Distribution Linear State Estimation to Improve PMU Data Quality: ComEd Experience

Shikhar Pandey, ComEd and Marianna Vaiman, V&R Energy

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2020-2021 project to test and validate performance of three-phase distribution linear state estimator at ComEd

Project team:

- ComEd
  - Shikhar Pandey, Kevin Chen, Aleksi Paaso
- NuGrid
  - Farnoosh Rahmatian
- V&R Energy
  - Michael Vaiman, Marianna Vaiman, Mark Povolotskiy, Mikhail Karpoukhin
The platform is a key “quality control” layer between the sensors providing raw measurement data, and the application software requiring reliable trustworthy data.

- Provides real-time situational awareness in order to improve resilience of the distribution grid and enhance its reliability.

**D-PMU ROSE** platform consists of the following functionalities:

- Three-phase distribution linear state estimation (D-LSE)
- Bad PMU data detection and correction
- Observability analysis
- Identifying switching events
- Advanced visualization of distribution grid state, archiving and alarming

- Validating model and PMU measurements
- Optimal PMU placement for full distribution grid observability (off-line)
Components of D-LSE Framework

- Multi-step process:
  1. Bad data detection, correction, alarming and reporting
  2. Combination of filtering and smoothing techniques
  3. Observability analysis
  4. Three-phase Distribution Linear State Estimation
  5. Detection of switching events (only based on PMU data)
  6. Real-time system monitoring (voltage and thermal)
  7. Visualization, archiving

- Machine learning is used to improve accuracy of event detection in real-time
Purpose of Bad Data Detection

- Bad data detection identifies and conditions any erroneous PMU measurements, assuring the quality of synchrophasor data using a computationally efficient process.
- After detecting bad data, D-PMU ROSE filters these bad data and blocks their flow to the downstream applications.
- When any type of bad data is determined, Bad Data Alarm is issued and logged.
- Bad data processing:
  - The bad signal’s value is replaced by the value received before bad signal was identified.
  - When bad data stops, PMU data from the stream is used again.
  - If duration of bad data exceeds a user-defined period, bad data is removed from the stream, observability analysis is initiated, and a new power system configuration (e.g., position of switches – Open/Close, generation On/Off) is created.
Types of Bad Data

- D-PMU ROSE considers data to be bad if at least one of the following criteria is met:
  1. Change (increase or decrease) in voltage or current amplitude is greater than a user-defined Voltage or Current Outlier Magnitude Threshold, respectively.
  2. PMU status word (STAT) has a non-zero value.
  3. PMU is not available.
  4. Data contains stale data.
  5. Data contains timestamps error.
  7. Data delay or data drop are identified.
Network Model for Testing DLSE

- **Model:**
  - Bronzeville Community Microgrid (BCM):
    - A 7-MW community microgrid
    - Two feeders
    - Over 200 nodes in BCM

- **PMUs:**
  - 46 PMUs

- **Testing environment:**
  - ComEd’s Grid Integration and Technology (GriT) Lab using real-time digital simulation (RTDS)
DLSE has been validated and tested for its accuracy and real-time performance (at the PMU streaming rate of 60 times per second) in GriT Lab.

- Created a test setup that emulates realistic field operations:
  - PMU measurements are aggregated into a PDC.
  - A real-time synchrophasor stream is established over TCP-IP protocol.
  - Sent to the DLSE for state estimation.
To emulate the effects of CT bias, PT bias, GPS error, timestamp errors, outliers, data drops and network congestion, the input signals to the virtual PMUs were altered.

Various types of bad data were simulated and tested:

- **Case 1:** Magnified voltage magnitude
- **Case 2:** Signal delay
- **Case 3:** Outlier (single point anomaly)
- **Case 4:** Missing data (packet received but data was not available)
- **Case 5:** Timestamp error
- **Case 6:** Data packet drop (packet not received)
The case of magnified voltage can be detected by DLSE, and the PMU is taken out of service.
Case 1: Oneline Visualization

- One-line shows in real time that the PMU detected data quality issues by displaying buses in red and PMUs in grey.

- DLSE detects that PMU ‘318.1’ is bad and removes it from calculation – the one line turns back to normal, and the bad PMU is colored in red.
Phase A signal was delayed

As a result, an error was introduced in the voltage angle

The DLSE can accurately estimate the angle, provide the correct angle, and notify the user about the bad PMU measurement
This case of outliers involves PMU measurements that go bad (significantly different from what is expected) and can be termed as outliers.

An example is shown for one cycle:

- DLSE detects outliers accurately and provides the accurate estimates of what those outlier measurements should have been.
- Though measured PMU voltage is around 9.8 kV, DLSE estimates the accurate voltage of 7.15 kV.
Case 4: Missing Data

- The DLSE simply removed the PMU from state estimation calculation and deemed it to be bad
- It can also notify the downstream applications that PMU data is missing
Two types of timestamp errors were simulated:
  • A repeated timestamp
  • An out-of-sequence timestamp

The DLSE removes the PMU data with timestamp errors and can notify the downstream applications about the issue.

```plaintext
2021-03-10 16:09:58.8992 PMU: Repeated timestamp = 2020.12.07 20:56:57.000
```
In case of PMU packet drop, the DLSE:

- Continues calculating and
- Works with the data that is available

Notifies the user of the congestion, and that the data was dropped:

- This notification helps to monitor any growing congestion in the network and enables better management of critical applications
Another form of bad data is “inaccurate” data:

- After state estimation is complete, if voltage/current values measured by a PMU are consistently off by more than a certain percentage or absolute value from the value determined by state estimation for the same bus/branch, D-PMU ROSE considers this PMU data to be “inaccurate”

Data is considered to be inaccurate if user-defined inaccurate data thresholds are being exceeded for a user-defined time interval:

- When inaccurate data is detected, an Inaccurate Data Alarm is issued and logged
- PMUs having inaccurate data may be shown in a user-defined color on the single-line diagram
Additional Information

- Additional details in the paper:

Shikhar Pandey, Heng (Kevin) Chen, Esa A. Paaso, Farnoosh Rahmatian, Michael Vaiman, Marianna Vaiman, Mark Povolotskiy, and Mikhail Karpoukhin, “PMU-Based Distribution Linear State Estimation to Improve Data Quality and Application Reliability”, accepted to IEEE PES T&D Conference & Exposition, 2022, New Orleans, LA
Conclusion

- A PMU-based platform, including pre- and post-LSE bad data detection and conditioning functions, has been developed and tested at ComEd’s GriT Lab.
- Software tool is extremely effective for detecting and filtering bad measurement data.
- Demonstrated software can improve dependability of PMU-based real-time grid monitoring and control applications.
- Ability to ensure data quality brings deployment of practical and reliable measurement-based, wide-area monitoring and control systems for advanced distribution grids closer to reality.
Thank you!

Shikhar Pandey
Shikhar.Pandey@ComEd.com

Marianna Vaiman
marvaiman@vrenergy.com