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

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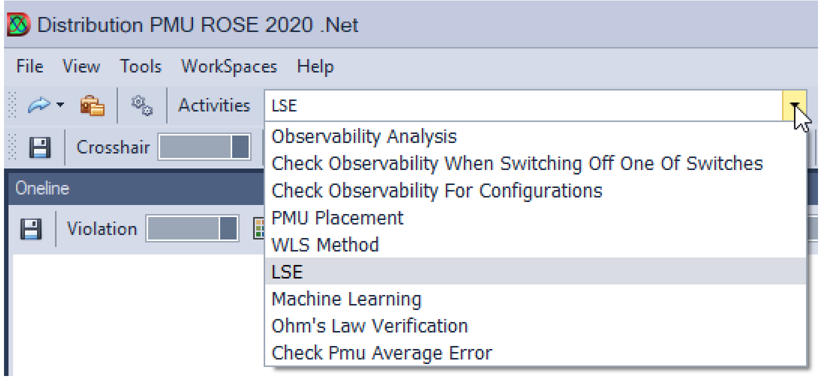
- 2020-2021 project to test and validate performance of three-phase distribution linear state estimator at ComEd
- Project team:
  - ComEd
    - Shikhar Pandey, Kevin Chen, Aleksi Paaso
  - NuGrid
    - Farnoosh Rahmatian
  - V&R Energy
    - Michael Vaiman , Marianna Vaiman, Mark Povolotskiy, Mikhail Karpoukhin

Real-Time Distribution System Monitoring Platform

- 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

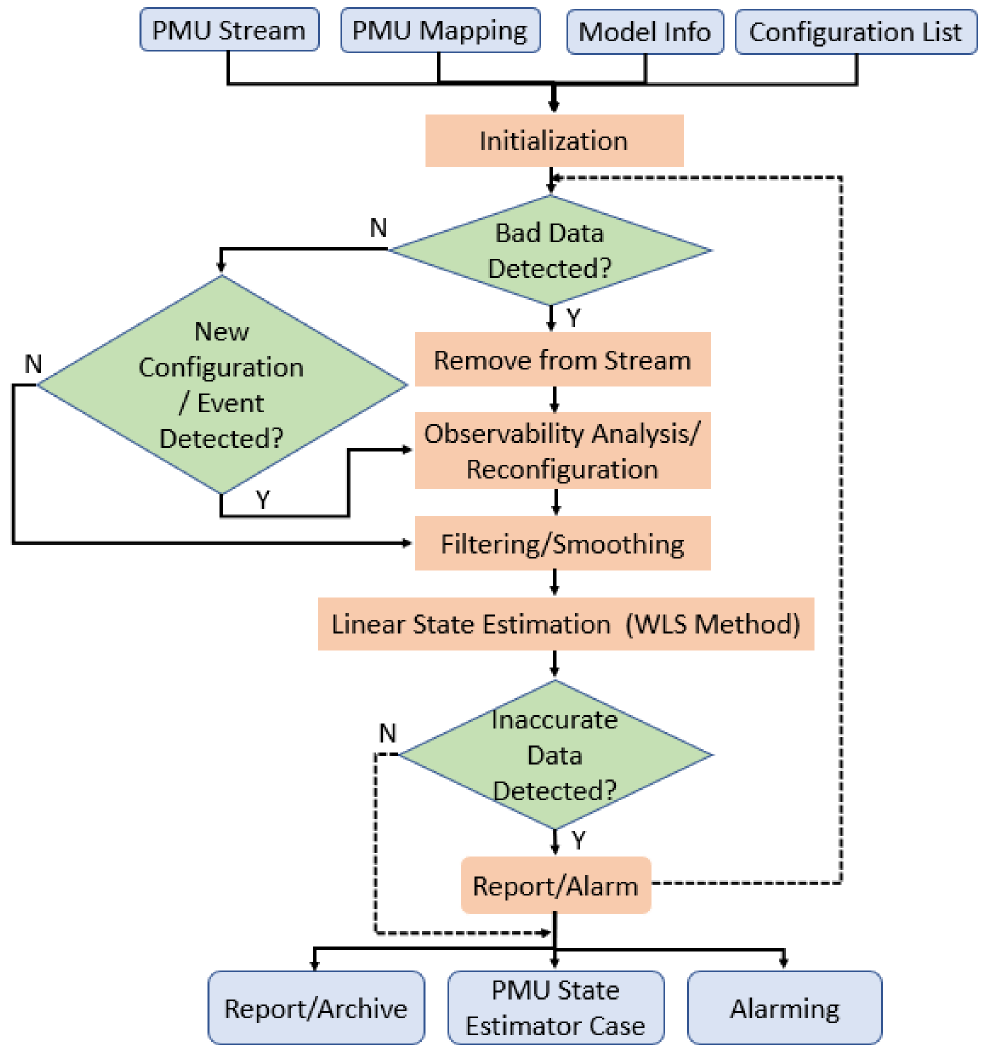


  - Validating model and PMU measurements
  - Optimal PMU placement for full distribution grid observability (off-line)

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



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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

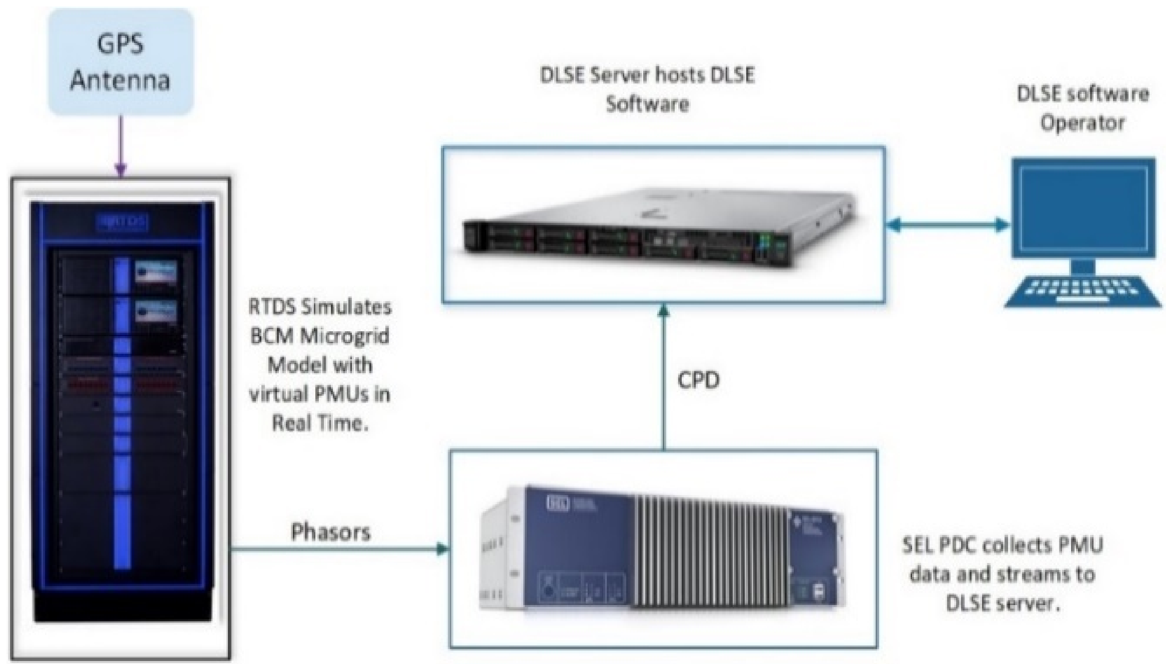
- D-PMU ROSE considers data to be bad if at least one of the following criteria is met:
  1. Change (increase or decrease) in voltage or current amplitude is greater than a user-defined Voltage or Current Outlier Magnitude Threshold, respectively.
  2. PMU status word (STAT) has a non-zero value.
  3.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

Test Setup

- 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



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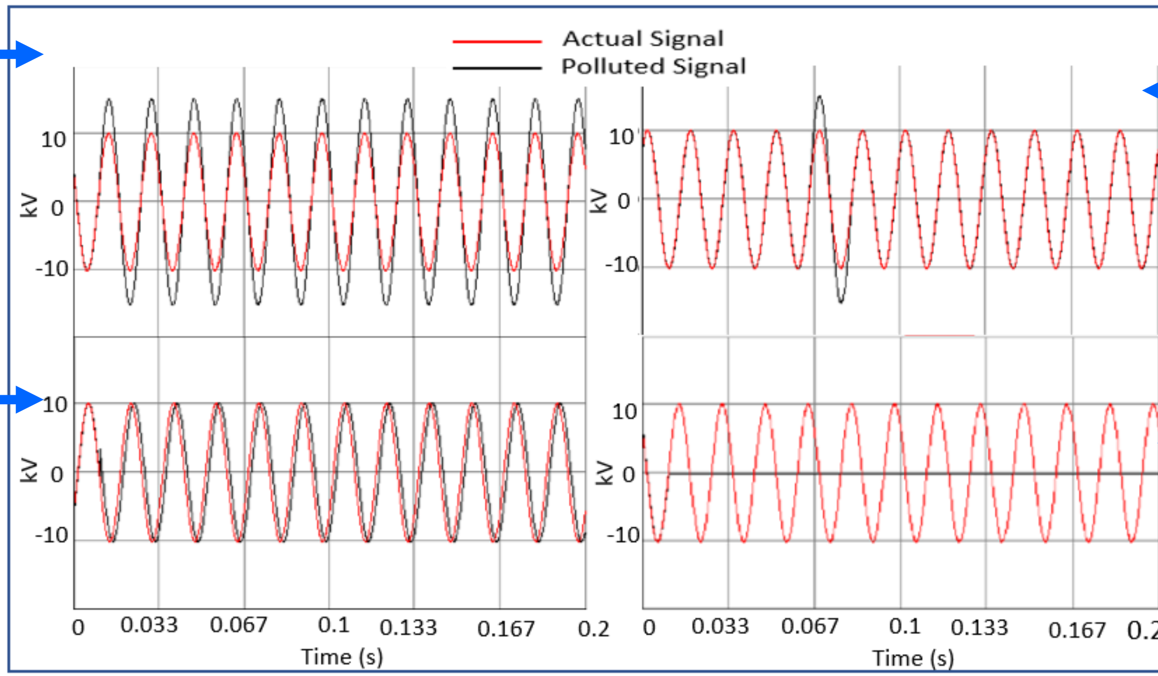
Bad Data Creation in RTDS

- 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)

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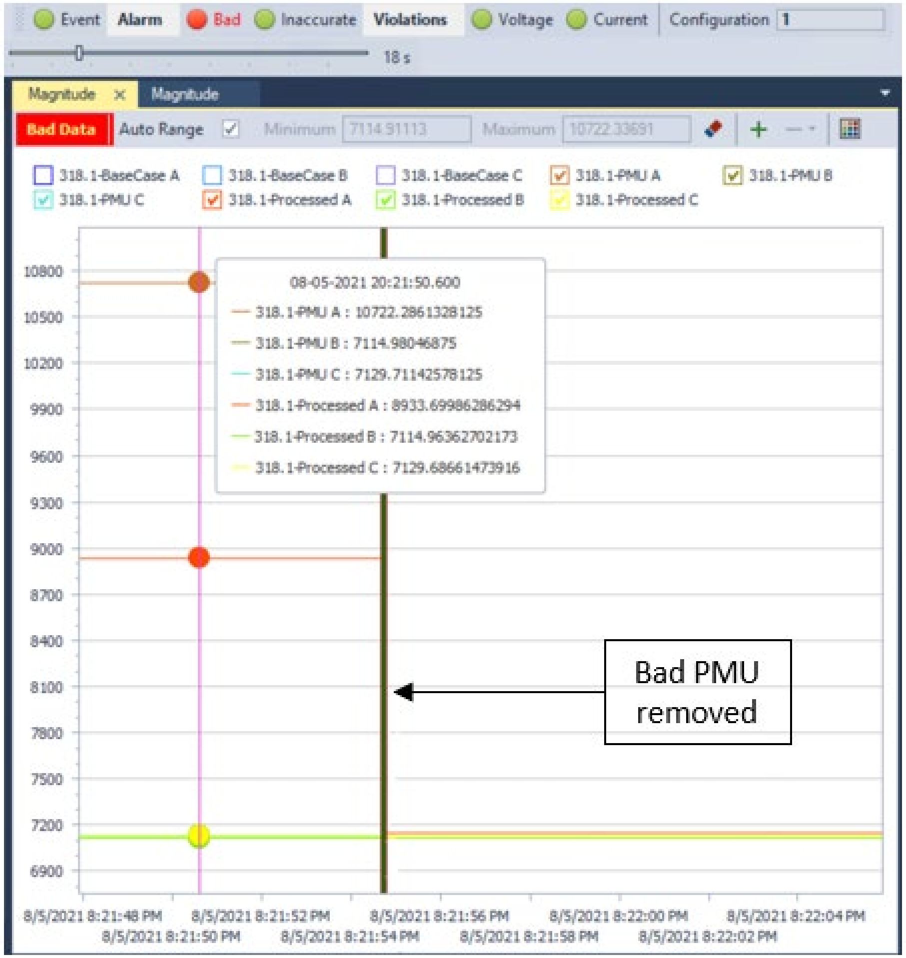
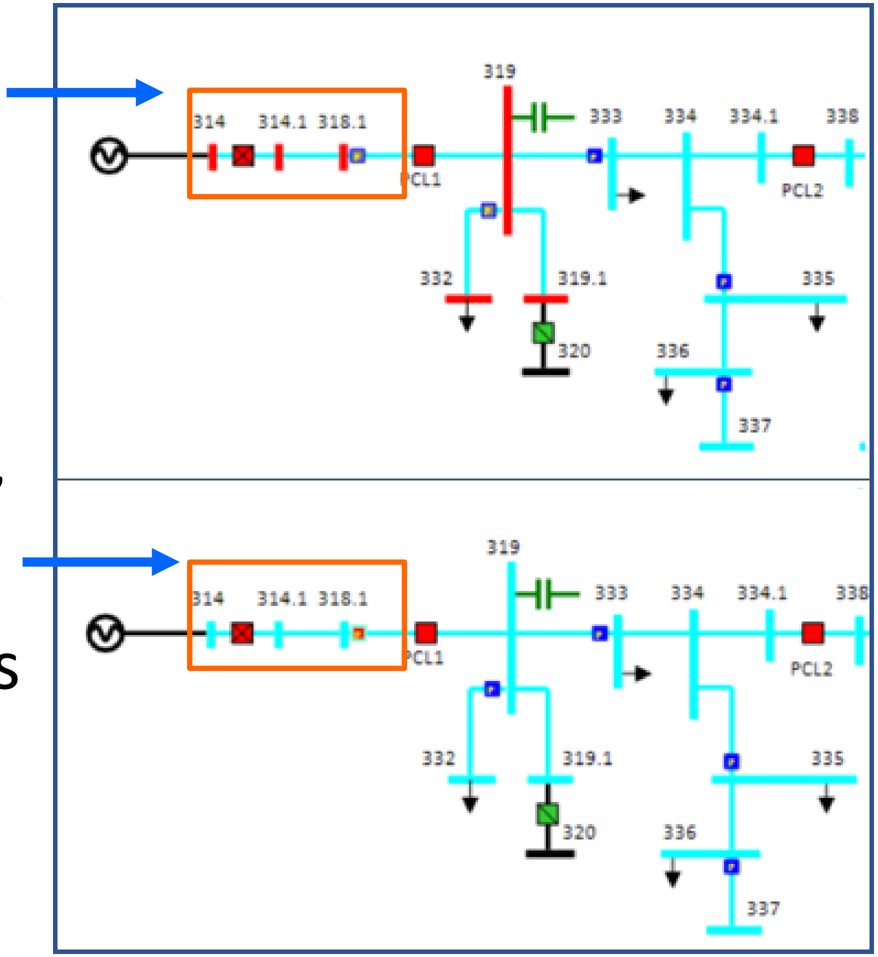
Case 1: Magnified Voltage Magnitude

- The case of magnified voltage can be detected by DLSE, and the PMU is taken out of service



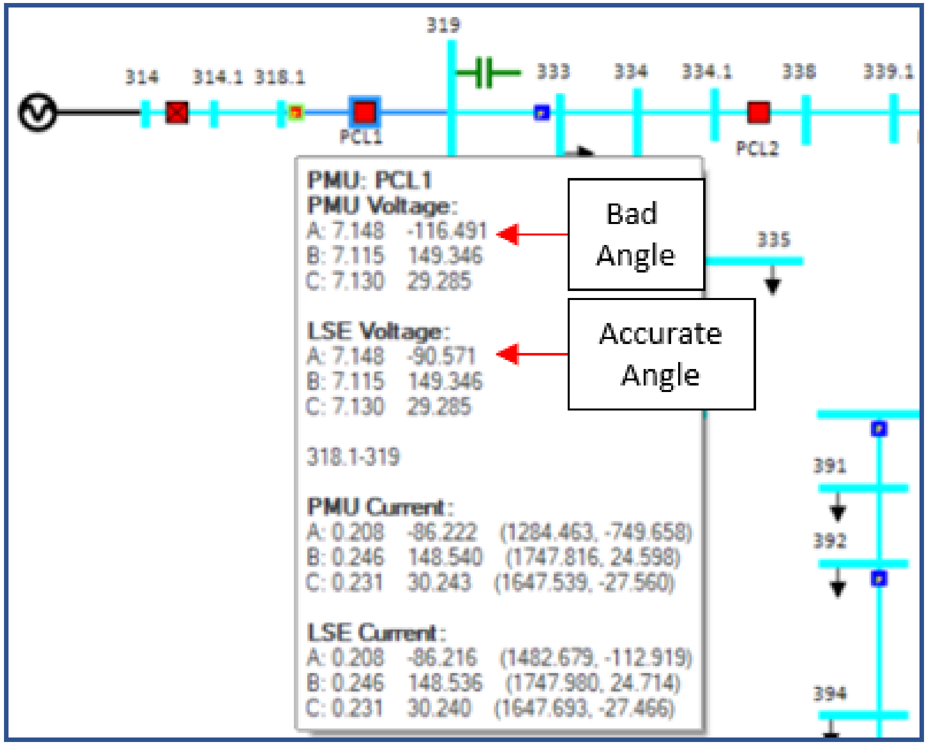
Case 1: Oneline Visualization

- 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



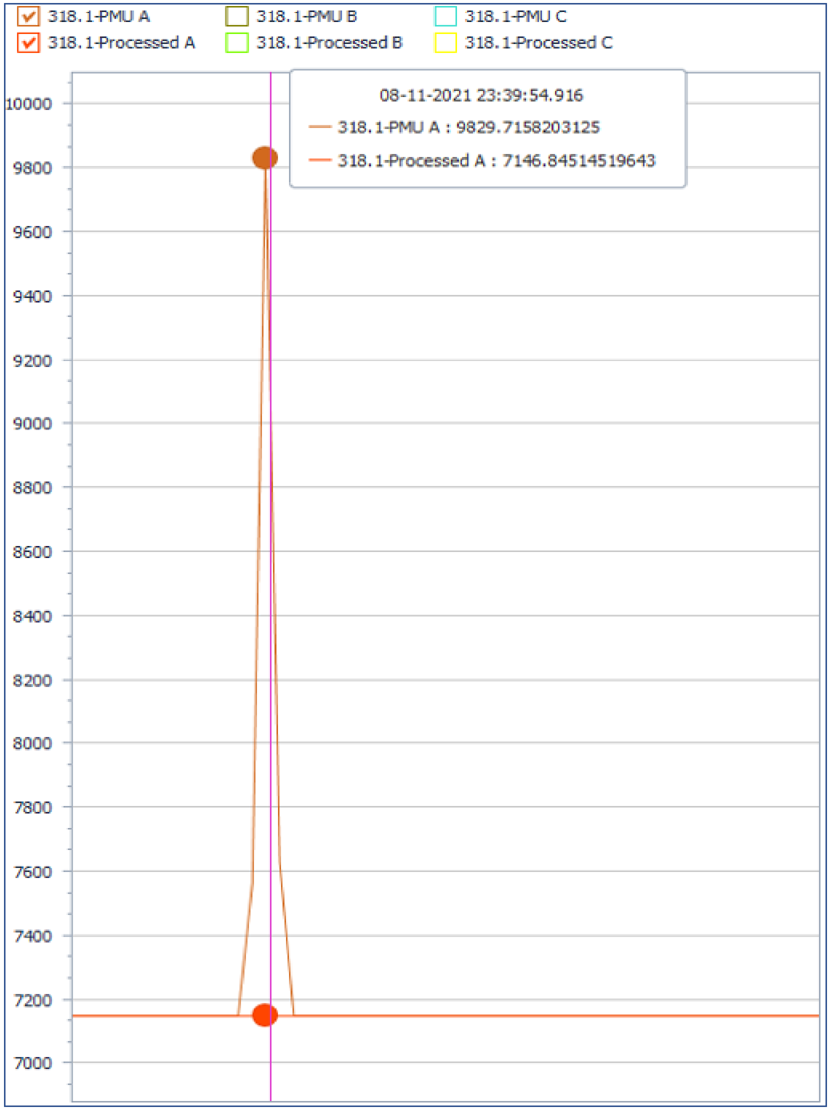
Case 2: Signal Delay

- 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



Case 3: Outlier

- 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



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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

Case 5: Timestamp Error

- 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

```
2021-03-10 16:09:58.8992 PMU: Repeated timestamp = 2020.12.07 20:56:57.000
2021-03-10 16:10:03.8403 PMU: Out-of-sequence timestamp = 2020.12.07 20:57:17.033
                              Last TimeStamp = 2020.12.07 20:57:18.567
```

Case 6: PMU Packet Drop

- 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

```
New event at time (2021.02.10 20:53:17.466):
Configurations:
2.3. DER On-Generator

Total Frames: 1822 Total Calculation: 1754 Not Processing Frames: 36
Total Frames: 1973 Total Calculation: 1842 Not Processing Frames: 130
Total Frames: 2123 Total Calculation: 2017 Not Processing Frames: 105
Total Frames: 2274 Total Calculation: 2215 Not Processing Frames: 58
Total Frames: 2424 Total Calculation: 2416 Not Processing Frames: 7
Total Frames: 2574 Total Calculation: 2574 Not Processing Frames: 0
Total Frames: 2726 Total Calculation: 2725 Not Processing Frames: 0
ZERO: SW235, SWBAT, VISTAE, VISTAS, VISTAB, PMU2_N
BAD: NO
```

Inaccurate Data

- 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!

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