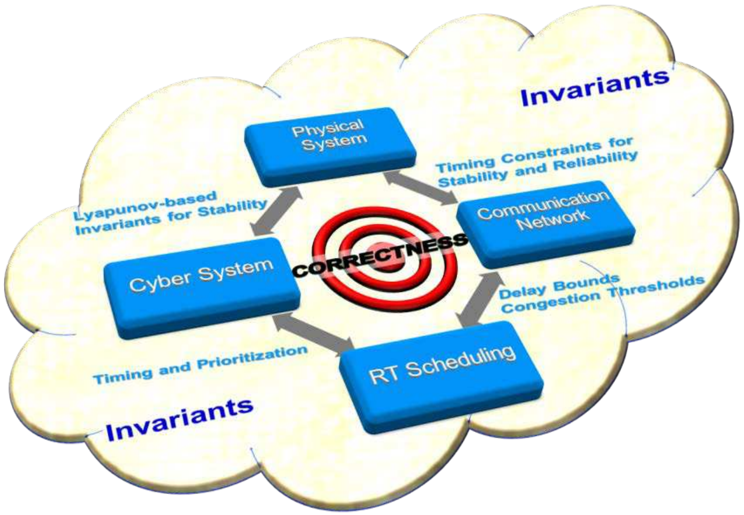
Objective

- Secure Algorithms & Invariants
  - Develop Secure Power and Energy Management
  - Develop Secure Volt/VAR
  - Develop Secure Attestation
  - Invariants Crucial for Integration of DGI with SMC/Controls Thrust
  - Integration of MQTT into DGI
  - Integration of DGI into GEH



Technical Approach

- Develop distributed Volt/Var algorithm within DGI
- Continue with Invariants for governing system dynamics implemented in HIL
- Continue to use Invariants as attestation algorithms for security
- Implement consensus-based energy management with energy storage dispatch
- Implement Federated Groups
- Implement MQTT integrated with DGI



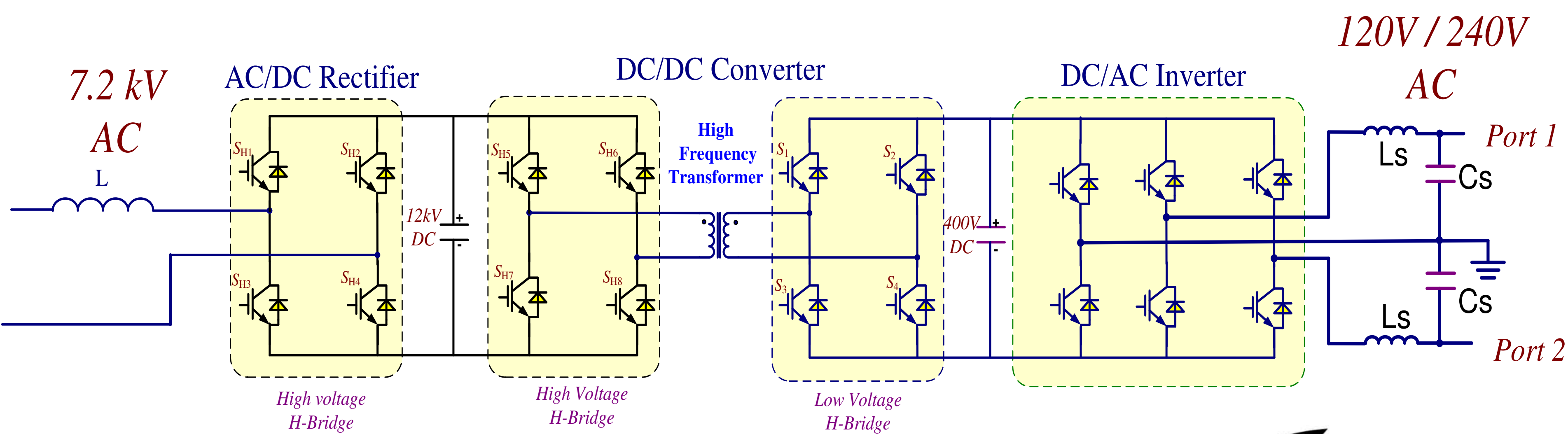
Schedulable Entity

….Advanced Power Electronics….

The Solid State Transformer

Inside an IEM Node

- Solid State Transformer (SST)
  - Power Electronics
  - Schedulable Entity



How to use it?

Distributed Power Balancing

- Correctness: Keep all nodes' "balanced" in terms of Supply and Demand and minimize energy cost
- Pass messages negotiating load changes until the system has stabilized
- Global optimization decomposed into individual processes that cooperate to meet the global correctness.

$$X_{Actual} = X_{Load} - X_{DRER}$$

System Load	State
$X_{Actual} < 0$	Low (Supply)
$X_{Actual} > Threshold$	High (Demand)
$0 <= X_{Actual} <= \text{Threshold}$	Normal

IEM 0		
IEM 0	20.551	L
IEM 1		H
: :		
IEM n		H

More Critical need

IEM 1		
IEM 0		N
IEM 1	32.834	H
: :		
IEM n		N

Lesser need

IEM n		
IEM 0		N
IEM 1		H
: :		
IEM n	30.721	H

I CAN SUPPLY

Migrate 1 quantum of Power per successful request

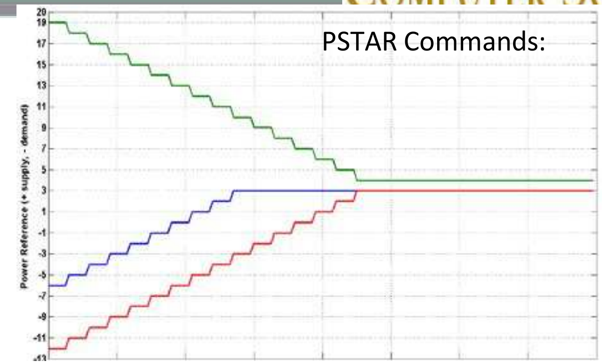
After Load Balancing

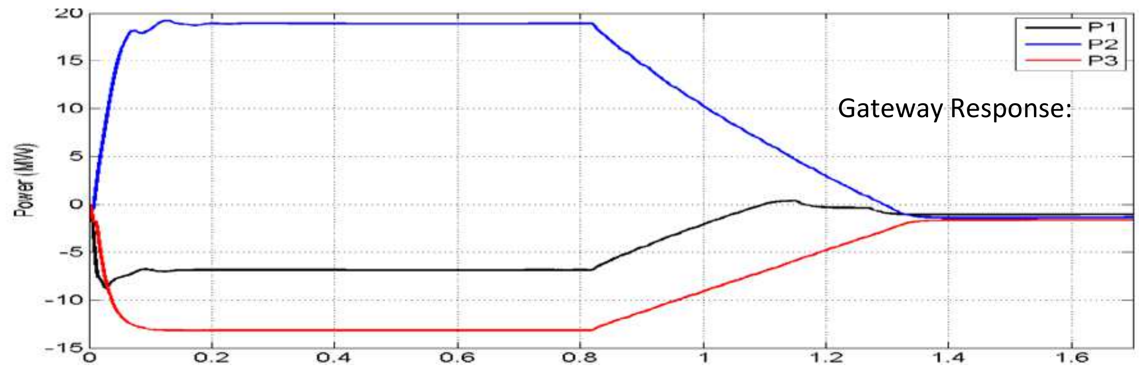
IEM 0		
IEM 0	25.551	N
IEM 1		N
: :		
IEM n		H

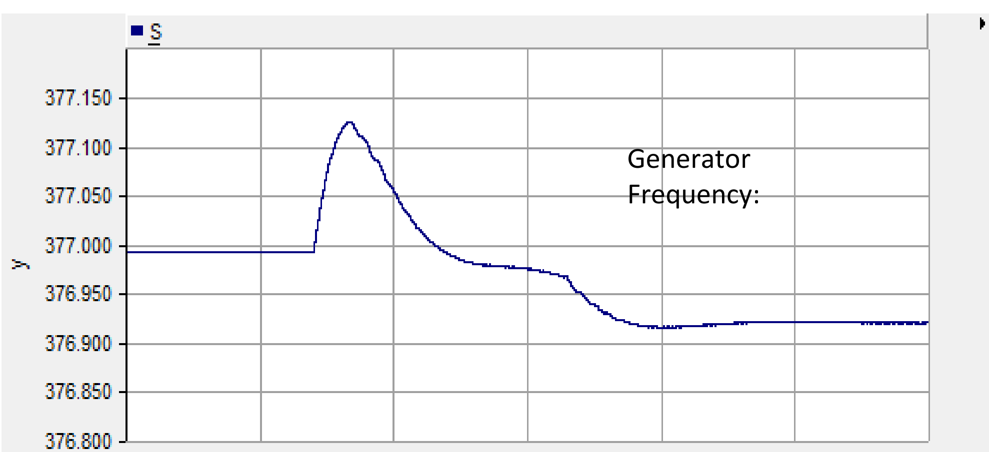
IEM 1		
IEM 0		N
IEM 1	27.834	N
: :		
IEM n		N

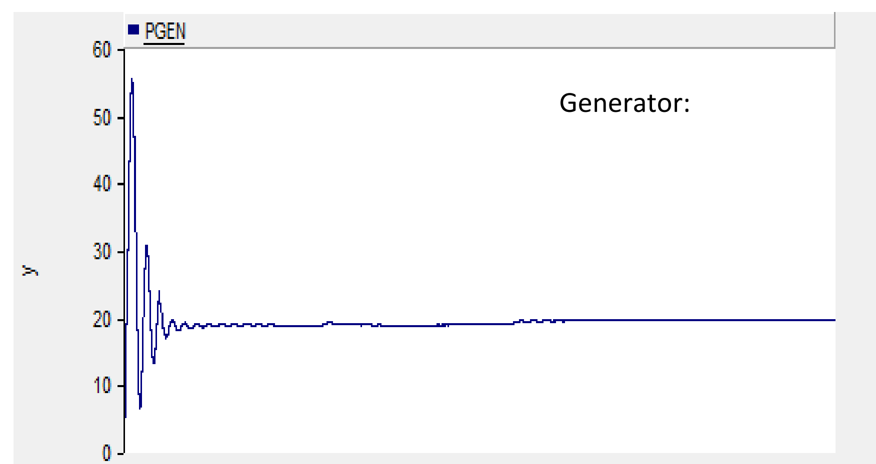
IEM n		
IEM 0		L
IEM 1		H
: :		
IEM n	30.721	H

“Peer-to-peer power migration – balance the load









Switched System Dynamics

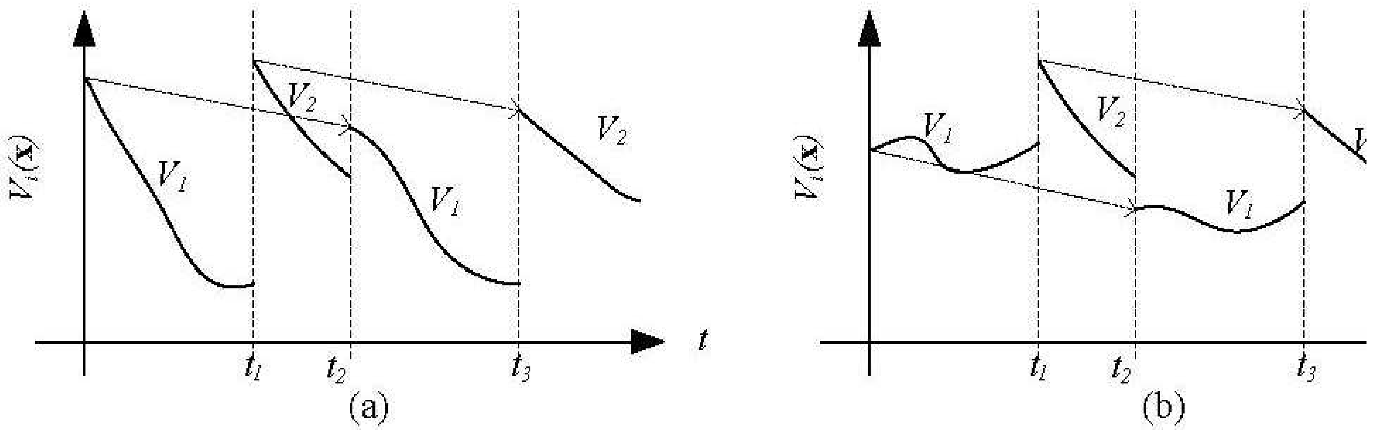


Figure: Asymptotic stability using multiple Lyapunov functions (V_1 and V_2). (a) Two true Lyapunov functions. (b) One Lyapunov function (V_2), one Lyapunov-like function (V_1).

Lyapunov

1. $V(\mathbf{x})$ is positive definite, that is, $V(\mathbf{x}) > 0 \ \forall \mathbf{x} \neq 0, V(0) = 0$.
2. $V(\mathbf{x})$ is radially unbounded.
3. $\frac{dV}{dt} \leq 0$ along all trajectories ($\frac{\partial V}{\partial x}\mathbf{f}(\mathbf{x}) \leq 0$).

If $\frac{dV}{dt}$ is non-positive, the system is stable. If $\frac{dV}{dt}$ is strictly negative, the system is asymptotically stable.

Governing Voltage Invariant

- Measure voltage and power at every bus
- Compute “L” indicator and compare it to voltage
- Prevents voltage oscillations and collapse when embedded as a distributed invariant in load balancing.

$$L_j = \frac{S_j^{'}}{V_j^2 Y_{jj}}$$

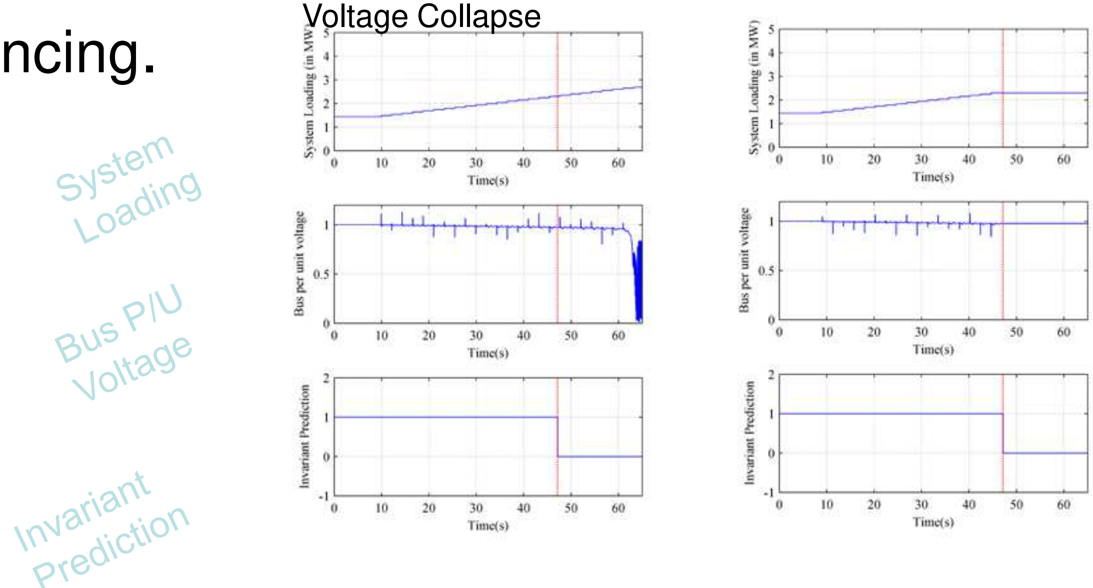
$$S_j^{'} = S_j + \sum_{\substack{i=1 \\ i \neq j}}^{N} \frac{Z_{ji}^{*} S_i}{Z_{jj}^{*} V_i} V_j$$

$$L_{System} = Max_{i \in \{1 \cdots N\}}(L_i)$$

$$\{ I_V : L_{system} < V_i \ \forall i \}$$

Without Invariant in DGI,
Voltage Collapse

With Invariant, DGI
Stops Power Injection



Line Invariants

- Compare every DGI migration with available transfer capacity (ATC) based line invariant value
- Prevents overloading when embedded as a distributed invariant in load balancing.

$$P_{mn}^{New} = P_{ij,mn}^{Max} = \frac{P_{ij}^{Max} - P_{ij}^{0}}{PTDF_{ij.mn}}; PTDF_{ij.mn} > 0$$

$$P_{mn}^{New} = P_{ij,mn}^{Max} = \infty; PTDF_{ij.mn} = 0$$

$$P_{mn}^{New} = P_{ij,mn}^{Max} = \frac{-P_{ij}^{Max} - P_{ij}^{0}}{PTDF_{ij.mn}}; PTDF_{ij.mn} < 0$$

$$ATC_{mn} = Min(P_{ij.mn}^{Max})\forall ij$$

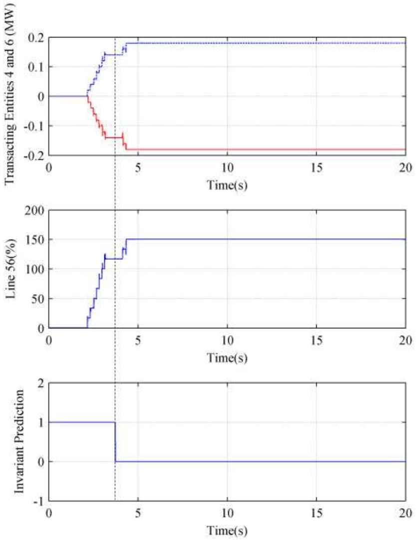
Governs Unanticipated, Deleterious, and Insecure Behavior

Transacting entities

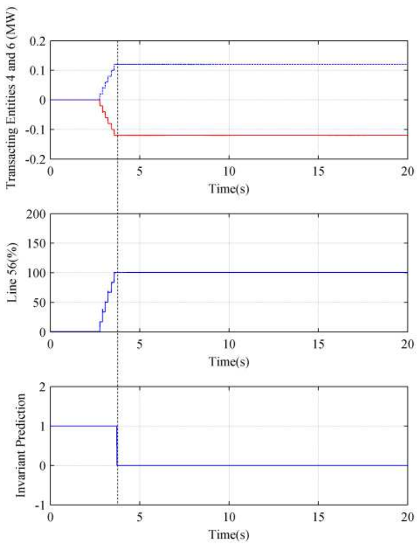
Line Overloading %

Invariant Prediction

Without Invariant in DGI,
Voltage Collapse

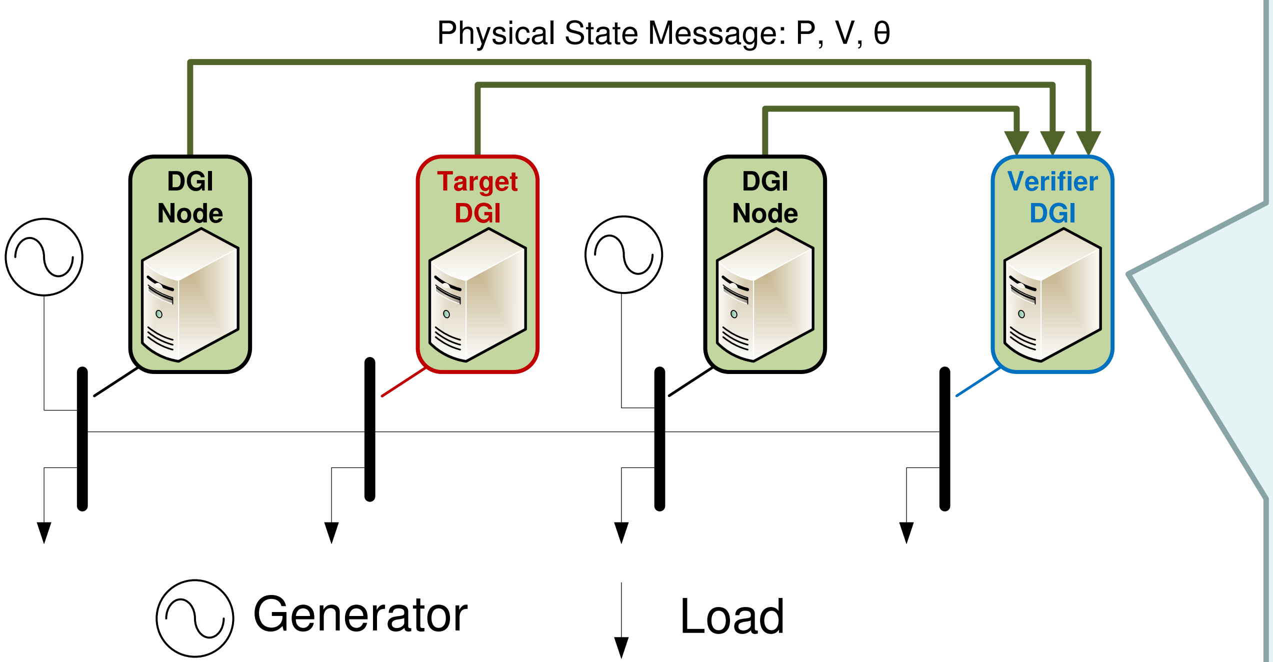


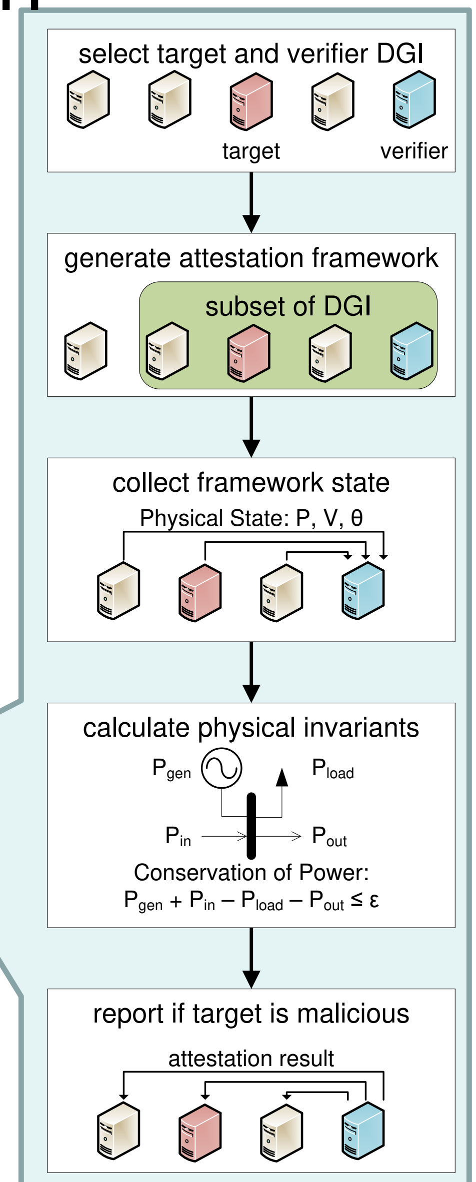
With Invariant, DGI Stops Power Migration



Physical Attestation

A distributed security mechanism in the DGI that detects malicious peers using physical feedback

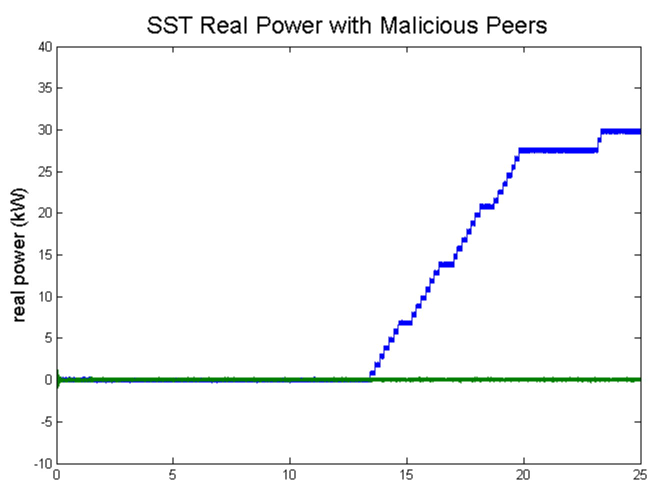


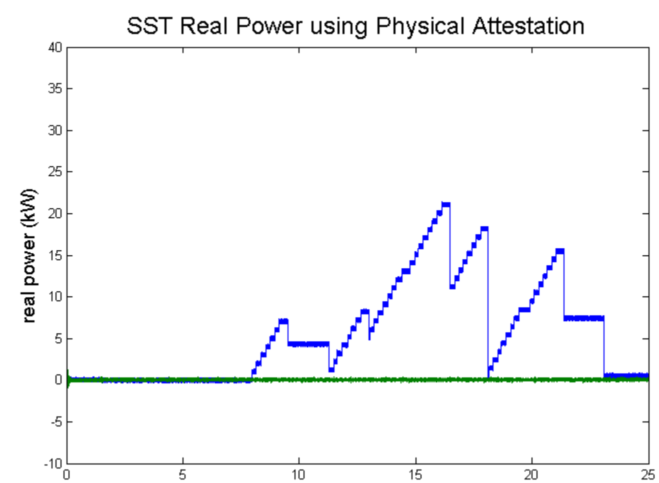


PSCAD/DGI Results for Attestation

- **Before Attestation**
  A DGI in the supply state increases its generation despite its malicious peer not doing a corresponding increase in load.

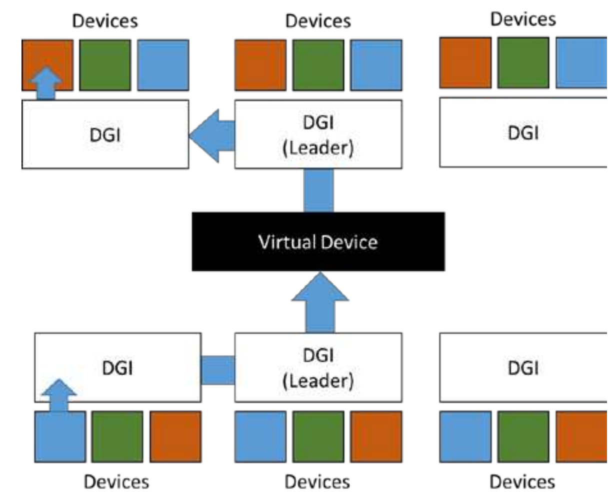
- **After Attestation**
  The supply DGI performs attestation and undoes its generation increase when it observes no change in load from the malicious peer.

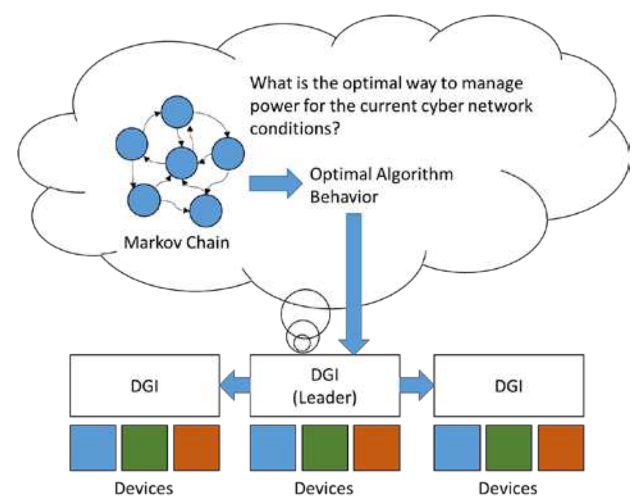




Federated Groups and Group Models

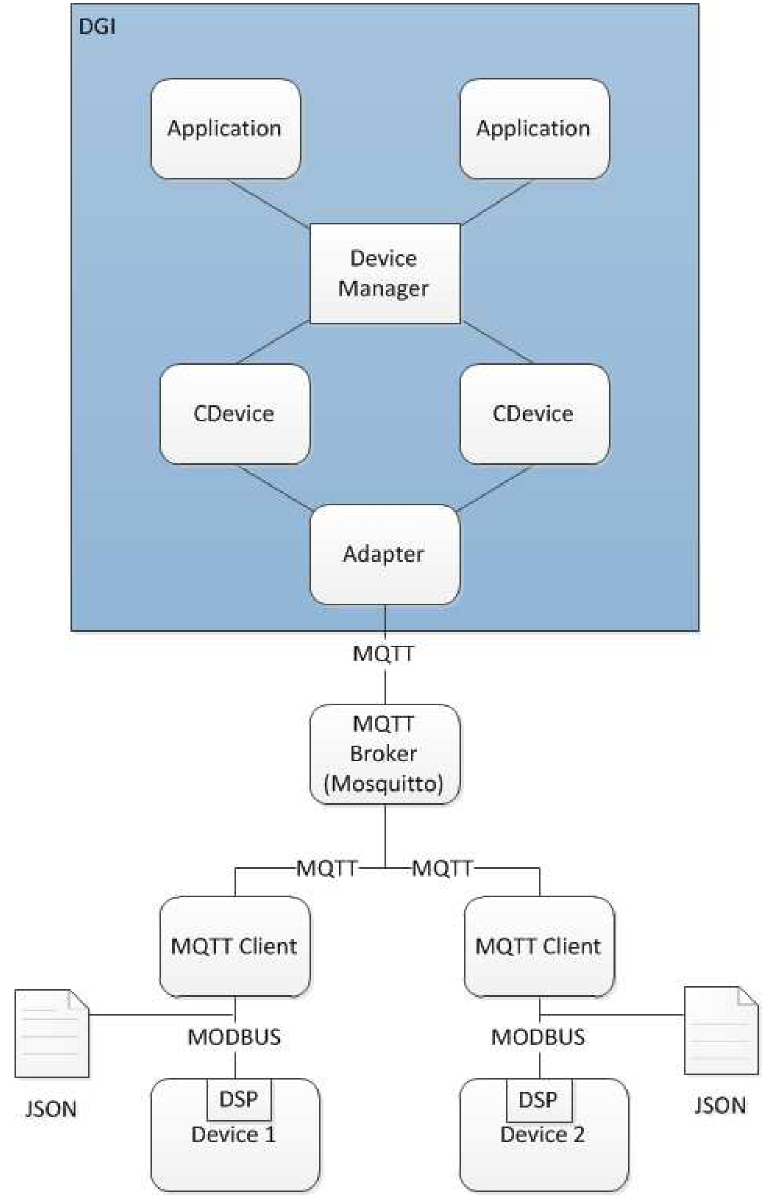
- Federated groups use a virtual device to transfer power between groups
  - Affords hard real-time within a group and soft real-time across multiple groups
- Markov Model of Group Performance
  - Big issue was making the DGI operation memoryless – this allows close calibration with the model.
- Adaptive Protocols
  - ECN – notification of impending congestion, so reconfigure the groups to require less messaging

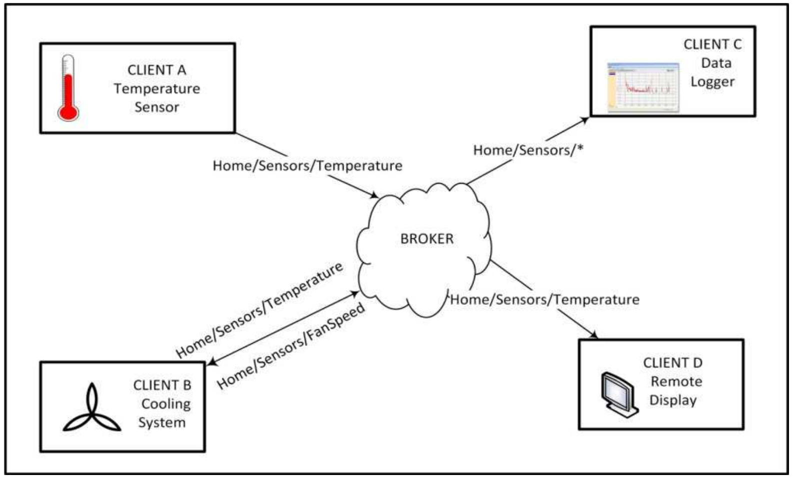




MQTT Implementation

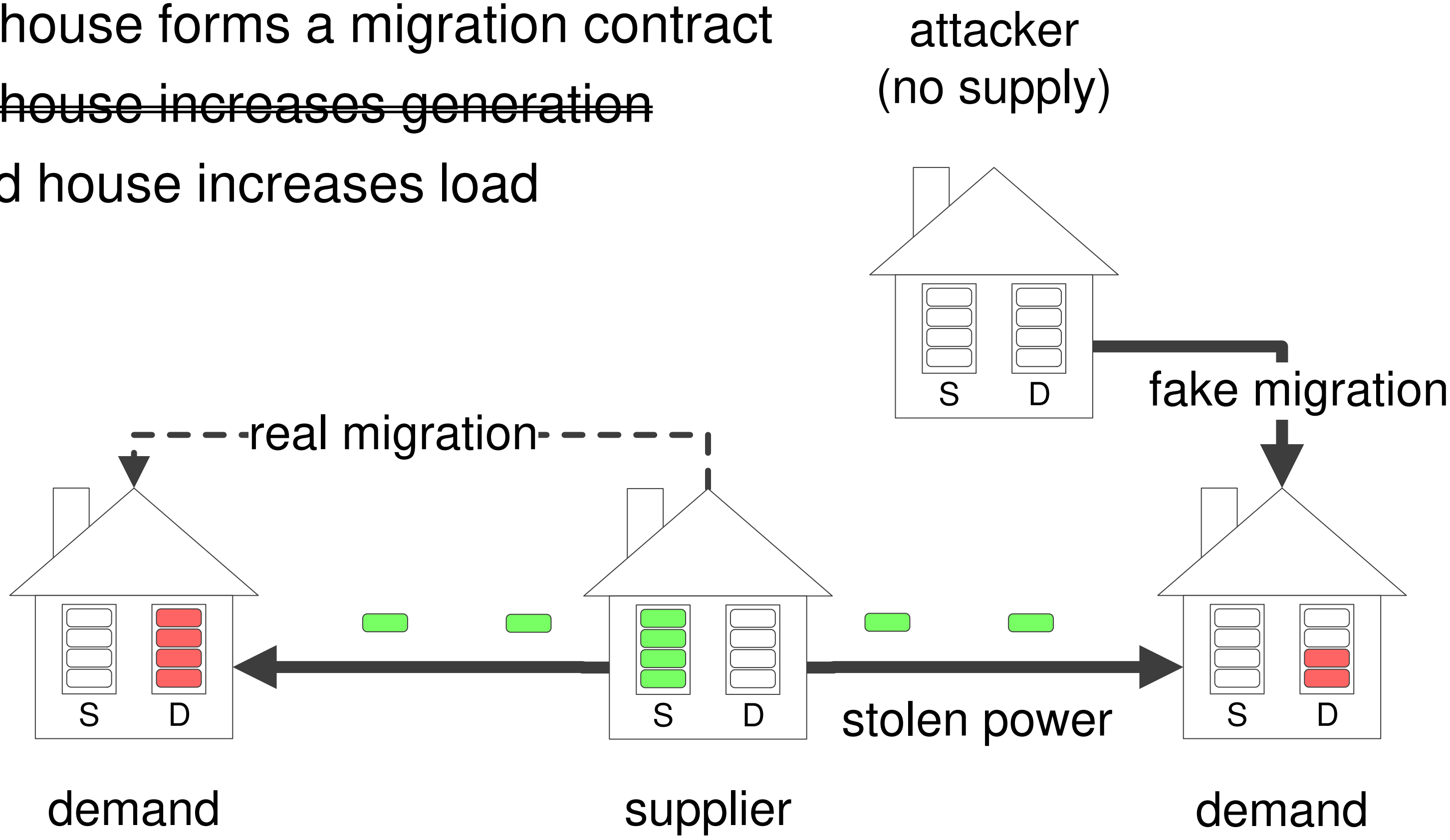
- Replace DGI's PnP with MQTT (Message Queueing Telemetry Transport)
  - Broker hosted in DGI
  - Device attributes sent to DGI and made available to applications
  - Standardize a device profile





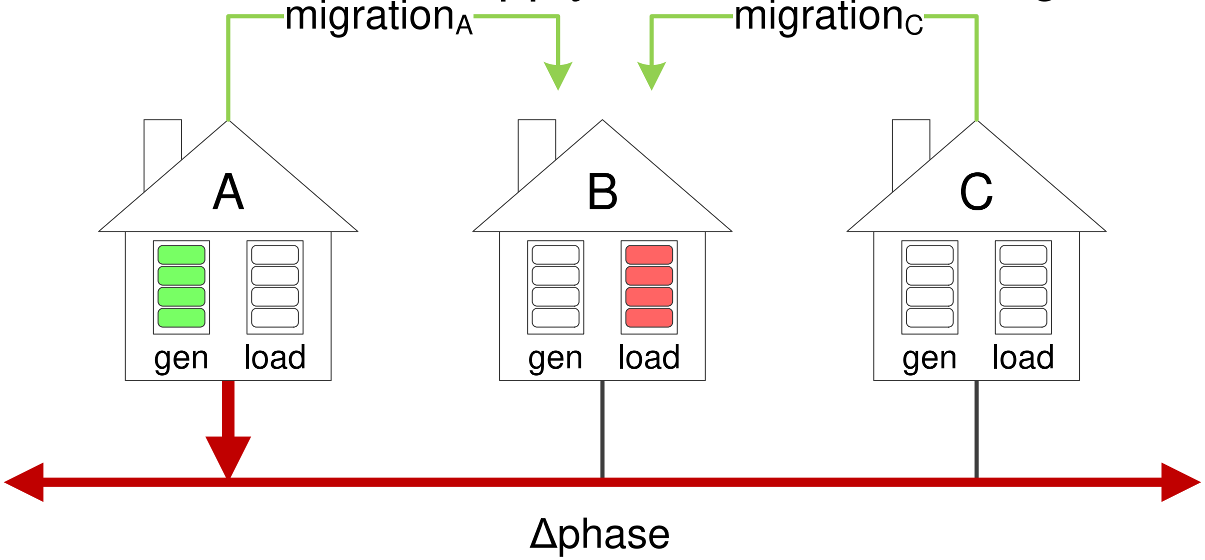
Fake Supply Attack

1. Supply house advertises its excess generation
2. Demand house requests power from supplier
3. Supply house forms a migration contract
4. ~~Supply house increases generation~~
5. Demand house increases load

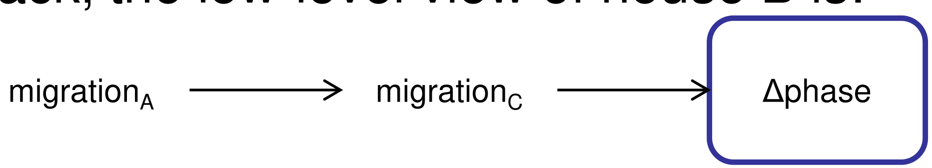


Concurrent Fake Supply Attack

- House C launches a fake supply attack during a migration from A:



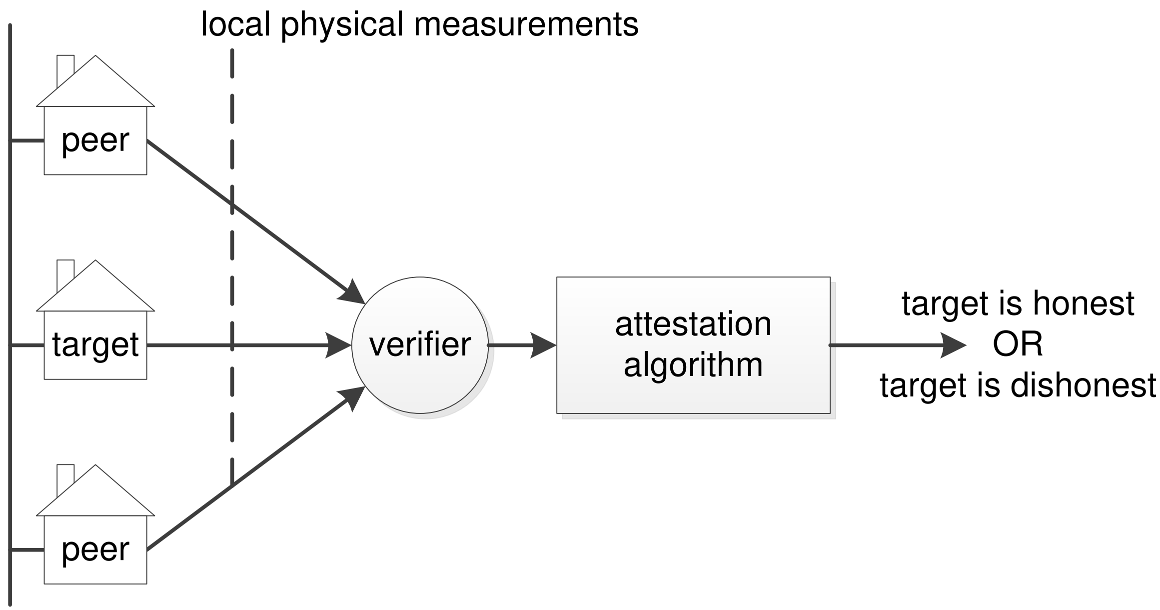
- During the attack, the low-level view of house B is:



- This view is consistent with either *increase*$_A$ or *increase*$_C$!

Physical Attestation

- A verifier checks if another cyber process is compromised using physical measurements.

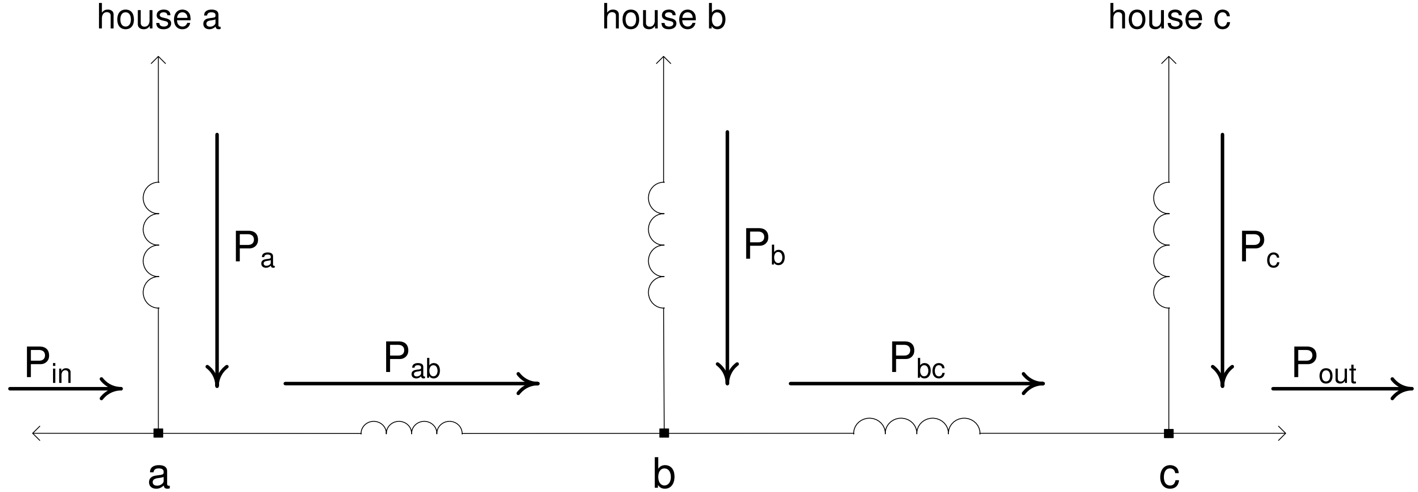


- Similar to a remote attestation algorithm that uses the physical layer as a shared memory.

Conservation of Power

- Conservation of Power at b:

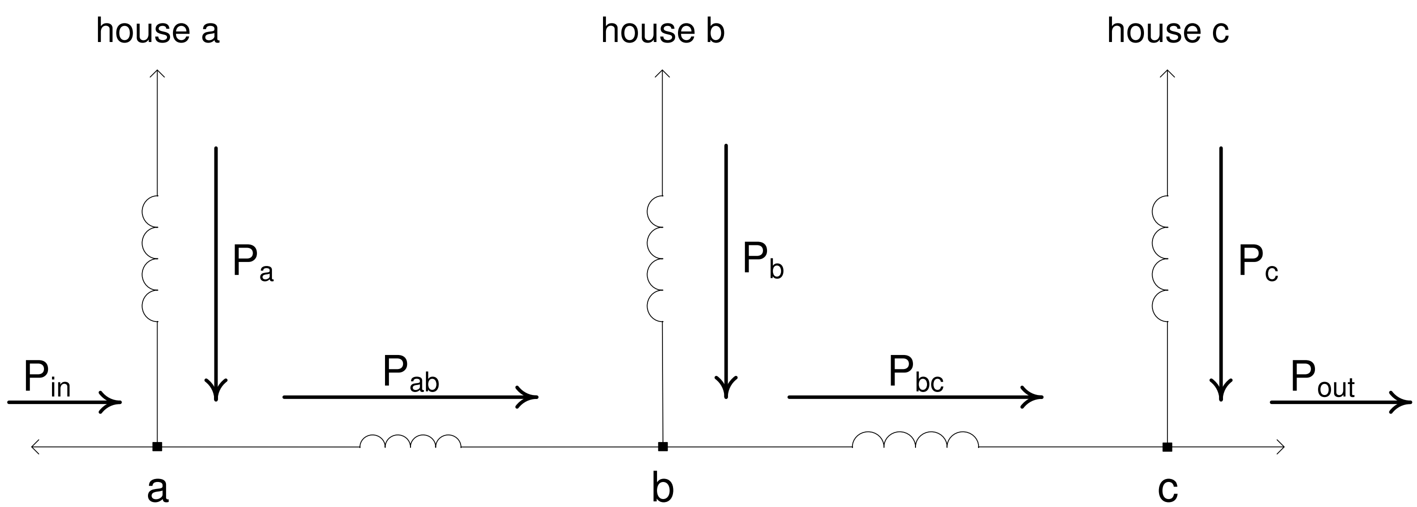
$$\{I_b : P_{ab} + P_b - P_{bc} = 0\}$$



- I_b is an invariant that must be true for the physical system.
- If I_b is violated, then at least one house must be dishonest.

Physical Measurements

- The invariant is instantiated using measurements from each house:



$$\{I_b : P_{ab} + P_b - P_{bc} = 0\}$$

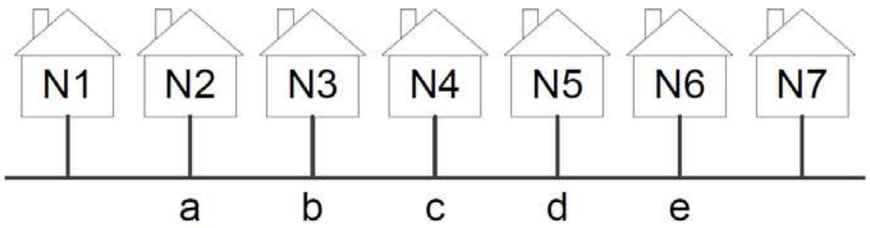
$$P_{ab} = \frac{V_a V_b}{X_{ab}} sin(\theta_b - \theta_a)$$

$$P_{bc} = \frac{V_b V_c}{X_{bc}} sin(\theta_c - \theta_b)$$

House	Measurements
A	$V_a \theta_a$
B	$P_b V_b \theta_b$
C	$V_c \theta_c$

Unique Violation Pattern

- It requires observations from 7-houses to find a unique violation pattern:

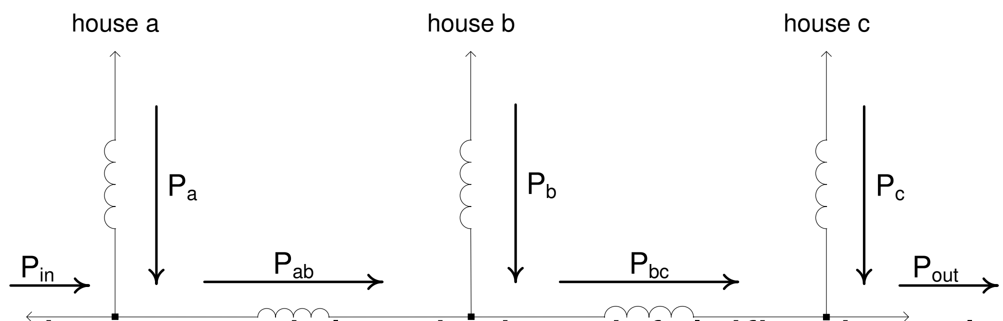


- It is not possible to produce a unique pattern with fewer observations.
- This set of observations can be used to detect when house 4 performs a fake supply attack

N	Falsified	Violations
1	$V_1\theta_1$	I_a
2	P_2	I_a
	$V_2\theta_2$	$I_a I_b$
	$P_2 V_2\theta_2$	I_b
3	P_3	I_b
	$V_3\theta_3$	$I_a I_b I_c$
	$P_3 V_3\theta_3$	$I_a I_c$
4	P_4	I_c
	$V_4\theta_4$	$I_b I_c I_d$
	$P_4 V_4\theta_4$	$I_b I_d$
5	P_5	I_d
	$V_5\theta_5$	$I_c I_d I_e$
	$P_5 V_5\theta_5$	$I_c I_e$
6	P_6	I_e
	$V_6\theta_6$	$I_d I_e$
	$P_6 V_6\theta_6$	I_d
7	$V_7\theta_7$	I_e

Detecting the Compromised Node

- Assume *b* is malicious and the other two houses are honest.

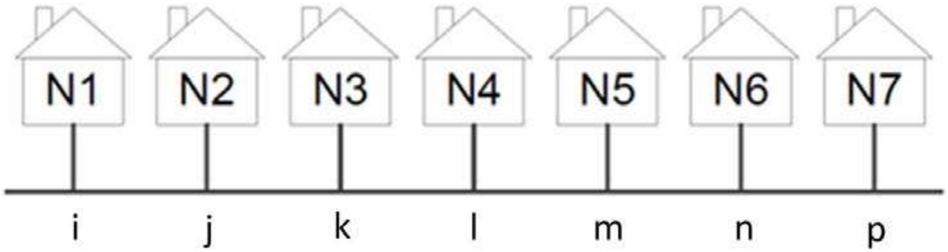


- A set of invariants are violated when *b* falsifies its values:

Falsified Values	Violated Invariants
P_b	I_b
$V_b \theta_b$	$I_a I_b I_c$
$P_b V_b \theta_b$	$I_a I_c$

- The dishonest house is the midpoint of each violation set.

MSDND in Attestation



Pattern	Node	Falsified Values	Violated Invariants
...			
ψ_1	j	P_j	I_j
ψ_2	j	$V_j\theta_j$	$I_iI_jI_k$
ψ_3	j	$P_jV_j\theta_j$	I_k
κ_1	k	P_k	I_k
κ_2	k	$V_k\theta_k$	$I_jI_kI_\ell$
κ_3	k	$P_kV_k\theta_k$	I_jI_ℓ
...			

Node k is malicious.

If node k reports false values for P_k, the invariant I_k will be violated which corresponds to $\kappa_1 = true$. However, the same pattern of violations occurs when node j lies about the values $P_jV_j\theta_j$ which is $\psi_3 = true$. Thus, we can show MSDND(ES) as follows:

1.	ψ_3 **xor** κ_1	there is only one malicious node
2.	$\nexists\, \mathbb{V}_{P_k}$	no one but k can read P_k
3.	$\therefore \nexists\, \mathbb{V}_{\psi_3}(w)$	privacy
4.	$\therefore \nexists\, \mathbb{V}_{\kappa_1}(w)$	similar reasoning.

Therefore, an intelligent node j can launch at least one attack that is MSDND(ES):

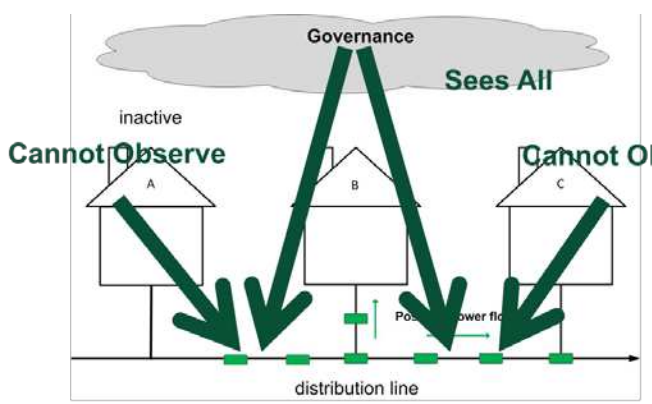
$$w \vdash [(\kappa_1 \textbf{ xor } \psi_3)] \wedge w \vDash \left[\left(\nexists \Vdash_{\kappa_1}(w)\right) \wedge \left(\nexists \Vdash_{\psi_3}(w)\right)\right].$$

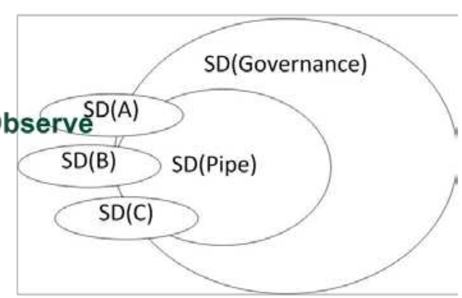
Fundamental Barriers and How Addressed

- Systems Integration → Determine and Mitigate Interfering actions
- Transition to Testbeds → Power Engineers coding their applications directly in DGI for LSSS/HIL/GEH

Associated Work within DGI

- HIL Implementation (Steurer, Leonard)
- Additional **NSF Grant** from CPS Program (Kimball, McMillin, Chow) for Invariant Development
- **NIST Funding** (McMillin) to extend the FREEDM security concepts to the openFMB SGIP/CPS PWG and other infrastructures
- **NSF SFS** Program to train cybersecurity researchers for government service.
- Protection System Development and future integration with DGI (Karady)





Read more about it

- Tamal Paul, Jonathan W. Kimball, Maciej Zawodniok, Thomas P. Roth and Bruce McMillin, “Invariants as a Unified Knowledge Model for Cyber-Physical Systems,” IEEE Trans on Smart Grid, January, 2014
- Information Flow and Verification: R. Akella, H. Tang, and B. McMillin, “Analysis of information flow security in cyber-physical systems,” *International Journal of Critical Infrastructure Protection, vol. 3-4, pp. 157–173,* December 2010.
- T. Roth; B. McMillin, "Physical Attestation in the Smart Grid for Distributed State Verification," in *IEEE Transactions on Dependable and Secure Computing* , vol.PP, no.99, pp.1-1 (2016) Gamage, Thoshitha, Roth, Thomas, McMillin, Bruce, and Crow, Mariesa, “Mitigating Event Confidentiality Violations in Smart Grids: An Information Flow Security-based Approach,” *IEEE Transactions on Smart Grid, 2013*
- G. Howser and B. McMillin, "A Modal Model of Stuxnet Attacks on Cyber-physical Systems: A Matter of Trust," *Software Security and Reliability (SERE), 2014 Eighth International Conference on*, San Francisco, CA, 2014, pp. 225-234.
- Marina Krotofil, Jason Larsen, and Dieter Gollmann. 2015. The Process Matters: Ensuring Data Veracity in Cyber-Physical Systems. In *Proceedings of the 10th ACM Symposium on Information, Computer and Communications Security* (ASIA CCS '15). ACM, New York, NY, USA, 133-144.
- A funny podcast on the subject, 16360: The Cybersecurity Episode http://managefeed.djaghe.com/ (2016)

FREEDM
SYSTEMS CENTER

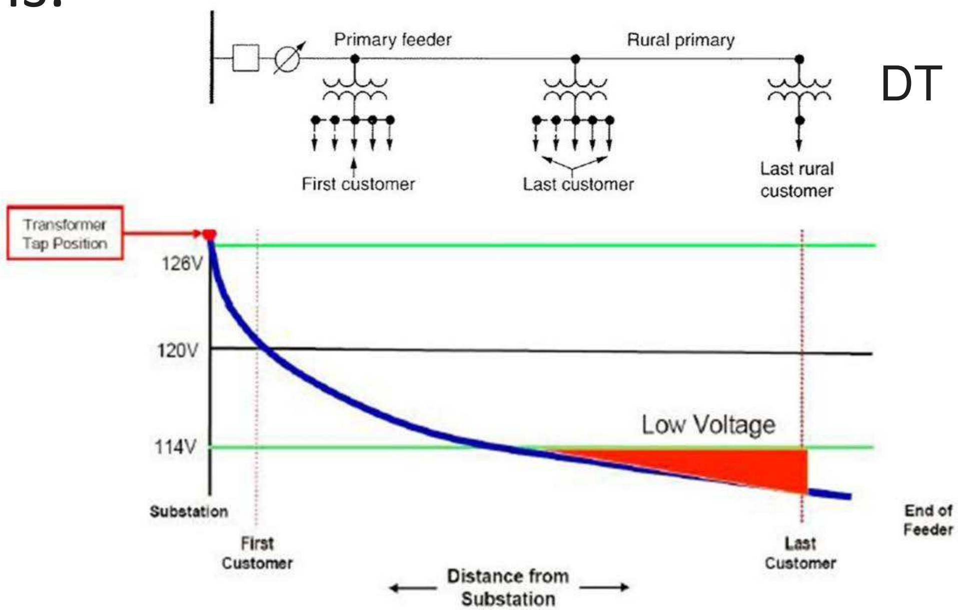
Volt-Var Control (VVC) on FREEDM Systems

Mesut Baran
NC State University

Objectives of VVC

- Primary goal

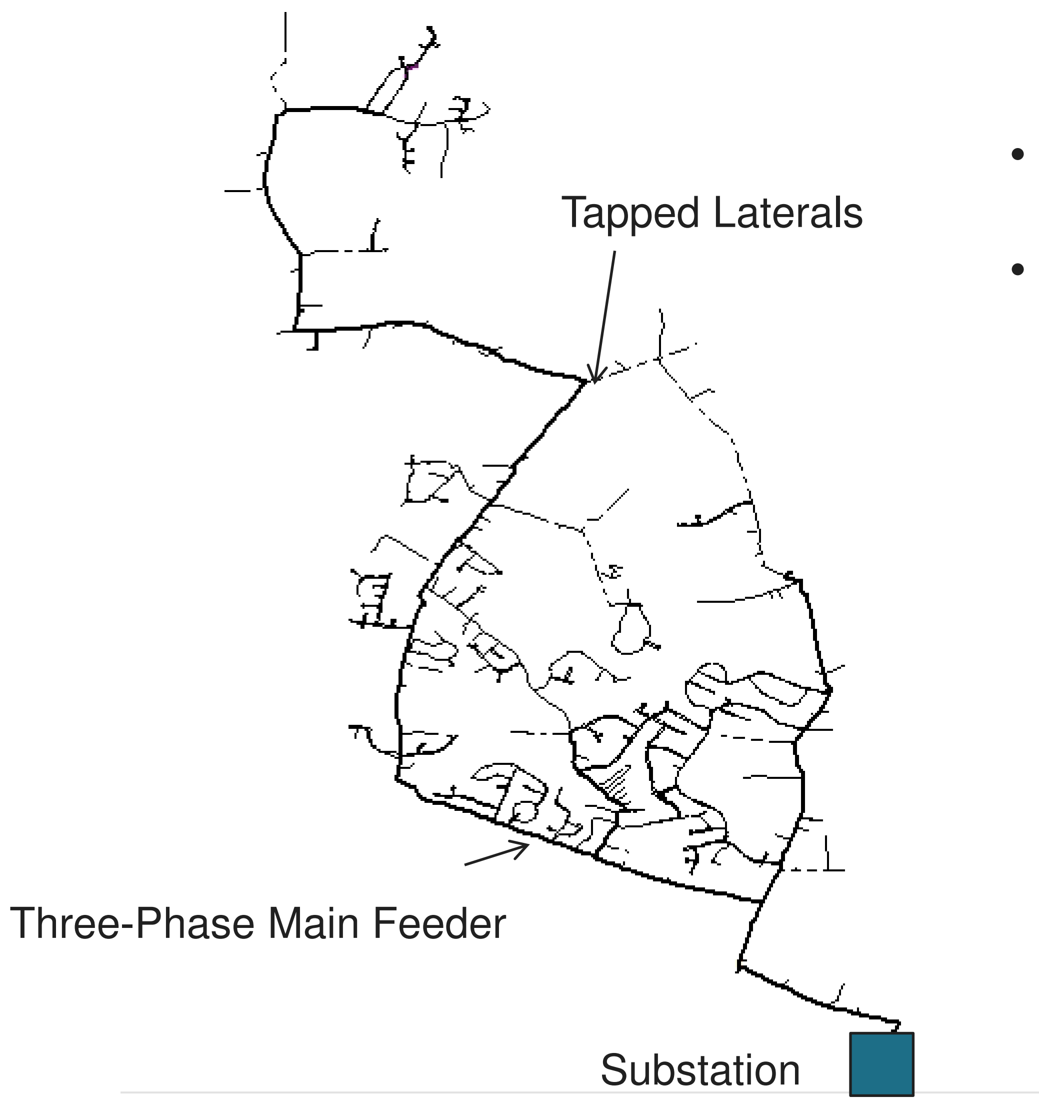
  To maintain the voltages along the distribution feeder within an appropriate range under all operating conditions.



- Secondary goal

  To reduce power loss and energy loss

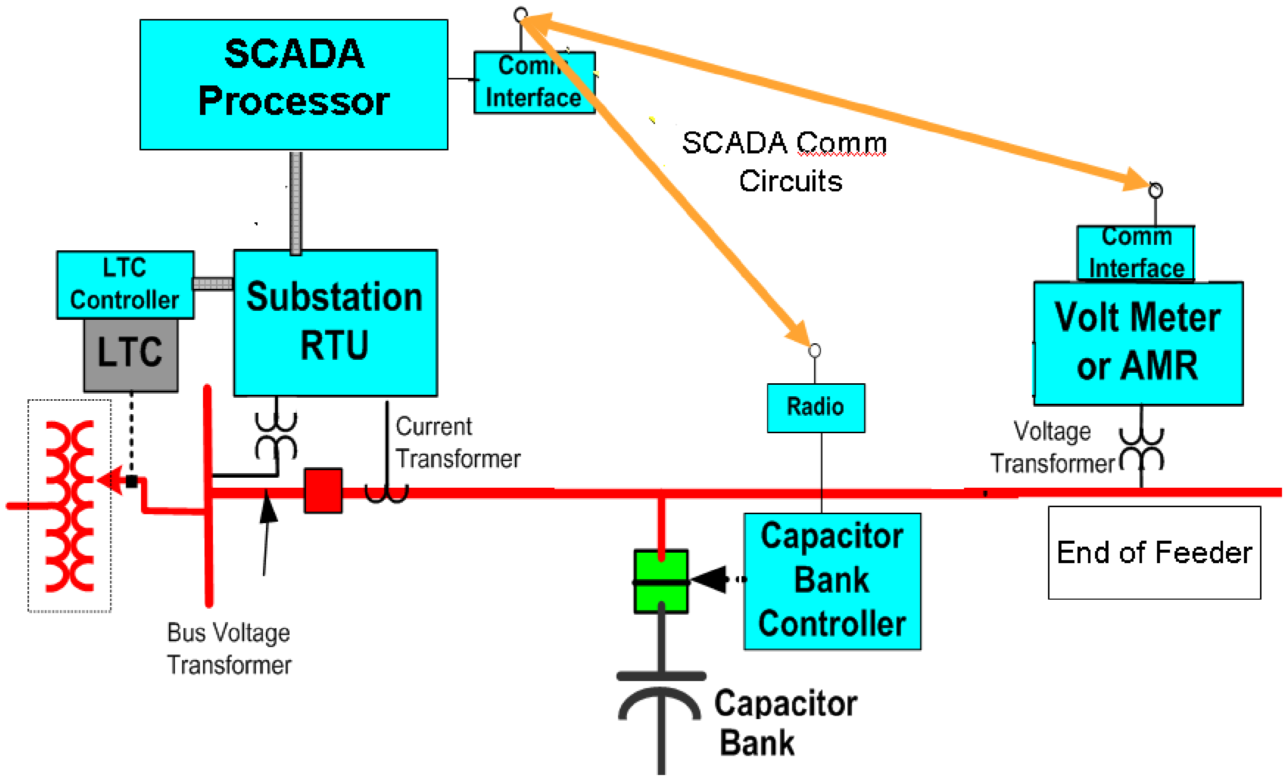
Distribution Feeder Topology



- No of service:
  600-1200 DT
- Total load
  4-6 MW peak (12 kV)

Conventional VVC

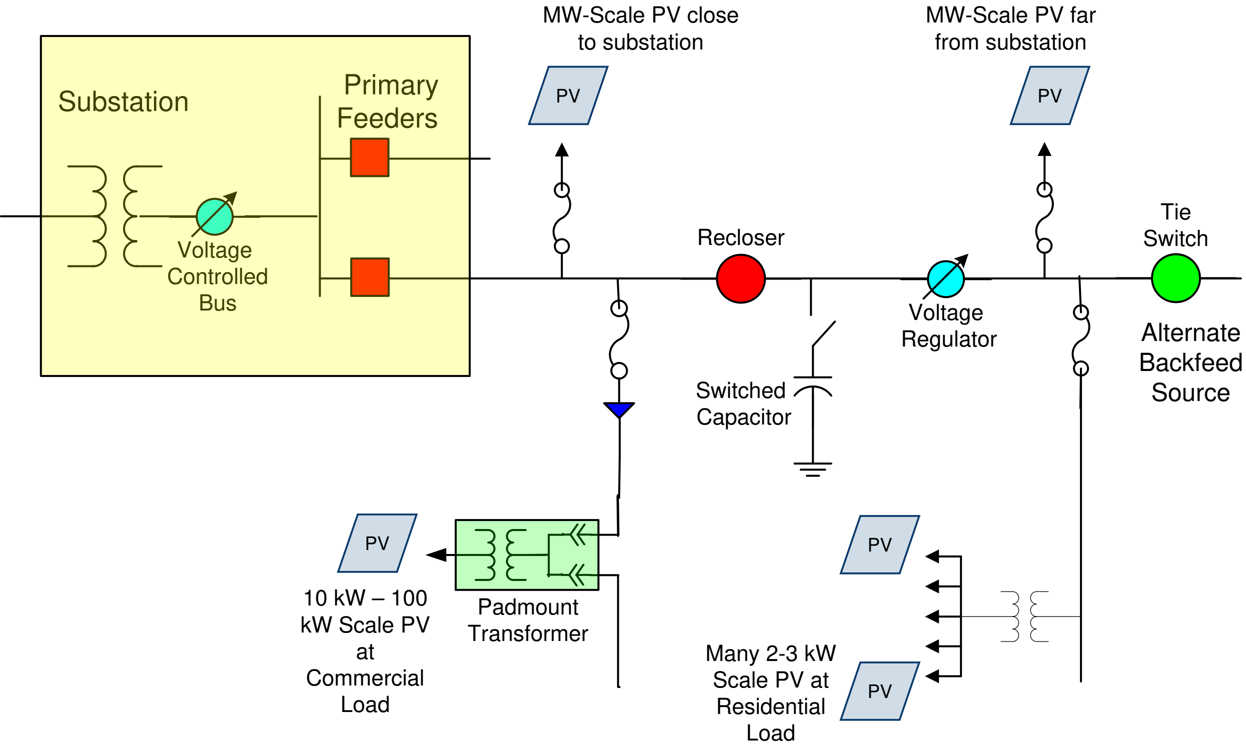
Centralized SCADA based control



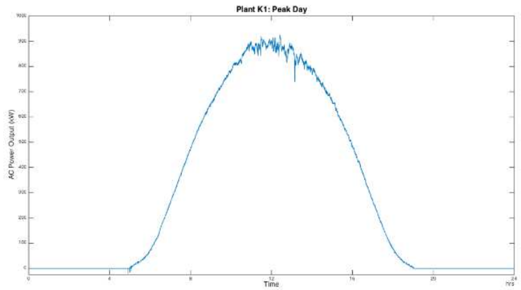
Source: Bob Uliski

- VVC employs simple rules on conventional system
- VVC needs more complex algorithms when DER penetration is high

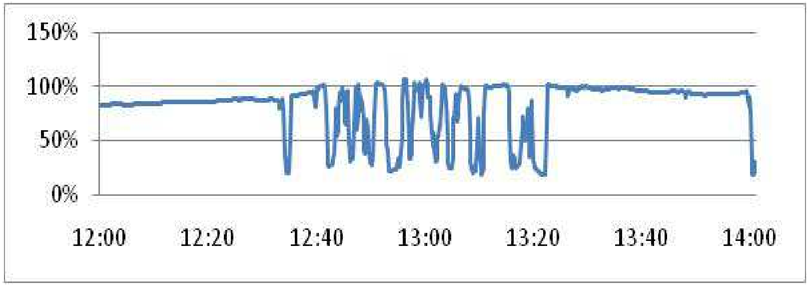
Impact of PV on Voltage



Source: D. Lubkeman



Sunny Day

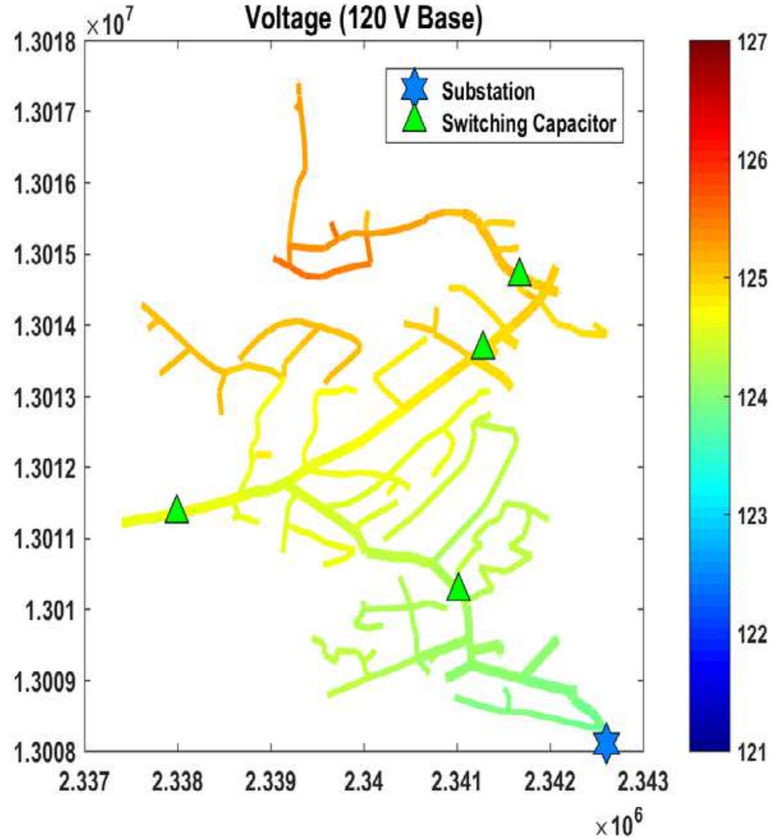


Impact of Cloud Cover

Light Loading With PV

- Light Loading Condition
  - Load: 2.8 MW
  - PV: 6.7 MW
- Simulation Results

Top of the Feeder	-3.9 MW
High Customer Voltage	126.7 V
Low Customer Voltage	123.9 V
Losses	97 kW



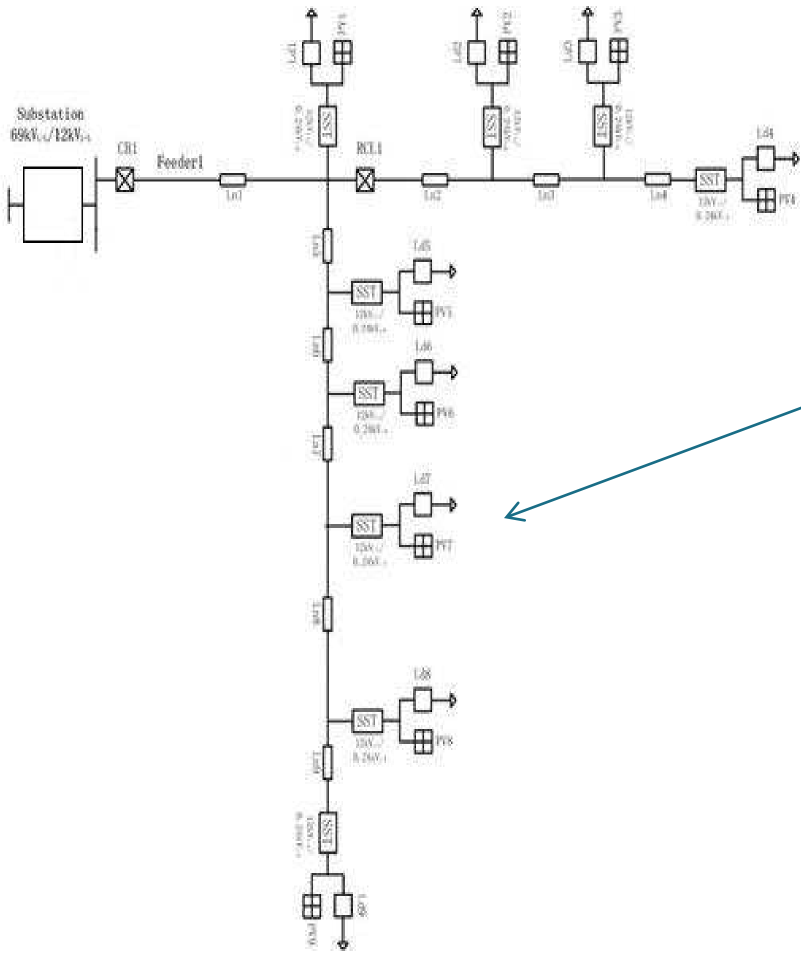
PV is back feeding into the grid.
A little bit increase in losses.
Overvoltage issues!

Source: D. Lubkeman

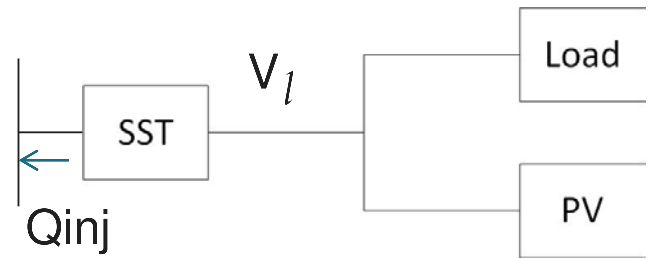
FREEDM SYSTEMS CENTER

FREEDM System

- Feeder with high PV penetration



- SST Replaces DT



- SST VVC capabilities
  - Regulate Secondary V_l
  - reactive power comp, Qinj

SSTs can be used for VVC!

Decentralized VVC on FREEDM systems

- VVC goal: minimize power loss while keeping voltages within limits

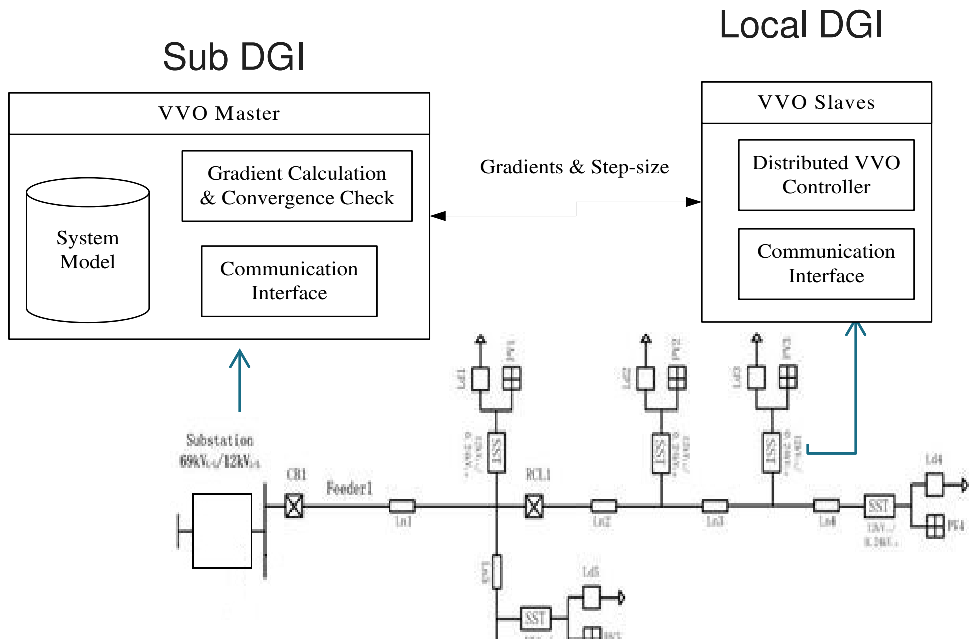
VVC problem : $min \quad P_{loss}(x)$

$s.t.$

- power flow: $g(x, Q_{SST}) = 0$
- volt limits: $V^{min} \leq V \leq V^{max}$
- Qsst limits: $Q_{SST}^{min} \leq Q_{SST} \leq Q_{SST}^{max}$

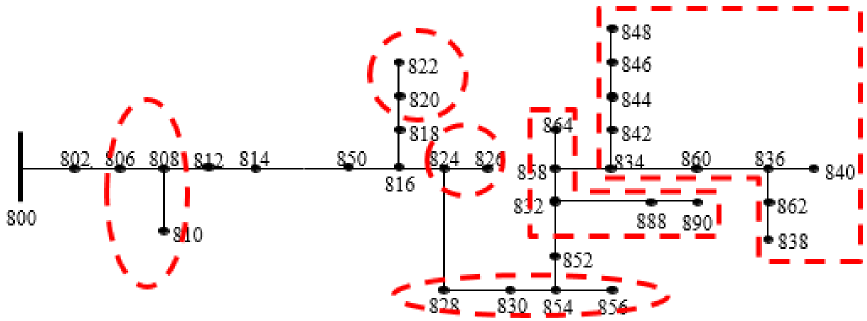
- Decentralized Scheme

  - Master – Slave scheme
  - Gradient based method

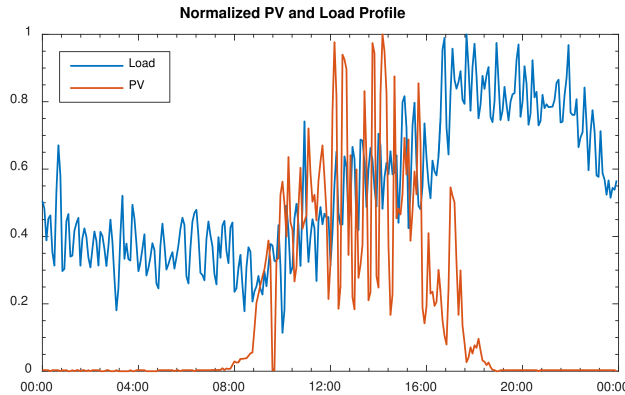


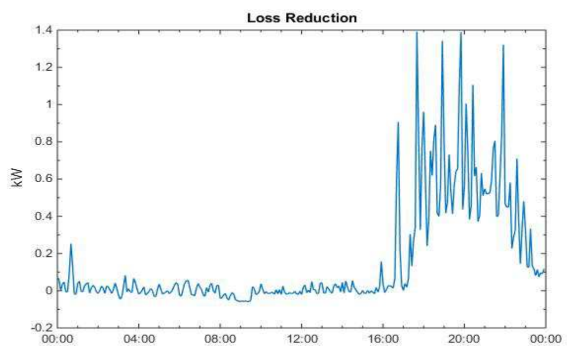
Case Study

Test System

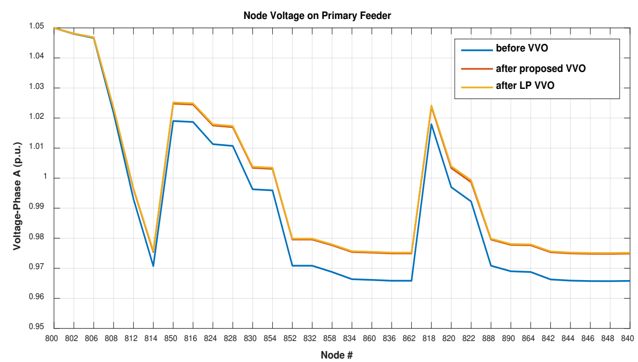


Load and PV profiles

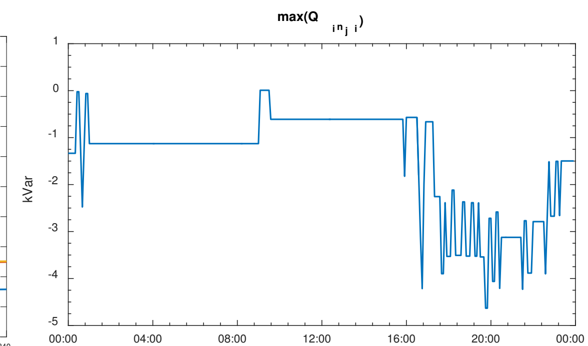




power loss reduction



voltage profile



Qinj from SSTs

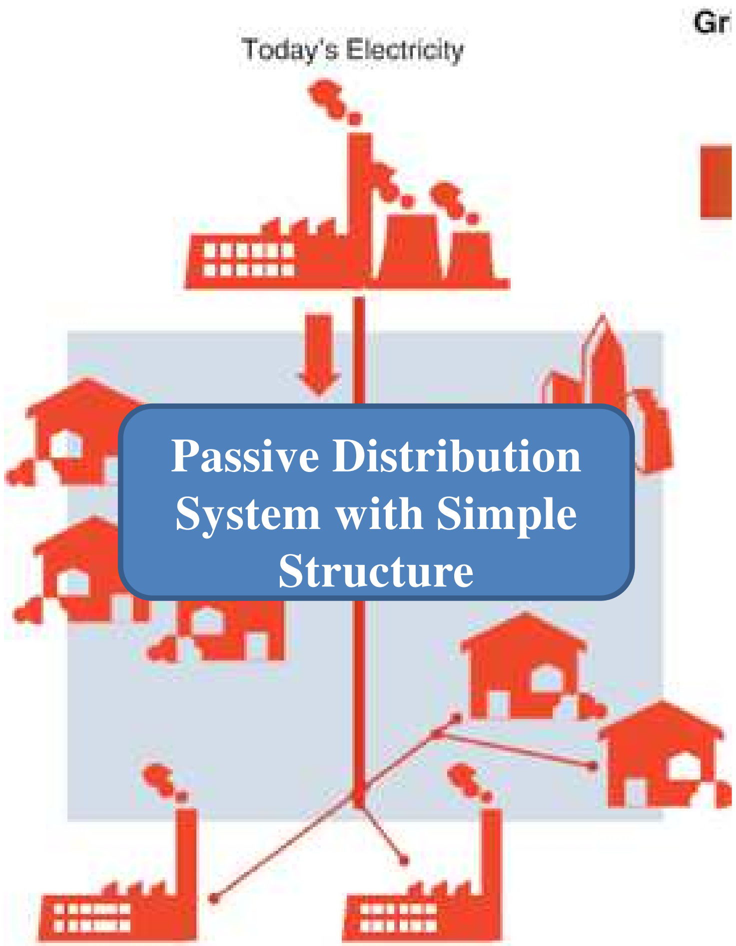
Collaborative Distributed Control with Applications on Smart Micro-Grid Energy Management

Mo-Yuen Chow, Ph.D.

Advanced Diagnosis, Automation, and Control (ADAC) Laboratory
Department of Electrical and Computer Engineering
North Carolina State University
Raleigh, North Carolina
USA

The Grid is Changing…

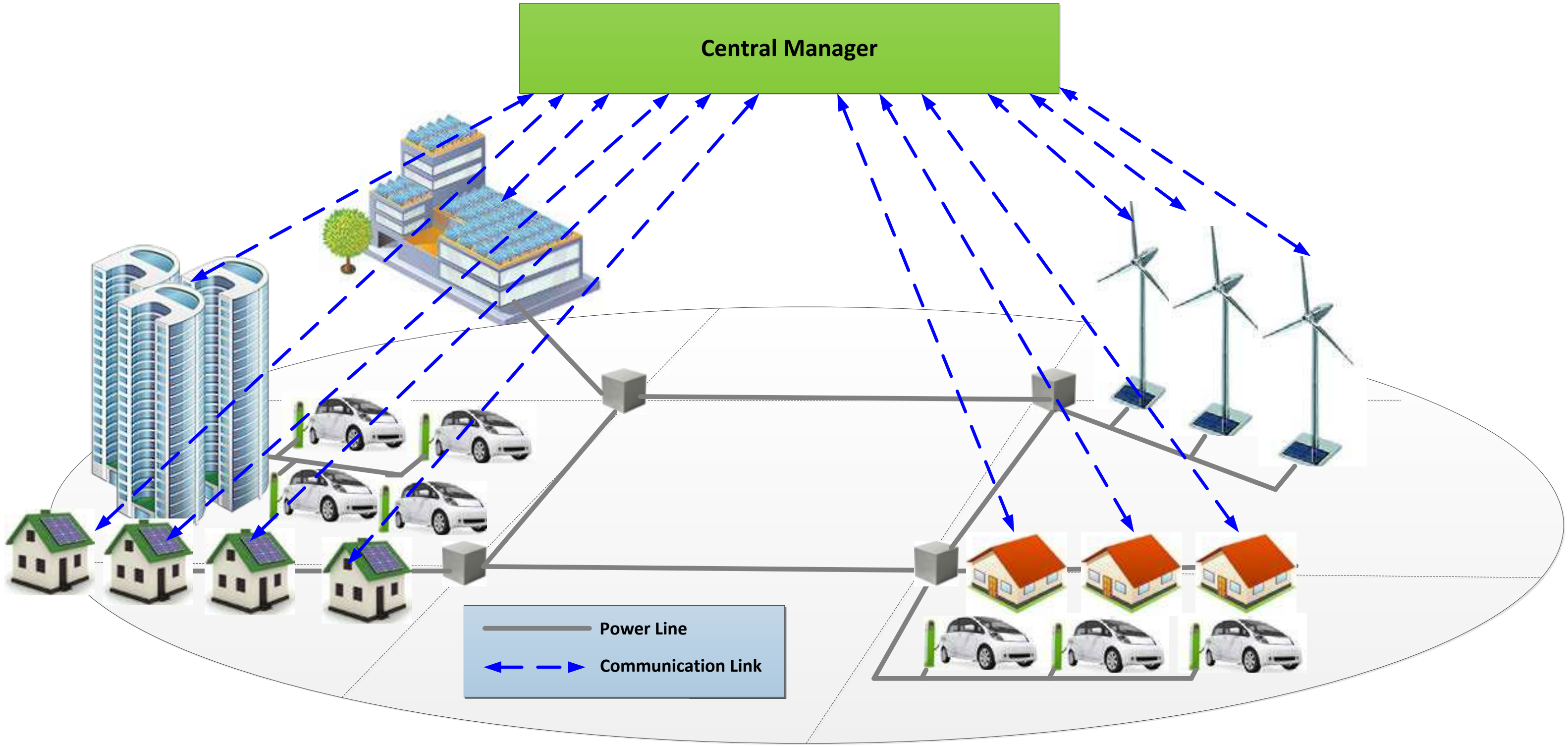
In recent years the grid is changing….



Inter-connected controllable energy devices increase from thousands to millions

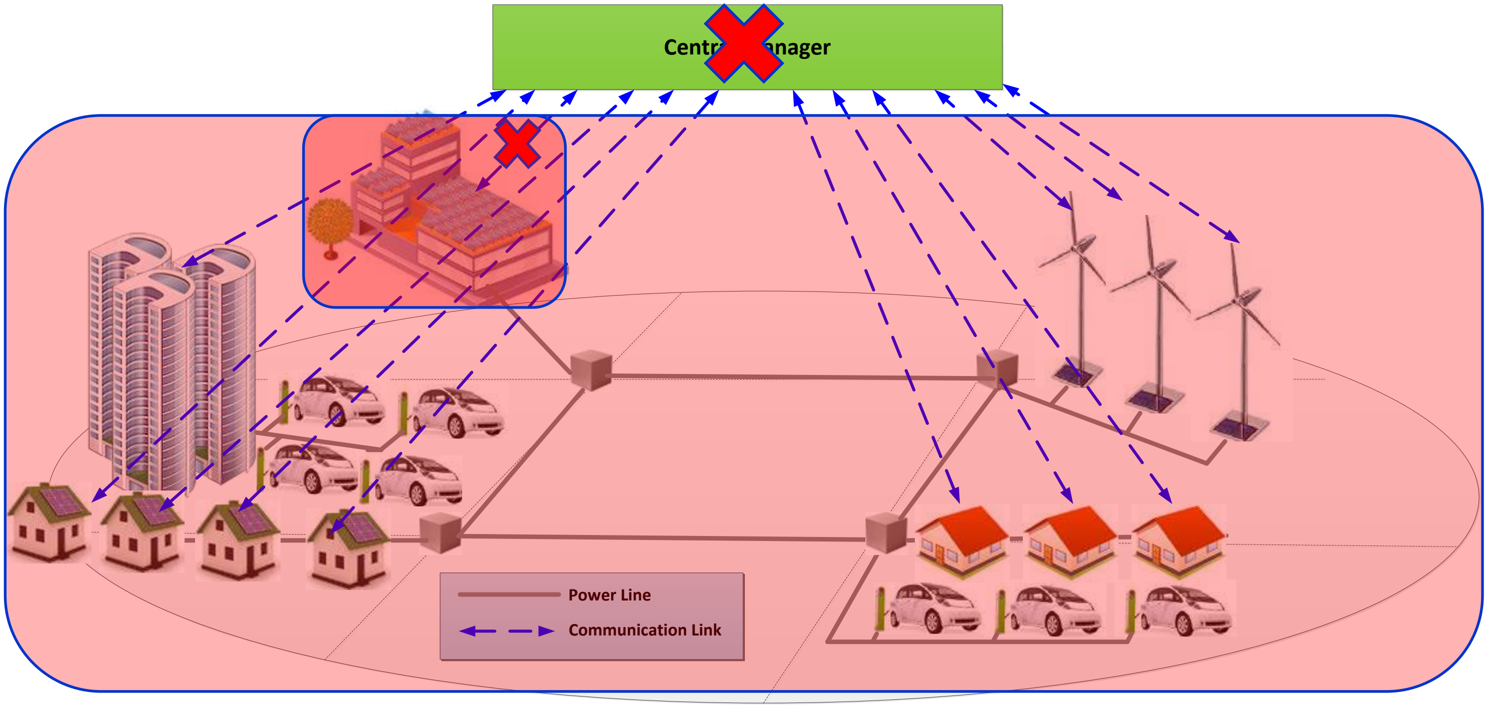
Solution 1: Centralized Approach

- All units send their information regarding their demand, generation, preferences, and specifications to a central manager.
- The central manager uses the information to coordinate the resources and make optimal decisions about each unit.



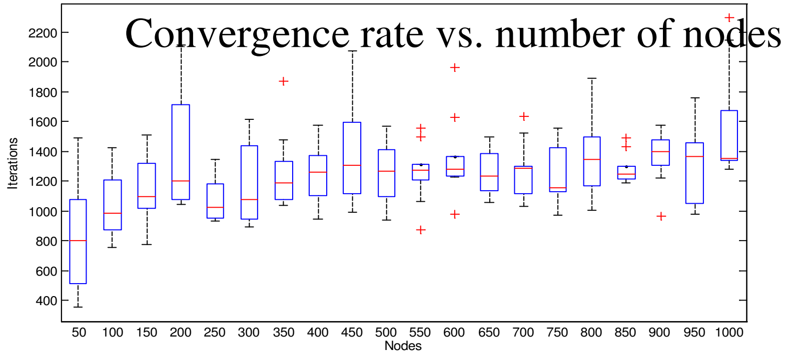
Challenges of Centralized Approach

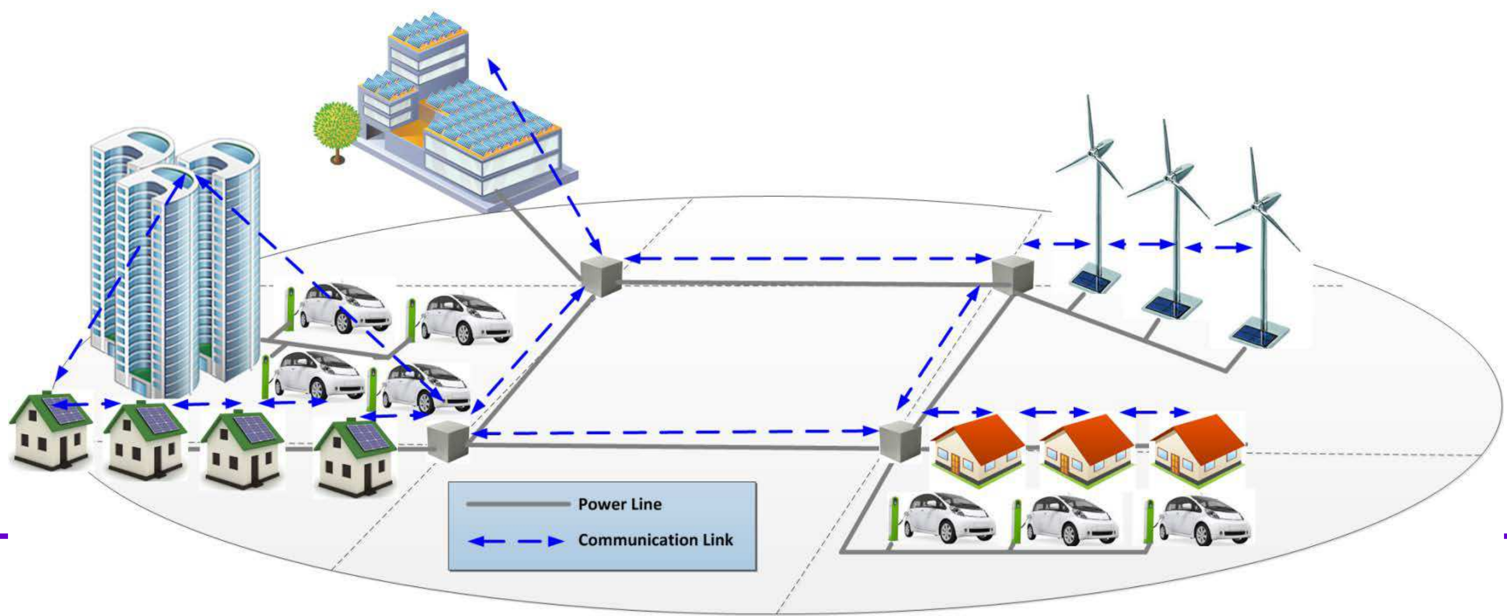
- Not Scalable
- Vulnerability to central point of failure
- Vulnerability to communication link failures
- Global communication requirement



Solution 2: Distributed Approach

- Each unit in the system exchanges information with its neighbors, makes local decisions, and iteratively updates its decisions.
- Advantages:
  - Scalable
  - Robust to central point of failure
  - Robust to communication failures
  - Requires only local communication capability

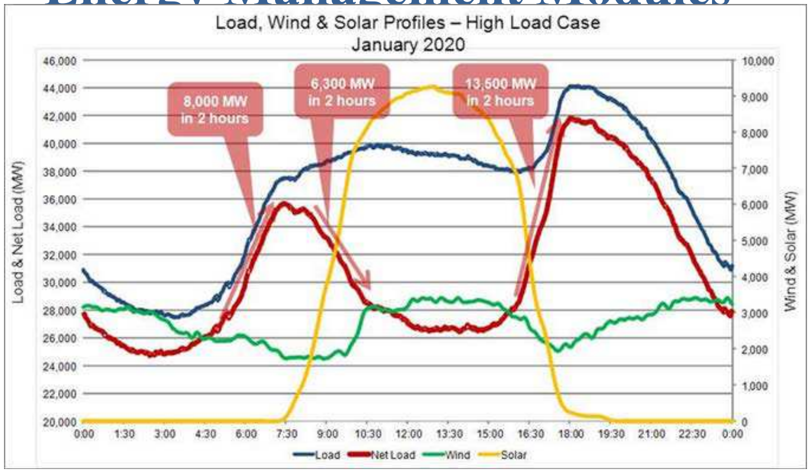


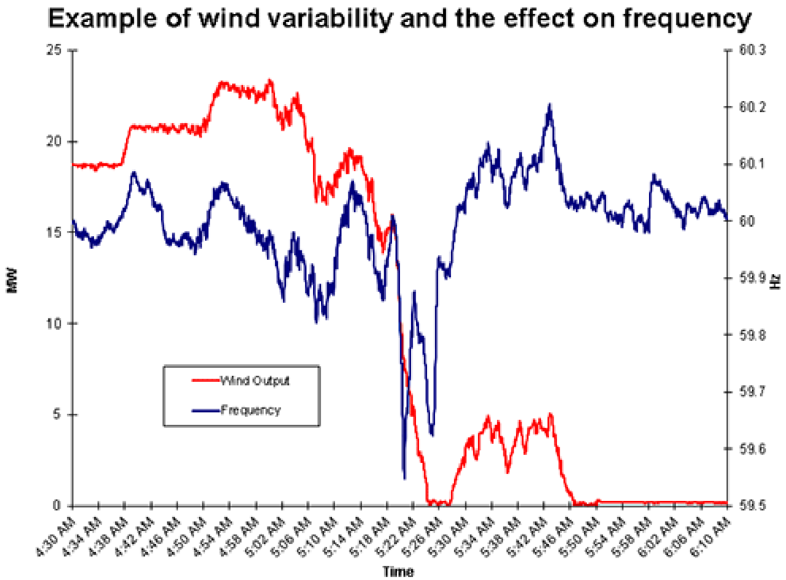


Intermittence and Uncertainties

- Energy Providers
  - Distributed generation
    - Renewable resources are geographically dispersed
  - Weather/time dependent
    - Steep ramp up/ramp down rate
  - Intermittency
    - Frequency regulation and load balancing
  - …
- Customers
  - Load profile
  - Utility customer billing
  - Reverse Power flow
  - …

Energy Management Modules





Cooperative Distributed Energy Management

NC STATE UNIVERSITY

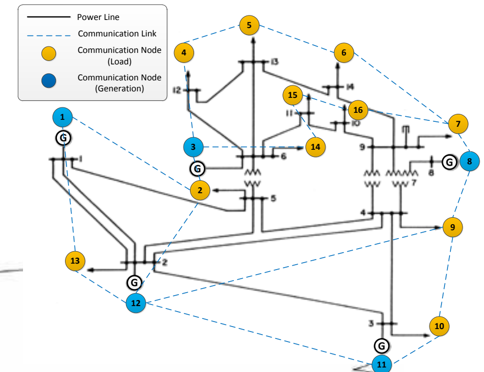
ADAC

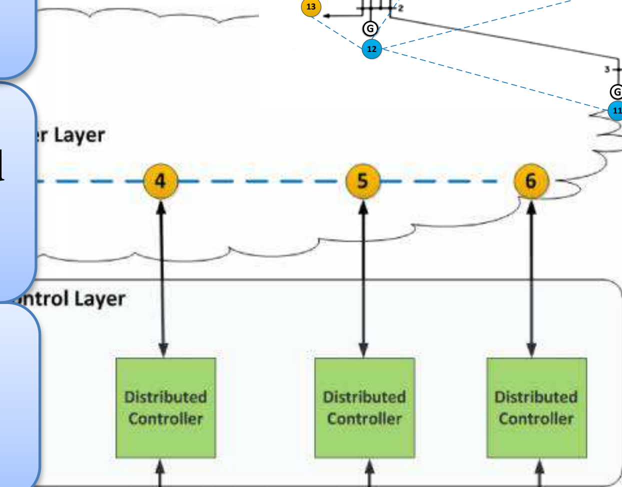
ADAC's Distributed Technologies for Energy Management:

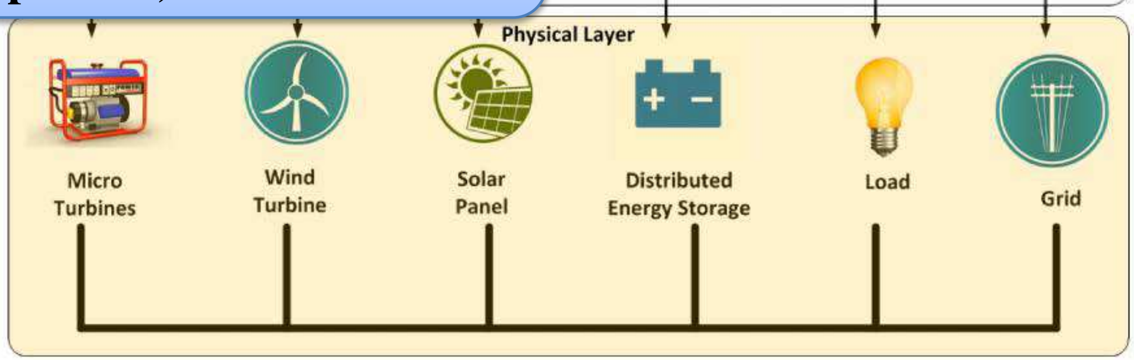
Incremental Cost Consensus (ICC) Algorithm for Distributed Economic Dispatch (2009-2012)

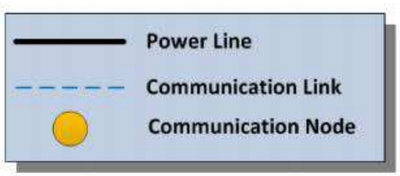
Incremental Welfare Consensus (IWC) Algorithm for Distributed Demand Response and Generation Management (2012-2014)

Cooperative Distributed Energy Scheduling (CoDES) for Storage Devices and Renewables (2014 – present)







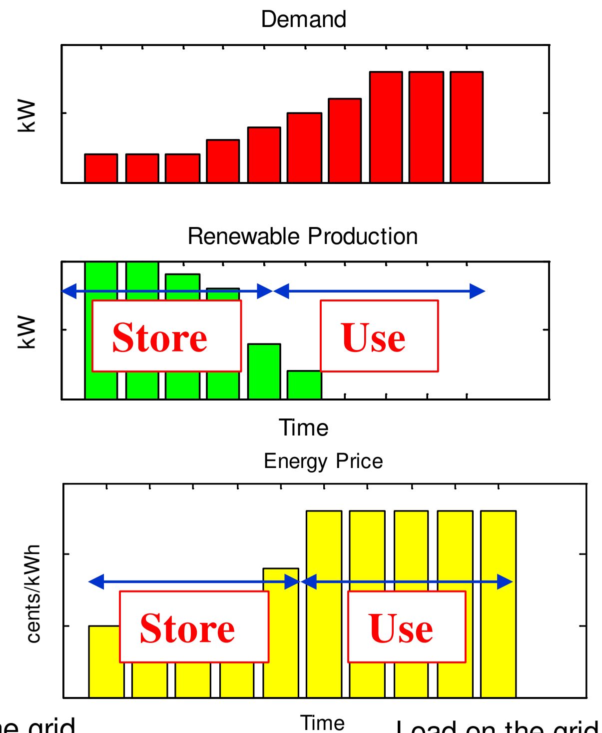


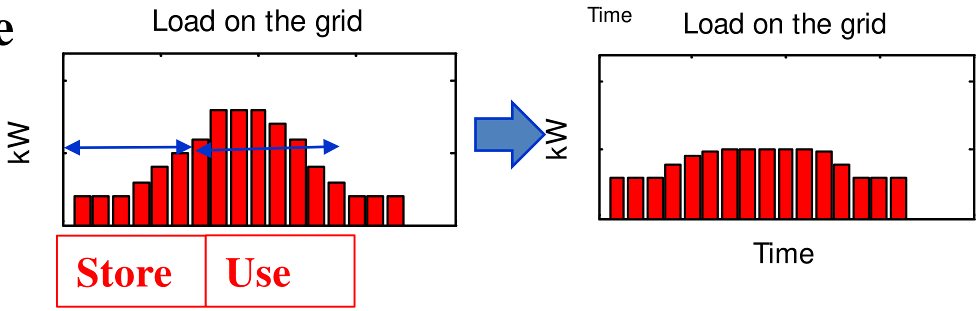
Why scheduling for storage devices is important ?

- **Improves dispatchability of renewables:** Store the renewable energy in time of production and use it in time of need.

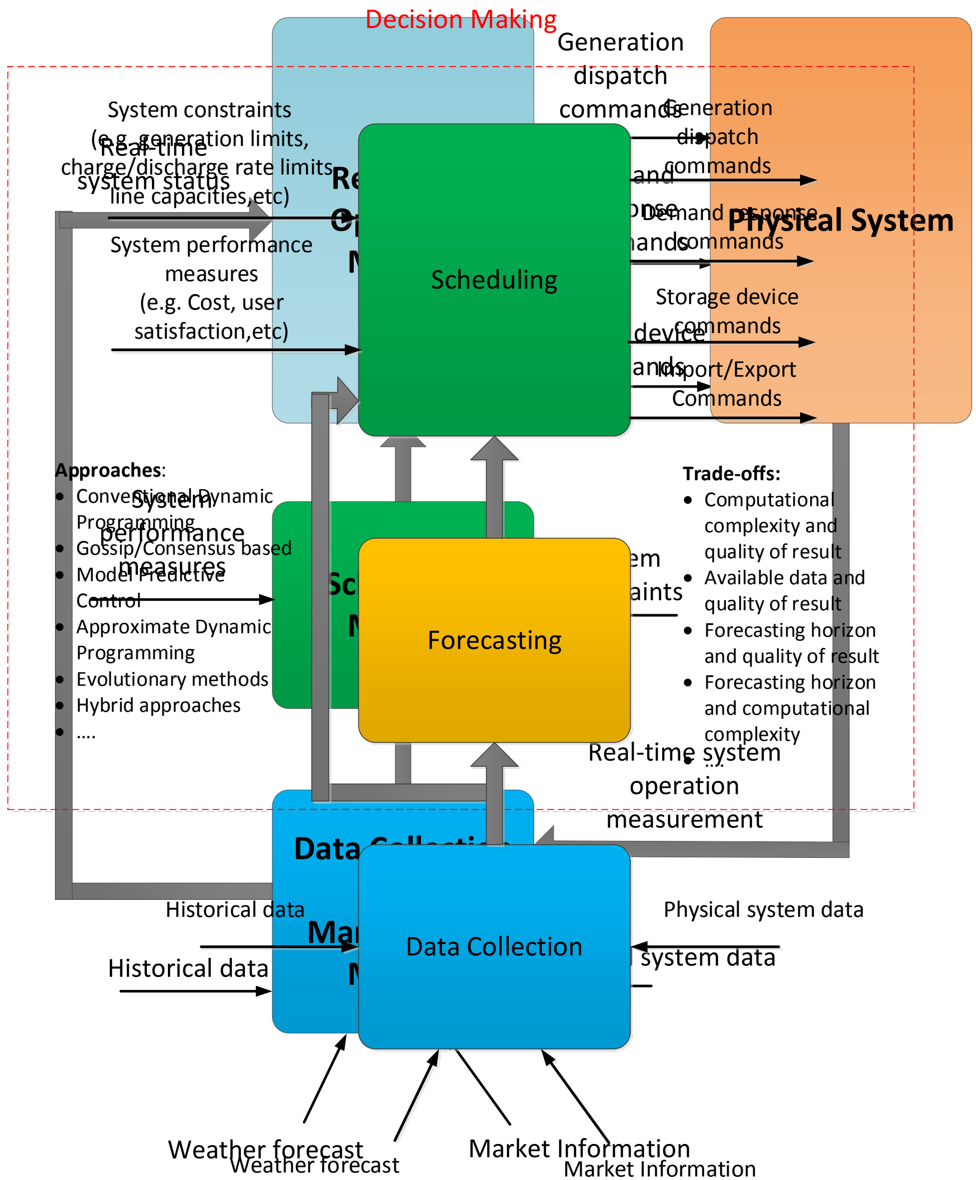
- **Reduce power bill:** Store energy when it is cheap and use it when it is expensive.

- **Reduce the peak demand on the grid:** store the energy during off-peak hours and use it during on peak hours





Cooperative Distributed Energy Scheduling Framework



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Cooperative Distributed Energy Scheduling (CoDES) Algorithm

ADAC

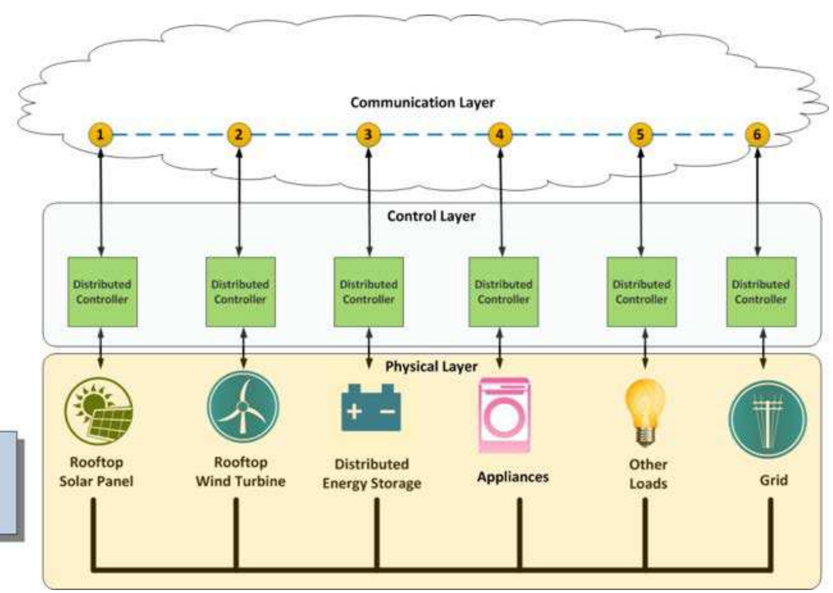
Objective: Schedule energy generation, and energy storage in a distributed way from now to future to optimize the specified performance metrics.

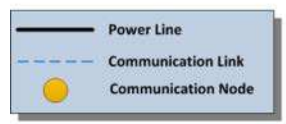
$$\min_{\{P_i(k):k=1,\ldots,T,\, i\in G_d \cup D_d\}} \left(J = \sum_{k=1}^{T} \gamma^{k-1} C(k) \right)$$

T : Horizon of scheduling

$C(k)$: Cost at time step k (Generation Cost, Power Loss, etc.)

$0 \le \gamma \le 1$: Discount factor for future performance





Constraints:

1) Power Balance Constraint

$$\forall k = 1,\ldots,T : \sum_{i\in G_d \cup G_{nd}} P_i(k) = \sum_{i\in D_d \cup D_{nd}} P_i(k) + P_{loss}$$

2) Power Rating Constraint

$$\forall k = 1,\ldots,T, \forall i \in G_d \cup D_d :$$

$$P_{i,\min} \le P_i(k) \le P_{i,\max}$$

3) Energy Constraint (for Storage Devices)

$$\forall i \in B, t \in \{1,\ldots,T\} :$$

$$Cap_i \left(1 - SoC_{i0}\right) \le \sum_{k=1}^{t} P_i(k)\Delta t \le Cap_i SoC_{i0}$$

D_d	Set of indices of dispatchable demand units
D_{nd}	Set of indices of non-dispatchable demand units
G_d	Set of indices of dispatchable generation units
G_{nd}	Set of indices of non-dispatchable generation units
B	Set of indices of storage devices ($B \subseteq G_d$)
$SoC_i(k)$	State of charge of the storage device with index i at time step k
Cap_i	Capacity of the storage device with index i (kWh)
Δt	Length of scheduling time step

N. Rahbari-Asr, Y. Zhang and M. Y. Chow, "Consensus-based distributed scheduling for cooperative operation of distributed energy resources and storage devices in smart grids," in *IET Generation, Transmission & Distribution*, vol. 10, no. 5, pp. 1268-1277, 2016.

CoDES v.s. Centralized approach

Augmented Lagrangian

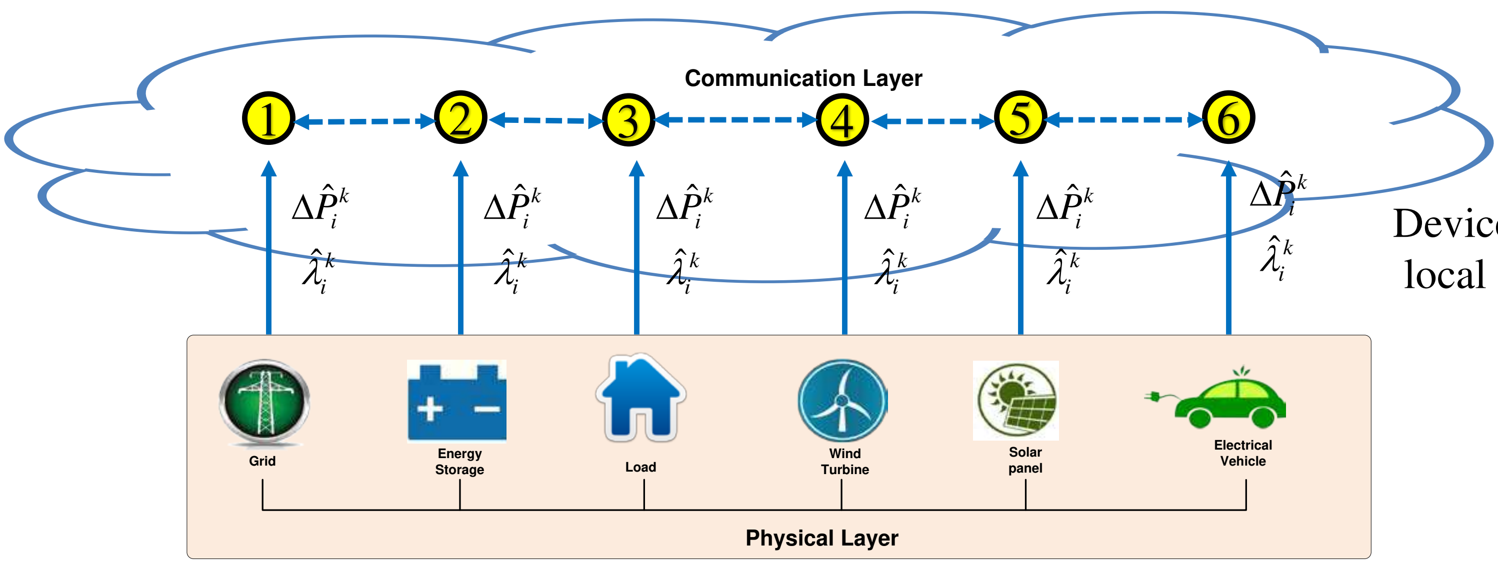
Add KKT multipliers, constraints and penalty terms to the objective function

Primal-dual Decomposition

Parallel calculation, not fully distributed

Consensus Algorithm

Each node coordinates with neighbors to estimate global information



Devices exchange local estimations

N. Rahbari-Asr and M. Y. Chow, " Incremental Welfare Consensus Algorithm for Cooperative Distributed Generation/Demand Response in Smart Grid," in *IEEE Transactions on Industrial Informatics*, vol. 10, no. 3, pp. 1907-1916, Aug. 2014.

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Cooperative Distributed Scheduling

ADAC

Lagrangian of the problem

$$L=\sum_{t=1}^{T}\gamma^{t-1}\left(p(t)P_{i,grid}(t)\Delta t+\sum_{i\in G}\left(a_iP_{i,G}(t)^2+b_iP_{i,G}(t)+c_i\right)\Delta t\right)$$

$$+\sum_{t=1}^{T}\lambda(t)\left(\sum_{i\in D}P_{i,D}(t)-\sum_{i\in B}P_{i,B}(t)-\sum_{i\in R}P_{i,R}(t)-P_{i,grid}(t)\right)$$

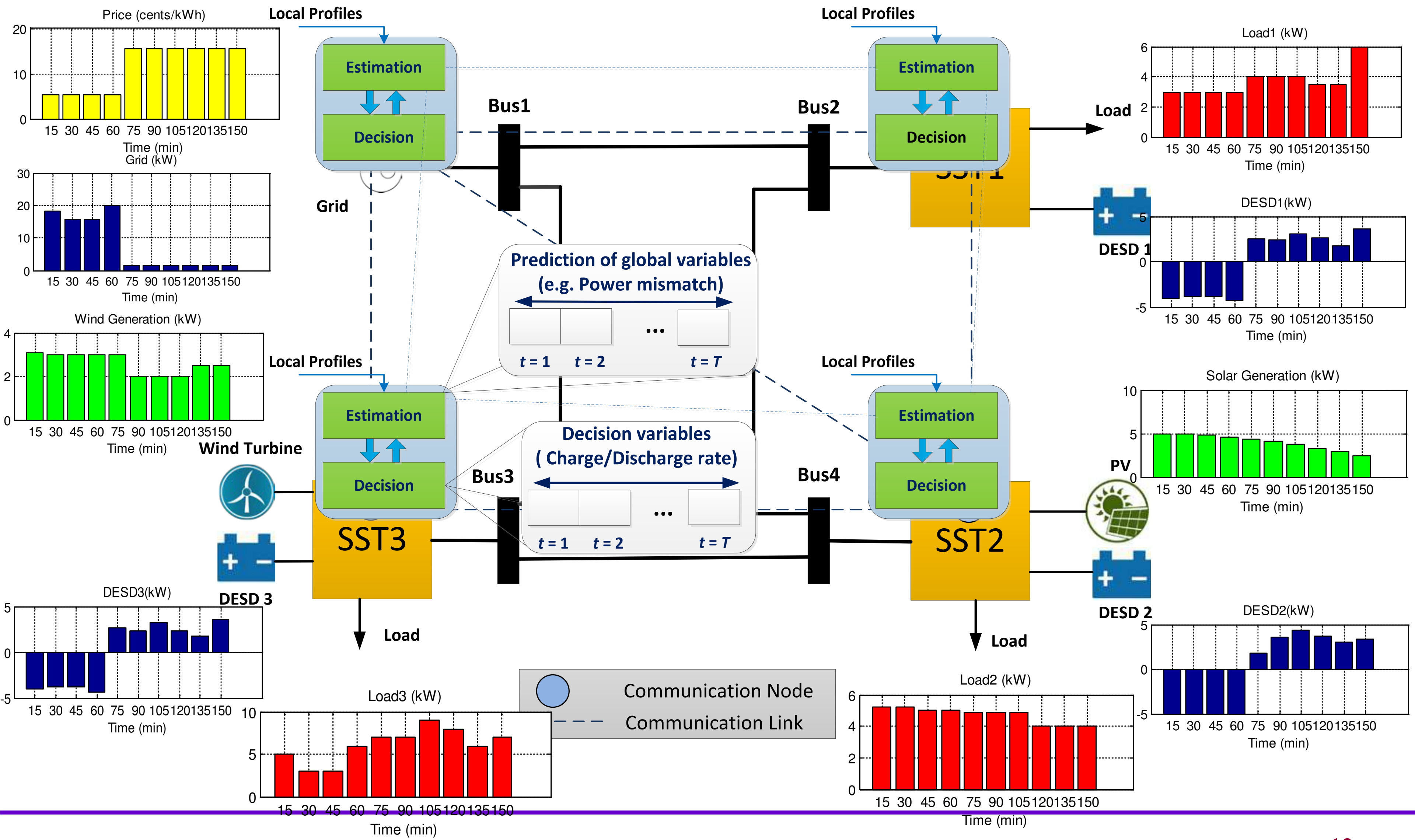
$$+\sum_{t=1}^{T}\sum_{i\in B}\mu_{1i}(t)\left(E_{i0}-E_{i,full}-\sum_{s=1}^{t}P_{i,B}(s)\Delta t\right)+\sum_{t=1}^{T}\sum_{i\in B}\mu_{2i}(t)\left(\sum_{s=1}^{t}P_{i,B}(s)\Delta t-E_{i0}+E_{i\min}\right)$$

$$+\frac{\rho}{2}\sum_{t=1}^{T}\left(\sum_{i\in D}P_{i,D}(t)-\sum_{i\in B}P_{i,B}(t)-\sum_{i\in R}P_{i,R}(t)-P_{i,grid}(t)\right)^2$$

$$+\frac{\rho}{2}\sum_{t=1}^{T}\sum_{i\in B}\left(\left[E_{i0}-E_{i,full}-\sum_{s=1}^{t}P_{i,B}(s)\Delta t\right]_{[0,\infty]}\right)^2$$

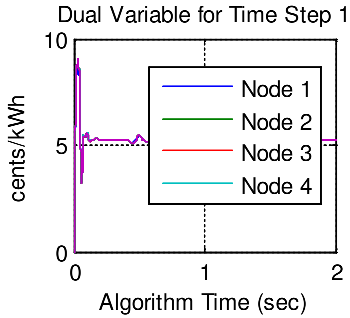
$$+\frac{\rho}{2}\sum_{t=1}^{T}\sum_{i\in B}\left(\left[\sum_{s=1}^{t}P_{i,B}(s)\Delta t-E_{i0}+E_{i\min}\right]_{[0,\infty]}\right)^2$$

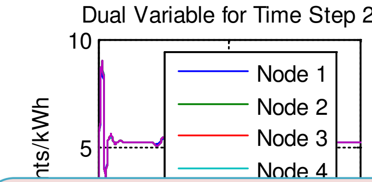
Distributed Energy Scheduling



Results

Convergence of estimations (global variable estimations)





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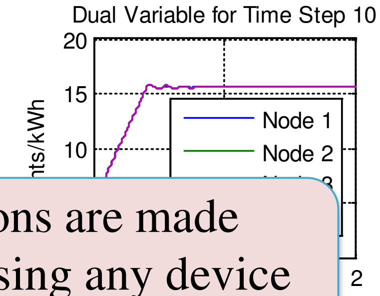
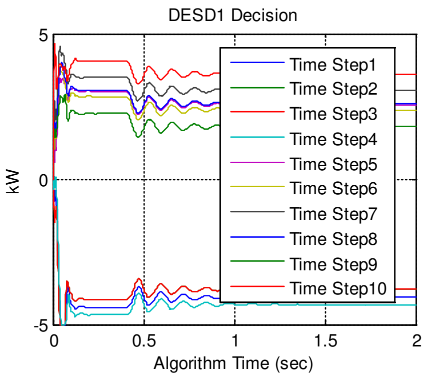
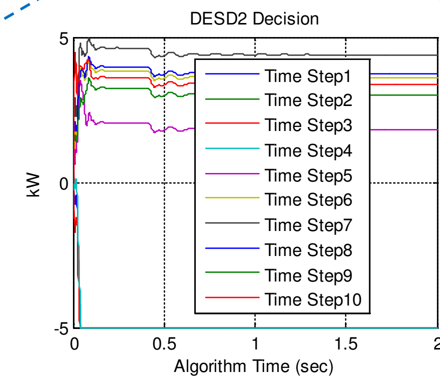
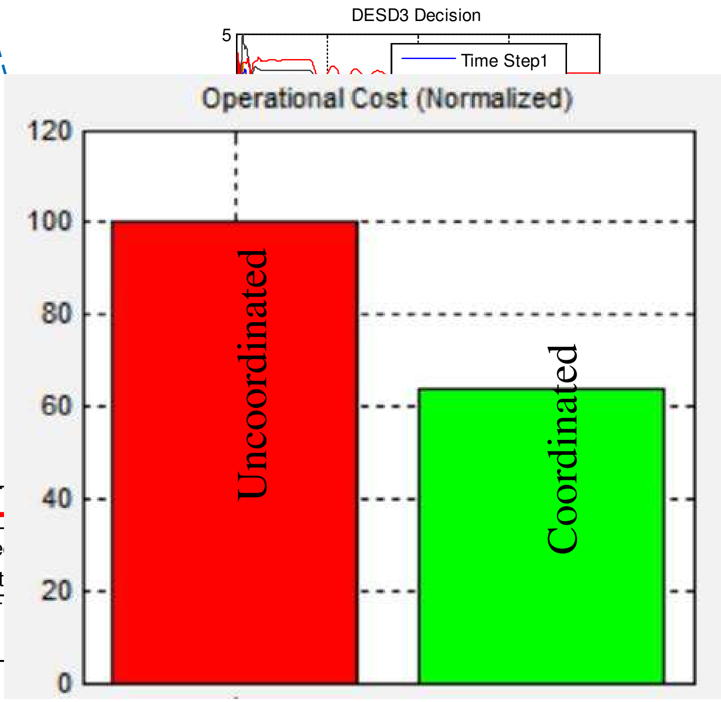


As estimations converge, optimal decisions are made without a control center and without disclosing any device specific information

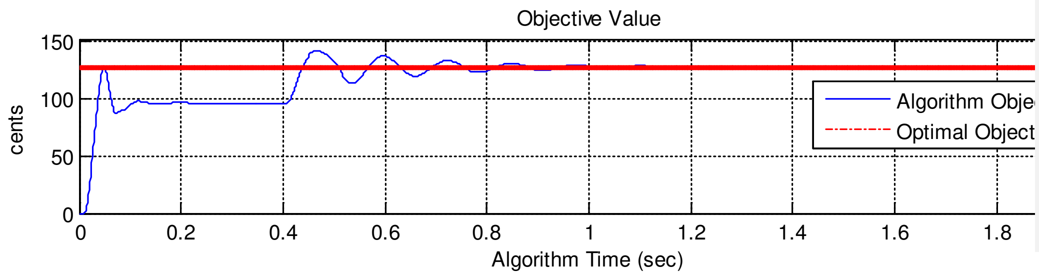
Convergence of decisions







Convergence of objective value



N. Rahbari-Asr, Y. Zhang and M. Y. Chow, "Cooperative distributed scheduling for storage devices in microgrids using dynamic KKT multipliers and consensus networks," *2015 IEEE Power and Energy Society General Meeting*, July 26-30, 2015, Denver, CO, USA.

Selected Recent Related Publications and Patents

- Recent CoDES related papers (since 2015)

[B1] W. Zeng and M.Y. Chow, "Resilient Distributed Control in Cyber-Physical Energy Systems," *Cyber Security for Industrial Control Systems: From the Viewpoint of Close-Loop*, CRC Press, 2016

[J1] Jie Duan, Wente Zeng and Mo-Yuen. Chow, "Resilient Distributed DC Optimal Power Flow Against Data Integrity Attack", *in IEEE Transaction on Smart Grid*, under 2nd review

[J2] Wente Zeng; Yuan Zhang and Mo-Yuen Chow, "Resilient Distributed Energy Management Subject to Unexpected Misbehaving Generation Units," *in IEEE Transactions on Industrial Informatics* , 2016, in press.

[J3] Y. Zhang, N. Rahbari-Asr, J. Duan and M. Y. Chow, "Day-Ahead Smart Grid Cooperative Distributed Energy Scheduling With Renewable and Storage Integration," *in IEEE Transactions on Sustainable Energy*, vol. 7, no. 4, pp. 1739-1748, Oct. 2016.

[J4] N. Rahbari-Asr, Y. Zhang and M. Y. Chow, "Consensus-based distributed scheduling for cooperative operation of distributed energy resources and storage devices in smart grids," *in IET Generation, Transmission & Distribution*, vol. 10, no. 5, pp. 1268-1277, 2016.

[J5] Yuan Zhang, Navid Rahbari-Asr, and Mo-Yuen Chow, "A Robust Distributed System Incremental Cost Estimation Algorithm for Smart Grid Economic Dispatch with Communications Information Losses", *Journal of Network and Control Applications, 2015*

[C1] J. Duan; W. Zeng and M.Y. Chow, "Attack Detection and Mitigation for Resilient Distributed DC Optimal Power Flow Algorithm in the IoT Environment," *in proceedings of 2016 IEEE International Symposium on Industrial Electronics (ISIE).*

[C2] J. Duan; W. Zeng and M.Y. Chow, "An Attack-Resilient Distributed DC Optimal Power Flow Algorithm via Neighborhood Monitoring," in *proceedings of 2016 IEEE Power & Energy Society General Meeting*.

[C3] J. Duan; W. Zeng and M.Y. Chow, "Economic impact of data integrity attacks on distributed DC optimal power flow algorithm," *in North American Power Symposium (NAPS)*, 2015 , vol., no., pp.1-7, 4-6 Oct. 2015.

[C4] W. Zeng, Y. Zhang and M.Y. Chow, "A resilient distributed energy management algorithm for economic dispatch in the presence of misbehaving generation units," *Resilience Week (RWS),* 2015, Philadelphia, PA, 2015, pp. 1-5.

[C5] Y. Zhang, N. Rahbari-Asr, and M.Y. Chow, "Online Convergence Factor Tuning for Robust Cooperative Distributed Economic Dispatch", in *proceedings of 2015 IEEE Power and Energy Society General Meeting*, vol., no., pp.1-5, 26-30 July 2015, Denver, CO, USA.

[C6] N. Rahbari-Asr, Y. Zhang , and M.Y. Chow, "Cooperative Distributed Scheduling for Storage Devices in Microgrids using Dynamic KKT Multipliers and Consensus Networks", in *proceedings of 2015 IEEE Power and Energy Society General Meeting*, July 26-30, 2015, Denver, CO, USA.

Thank you!