# Challenges and Opportunities to Apply Distributed Technologies for Managing a Modern Electrical Grid

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NSIF Workshop: Frontiers in Distributed Optimization & Control of Sustainable Power Systems
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**Imagination at work.**

GE + ALSTOM

Over 200 years

combined experience in providing advanced energy solutions

# GE Grid Solutions

Grid Solutions, a GE and Alstom joint venture, is serving customers globally with over 20,000 employees in 80 countries. Grid Solutions equips 90% of power utilities worldwide to bring power reliably and efficiently **from the point of generation to end power consumers**.

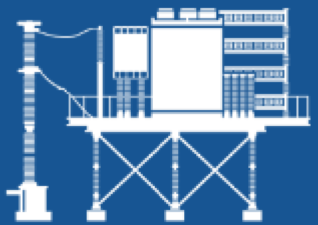
Helping to meet growing energy demands

Improving grid resiliency and energy efficiency

Upgrading and digitizing aging infrastructure

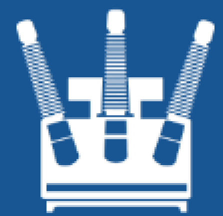
Enabling renewables and a diversified energy mix

# A Key Element of Grid Solutions



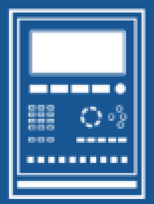
## Power Electronics

High Voltage DC
Flexible AC Transmission Systems
Reactive Power Compensation
Energy Storage



## HV Equipment

Power Transformers
Gas Insulated Substation
Air Insulated Substation
Capacitors & Voltage Regulators



## Grid Automation

Protection & Control
Substation Automation
Communications
Monitoring & Diagnostics

## Software Solutions

Distribution & Outage Management
Energy Management
Market Management
Geospatial & Mobile Solutions
Gas & Pipeline Management

## Projects & Services

Turnkey Projects & Consulting
Electric Balance of Plant
High Voltage Substations
Maintenance & Asset Management

# Agenda

Industry challenges, needs and transformation

Areas of opportunities to apply distributed optimization

- Wide-area management system (WAMS)
- Market-based deep demand response (DR) management
- Volt-var optimization (VVO) with distributed energy resources

Other distributed technologies

Final remarks

# Industry Challenges

Retiring
**Workforce**

**Big Data**
Meters, PMU, …

Critical mission
**Communication**

**Cyber-Security**

**New Electrical Equipment**
(FACTS, HVDC, …)

**Sustainability**
Renewable deployment & $CO_2$ free energy
New Generation Mix

**Business Model Change**
New regulation

**Environment**
Public Safety
Storm Restoration GHG

**IT Architecture & Services**
Control Room

**System Dynamics**
Operating near to true real time limits

**System Scalability**
From energy cluster to large Interconnected grids

# Smart Grid Challenges

- Global energy & environmental movement
  - Emphasis on low carbon energy mix and Demand Response (DR)
  - Increasing presence of renewable power
  - Increasing presence of Distributed Energy Resources (DER), storage, PHEV
- Smart Grid Transformation
  - From centralized to more decentralized generation and control architecture
  - Bi-directional flow of energy (“Prosumers”)
  - Automation of distribution management
  - Retail electricity market and gas/electricity market coordination
  - Situational awareness and grid visibility/predictability is becoming more critical
  - New applications/services based on new equipment and more active network
  - Optimization: larger footprint and deeper in the hierarchy
  - Operational challenges: Uncertainty management
- Unrelenting complexity in business & technical decision process
  - Smart devices/resources with distributed intelligence
  - Coordinated decision making
  - Big Data

# Four V's of Big Data for Smart Grid


Source: SAP

## Volume (Scale of data)

- Technological advances (PMU, AMI, IDMS)
- New and more devices (Smart appliances)

## Velocity (Speed of data)

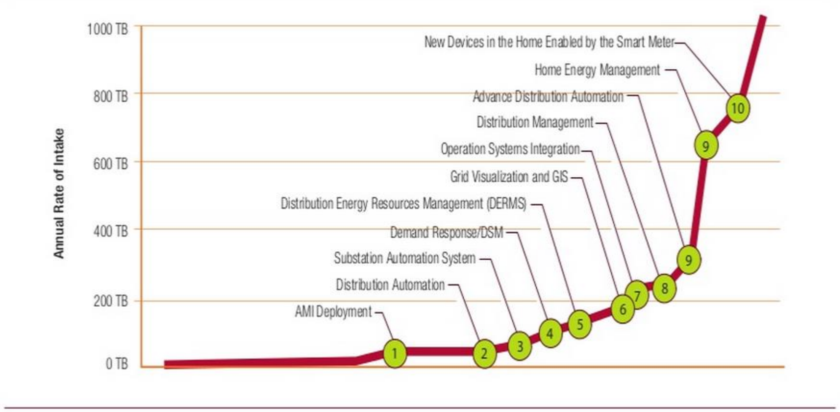
- Analysis of streaming data from IED, PMU
- Real-time control and decision-making

## Variety (Forms of data)

- Handling of all forms of structured and unstructured data (video, social media)
- Many different types of data repositories

## Veracity (Uncertainty of data)

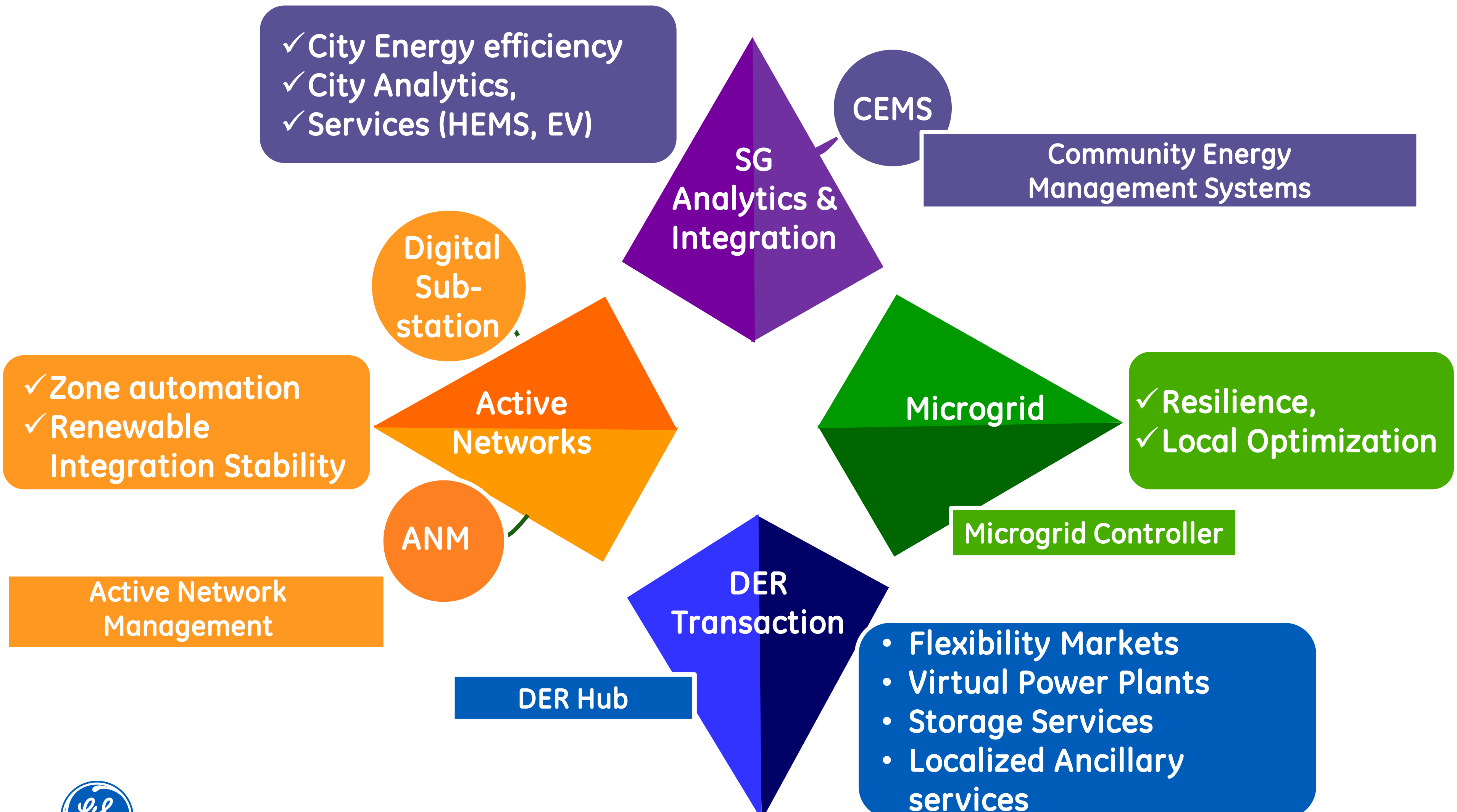
- Data cleansing/conditioning (data quality)
- Confidence measure (e.g. forecasting)
- Optimization application robustness




Source: EPRI Intelligrid Via Lockheed Martin Presentation, "Solving Big Data Challenges US Electric Utility Industry", July 2014

# Distributed Energy Resources

## *New Emerging Solutions & Services*



# Key Industry Needs

## RELIABLE POWER

**Maintain grid stability**

- Improved operational decision support (Asset conditions & limits)
- Mitigate blackouts and outages impacts
- Manage aging workforce
- Outage Reduction

## AFFORDABLE POWER

**Improve energy efficiency**

- Maximize energy flows in constrained and aging grids
- Enable end-user DERs with the energy system (“prosumers”)
- Leverage information across business silos (bridging OT & IT)
- Increase operational efficiency

## RENEWABLE POWER

**Integrate CO2 free energy**

- Enable renewable DER (wind, solar) grid connection & dispatch
- Develop back up energy asset flexibility (generation & distributed storage)
- Integrate distributed renewable, Energy Positive buildings and Electric Vehicles

# A Continually Transforming Landscape

## Market Drivers

### GENERATION
- Renewable massive deployment
- Energy storage deployment
- Aggregator and Demand Response player
- New market places and Regulation change

### TRANSMISSION
- Interconnected networks and coordination
- WAMS Stability & Protection control
- VAR Control, Look ahead
- Dynamic line rating
- AC and DC network
- CIM model
- Cyber security

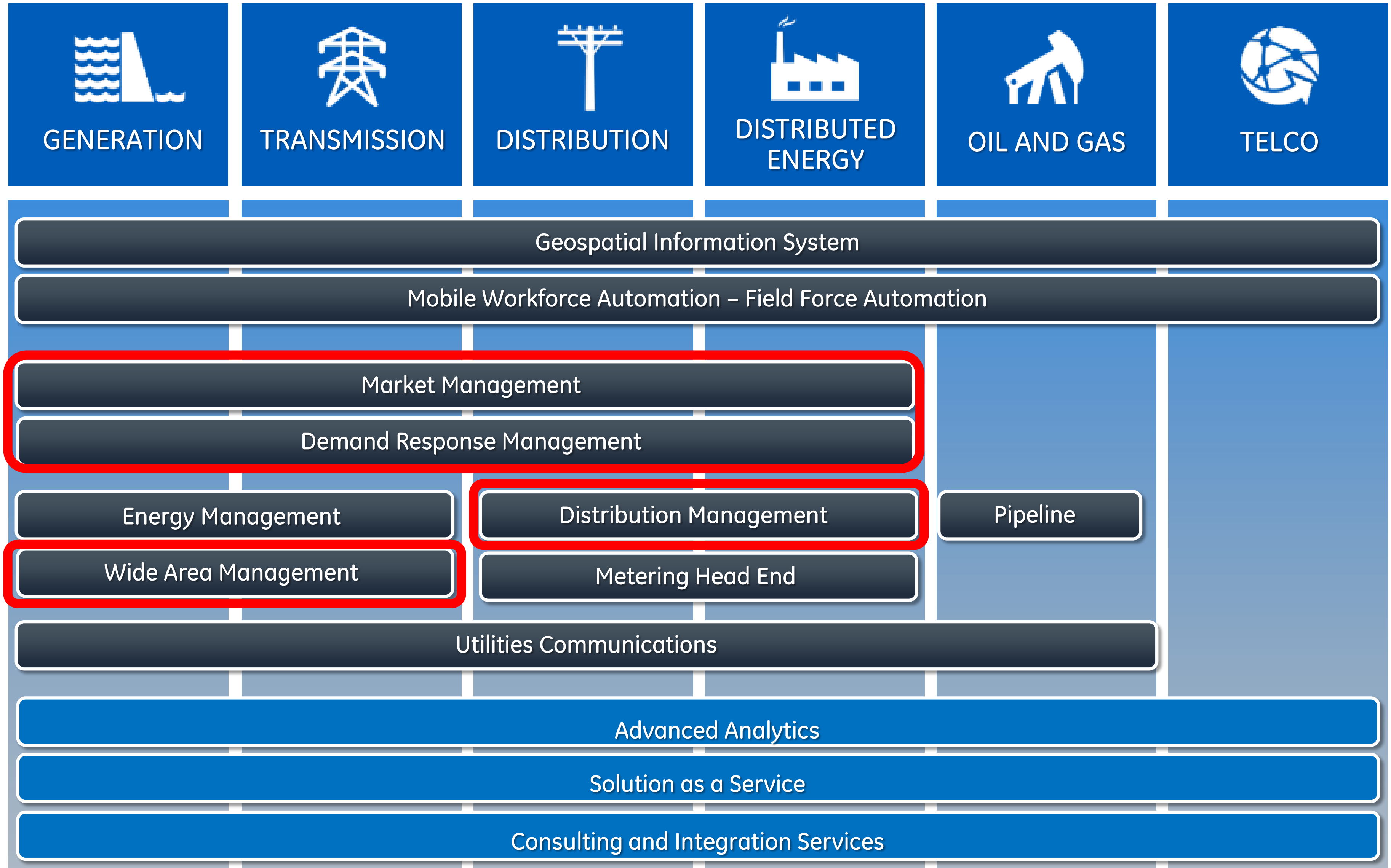
### DISTRIBUTION
- DA centralized (FLISR)
- Distributed Energy
- Voltage optimization
- Operation Efficiency from Analytics
- Network digitalization with connected objects

### DISTRIBUTED ENERGY
- Local generation (PV)
- Multi shape grids : feeder, microgrid, homegrid, picogrid
- Metering
- Energy efficiency
- Demand response
- Local market place

### OIL AND GAS
- Gas pipeline expansion as gas extraction sites move
- Pipe capacity
- Oil / Gas market price +/-
- Physical and Cyber security
- PHMSA Standard

### TELCO
- Technology (MPLS, 4G 5G …)
- Regulatory service covering and quality
- WAC and Distribution automation
- IT / OT convergence

# Software Solutions



# Wide Area Management System

# What is SynchroPhasor Technology?

## *Phasor Measurement Units (PMUs)*

Next generation measurement technology (voltages, currents, frequency, rate-of-change of frequency, etc)

Higher resolution scans

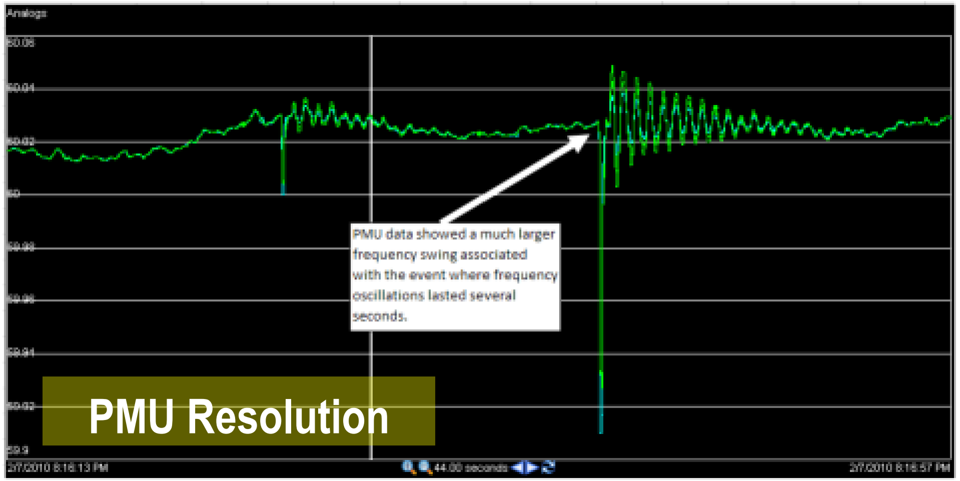
(e.g. 30 or 60 samples/second).

- *Improved visibility into dynamic grid conditions.*
- *Early warning detection alerts*

Precise GPS time stamping

- *Wide-area Situational Awareness*
- *Faster Post-Event Analysis*

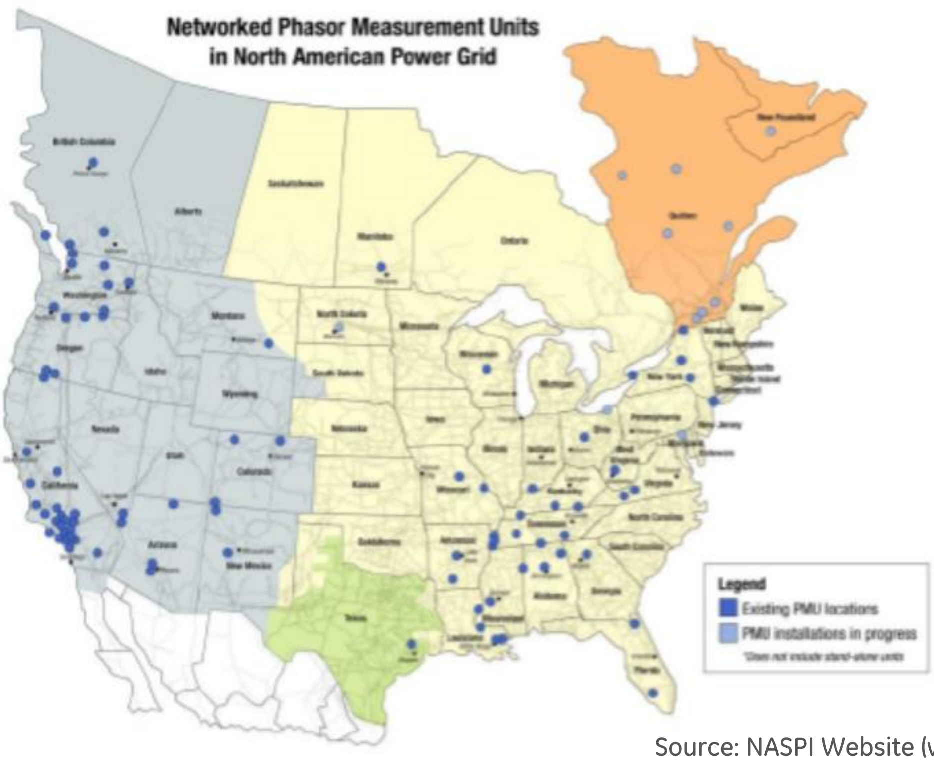
*"MRI quality visibility of power system compared to x-ray quality visibility of SCADA"* *– Terry Boston (PJM)*

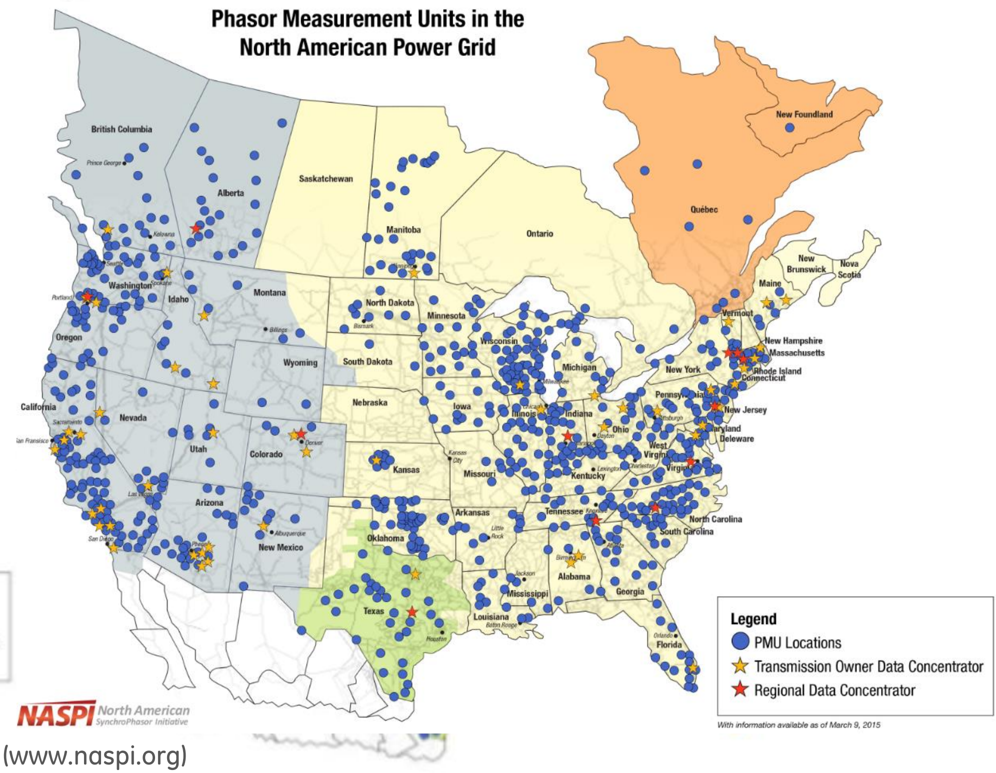
# Synchrophasor Deployment in North America

## *Changing Landscape*

**April 2007**




**March 2015**




Source: NASPI Website (www.naspi.org)

- Approx. 200 PMUs in 2007
- Most R&D grade deployments

- Over 1700 PMU deployed by 2014
- Production grade & redundant networks

# WAMS: Transformational solution

- PMU’s are becoming the RTU’s of the present
- WAMS is shaping the next generation EMS and fundamentally transforming the way we manage and operate the grid
- WAMS provides early warning of potential blackouts
- WAMS identifies the source of the instability
- WAMS + EMS provides corrective action to the problem
- WAMS provides accurate post-event analysis
- WAMS allows to respond faster to renewable variability
- WAMS validates dynamic models for planning and look-ahead

# WAMS : Control Room Operations

**Transitioning from traditional "steady-state" view to enhanced "dynamic" situational awareness.**

## The Next Generation Energy Management System!

**EMS**
MODEL-BASED ANALYSIS


**WAMS**
MEASUREMENT-BASED ANALYSIS

| Other EMS Applications | | New Applications |
|---|---|---|
| SCADA & Alarms | ↔ | WAMS Alarms |
| State Estimator | ↔ | State Measurement |
| Small Signal Stability | ↔ | Oscillation Monitoring |
| Transient & Voltage Stability | ↔ | Stability Monitoring & Control |
| Island Management | ↔ | Island Detection, Resync, & Blackstart |

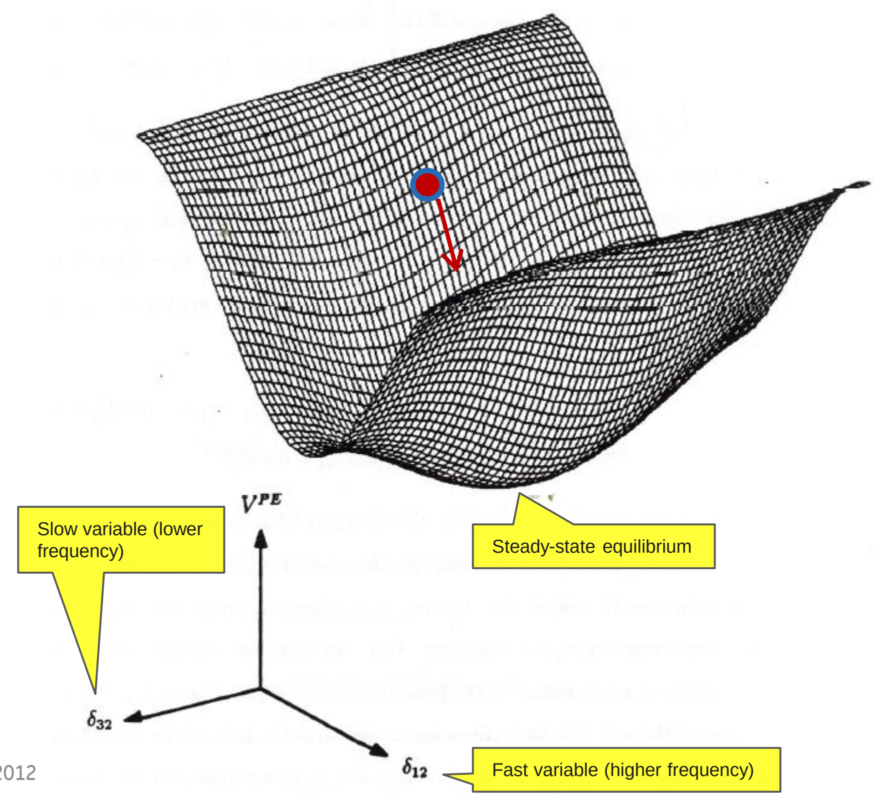
**Control Center - PDC**

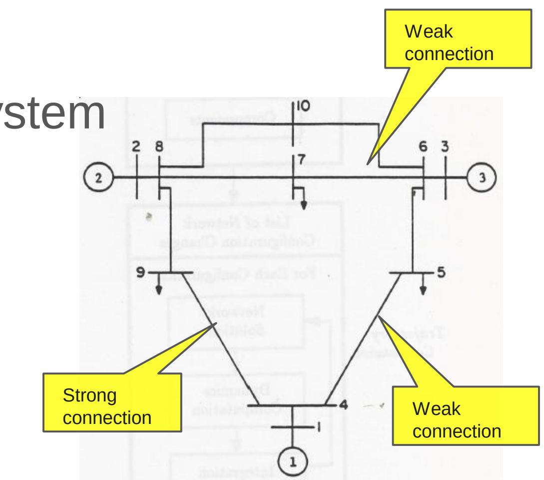
# State-of-the-Art of Dynamic Security Assessment

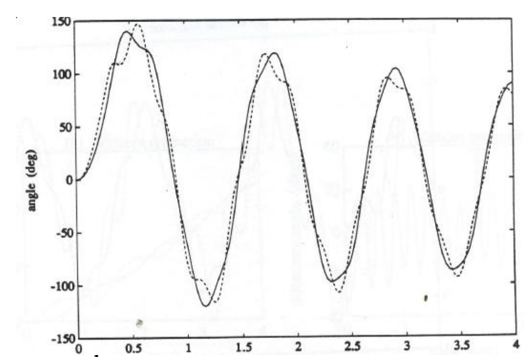
- A power system represented by the following differential-algebraic system

$$\dot{x} = f(x, y)$$
$$0 = g(x, y) \qquad (*)$$

- An illustration - Potential Energy Surface of a 3-Machine System



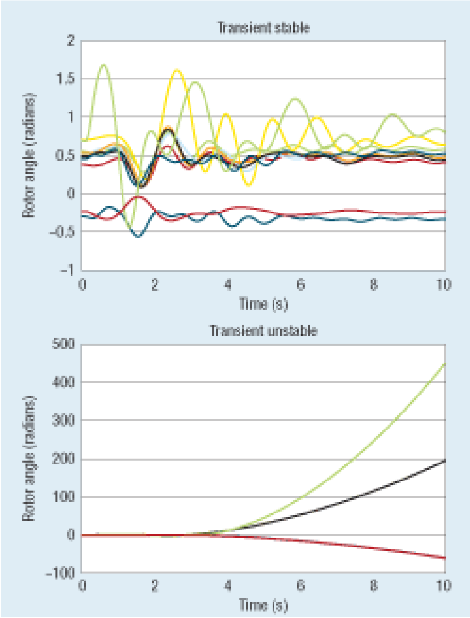



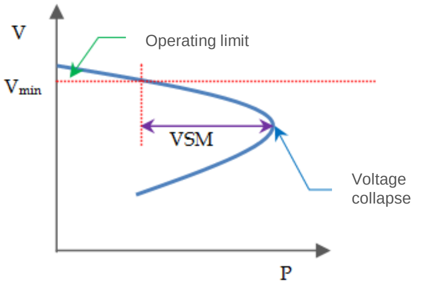



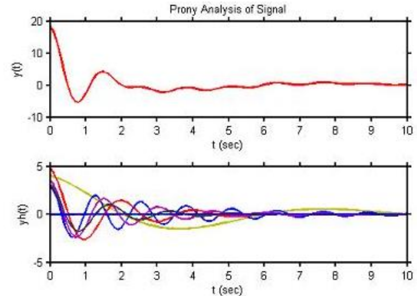
# State-of-the-Art of Grid Security

- Network security analysis in classical EMS is solving a steady-state solution ( $\dot{x}=0$) of the (*). Some basic network analysis functions (Static security assessment) include
  - **State estimation** – Least-square
  - **N-1 contingency analysis** – fast decoupled power flow

- Power system stability (dynamic security assessment) is traditionally studied *off-line*
  - **Transient stability analysis (TSA)** – Time-domain simulation
  - **Voltage stability analysis (VSA)** – P-V, Q-V curve analysis
  - **Small signal stability analysis (SSSA)** – Prony analysis




Source: Wikipedia

GRID ALSTOM

# Synchrophasor Applications in the Control Room

## e-terra*phasorpoint*

Leveraging time-synchronized and high fidelity PMU measurements in Operations

**PDC**

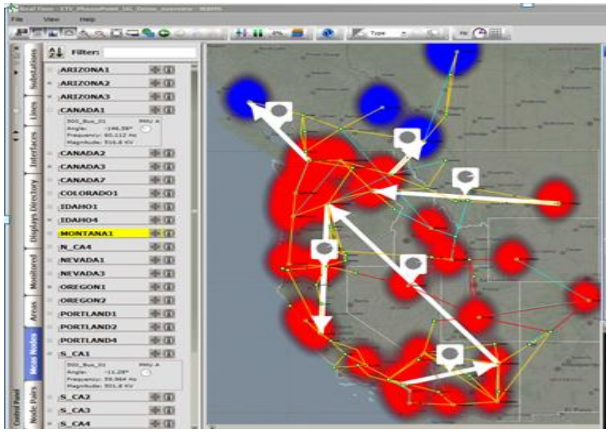
- C37.118/2005/2011/2014 compliant
- Exterme performance (5000 PMUs)
- Multiple inputs/outputs

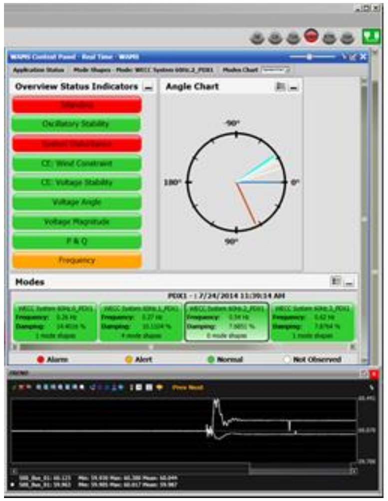
**Historian**

- High Resolution Rolling Buffer / Triggered Storage
- Low Resolution Rolling Buffer
- Optimized data storage technology

**Applications**

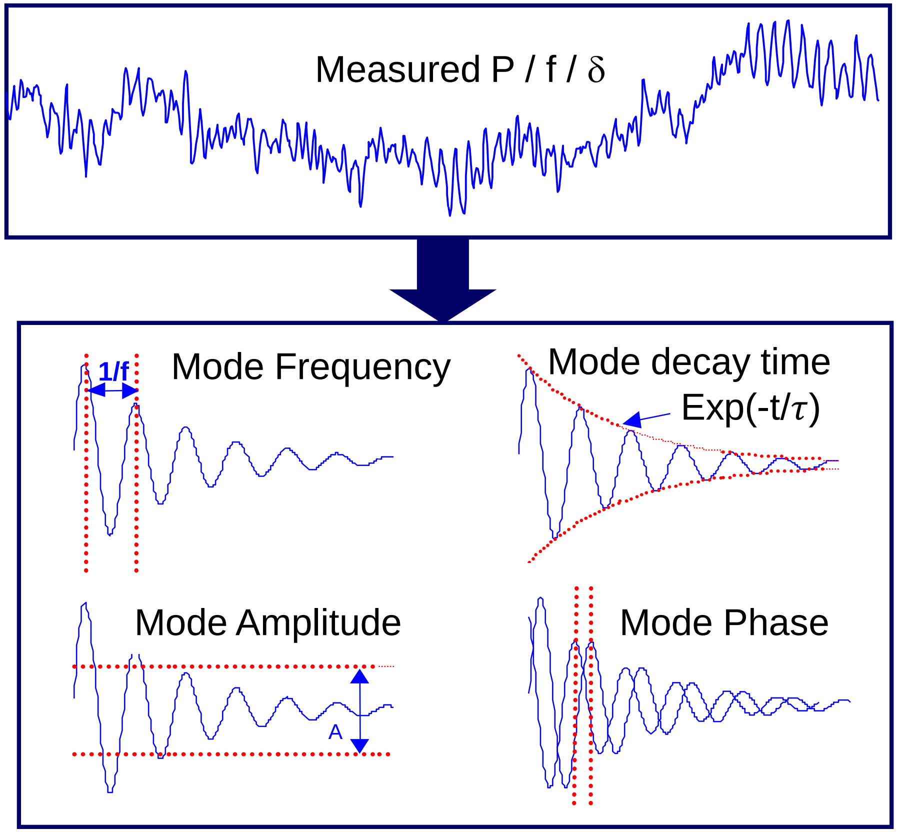
- Full Oscillation Monitoring (0.002 Hz to 46 Hz)
- Oscillation Source Location
- Islanding Detection
- System Disturbance Detection and Characterization





# Monitoring Oscillatory Stability (**e-terra***phasorpoint*)

Simultaneous multi-oscillation detection and characterization direct from measurements




Fast Modal Analysis: **Alarms**

Trend Modal Analysis: **Analysis**

*Does not use system model*

## Operations

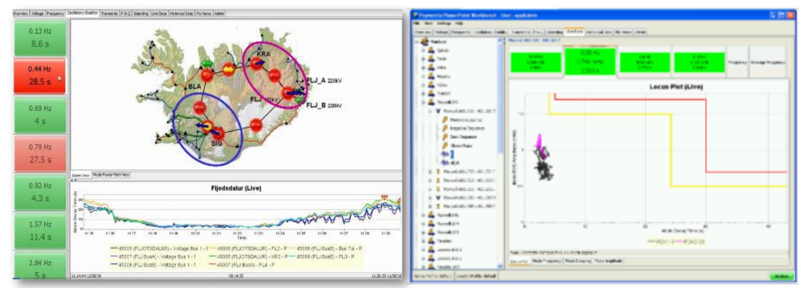
Early warning of poor damping (two level alarms)

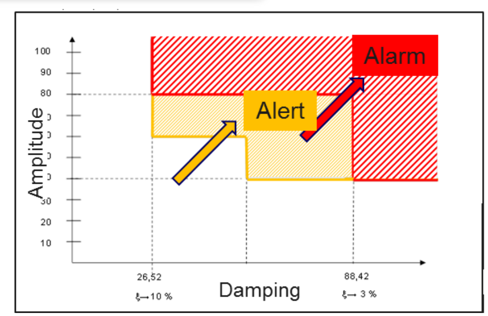
Unlimited oscillation frequency sub-bands

Individual alarm profiles for each sub-band

For each oscillation detected, alarm on:

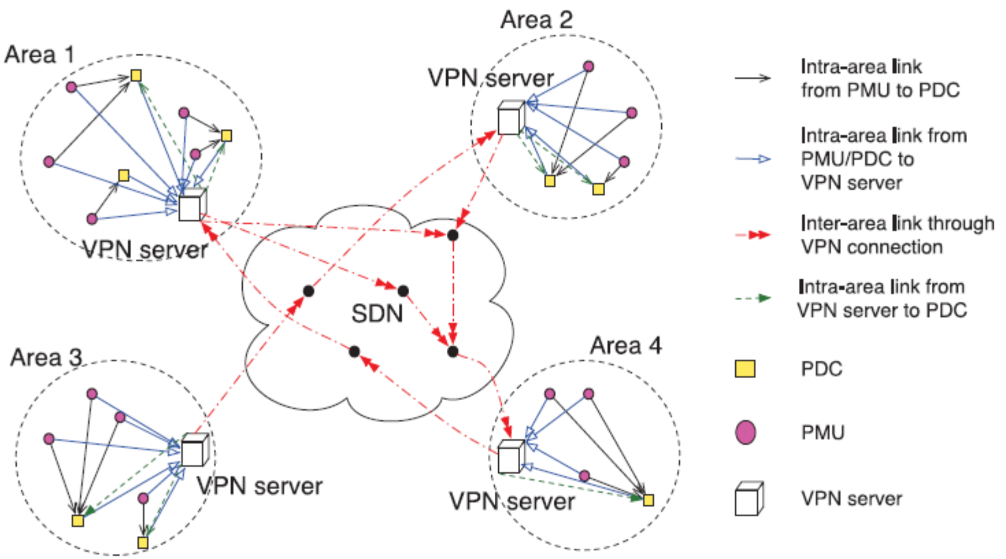
- mode damping
- mode amplitude





# Challenges and Opportunities for WAMS

- The number of PMU's scale up to the thousands in North America and other parts of the world (e.g. India).
- Current state-of-the-art centralized communication and information processing architecture of WAMS is not sufficient.
- Decentralized WAMS architecture (NASPI) is coming but not much progress on decentralized algorithmic applications.



# Wide-Area Oscillation Monitoring Applications

- Problem formulation

$$\begin{bmatrix} \Delta\dot{\delta}(t) \\ \hline \Delta\dot{\omega}(t) \end{bmatrix} = \underbrace{\left[\begin{array}{c|c} \mathbf{0}_{n\times n} & \omega_s I_n \\ \hline \mathcal{M}^{-1}L & -\mathcal{M}^{-1}\mathcal{D} \end{array}\right]}_{A} \begin{bmatrix} \Delta\delta(t) \\ \hline \Delta\omega(t) \end{bmatrix}$$

$$\mathbf{y}(t) = [\Delta\theta_1(t), \ldots, \Delta\theta_p(t)]^T$$

**Phase angle measurement**

(S1) Find *a* by solving the LS problem

$$\min_{\boldsymbol{a}} \frac{1}{2} \left\| \begin{bmatrix} H_1 \\ \vdots \\ H_p \end{bmatrix} \boldsymbol{a} - \begin{bmatrix} \mathbf{c}_1 \\ \vdots \\ \mathbf{c}_p \end{bmatrix} \right\|^2$$

- Modal estimation using Prony Method

$$\Delta\theta_i(t) = \sum_{l=1}^{n} \left( r_{il} e^{(-\sigma_l + j\Omega_l)t} + r_{il}^* e^{(-\sigma_l - j\Omega_l)t} \right)$$

$$\Delta\theta_i(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_{2n} z^{-2n}}{1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_{2n} z^{-2n}}$$

$$\underbrace{\begin{bmatrix} \Delta\theta_i(2n) \\ \Delta\theta_i(2n+1) \\ \vdots \\ \Delta\theta_i(2n+\ell) \end{bmatrix}}_{\mathbf{c}_i} = \underbrace{\begin{bmatrix} \Delta\theta_i(2n-1) & \cdots & \Delta\theta_i(0) \\ \Delta\theta_i(2n) & \cdots & \Delta\theta_i(1) \\ \vdots & & \vdots \\ \Delta\theta_i(2n+\ell-1) & \cdots & \Delta\theta_i(\ell) \end{bmatrix}}_{H_i} \underbrace{\begin{bmatrix} -a_1 \\ -a_2 \\ \vdots \\ -a_{2n} \end{bmatrix}}_{\boldsymbol{a}}$$

(S2) Find eigenvalue of *A*

$$\ln(\bar{z}_l)/T$$

(S3) Find residues *r using* Vandermonde equation

$$\begin{bmatrix} \Delta\theta_i(0) \\ \Delta\theta_i(1) \\ \vdots \\ \Delta\theta_i(m) \end{bmatrix} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ (\bar{z}_1)^{1/T} & (\bar{z}_2)^{1/T} & \cdots & (\bar{z}_{2n})^{1/T} \\ \vdots & \vdots & & \vdots \\ (\bar{z}_1)^{m/T} & (\bar{z}_2)^{m/T} & \cdots & (\bar{z}_{2n})^{m/T} \end{bmatrix} \begin{bmatrix} r_{i1} \\ r_{i1}^* \\ \vdots \\ r_{in} \\ r_{in}^* \end{bmatrix}$$

# Distributed Optimization using ADMM

$$\underset{a_1,\ldots,a_N,\mathbf{z}}{\text{minimize}} \quad \sum_{j=1}^{N} \frac{1}{2}\|\hat{H}_j a_j - \hat{\mathbf{c}}_j\|^2$$

subject to $a_j - \mathbf{z} = 0$, for $j = 1, \ldots, N$.

- Augmented Lagrangian

$$L_\rho = \sum_{i=1}^{N}\left(\frac{1}{2}\left\|\hat{H}_j a_j - \hat{\mathbf{c}}_j\right\|^2 + \mathbf{w}_j^T(a_j - \mathbf{z}) + \frac{\rho}{2}\left\|a_j - \mathbf{z}\right\|^2\right)$$

where

$$\hat{H}_j^k \triangleq \left[\left(H_{j,1}^k\right)^T \cdots \left(H_{j,N_j}^k\right)^T\right]^T, \ \hat{\mathbf{c}}_j^k \triangleq \left[\left(\mathbf{c}_{j,1}^k\right)^T \cdots \left(\mathbf{c}_{j,N_j}^k\right)^T\right]^T$$

$$H_{j,i}^k \triangleq \begin{bmatrix} \Delta\theta_{j,i}(2n-1) & \cdots & \Delta\theta_{j,i}(0) \\ \Delta\theta_{j,i}(2n) & \cdots & \Delta\theta_{j,i}(1) \\ \vdots & & \vdots \\ \Delta\theta_{j,i}(m^k-1) & \cdots & \Delta\theta_{j,i}(m^k-2n) \end{bmatrix}$$

$$\mathbf{c}_{j,i}^k \triangleq \left[\Delta\theta_{j,i}(2n) \ \Delta\theta_{j,i}(2n+1) \cdots \Delta\theta_{j,i}(m^k)\right]^T$$

1) Each PDC $j$ initializes $a_j^0$, $\mathbf{z}^0$, and $\mathbf{w}_j^0$, $j = 1, \ldots, N$.
2) At iteration $k$:
   a) PDC $j$ constructs $\hat{H}_j^k$ and $\hat{\mathbf{c}}_j^k$ from (9).
   b) PDC $j$ updates $a_j$ as

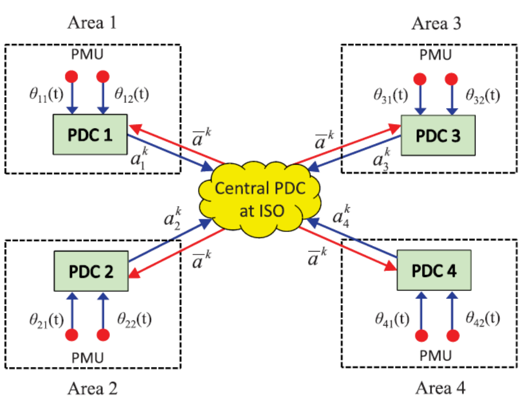
$$a_j^{k+1} = \arg\min_{a_j} L_\rho = \left(\left(\hat{H}_j^k\right)^T \hat{H}_j^k + \rho I_{2n}\right)^{-1} \left(\left(\hat{H}_j^k\right)^T \hat{\mathbf{c}}_j^k - \mathbf{w}_j^k + \rho\mathbf{z}^k\right).$$

   c) PDC $j$ transmits $a_j^{k+1}$ to the central PDC.
   d) Central PDC calculates

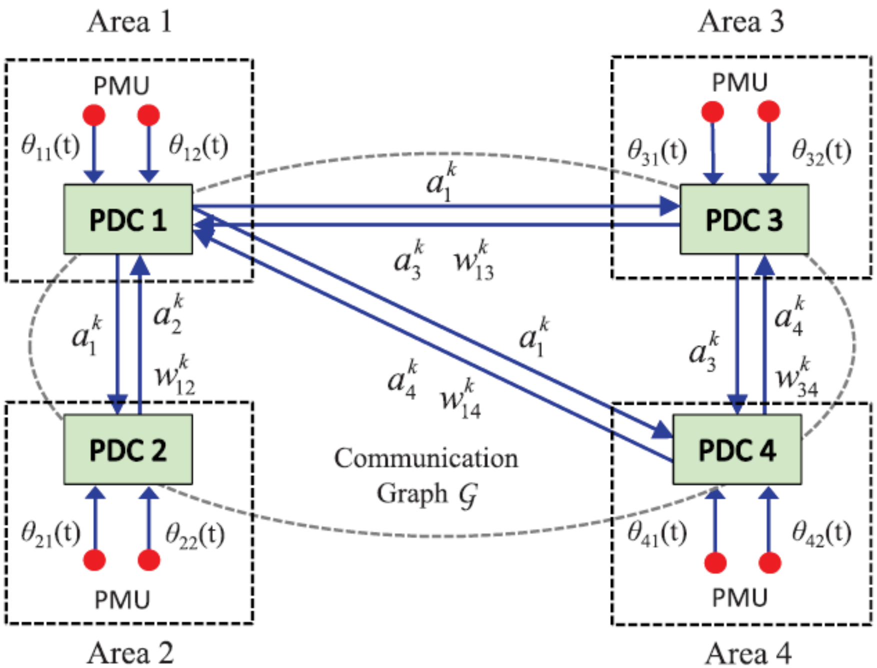
$$\mathbf{z}^{k+1} \triangleq \bar{a}^{k+1} = \frac{1}{N}\sum_{j=1}^{N} a_j^{k+1}.$$

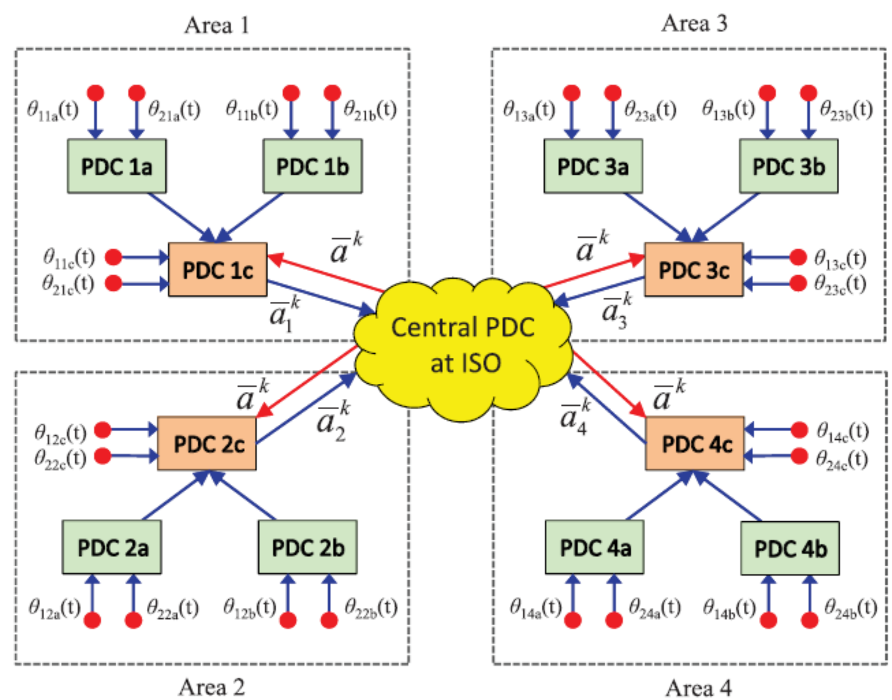
   e) Central PDC broadcasts $\mathbf{z}^{k+1}$ to all local PDCs.
   f) PDC $j$ updates $\mathbf{w}_j$ as

$$\mathbf{w}_j^{k+1} = \mathbf{w}_j^k + \rho\left(a_j^{k+1} - \mathbf{z}^{k+1}\right).$$



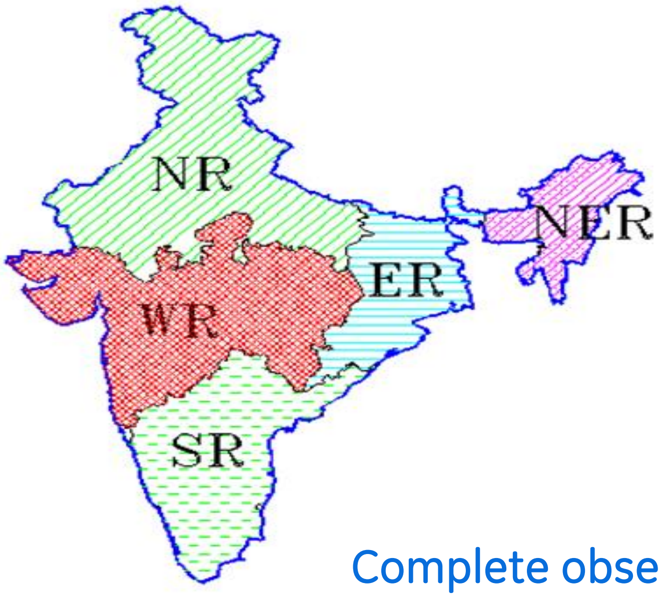
# Other Architectures for Distributed Optimization



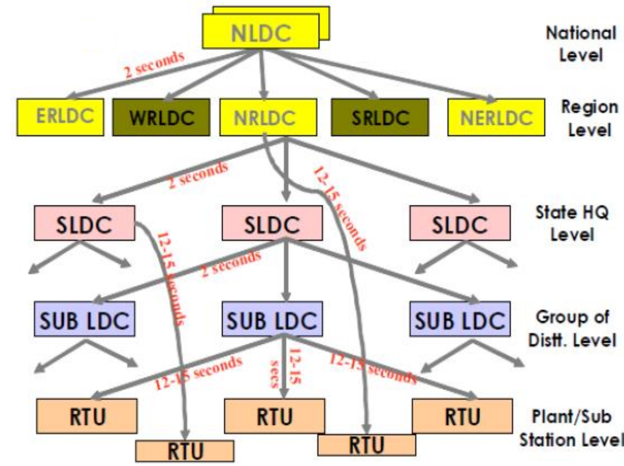



# PowerGrid India - URTDSM

## Unified Real Time Dynamic State Measurement




Current SCADA measurement hierarchy




Complete observability of the Indian Power system in real time

**World Largest WAMS dynamic monitoring system serving a billion people.**

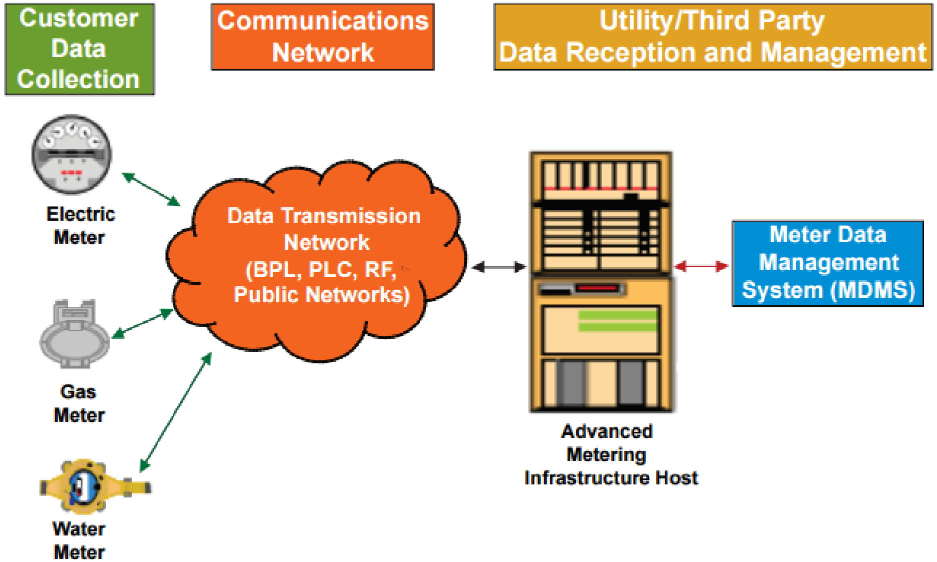
- 33 PDCs: 26 States; 5 Regions; 2 National Control Centers
- 359 Substations with 3,400 PMUs sending 25 samples per second
- Over 25,000 synchrophasors (positive sequence, 3 phases, voltage and current, MW and MVAR)
- 1 Year of long term data: 0.5 Peta Bytes

# Market Management System
# Demand Response Management System

# What is Advanced Metering Infrastructure (AMI)?

## *Smart Meter*

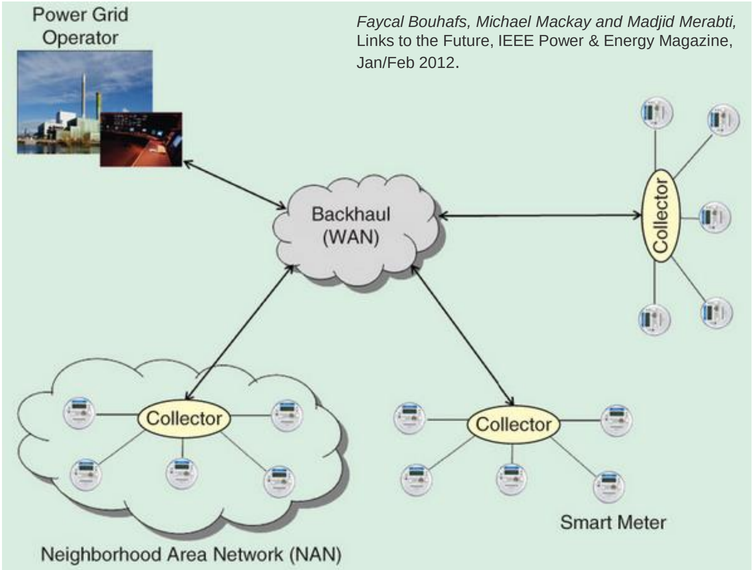
- AMI is comprised of state-of-the-art electronic/digital hardware and software, which combine interval data measurement with communications.
- Smart meters – advanced solid state, electronic meters collect time-based data.
- Smart meter has the ability to transmit and collected data through commonly available communication network such as Broadband over Power Line (BPL), Power Line Communication (PLC), Fixed Radio Frequency (RF) networks, and public networks (e.g. cellular).
- The meter data are received by AMI host system and sent to the Meter Data Management System (MDMS) that manages data storage and analysis for electric utilities.

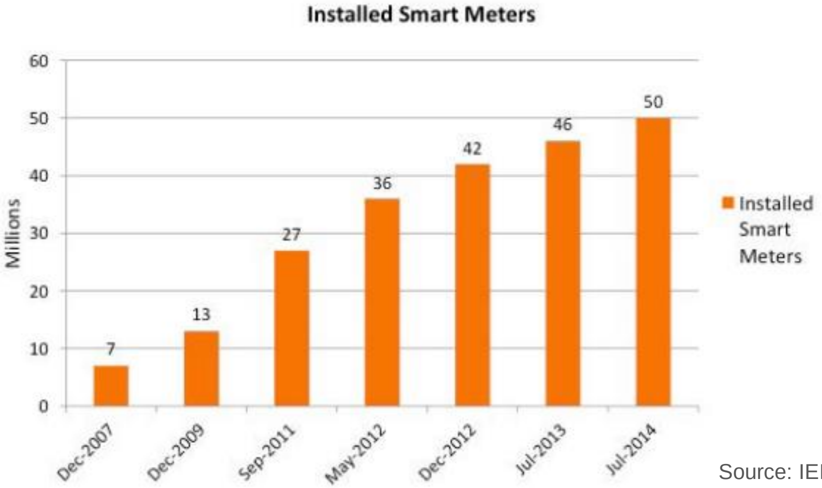




Source: IEI

# AMI Deployment

- AMI includes meters that measure and record electricity usage at a minimum of hourly intervals and that provide the data to both the utility and the utility customer at least once daily.
- AMI (with real-time meters) facilitates two-way communication between the utility and the customer.
- Smart meters are expected to facilitate customer participation in the Smart Grid.
- As of July 2014, over 50 million smart meters had been deployed in the U.S., covering over 43 percent of U.S. homes.



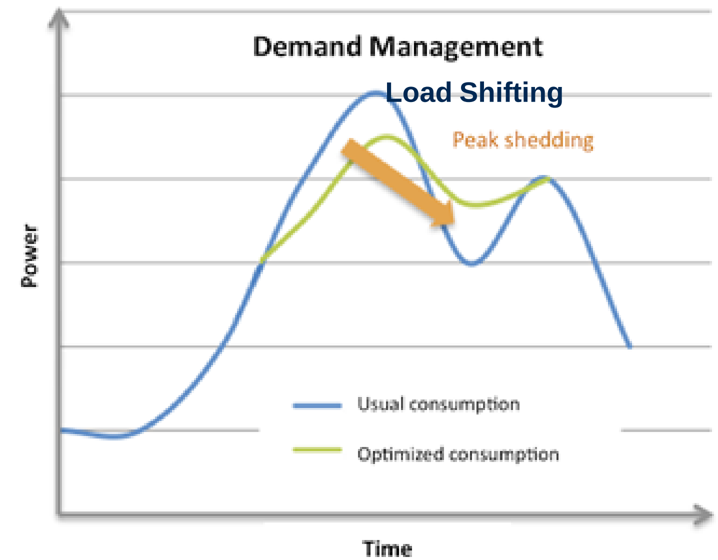



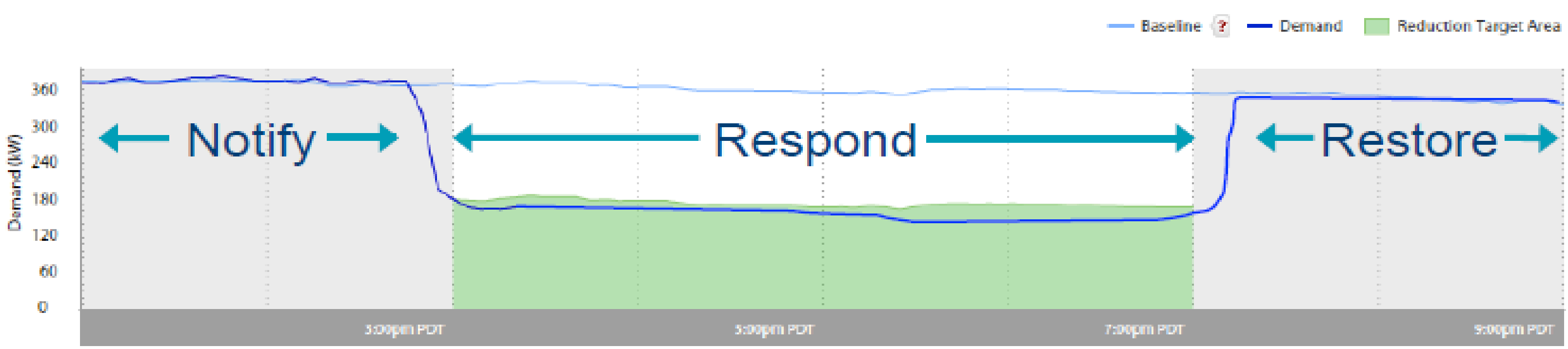

Source: IEI

# Market Management

## *Demand Response (DR)*

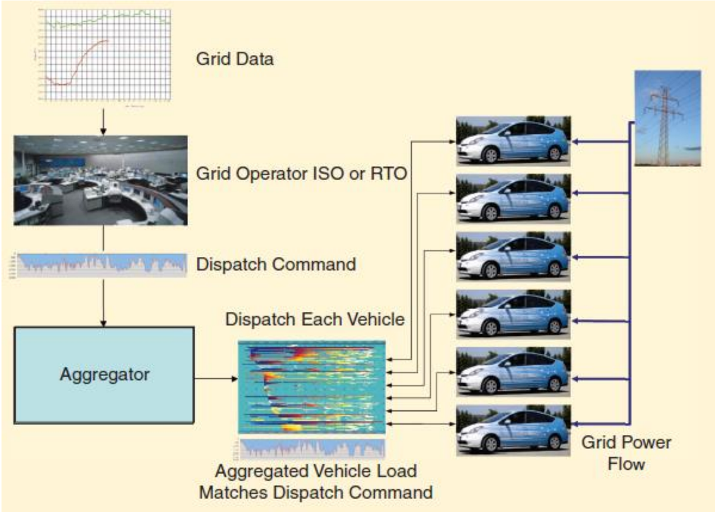
- **Demand Response** - Changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized. (FERC 2012)
- Historical electricity demand is rather inelastic
- DR is a new class of controllable resources
  - Load to follow generation for system balancing
- DR was first introduced for peak load reduction.



# Demand Dispatch

- AMI technology such as high-speed, two-way communication enhances the ability of system operators to integrate new forms of demand response or “demand dispatch” into normal system operations during any hour rather than just peak demand periods.
- Market-based demand response vs. market-reactive demand response
- Deep demand-side management
- Roles of DR
  - **Energy** resource – dispatch for economic reasons
  - **Capacity** resource – resource adequacy
  - **Ancillary services** resource – dispatch for reliability
- DR Services
  - Load shifting, absorption of excess generation
  - Dispatchable quick start
  - Regulation, fast ramping, frequency response

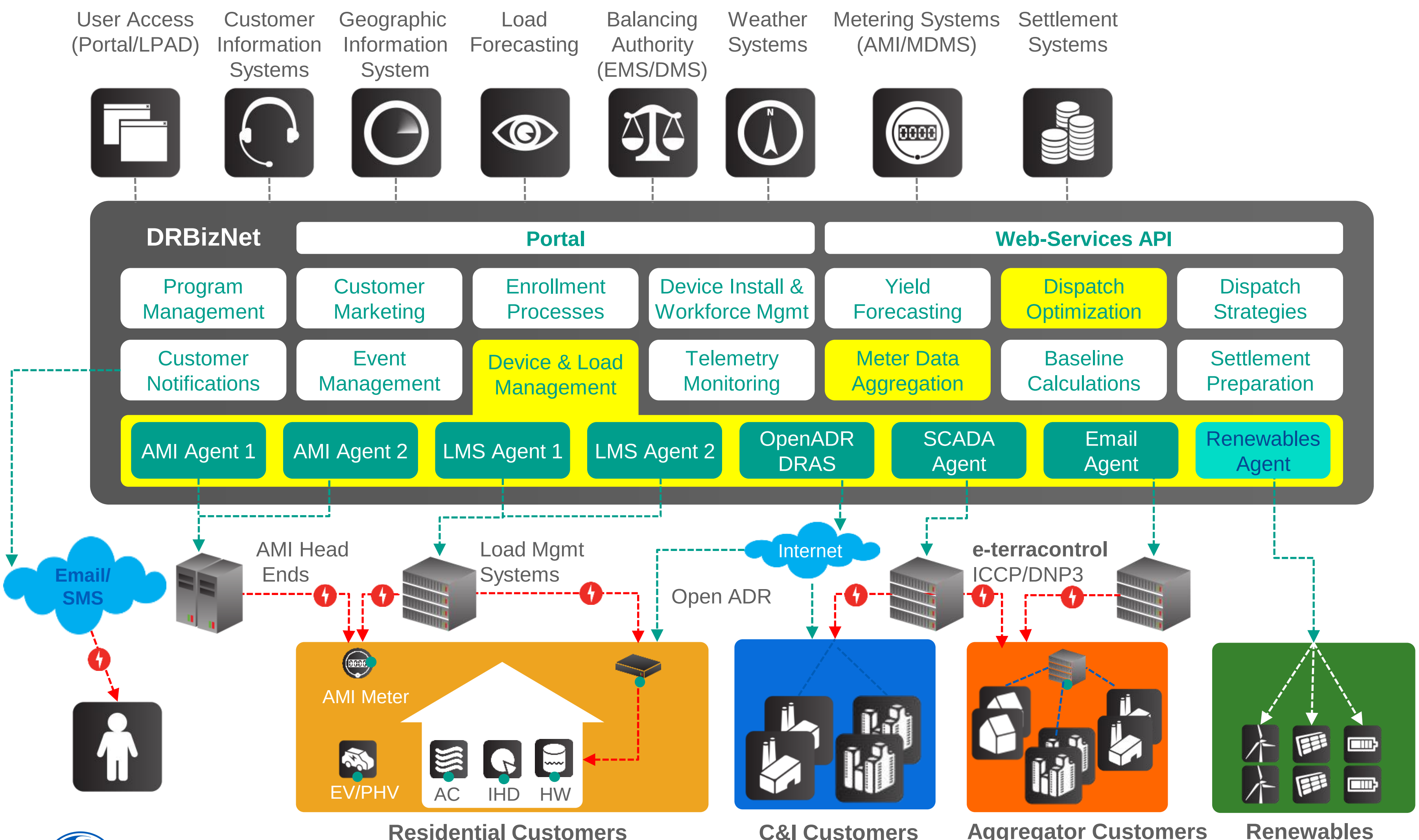



Source: Alec Brooks, Ed Lu, Dan Reicher, Charles Spirakis, and Bill Weihl, "Demand Dispatch", IEEE power & energy magazine, pp. 20-29, 2010.

*Aggregation of DR is the key for grid integration.*

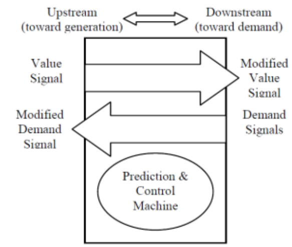
# Demand Response Management (e-terra*DRBizNet*)

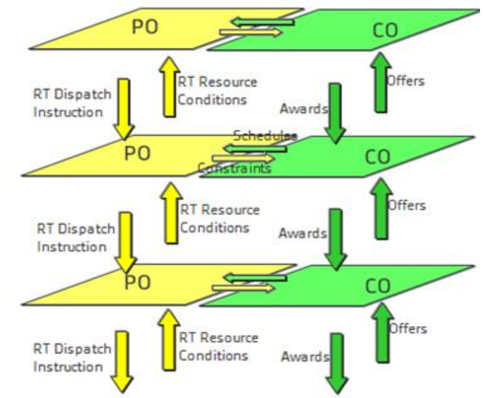
## *Configured for wholesale/retail in market/non-market environment*

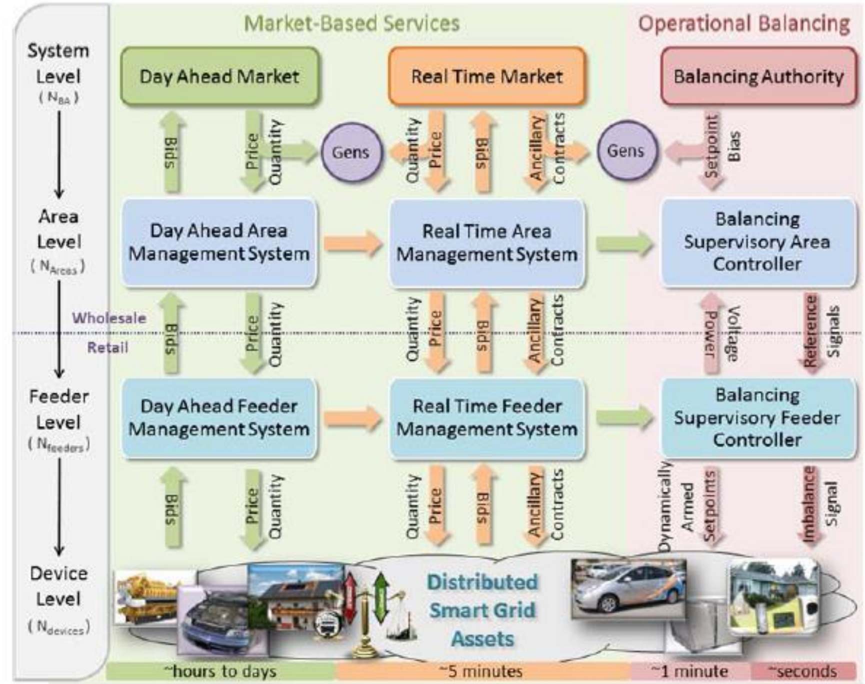


# Transactive Control and Coordination (TC2)

- Uses economic or market-like constructs to manage generation, consumption, & flow of electric power including reliability constraints by coordinating assets from generation to end use with precision.
- Uses local conditions and global information to make local control decisions at points (nodes) where the flow of power can be affected.
- Nodes indicate their response to the network via transactive incentive and feedback signals (TIS/TFS)
- TC2 is flexible and efficient design allowing deployment at all levels of the energy hierarchy.



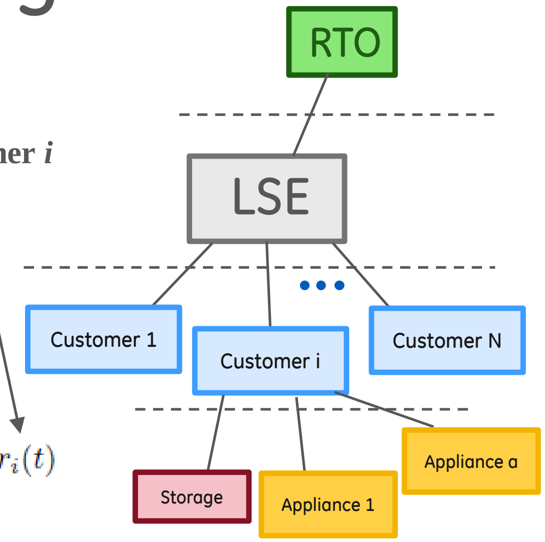



# Challenges Addressed by TC2

| Challenges | Approaches |
|---|---|
| • Centralized optimization is unworkable: large number of controllable assets (~1e9) | • Distributed approach with self-organized, self-optimizing properties of market-like constructs |
| • Interoperability | • Simple information protocol, common between all nodes at all levels of system: quantity, price or value, & time |
| • Privacy & security | • Minimize risks & sensitivities by limiting content of data exchange to simple transactions |
| • Scalability | • Self-similar at all scales in the grid<br>• Common paradigm for control & communication among nodes of all types<br>• Ratio of supply node to served nodes (~1e3) |

# DR Coordination via Dynamic Pricing

## *Centralized vs. Distributed*




**Utility's objective (max welfare):**

**Cost for LSE to provide *Q***

**Storage charge rate of customer *i***

$$\max_{q,r} \quad \sum_i \left( \sum_{a \in \mathcal{A}_i} U_{i,a}(q_{i,a}) - D_i(r_i) \right) - \sum_t C \left( \sum_i Q_i(t) \right)$$

$$\text{s. t.} \quad A^{i,a} q_{i,a} \le \eta_{i,a}, \quad \forall a, i$$

$$0 \le Q_i(t) \le Q_i^{\max}, \quad \forall t, i \qquad Q_i(t) := \sum_{a \in \mathcal{A}_i} q_{i,a}(t) + r_i(t)$$

$$r_i \in \mathcal{R}_i, \quad \forall i$$

**Power consumption for appliance *a* of customer *i***

**Customer $i$'s objective (max own benefit):**

$$\max_{q_i, r_i} \quad \sum_{a \in \mathcal{A}_i} U_{i,a}(q_{i,a}) - D_i(r_i) - \sum_t p(t) Q_i(t)$$

$$\text{s. t.} \quad A^{i,a} q_{i,a} \le \eta_{i,a}, \quad \forall a$$

$$0 \le Q_i(t) \le Q_i^{\max}, \quad \forall t$$

$$r_i \in \mathcal{R}_i$$

$$Q_i(t) := \sum_{a \in \mathcal{A}_i} q_{i,a}(t) + r_i(t)$$

Distributed algorithm:

**Marginal Cost**

$$p^k(t) = C' \left( \sum_i Q_i^k(t) \right)$$

$$\bar{q}_{i,a}^{k+1}(t) = q_{i,a}^k(t) + \gamma \left( \frac{\partial U_{i,a}(q_i^k)}{\partial q_{i,a}^k(t)} - p^k(t) \right)$$

$$\bar{r}_i^{k+1}(t) = r_i^k(t) - \gamma \left( \frac{\partial D_i(r_i^k)}{\partial r_i^k(t)} + p^k(t) \right)$$

$$(q_i^{k+1}, r_i^{k+1}) = [\bar{q}_i^{k+1}, \bar{r}_i^{k+1}]^{S_i}$$

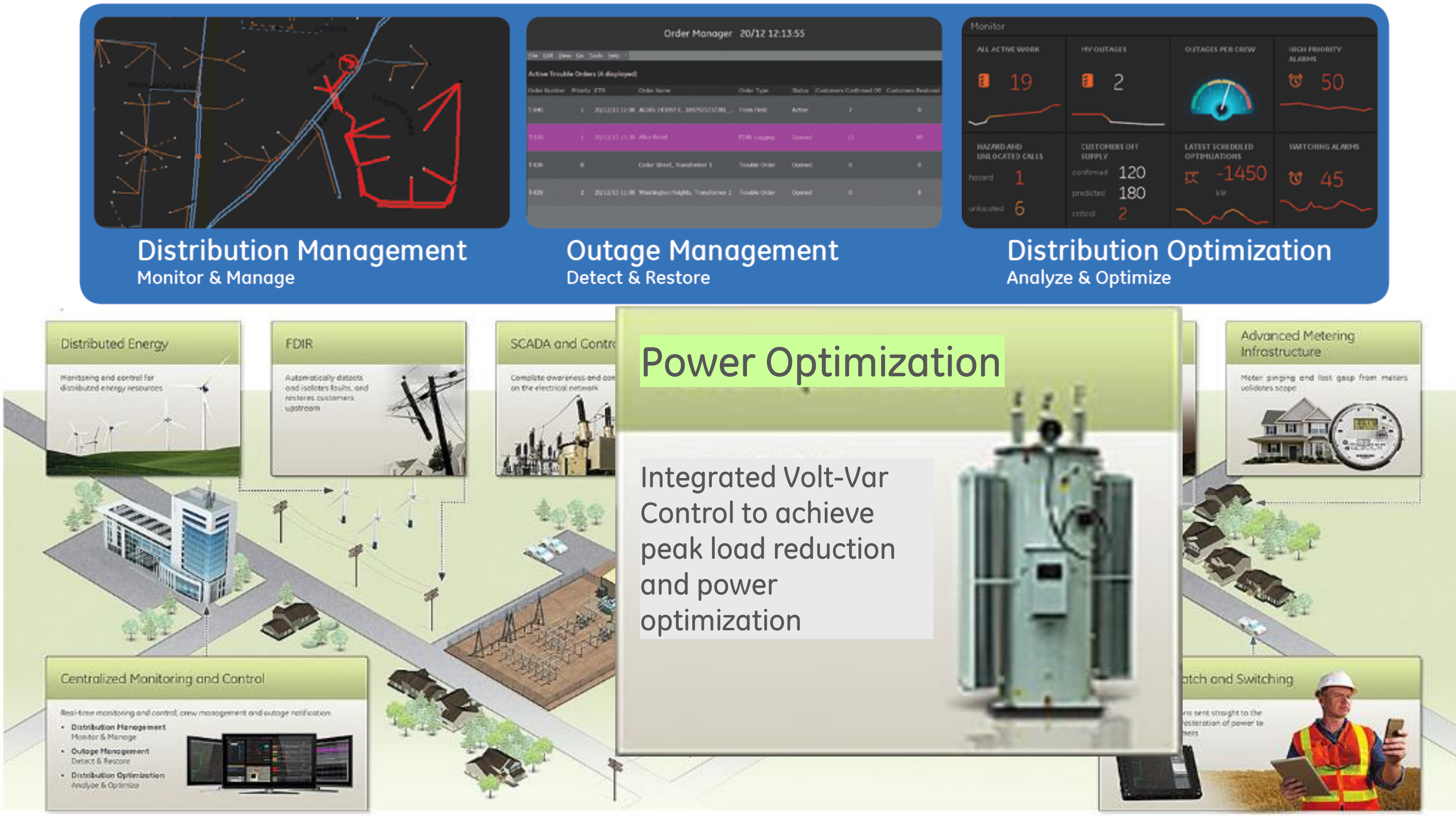
# Pacific Northwest Smart Grid Demonstration

- 5 year ARRA funded; ended in 2015
- Largest demonstration project in the nation ($179M)
- Battelle and BPA with 6 technology partners and 11 field demonstrations
- Demonstration of Transactive Control and Coordination (TC2)
- www.pnwsmartgrid.org

# Distribution Management System and Distributed Energy Resources Management System

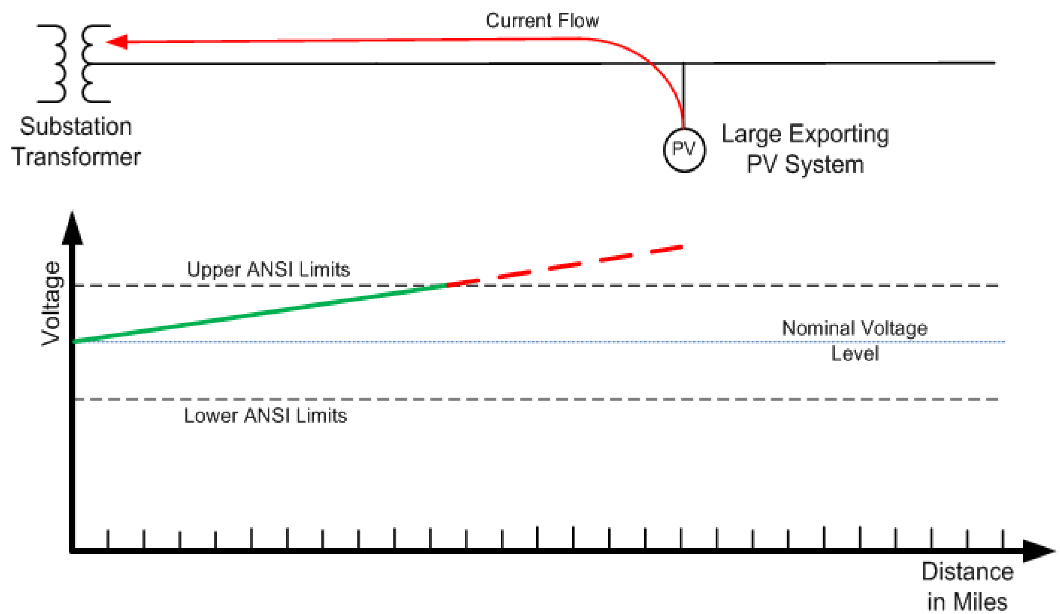
# Advanced Distribution Management System

## *A Digital Cockpit for Grid Modernization*



# Challenges of Distributed Solar
## (with traditional PV inverters)

- Disconnect during grid disturbances
- Voltage rise




- Voltage transients: Extra tap changes, etc.
- Unobservable and uncontrollable
- Protection

# The advanced (PV) inverter opportunity

## Advanced (or "Smart") inverters offer features to overcome these traditional inverter challenges

## Technologically "Easy"

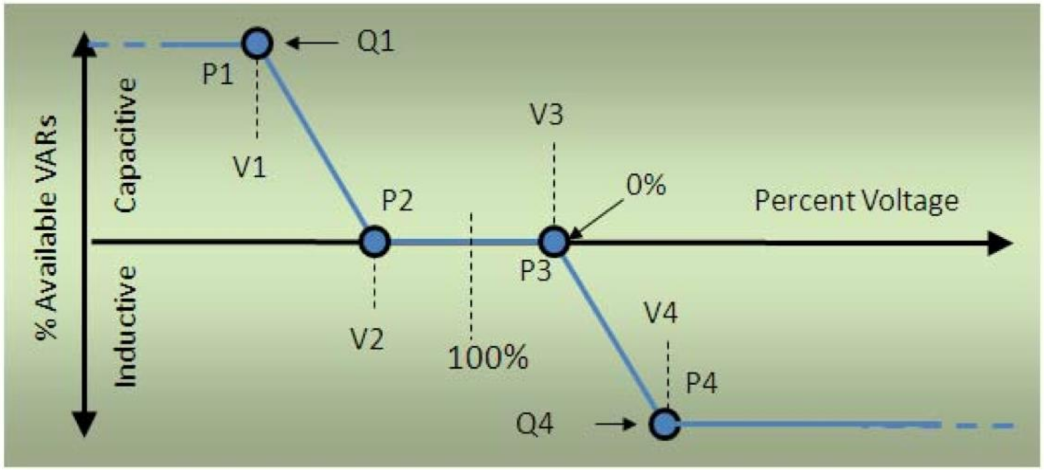
- Leverage existing power electronics
- Enabled by software/control capabilities
- On the market today in US
  - May not be advertised
  - Both utility/commercial and residential-scale

## Active standards development

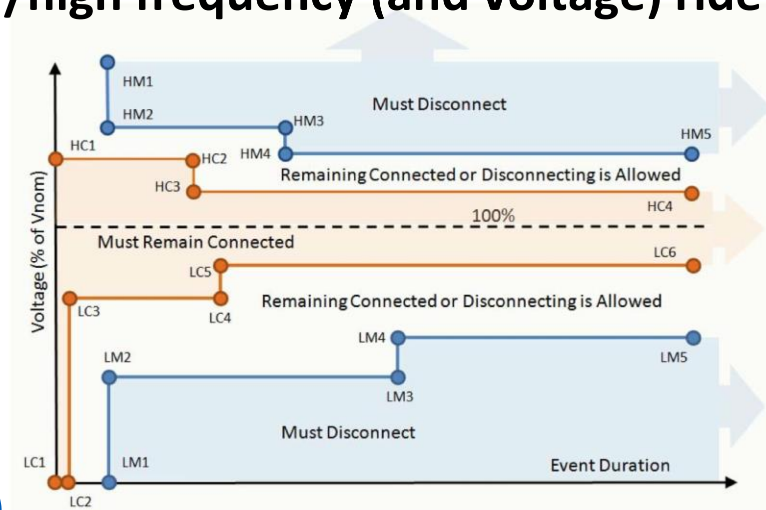
- (SGIP: coordinating, convening, & suggesting priorities: PAPs)
- IEEE1547A (2014): allows DG voltage control (if Utility OK)
- IEEE1547-revision (& UL1741): Likely to require advanced features, debate defaults vs utility left to specify
- CA Rule 21 & SIWG: Interconnect and Communication
- IEC 61850-90-7: Description of Adv. Inv. in CIM
- SunSpec: Standard Modbus Communication (Lower-level)
- SEP2/IEEE P2030.5: Smart grid control
- OpenFMB: hub/exchange. Builds on Duke's DIP

# Advanced PV inverter features

**Active Voltage Control: Q(V)**




**Low/high frequency (and voltage) ride through**




- Connect/disconnect settings
- Anti-islanding
- Maximum generation limit
- Fixed power factor (PF≠1)
- Active Voltage control: Q(V)
- Volt-watt (auto curtailment)
- Frequency-watt
- Watt-powerfactor
- Price/temperature driven
- Low/high frequency ride through
- Low/high voltage ride through
- Dynamic reactive current
- Real power smoothing
- Dynamic volt-watt
- Peak power limiting
- Load and generation following
- Communications

*Source: Common Functions for Smart Inverters, Version 3. EPRI: 2014. Report Number 3002002233*

# Problem Formulations

## *VVO with PV inverter output regulation*

- PV Inverter dynamics

$$\dot{\mathbf{x}}_i(t) = \mathbf{f}_i\Big(\mathbf{x}_i(t), \mathbf{d}_i(t), \mathbf{u}_i(t)\Big)$$

$$\mathbf{y}_i(t) = \mathbf{r}_i\Big(\mathbf{x}_i(t), \mathbf{d}_i(t)\Big), \quad i \in \mathcal{N}_D := \{1, \ldots, N_D\}$$

**Network performance objective** → $H(\mathbf{v})$; **PV inverter costs/rewards** → $G_i(P_i, Q_i)$

$$\text{(OPF)} \quad \min_{\mathbf{v}, \mathbf{i}, \{P_i, Q_i\}} H(\mathbf{v}) + \sum_{i \in \mathcal{N}_D} G_i(P_i, Q_i)$$

$$\begin{aligned} &\text{subject to } \mathbf{i} = \mathbf{Y}\mathbf{v}, \text{and} \\ &V_i I_i^* = P_i - P_{\ell,i} + \mathrm{j}(Q_i - Q_{\ell,i}), && \forall i \in \mathcal{N}_D \\ &V_n I_n^* = -P_{\ell,n} - \mathrm{j}Q_{\ell,n}, && \forall n \in \mathcal{N}_O \\ &V^{\min} \le |V_i| \le V^{\max} && \forall i \in \mathcal{N} \\ &\mathbf{u}_i \in \mathcal{Y}_i && \forall i \in \mathcal{N}_D \end{aligned}$$

- Dual gradient method

$$L(\mathbf{V}, \{\mathbf{u}_i\}, \{\boldsymbol{\lambda}_i\}) := H(\mathbf{V}) + \sum_{i \in \mathcal{N}_D} G_i(\mathbf{u}_i) + \sum_{i \in \mathcal{N}_D} \boldsymbol{\lambda}_i^{\mathsf{T}} (\mathbf{h}_i(\mathbf{V}) - \mathbf{u}_i + \mathbf{d}_i)$$

$$\boldsymbol{\lambda}_i[k+1] = \boldsymbol{\lambda}_i[k] + \alpha_{k+1} (\mathbf{h}_i(\mathbf{V}[k]) - \mathbf{u}_i[k] + \mathbf{d}_i)$$

$$\mathbf{u}_i[k+1] = \arg\min_{\mathbf{u}_i \in \mathcal{Y}_i} G_i(\mathbf{u}_i) - \boldsymbol{\lambda}_i^{\mathsf{T}}[k+1]\mathbf{u}_i$$

$$\mathbf{V}[k+1] = \arg\min_{\mathbf{V} \in \mathcal{V}} H(\mathbf{V}) + \sum_{i \in \mathcal{N}_D} \boldsymbol{\lambda}_i^{\mathsf{T}}[k+1]\, \mathbf{h}_i(\mathbf{V})$$

- SDP relaxation of the OPF problem

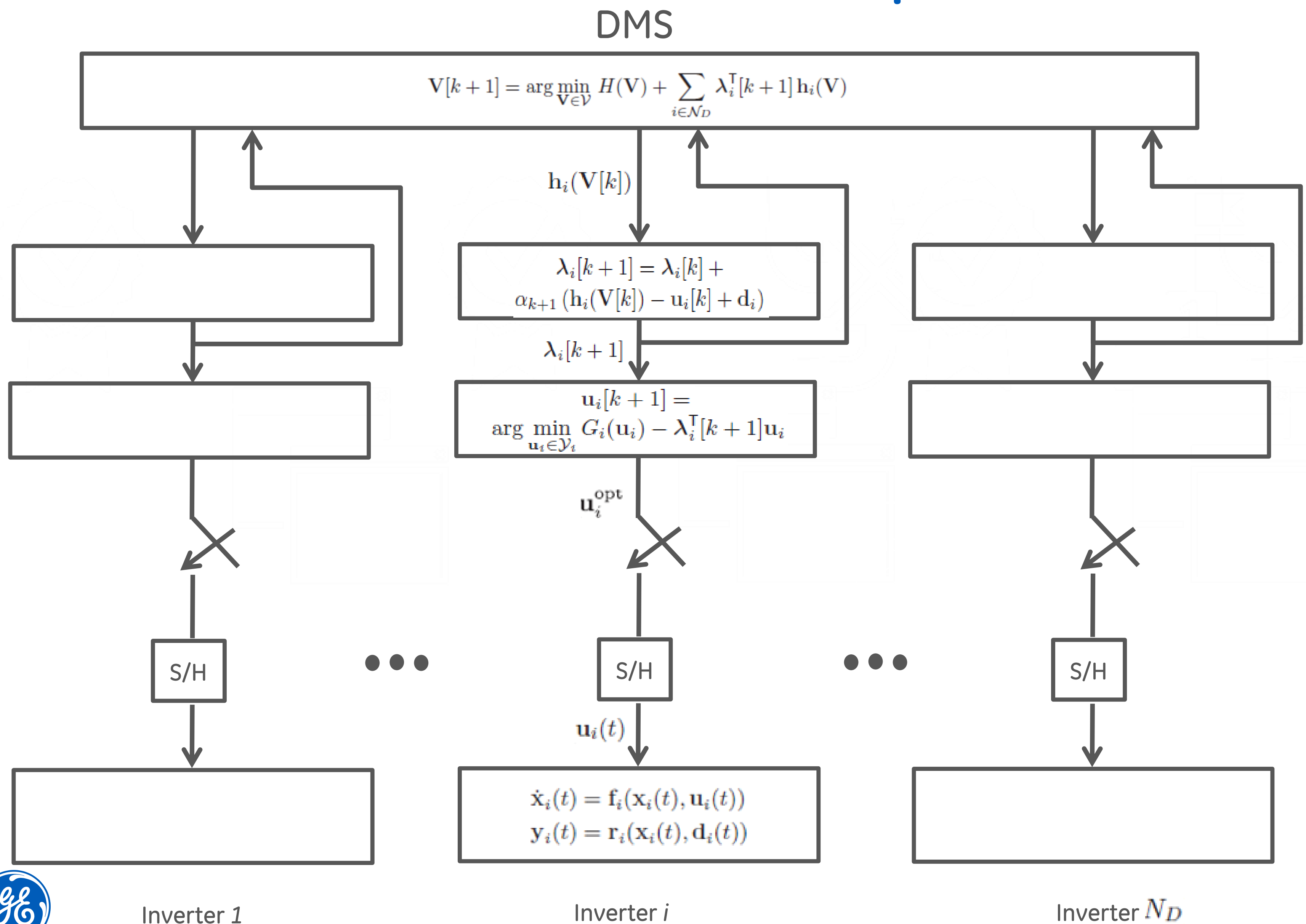
$$\begin{aligned} \min_{\mathbf{V} \in \mathcal{V}, \{\mathbf{u}_i \in \mathcal{Y}_i\}} \; & H(\mathbf{V}) + \sum_{i \in \mathcal{N}_D} G_i(\mathbf{u}_i) \\ \text{subject to } & \mathbf{h}_i(\mathbf{V}) - \mathbf{u}_i + \mathbf{d}_i = \mathbf{0}, \; \forall i \in \mathcal{N}_D \\ & \mathrm{rank}(\mathbf{V}) = 1. \end{aligned}$$

$$\mathbf{u}_i = [P_i, Q_i]^{\mathsf{T}}$$

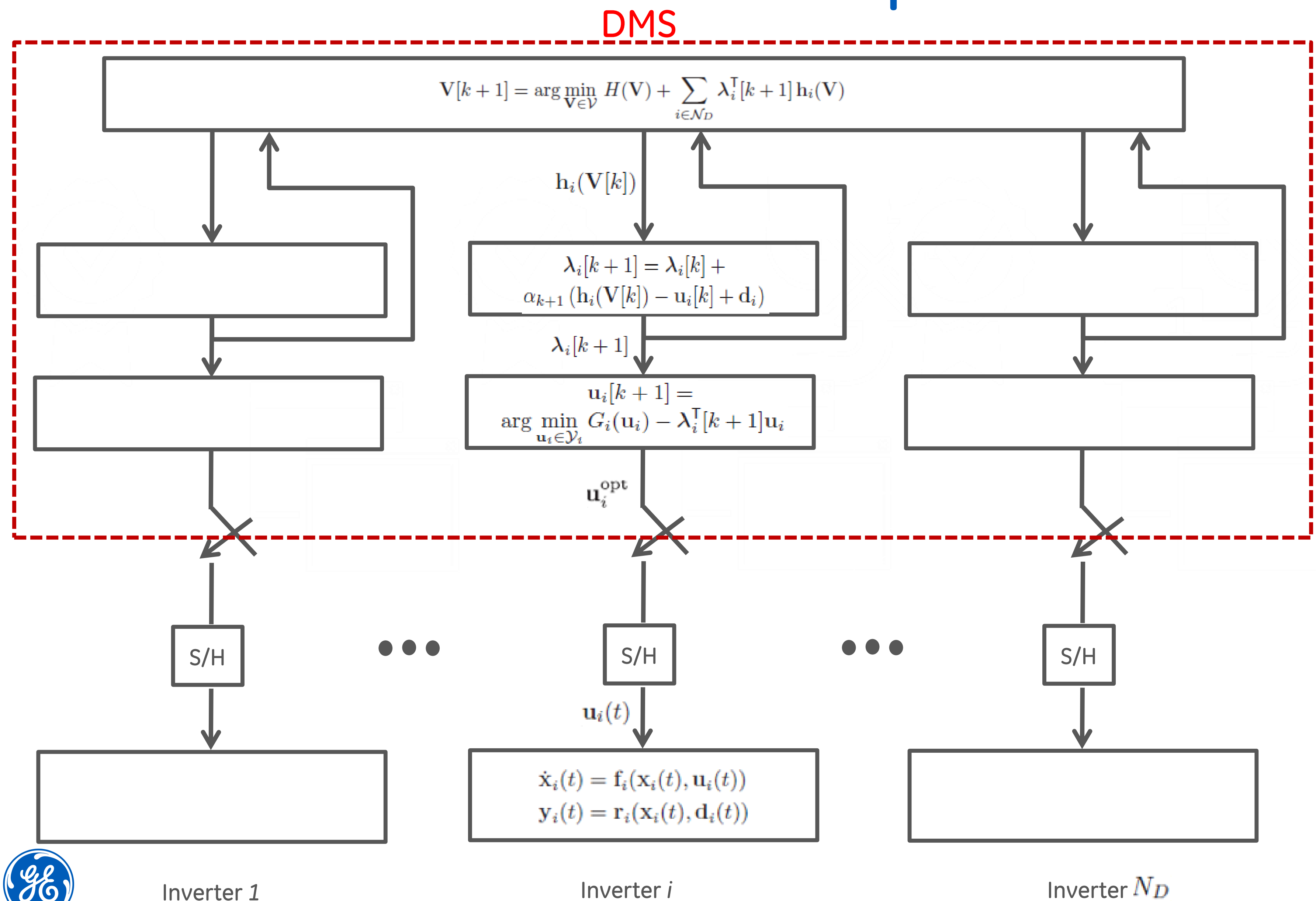
$$\mathbf{V} := \mathbf{v}\mathbf{v}^{\mathsf{H}}$$

$$\mathbf{d}_i = [P_{\ell,i}, Q_i]^{\mathsf{T}}$$

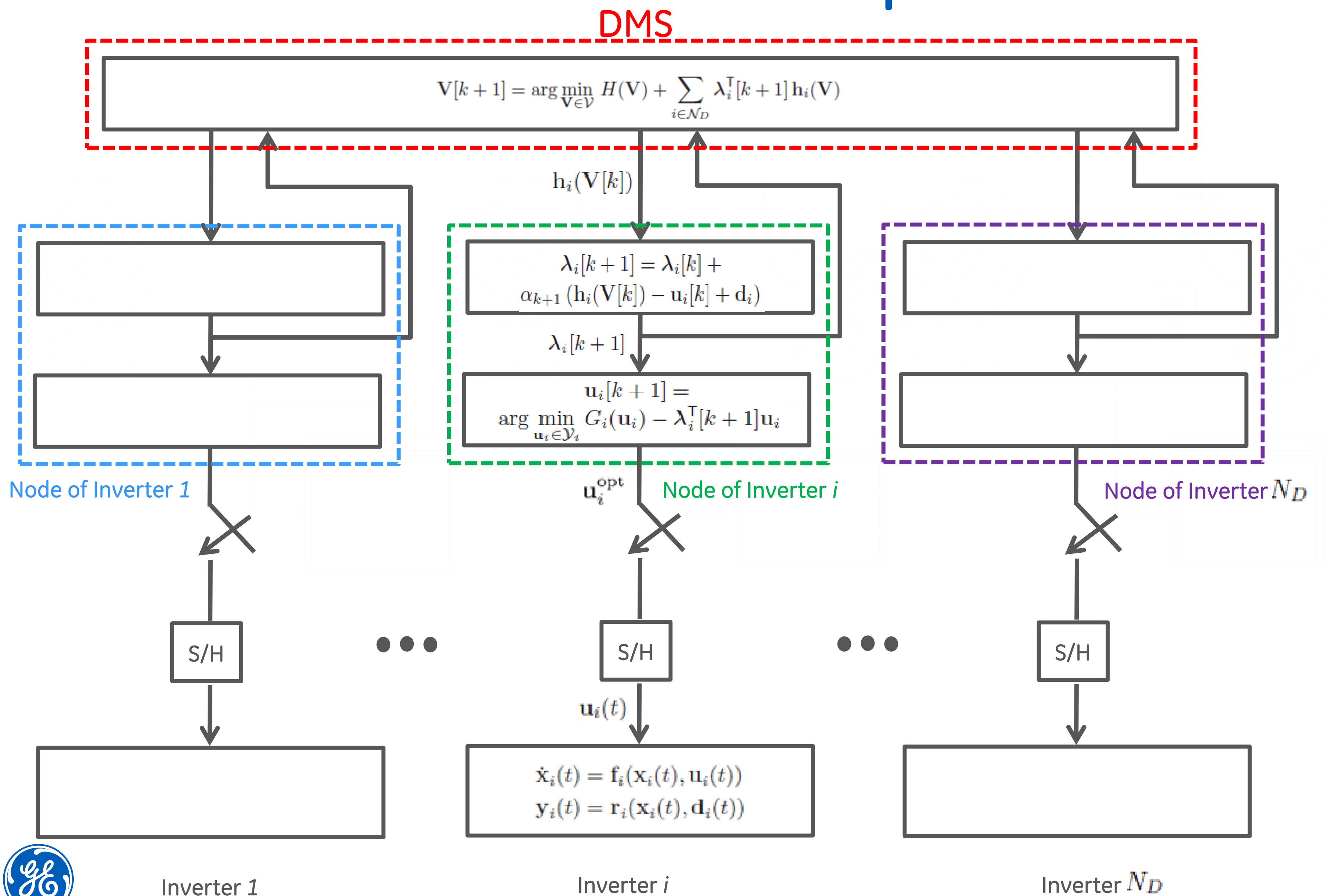
# Conventional Distributed Optimization



# Conventional Distributed Optimization

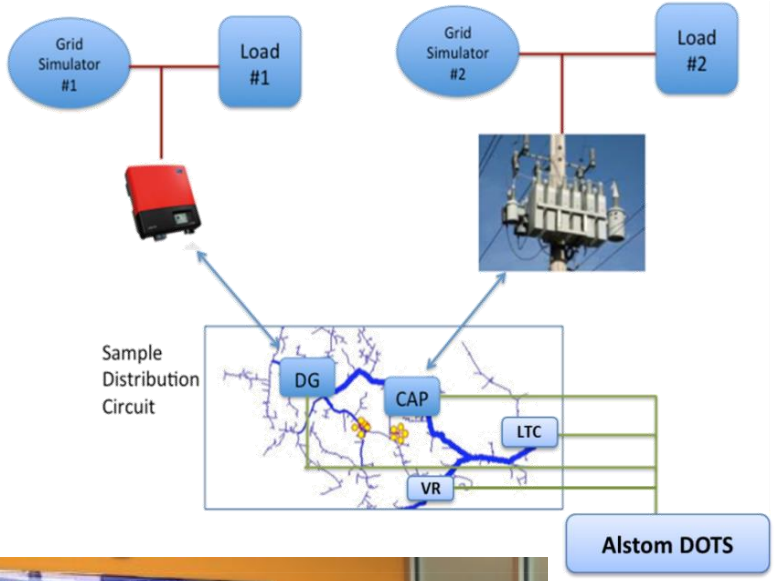


# Conventional Distributed Optimization



# Duke, NREL, & GE: Operational Impacts of Hi-Pen PV

**Summary:** Detailed system modeling, combined with Power-Hardware-in-the-Loop verification to compare local vs centralized management of voltage with utility-scale inverters in Duke territory




**Simulation**

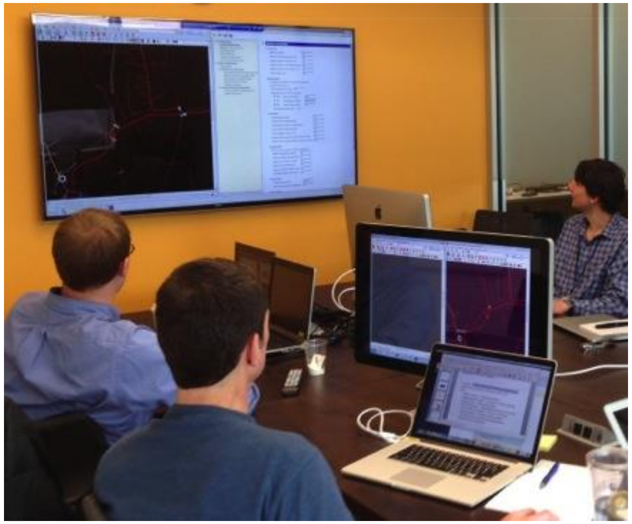
- Simulation using actual DMS system deployed at Duke (via GE's ***e-terra*** Distribution Operations Training System (DOTS))
- GE has enabled faster than real-time time series analysis and supports advanced inverter modeling through Python
- Simulation for:
  - Baseline: PV active power only
  - Local Control: PV Volt/VAr modes
  - Central control: GE IVVC application

**Power Hardware-in-the-Loop (PHIL) in ESIF**

- Co-simulation with DOTS to capture entire feeder
- Validate simulations: actual hardware at power
- 500kVA advanced inverter
- Utility voltage control (e.g. Cap Bank)

**Cost-Benefit Analysis**

- Compare operational cost impacts across scenarios
- Work closely with Duke for input and assumptions



# Distributed Technologies

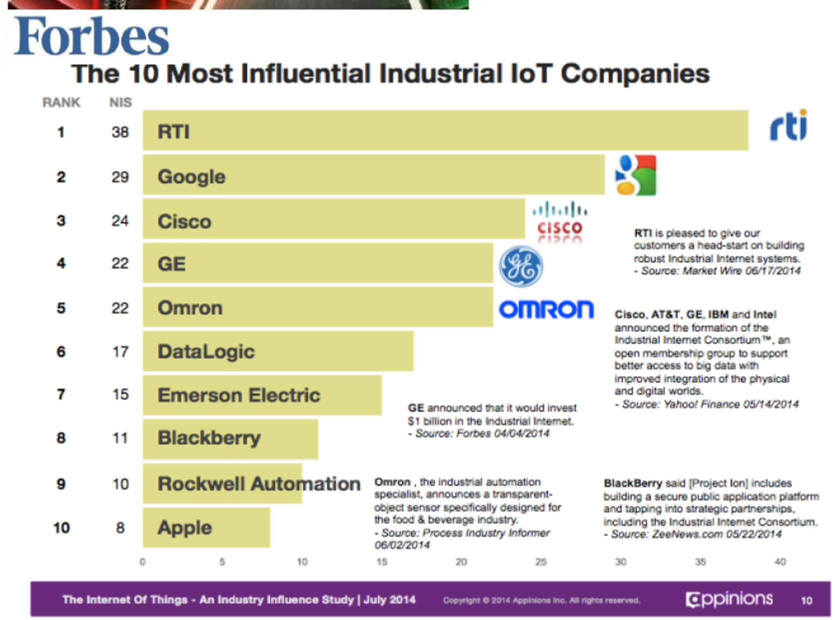
# Industrial Internet of Things (IIoT)

…the "Industrial Internet" <will> start the next Industrial Revolution.

Joe Salvo, GE


IIoT – machines, computer and people, enables intelligent industrial operations

The IIoT needs an architecture that spans industries and unites sensor to cloud.

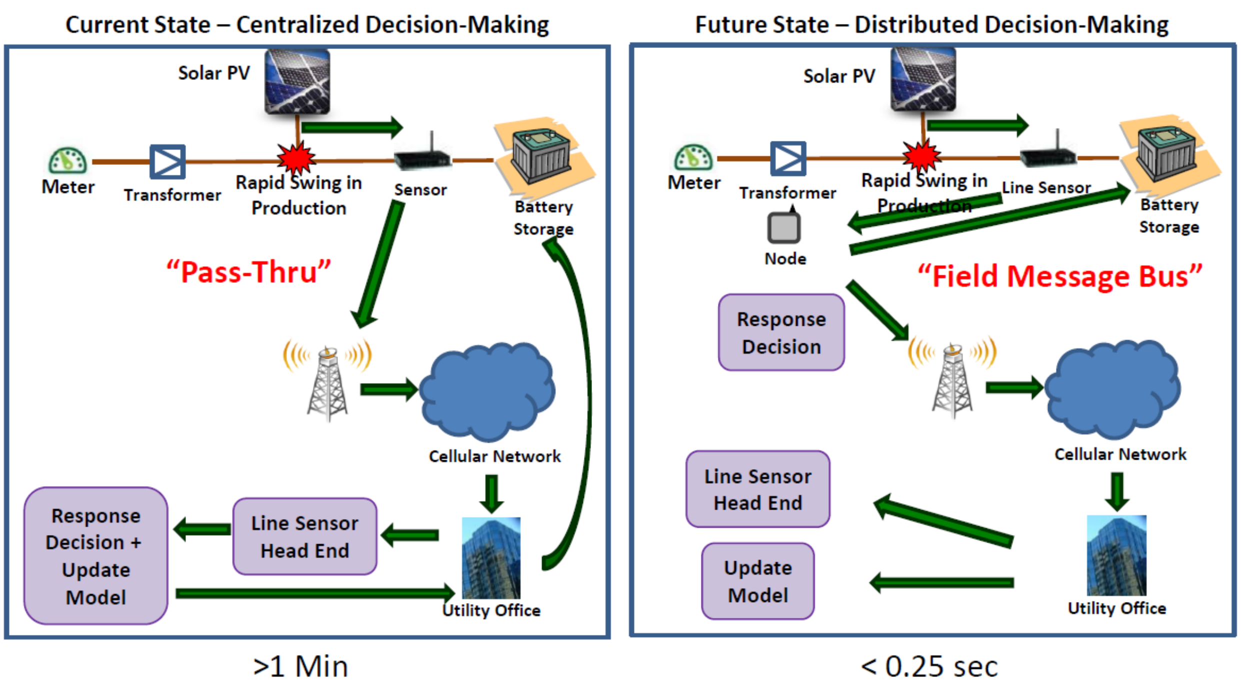



The IIoT will transform many industries, including

- Manufacturing
- Energy and Power
- Oil and gas
- Agriculture
- Mining
- Transportation
- Healthcare, etc.

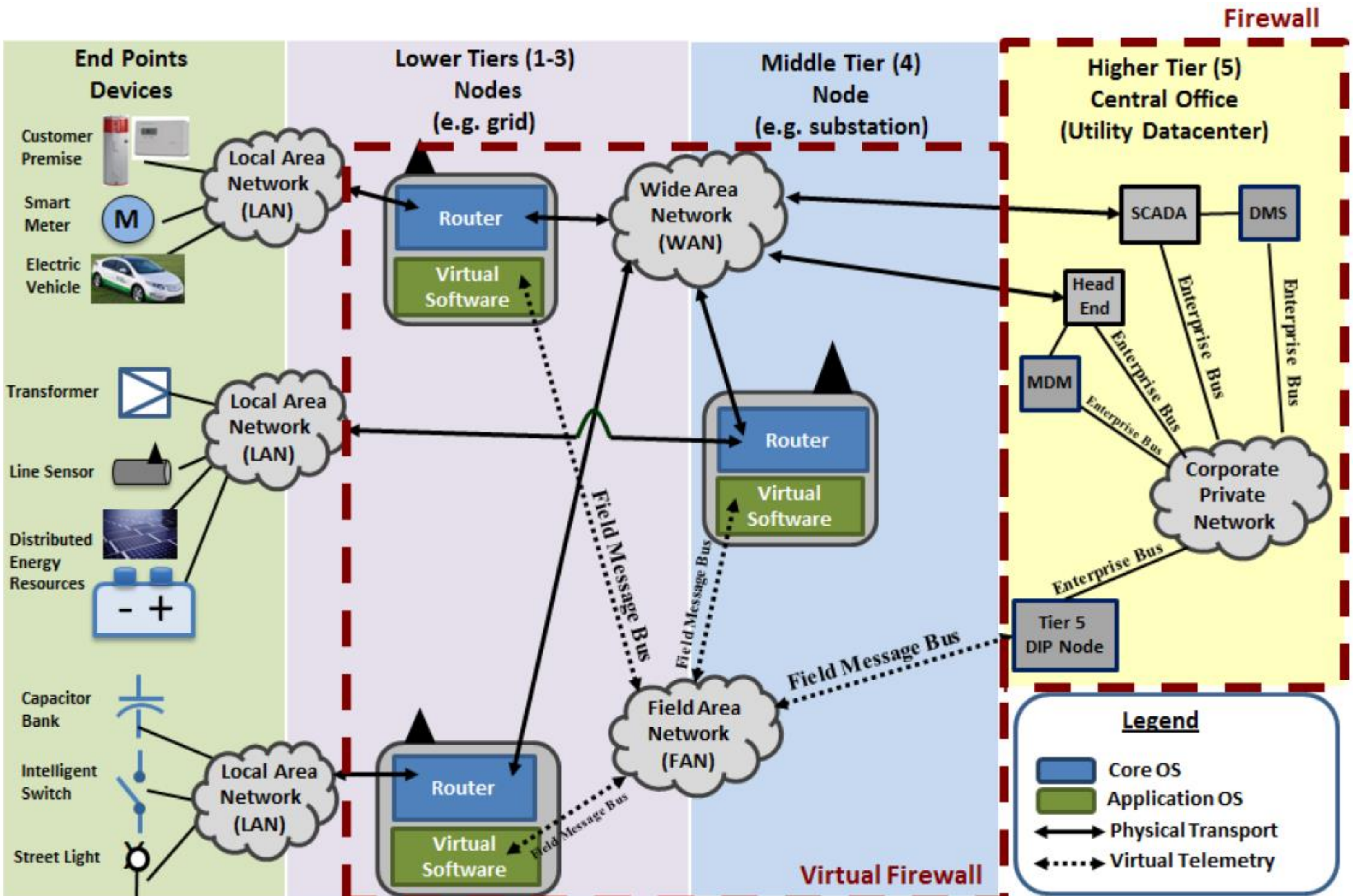
# Intelligence at the Edge for Utility Operations

- Issues with centralized decision-making:
  1. Never have enough bandwidth on IIoT platforms to effectively backhaul all the data to a centralized point.
  2. Latency to do most data processing and make decisions far from the edge is too high for many applications.
- Doing data processing as close to the collection point (node) as possible and allowing system to make some operational decisions there possibly semi-autonomously.



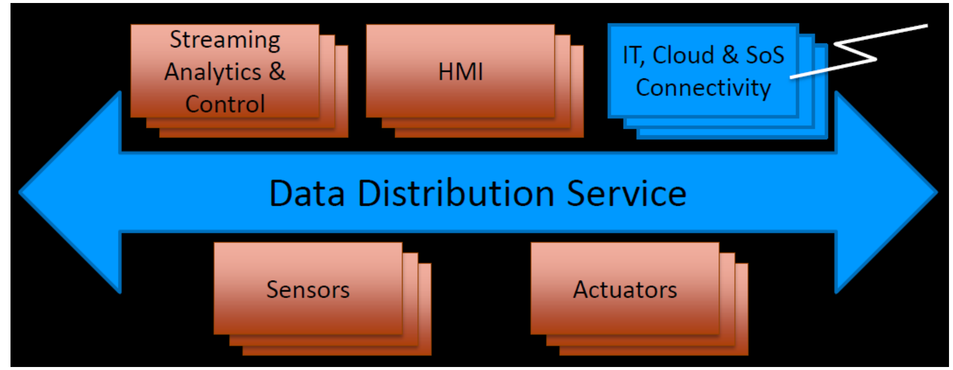
# Distributed Intelligence Platform (Duke Energy)

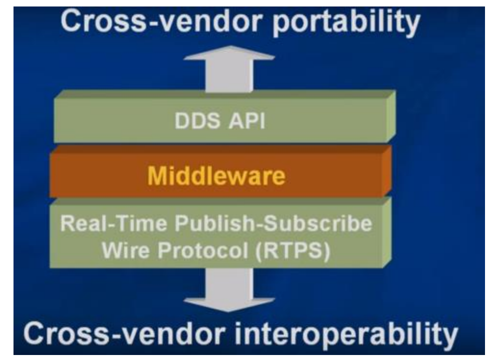
## *Reference Architecture*

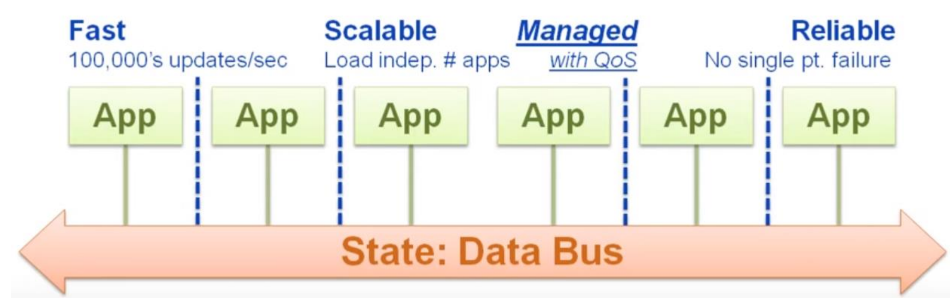


# Data Distribution Service (DDS)

- DDS is networking middleware that simplifies complex network programming.
- DDS handles transfer chores: message addressing, data marshalling and demarshalling.
- DDS implements a publish/subscribe model for sending and receiving data, events, and commands among the nodes.
- DDS has a data-centric architecture.
- DDS is decentralized.
- DDS avoids single point of failure with distributed peer-to-peer technology.
- DDS monitors and governs data delivery quality of service (QoS).



# Final Remarks

- The current state-of-the-art centralized communication and information processing architecture will no longer be sustainable for IIoT and smart grid.
- Distributed technologies have an important role in addressing the challenges of grid modernization with high penetration of DERs.
- Advances of distributed optimization in both hardware and software are required in order to realize the grid of the future.
- A hybrid, of both centralized and decentralized, information system uses advanced telecommunications (wired & wireless) to bi-directionally network operational technology devices.

# Power Industry Transformation

*Past, Present, Future*

## Classic Utility

- Vertically integrated
- Cost-based operation
- Physical infrastructure

Reliable

## Competition

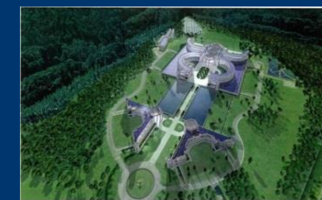
- Open transmission access
- Genco divestiture
- Wholesale electricity market

Reliable & Affordable

## Smart-Grid

- Distributed intelligence
- Service valuation
- Prosumer choices

## Smart City



- Sustainability
- Resiliency
- Connectivity

Reliable, Affordable & Sustainable

1980 1990 2000 2010 2020

# References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