A New Industry: Electric Power and Light

- Edison opened his first electric power plant in New York in 1882. *Was it a microgrid?*
- Within a decade, electric power had spread to every corner of the globe, with many new applications!
- Why was the grid interconnected throughout the years?

*Future: Distributed vs. Centralized Generation?*

*Role of Synchronized Measurements*
If Edison and Tesla Returned…
Arun Phadke and Jim Thorp - Joint Franklin Award Recipients

“Working in a team, does not reduce contribution and importance of an individual; it makes it much stronger”

Life Has More Light With Arun, Jim & PMUs

$\theta_2 = \theta_1 + k\phi$
Need for Phase Angle Monitoring and Control

Needs:
- Provide operators with real-time angle and angle change
- Avoid incorrect out-of-step operation
- Improved planned power system separation

Benefits:
- Improved real-time awareness, incl. neighboring systems
- Improved out-of-step tripping and blocking
- Separate the system on most-balanced way
- Assist operator during manual reclosing of tie lines

Technology:
- Synchrophasor visualization tools
- Advanced algorithms using wide-area information
- Smart algorithms for instability and coherency detection, separation boundary identification

Gap:
- Operator acceptance, incorporation in the utility/ISO process/rules
- System studies and testing

Source: TVA
• Resynchronization attempts:
  • [7]: difference of 180mHz and 10 degrees
  • [8]: difference of 40mHz
• System re-established in 2 hours
WECC and EIPP Synchronized Phasor Network - 2005

EIPP PMU Companies*


- 57 connected PMUs

* PMU Companies
EIPP PMU Map - 2006

Early 2006

Late 2006
NASPI PMU Map - 2012

NASPI PMU Map - 2016

All PMUs displayed are connected to their local network.

Major data paths for sharing information among operating entities are shown.
NASPI Task Teams List - 2007
NASPI PSTT Activities and Goals

2008

- PMU Hardware
  - PMU Testing And Calibration
  - Phasor Accuracy
  - Define PMU
  - PMU Maintenance
  - IED PMUs
  - PMU Comm. Test
  - IEC 61850 for PMU
  - “Dynamic” Phasor
  - Advanced Applications & Deployment
- Phasor Network
  - Network Connection
  - System Deployment Requirement
  - Phasor Tools Techniques
  - HW & SW Upgrade
- Operations
  - Phase Angle Reference
  - Req’t for Visualization
  - Req’t for State Estimation
  - Phase Mapping
- Phasor Data
- PMU/PDC Hardware
- Phasor Network
- PMU Testing And Calibration
- Phasor Accuracy
- Define PMU
- Commissioning & Maintenance
- IED PMUs
- PDC Functions
- PDC Testing
- IEC 61850 for PMU
- C37.118 for “Dynamic” Phasor
- Advanced Applications & Deployment
- Advanced Applications & Deployment
- Performance Matrix
- Phasor Tools Repository
- PSTT-IEEE Standard Development
- Network Configuration
- Network Testing
- Naming Convention
- Cyber Security Std for Phasor
- Phasor Repository
- Phasing Survey
- Phase Mapping

2011

- Accompished
- Ongoing
- Ongoing 2008 Goals (High Priority)
- Ongoing 2011 Goals (High Priority)
- Format & compression std
- Network Configuration
- Network Testing
- Naming Convention
- Cyber Security Std for Phasor
- Phasor Repository
- Phasing Survey
- Phase Mapping
- *Coordination with DNMTT
NASPI/IEEE/IEC Developed Standards and Guides

### Standards and Guides

**Communication standards**
- IEEE C37.118.2-2011
- IEC 61850
- IEEE C37.118.2-2023
- IEEE P2664 (STTP)

**Data storage standards**
- IEEE C37.111 COMTRADE

**Timing standards**
- IEEE 1588 with IEEE C37.238 or IEC 61850-9-3

**Measurement standards**
- IEEE C37.118.1
- IEEE/IEC 60255-118-1

**Substation PDC**

**Installation, calibration, test guide**
- IEEE C37.242

**Phasor data concentrator**

**Other utility PDC**

**Future Needs**

- Beyond phasors – synchronized waves/samples/point-on-wave
- Using Data Analytics with synchronized measurements
- Addressing IBRs
- Updating existing standards and guides for new applications
- ??

**Third-party EMS**

**Applications**

**Data storage**

**Data storage standards**
- IEEE C37.111 COMTRADE
NASPI Transmission PMU Roadmap 2007 - Past Results 16 Years Later – Present

- Developed based on CEC and DOE PMU benefit-cost analysis project
- Served as a blueprint for successful transmission PMU deployment

- Angle/frequency monitoring
- Post-event analysis (including compliance monitoring)
- Voltage stability monitoring
- Thermal overload monitoring
- Improved state estimation
- Steady-state model benchmarking
- DG/IPP applications
- Power system restoration

**Short-term**
- Congestion management
- Dynamic model benchmarking
- Planned power system separation
- State estimation (boundary conditions)

**Mid-term**
- Linear state measurement
- Real-time control
- Adaptive protection
- WA-PSS stabilization

**Long-term**

- Synchronized measurements value:
  - Necessary and critical
  - Critical with added benefits
  - Moderate need, added benefits
  - Requires more investigation

- Deployment challenge:
  - Presently deployed
  - Limited deployment
  - Requires more investigation

Source: NASPI
Distribution Synchronized Measurements – Present and Future

DissTT 2020 Synchronized Measurements and their Applications in Distribution Systems

DOE 2021 Distribution Synchronized Measurements Roadmap

AG13: Advanced microgrid applications and operation
AG11: High-accuracy fault detection and location
AG2: Advanced monitoring of distribution grid
AG14: Improved load shedding schemes
AG4: Wide area visualization

AG6: Real-time distribution system operation
AG5: DER integration and control
AG12: Advanced distribution protection and control
AG10: Improved stability management
AG16: Technical and commercial loss reduction
AG8: Advanced distribution system planning
AG19: Power quality assessment and analysis
AG1: AVVC

AG7: Enhanced reliability and resilience analysis
AG15: Advanced distribution automation
AG3: Asset management of critical infrastructure
AG17: Monitoring & control of electric transportation infrastructure
AG9: Distribution load, DER, and EV forecasting
AG18: Integrated resource, T&D system planning and analysis

Synchronized measurements:
- Provide added benefits for moderate applications
- Provide added benefits for critical applications
- Are necessary for critical applications

Deployment challenge:
- LOW
- MED
- HI

Short-term | Mid-term | Long-term
Systems with Inverter-based Resources (IBR) – Present and Future

Transformation from a few hundred large-scale, dispatchable generation resources to a system involving a large number of DERs located on the traditional “supply” and “demand” sides of the system, not fully visible to the operator.

- ERCOT Solar resource loss May 9, 2021
- Southern California Solar resource loss August 2016

Loads and IBRs need to participate in coordinated control by providing network regulation and flexibility services.

Fundamental changes in T&D planning, operation, protection, control, and monitoring:

- Need for integrated resource and T&D planning and operations
- Distribution networks no longer passive loads:
  - Drastically changed daily load curve, including effects of EV charging infrastructure
  - Weather conditions have major impact on both consumption and generation
  - Circuits with very different dynamic characteristics
  - Increased significance of near real-time communications
- Dynamic analysis requires accurate models – Digital Twin and EMT modeling
- Exponential growth of interconnection requests:
  - Hosting capacity maps are becoming a requirement
  - Need for creating a headroom for future renewable requests
Technology Solutions to Address Systems with Large Penetration of IBRs – *Present and Future*

Inverter-based resources ➔ Less inertia ➔ Things happen faster!

Enabling the electric grid to integrate new resources (DR and storage) and EV charging while improving the utilization of existing assets

- Faster monitoring and controls of DERs and energy storage addresses dynamic changes with IBRs and improving situational awareness for the safe, secure, and reliable operation of modern grids
- Sensors and tools for situational awareness and condition assessment:
  - Synchronized measurements
  - Power Quality and GIC monitors
  - Equipment monitoring (transformers, switchgear, etc.)
  - Drones
  - Etc.
- Adaptive protection for low fault currents and dynamic system changes
- T&D power flow and market models to handle widespread integration of DER and energy storage
- Analysis tools and models (i.e., weather forecasting, dynamic security assessment, electric, gas, and communication interdependencies, etc.)
- Microgrids to address resilience and decarbonization
- Communications infrastructure with the necessary speed and latency

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**Frequency decay for loss of 1,000 MW**

![Frequency decay graph](image)

Source: IEEE/NERC report on Impact of Inverter Based Generation on Bulk Power System Dynamics and Short-Circuit Performance

**Frequency excursions:**
Rate-of-change-of frequency proportional to inertia

\[ \Delta P = -k_{in} \frac{df}{dt} \]
Impact of IBRs – Present and Future

<table>
<thead>
<tr>
<th>Key Consideration</th>
<th>System Aspects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power ramping</td>
<td>High up and down intermittent “not forecast” power ramps can affect control area performance.</td>
</tr>
<tr>
<td>Low system inertia</td>
<td>High rate of change of frequency following a large loss causes resources to trip due to reduced synchronizing torques. Underfrequency relays respond to low frequency by tripping the load. The speed of system events is faster than the ability of protection system.</td>
</tr>
<tr>
<td>Low reserves</td>
<td>Renewables operate at maximum power tracking and do not leave headroom for reserves.</td>
</tr>
<tr>
<td>Low fault current levels</td>
<td>Ability of protection systems to detect faults.</td>
</tr>
<tr>
<td>Low short circuit ratio (weakened grid)</td>
<td>Instability in inverter controls (phase-locked loop synchronization and low-frequency oscillations) Challenges to inverter ride through and islanding Voltage flicker (especially in distribution feeders) Difficulty of voltage control due to high voltage sensitivity to reactive power changes (i.e., dV/dQ) Difficulty in energizing large power transformers</td>
</tr>
<tr>
<td>Low damping of system oscillations</td>
<td>Synchronous machines have rotor dampers. Use of grid-forming inverters and inverter control settings for mitigation</td>
</tr>
<tr>
<td>Voltage and power fluctuations</td>
<td>Intermittent renewables cause fluctuations in system voltages, especially when the grid short circuit current is low. Ensure compliance with IEEE 1453, &quot;Recommended Practice for the Analysis of Fluctuating Installations on Power Systems, for flicker.</td>
</tr>
<tr>
<td>Black start</td>
<td>Ability to restart a system with predominantly IBRs.</td>
</tr>
<tr>
<td>Scale and integration</td>
<td>IBRs tend to be smaller and distributed throughout a cross section of high-voltage, medium-voltage, and low-voltage distribution systems. Challenges for power system operators to integrate customer-owned IBRs</td>
</tr>
</tbody>
</table>

Properly designed automated control and protection can exploit:

- The fast response of IBRs
- Wide Area Monitoring Protection and Control (WAMPAC) data and actions
- Improving grid reliability and resilience

Unexpected consequences – Global blackout experiences and preventive solutions
Implementation Examples: Present

**CAISO** - Tracking overvoltages to address the drastic climate swings

**SDG&E** – Real-time situational awareness
LSE POM Server and Contingency analysis
Visual Client
Implementation Examples: Present

**NYISO** - PMUs grouped by electrical load zones and neighboring regions to reflect expected coherent generation response. [Source: http://readme.readmedia.com/officials-celebrate-nyisos-new-power-control-center/8437753]

**SwissGrid** - Hosting a WAMS application where the power system frequencies and angle differences of grid operators from Austria (APG), Denmark (Energinet.dk), Portugal (REN), Slovenia (ELES), Croatia (HEP), Italy (TERNA) and Greece (IPTO) are monitored. [Source: https://www.swissgrid.ch/swissgrid/en/home/reliability/wam.html]

**Inertia Metering & Forecasting**

*Control Room Operational Awareness*

- **Inertia Metering**
  - Pure WAMS sensing

- **Inertia Forecast**
  - Machine Learning Model from Grid Analytics
Distribution Implementation Example: Present

**Linear State Estimator for Increased Situational Awareness and Resilience**

**ComEd:** Solves 3 phase unbalanced DLSE
Bad data detection, correction, alarming and reporting
Observability analysis
Detection of switching events (only on PMU data)
Real-time system monitoring (voltage and thermal)
Distribution Implementation Example: Present and Future

Present - Fallen Conductor Protection

Deenergize the conductor before it hits the ground:
• Break isolated in 200–500 ms
• Avoids high-impedance fault arcing and fire risk
• In service since 2016
• SDG&E planning 70 circuits by 2023 and 135 by 2028 and deploying next-generation wideband Ethernet radio system using private cells

Future

Five top-priority application groups use synchronized measurements at medium cost with high benefit:
• High-accuracy fault detection and location
• Advanced microgrid applications and operation
• Advanced monitoring of distribution grid
• Improved load-shedding schemes
• Wide-area visualization

Mid-tier application groups with high benefits needing more development effort:
• Advanced distribution protection and control
• Real-time distribution system operation
• DER integration and control
**WAMPAC Monitors Sources and Communicates with Battery Energy Storage System (BESS) Units – Future**

- BESS units regularly inform WAMPAC of their capability.
- Upon detecting sudden imbalance $(-\Delta P) \Rightarrow$ WAMPAC instructs each BESS to inject $\Delta P_i$ so that $\sum_i \Delta P_i = +\Delta P$
- Comments:
  - Max $t_{\text{delay}}$ is due to long-distance communications and coordination of multiple devices.
  - Detects several events, but list of events is limited by WAMPAC coverage.
Distributed Sensors Offer New Options for an Evolving Grid – Past, Present, and Future

Inputs and Tools:
- IEDs (e.g., digital relays, digital reclosers, capacitor bank controllers)
- Synchronized measurements
- PQ meters
- IEC 61850 network data
- Field sensors (e.g., FCIs, line sensors)
- Smart meters and AMI headend systems
- SCADA, GIS, and Lightning data
- LIDAR/satellite imagery
- System model
- Protection settings
- Artificial Intelligence/Machine learning

Data Analytics:
- Event analysis
- Fault location
- Grid situational awareness and modeling (T&D)
- Model and Settings validation
- 61850 network monitoring
- Compliance
- Asset monitoring, predictive maintenance
- Dynamic ratings
- Reliability and resilience indices and metrics
Marching Towards The Future

Protection & Control
- Taking offline-calculations determined (re)actions
- Taking adaptive (re)actions based on online assessment
- Taking actions based on online predictions

Real-Time Operation
- Threshold alarms, SA for slow (re)actions
- Intelligent event alarms, SA for faster (re)actions
- Early warnings, SA for proactive/preventive actions

Data Analytics
- Hindsight
  - Descriptive
- Insight
  - Diagnostic
  - Discovery
  - Predictive
  - Prescriptive
  - Cognitive
- Foresight

Other Data
- Fuel Supply +Lightning/Storm/Fire/Earthquake/Vegetation/
- +Temp/Wind/Sunlight/Water/

System Data
- PMUs +IEDs/DFRs/DRRs/Meters/PQMeters/Sensors/
- +SMUs

Carbon Emission
- > 90%
- <70%
- <30%
- Net Zero
Synchronized Measurement Evolution

**Past**
- First PMU
- Analog displays

**Present**
- Standard features (relays, DFR, controllers, monitors)
- On major interconnections and generators
- Standard software tools included in EMS/SCADA
- Primary use for monitoring and event analysis but deployed for control
- Interoperability standards deployed
- Distribution PMUs expanding due to DER
- Improvements in communication infrastructure

**Future (2030)**
- Extensively deployed in Transmission
- Integrated in standard business and operational practices
- Integrated with EMS/SCADA
- Higher data rates
- Deployed in Distribution
- Distributed communications and processing architecture
- Fast control and adaptive protection
Solutions for the Energy Future

A resilient, modern electric grid is the foundation for our clean energy future, requiring renewables, energy storage, energy efficiency, and electrification.

Electricity is key for achieving societal and economic goals, such as decarbonization and growth:
- Demand for electricity increases electrification and fuel transformation
- Need for clear and balanced societal and regulatory policies

Essential factors for a resilient grid to protect against and recover from any event that would significantly impact the grid:
- Technology advancement
- Educated and diverse workforce
- Standards and sharing global best practices

Coordinated resource and T&D planning and operations for investment prioritization:
- Load, DER, and electrification forecasting
- Accurate system and equipment modeling
- Scenario planning
- Risk- and probabilistic-based investment decisions

Importance of diverse generation mix for uncertainties

Automated and Adaptive Monitoring, Protection, and Control: Synchronized Measurements
Coordinated Planning – Tools and Processes
Digital Transformation through Automation - Single Data Source
Long-Term Storage
Synthetic Gas
Small Modular Reactors
Hydrogen
...

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