Data and Analytics Extra Info: GMLC Sensors and Measurement Roadmapping Activity
Grid Modernization Laboratory Consortium

PROJECT 1.2.5: SENSING & MEASUREMENT STRATEGY

TASK 2: TECHNOLOGY ROADMAP DEVELOPMENT Technology Roadmap Slides: 3/27/2017 Draft

First Draft Submission to DOE for April 1st, 2017 Milestone
DESCRIPTION OF CONTENT:

These slides represent the first draft Technology Roadmap for the GMLC 1.2.5 Sensing & Measurement Strategy project that is due to DOE for review and comment on or before April 1st, 2016. This content is being developed by a broad team spanning the DOE national laboratory system as described in more detail in the project fact sheet with strong input and engagement from utilities and other industry stakeholders. Additional information and a list of references can be found in the corresponding Technology Review & Assessment Document developed and submitted to DOE on 9/30/2016.

CONTEXT FOR DISTRIBUTION:

The content within this draft will be refined and improved moving into future project years through strategic engagements with technical subject matter experts, utilities, and other stakeholder partners. Stakeholders are encouraged to send along detailed feedback and suggestions directly to Paul Ohodnicki (paul.ohodnicki@netl.doe.gov), Task 2 Roadmapping Activity Lead and Sensing & Measurement Project Co-PI as well as Tom Rizy (dtom@ornl.gov), Sensing & Measurement Project PI.

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## Technology Roadmap Development Process to Date

<table>
<thead>
<tr>
<th>Project Year 1</th>
<th>Project Year 2</th>
<th>Project Year 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develop Initial Draft of a Technology Review Assessment Document for DOE.</td>
<td>Improve Integration of Roadmap Documents with Extended Grid State Definition.</td>
<td>Further Develop Roadmap Content within Each Identified Focus and Thrust Area Including Gap Analysis.</td>
</tr>
<tr>
<td>(Due: 9/30/2016)</td>
<td>Establish Working Groups to Further Develop Roadmap Content within Each Identified Focus and Thrust Area Including Gap Analysis.</td>
<td>Hold an Annual Stakeholder Meeting to Discuss and Provide Feedback.</td>
</tr>
<tr>
<td>Develop an initial Roadmap Document Incorporating Stakeholder Feedback &amp; Input.</td>
<td>Hold an Annual Stakeholder Meeting to Discuss and Provide Feedback.</td>
<td>Refine, Revise, and Update Roadmap and Technology Assessment Documents.</td>
</tr>
<tr>
<td>(Due: 4/1/2017)</td>
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<td>(Due: 4/1/2019)</td>
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</tbody>
</table>
Organizing the Technology Roadmap

Mission

Drivers

Visibility of Extended Grid State

Initial Review Draft Development → Organize Based on (Devices, Communications, Data Management & Analytics) and Application Domains Consistent with 1.4.4 Sensor Development Project

Ultimate Goal → Map Research Thrusts / Focus Areas to Needs Identified by the Extended Grid State Definition

Low cost sensing, communication, and data management solutions that meet the needs of a future modernized electricity grid.

Modernized Electrical Grid That Balances Six Attributes:
- Reliable
- Secure
- Affordable
- Flexible
- Resilient
- Sustainable

1. ELECTRICAL STATE
2. TOPOLOGICAL STATE
3. COMPONENT STATE
4. BUILDING STATE
5. AMBIENT STATE
6. CONVERGENT NETWORK STATES
Technology Review and Assessment Document

**Devices**

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Application Domains Aligned with Sensor Development 1.4.4 Project

Conventional Generation Sensing for More Flexible Operation

Renewable Generation Sensing and Weather Monitoring

T&D System Power Flow and Grid State Monitoring

Asset Monitoring and Fault Diagnosis

End-Use / Buildings Monitoring for Responsive Loads
High-Level Findings of the Technology Review

Cross-cutting Findings Spanning the Application Domains

(1) Needs exist for advanced instrumentation at centralized generation and transmission levels, but a relative lack of visibility exists within the distribution system.

(2) The “per unit” value of a comparable sensor installed and deployed on the distribution system or at the end-user level is dramatically lower than the corresponding transmission level. Enhancing visibility in the distribution system and at the end-user level requires advances in (1) low-cost and (2) multi-function or multi-parameter sensors.

(3) Standards and interoperability will be an important aspect of new sensing and measurement device development and deployment.
Harsh-environment instrumentation relevant for conventional thermal-based generators (fossil, nuclear, etc.) could help to enable more flexible operation and minimize long-term impacts of cycling and ramping on plant longevity and efficiency.

Capabilities of existing automatic generation controllers (AGC) and associated sensing and measurement devices should be evaluated in terms of the potential for new technology innovations.
High-Level Findings of the Technology Review

Renewable Generation Sensing and Weather Monitoring

Weather monitoring and forecasting technologies exist at high technology readiness levels (TRL) for predicting renewable generation (solar, wind, etc.), and innovations often involve adaptation of mature sensing technology developed in other fields.

Emerging trends include data management and application of unmanned aerial vehicles and lidar-based techniques.

<table>
<thead>
<tr>
<th>States/Parameters</th>
<th>Directly measured or calculated from measurements</th>
<th>Sensors/meters required</th>
<th>Description and Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed</td>
<td>Measured</td>
<td>Anemometers or lidar remote wind sensors</td>
<td>Measures the resource available for wind turbines</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Measured</td>
<td>Thermocouples</td>
<td>Impacts turbine performance year-round, can indicate risk of plant shutdown for icing</td>
</tr>
<tr>
<td>Power (per turbine)</td>
<td>Measured</td>
<td>Current and voltage transducer or PMUs</td>
<td>Measured at the turbine bus bars</td>
</tr>
<tr>
<td>Power (plant)</td>
<td>Measured</td>
<td>Current and voltage transducer or PMUs</td>
<td>Measured at point of revenue metering</td>
</tr>
<tr>
<td>Irradiance (GHI)</td>
<td>Measured</td>
<td>Pyranometers*</td>
<td>Measures the resource available for the system but needs to be transformed to the plane of array</td>
</tr>
<tr>
<td>Irradiance (plane of array)</td>
<td>Measured</td>
<td>Pyranometers,reference cells**</td>
<td>Measures the resource available for panels</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Measured</td>
<td>Thermocouples</td>
<td>Second-order impact on panel performance</td>
</tr>
<tr>
<td>Cloud motion</td>
<td>Measured</td>
<td>Satellites or total sky imagers</td>
<td>Used for real-time and short-term power prediction</td>
</tr>
<tr>
<td>Power (per panel)</td>
<td>Measured</td>
<td>Power transducer or inverter</td>
<td></td>
</tr>
<tr>
<td>Power (plant)</td>
<td>Measured</td>
<td>Point of revenue metering</td>
<td></td>
</tr>
</tbody>
</table>
Phasor measurement units are a key technology for power flow and grid state monitoring, and opportunities still remain for improvements in reliability, speed, accuracy, cost, and their applications at distribution level.

Emerging electromagnetic phenomena-based current and voltage transducers show significant opportunity for new innovations.

Do you understand the difference between phasors and synchrophasors? The difference has significant implications.

Yes the team understands the difference. If you have specific feedback about a change requested, specify explicitly rather than asking questions which require interpretation of intent to address.
High-Level Findings of the Technology Review

Asset Monitoring and Fault Diagnosis

Asset monitoring of electrical grid assets can be classified into both “functional performance” and “health monitoring” with the former requiring predominantly electrical parameter sensors and the latter requiring sensors for a broad range of parameters such as temperature, chemistry, and strain.

Sensor instrumentation exists for established grid components, but costs currently limit deployment to the most critical assets. Also, new sensing technologies are required for emerging grid components and faster (near-real-time or dynamic) monitoring and controls.
High-Level Findings of the Technology Review

End-Use / Buildings Monitoring for Responsive Loads

<table>
<thead>
<tr>
<th>States/Parameters</th>
<th>Directly measured or calculated from measurements</th>
<th>Phasor or scalar</th>
<th>Sensors/meters required</th>
<th>Description and Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodal voltage</td>
<td>Measured</td>
<td>Phasor</td>
<td>VT</td>
<td>Measured by smart meter only</td>
</tr>
<tr>
<td>Nodal current</td>
<td>Measured</td>
<td>Phasor</td>
<td>CT</td>
<td>Measured by smart meter only</td>
</tr>
<tr>
<td>Frequency</td>
<td>Calculated</td>
<td>Scalar</td>
<td>FNENET Devices</td>
<td>Calculated by smart meter only</td>
</tr>
<tr>
<td>Real power</td>
<td>Measured/Calculated</td>
<td>Scalar</td>
<td>PQNode, Smart Meters</td>
<td>Measured by electromechanical meters/ Calculated by smart meter only</td>
</tr>
<tr>
<td>Reactive power</td>
<td>Calculated</td>
<td>Scalar</td>
<td>PQNode</td>
<td>Calculated by smart meter only</td>
</tr>
<tr>
<td>Power factor</td>
<td>Calculated</td>
<td>Scalar</td>
<td>PQNode</td>
<td>Calculated by smart meter only</td>
</tr>
<tr>
<td>Power quality</td>
<td>Calculated</td>
<td>Scalar</td>
<td>PQNode</td>
<td>RMS voltage, THD and phase balance</td>
</tr>
<tr>
<td>Temperature</td>
<td>Measured</td>
<td>Scalar</td>
<td>Thermometer</td>
<td>Measured</td>
</tr>
<tr>
<td>Luminance</td>
<td>Measured</td>
<td>Scalar</td>
<td>Illuminometer</td>
<td>Measured</td>
</tr>
<tr>
<td>Indoor air quality sensor</td>
<td>Measured</td>
<td>Scalar</td>
<td>Integrated health sensor</td>
<td>Measured CO2, H2O, etc.</td>
</tr>
<tr>
<td>Occupancy</td>
<td>Measure/Calculated</td>
<td>Scalar</td>
<td>Moving sensors</td>
<td>Measured by moving sensors or calculated with other measures</td>
</tr>
</tbody>
</table>

Trends of increased generation at residential and commercial scale as well as projections for widespread electric vehicle deployment require increased visibility at the load to enable demand response and transactive energy strategies.

Low-cost sensor technologies for monitoring power flow as well as parameters characteristic of the current and forecasted load will be of increasing importance.
High-Level Findings of the Technology Review

Communications

(1) A paradigm shift is anticipated toward broader implementation of distributed rather than centralized architectures characterized by communications and intelligence at lower levels.

(2) Reduced latencies and robust peer-to-peer communications in addition to communication between various nodes and the control center will be of increasing importance.

(3) A hierarchical communication architecture appears highly desirable based upon several key attributes:
   - Scalability for a large number of sensing and measurement devices
   - Flexibility to incorporate new types of data and applications
   - Efficiency to leverage unique features of different communication technologies
   - Reduced latency with more distributed data processing and control

Communications is a required part of the project from the very beginning and cannot be eliminated. This slide comes directly from the technology review and all previous slide versions. If there are specific points in the text to be addressed show explicitly.
High-Level Findings of the Technology Review

Data Management and Analytics

(1) The desire for dramatically increased visibility across the electricity grid infrastructure will necessarily increase the deployment of sensing and measurement devices and associated data management needs to unprecedented levels.

(2) A shift towards distributed data analytics methodologies rather than centralized approaches is a potentially key component of the required technical solution.

(3) For the existing sensing and measurement infrastructure, there remains a great amount of “value” yet to be extracted through advanced data management and analytics approaches especially at the distribution level, which has traditionally been limited to substation monitoring and control.
Extra Info – synchrophasors & distribution sychrophasors
Synchrophasors compare voltage phase angle at different locations

the small phase angle $\delta$ between different locations on the grid drives a.c. power flow

\[ P \approx \frac{V_1 V_2}{X} \sin \delta_{12} \]

power flows from Unit 1 toward Unit 2
State variables: voltage angle & magnitude at each bus drive power flow

\[ P_i = \sum_{k=1}^{n} |V_i||V_k|[g_{ik}\cos(\theta_i - \theta_k) + b_{ik}\sin(\theta_i - \theta_k)] \]

\[ Q_i = \sum_{k=1}^{n} |V_i||V_k|[g_{ik}\sin(\theta_i - \theta_k) - b_{ik}\cos(\theta_i - \theta_k)] \]
Voltage phase angles separating, just before a major blackout
Synchrophasors compare voltage phase angle at different locations.
Characteristic sub-synchronous oscillations impose significant transmission constraints in the Western U.S.

note: these oscillations existed before major renewables deployment

Alberta
0.45 Hz

East-West
0.6-0.7 Hz

North-South
0.25-0.3 Hz

California-Desert
Southwest 0.5 Hz
California-Oregon Intertie Aug 10, 1996 as seen with and without synchrophasors

Observed COI Power

Simulated COI Power
Situational Awareness with µPMUs: Transmission system event at different time resolutions
http://web.ecs.baylor.edu/faculty/grady/Texas_Synchrophasor_Network.html
looking at the transmission grid from distribution, behind the substation
Key Lesson for Today

If you need the loadflow voltage phase angle for West Texas, find out how fast the wind is blowing in Sweetwater.
Small But Unusual 2.7 Hz Voltage Angle Ringdown, West Texas w.r.t. Baylor, May 16, 2013, 04:03 GMT

Corresponding Frequencies at West Texas and Baylor

- Baylor
- McD
This application analyzes PMU data to show damping of characteristic sub-synchronous oscillation modes.

Courtesy CERTS
PMU’s in the US

2010

Phasor Measurement Units in North American Power Grid

Legend
- Networked
- Installed
- Aggregations

2012

Phasor Measurement Units in North American Power Grid

Legend
- Field Locations
- Elite Concentrators

2015

Phasor Measurement Units in the North American Power Grid

Legend
- Field Locations
- Transmission Power Data Concentrator
- Regional Data Concentrator

Courtesy NASPI
https://selinc.com/solutions/synchrophasors/
Micro-synchrophasor network concept:
Create visibility for distribution circuits behind the substation to support integration of distributed resources
Why PMUs mostly on transmission, not distribution systems to date?

- historically, no need (but this is changing):
  - unidirectional power flow, from substation to load
  - unquestioned stability of distribution system
- cost / value proposition
- more challenging measurements – fractions of a degree

Transmission PMU performance
~ 1% TVE is not small enough for distribution: \( \sin^{-1} 0.01 \approx 0.6^\circ \)
Distribution systems are tricky...

\[ P \neq \frac{V_1 V^2}{X} \sin 12 \]

This nice approximation doesn’t work well

\[
\begin{align*}
|V_{k-1}|^2 - |V_k|^2 & \approx 2(R_k P_k + X_k Q_k) \\
\delta_{k-1} - \delta_k & \approx \frac{X_k P_k - R_k Q_k}{|V_k||V_{k-1}|}
\end{align*}
\]

Both X and R show up in these expressions; P and Q are not decoupled like in transmission.

...and this doesn’t even include three-phase imbalance!

Linear approximations derived from DistFlow equations for radial feeders by Dan Arnold, Roel Dobbe and Michael Sankur, UCB
Illustration: Measured phase shift along 12kV distribution circuit

Voltage phase angle difference between PV array and substation

Current injected by PV array
Grizzly Substation feeds LBNL and UC Berkeley campus
115 kV from PG&E
12 kV distribution
ARPA-E μPMU Project

Field installations:

UC Berkeley/LBNL
Southern California Edison
Riverside Public Utilities

Alabama Power (Southern Co.)
Georgia Power (Southern Co.)
Tennessee Valley Authority
Pacific Gas & Electric Co.
Berkeley Tree Database (BTrDB)

ARPA-E research project configuration:
40+ µPMUs sending 120 Hz data via Ethernet or 3G/4G wireless, 12 streams per device (voltage and current magnitude & phase angle)

Michael Andersen, UC Berkeley
Use cases: Mitigating system vulnerability to disturbances

PMU data reveal dynamic response across transmission and distribution:

- assess stability operating limits
- identify exposure to large disturbances, e.g. geomagnetic (GMD)
- diagnose local control issues, oscillations
- understand implications of reduced system inertia with inverter-based generation: the design basis has changed
Use case example: Diagnose cause of DG unit trips

PV array trip caused by phase B-C fault (palm frond contact) down the feeder
Use case: Detect normal and mis-operation of equipment

Tap changer at substation transformer steps voltage up as load increases over the course of the day.

Example:
Anomaly in tap change signature can give early warning of transformer aging or incipient failure.

Tap change occurs over ~2 cycles
Graph shows individual 120-Hz samples
Use case: Detect normal and mis-operation of equipment

Example:
Anomaly in tap change signature gives early warning of transformer aging or incipient failure

Curious voltage sag characteristically follows tap change operation
Use cases: Feeder and load model validation, Reverse power flow detection

► Example: ascertain impacts of voltage regulation with hi-pen DG1.2% step down in voltage
► significant drop in kW due to highly voltage dependent load
► high-penetration solar PV feeder goes from net kW import to backfeed
Use case: Disaggregating net metered DG from load

Customer-owned solar generation can mask an unknown amount of load, creating vulnerabilities for the system (e.g. simultaneous DG trips, cold load pickup).

μPMU measurements on the utility side of the meter offer an alternative to telemetry on customer premises or 3rd party data, to create awareness for operators.

Ciaran Roberts and Emma Stewart, Lawrence Berkeley National Lab
Use Case: Disaggregating net metered DG from load

PV generation is estimated as a function of capacity, irradiance data and aggregate power measurement.

Model runs in real time to approximate actual performance of PV and identify masked load.

Test case: LBNL algorithm estimated actual PV generation (red) using only aggregate data from μPMU 1 and validated against direct PV measurement from μPMU 2 (black); performed within 6% RMSE over all sky conditions.
Incipient Failure Detection for Transformers (and other equipment)

- In the US – transformers are in general a big point of failure in the aging distribution system – when the fail, they cause an outage and $$ to replace
- Application picked up the signature below multiple times
  - Tap change followed by voltage sag – multiple times
  - We can only see this relational information with synchronized datasets from the uPMU
  - Tap changer oil leak – signature is evident before normal warning of failure

Tap changer close to failure