Experiences with PMU-Based Three Phase Linear State Estimator at Dominion Virginia Power

IEEE PES GM 2015 Panel Session on Experiences in Incorporating PMUs in Power System State Estimation

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Presented by: Kevin D. Jones, Ph.D.

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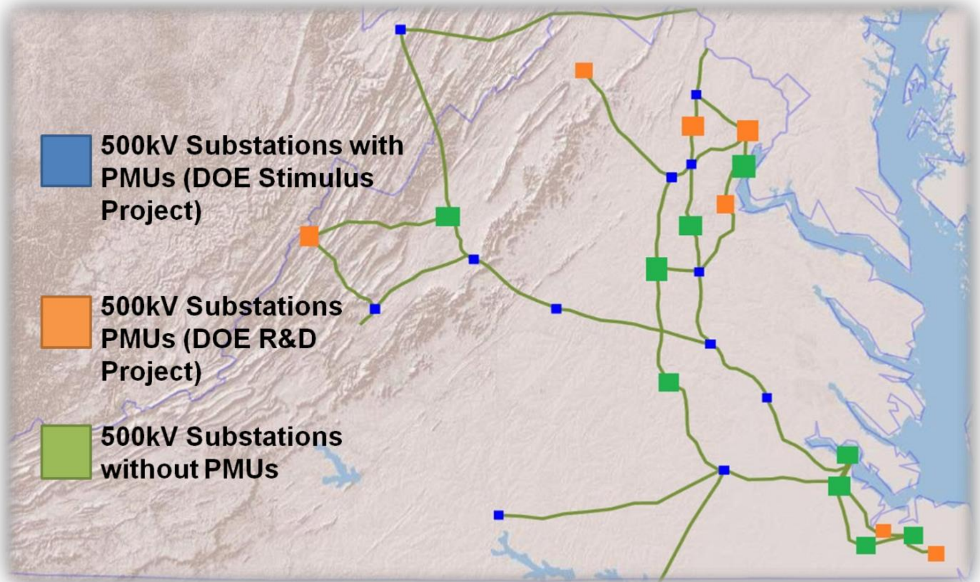
About Dominion Virginia Power

Electric Transmission

- **6,400 miles** of transmission lines
  - 500kV – 1250 miles
  - 230kV – 2600 miles
  - 115kV – 2300 miles

Electric Distribution

- **56,900 miles** of distribution lines
- **2.5 million** franchise retail customer accounts in VA and NC



PMU Integration began in 2009 with SGIG and Non-Stimulus grants completed in 2013

- **80 PMUs** in EHV network
- **21 500kV Substations** monitored with PMU
- **27 control houses** involved

Suite of PMU-based network applications

- **Three Phase Linear State Estimator**
- **CT & PT Calibration**
- **Sequence Component Monitoring**
- **Decision Tree Based Islanding Detection**

Presentation Agenda

- State Estimation
  - Purpose of State Estimation
  - Overview of (3ϕ) Linear State Estimation
- Some Practical Issues
  - Modeling, availability of telemetry, computation time
- Future of (3ϕ) Linear State Estimator

Why Do We Do State Estimation?

- Misconception of purpose
  - “SE gives me my base case!!” (true but narrow)
- Operator’s Load Flow drove adoption of state estimation
  - Raw SCADA data yielded poor input for power flow
- State estimation was/is just a form of data conditioning designed to provide high fidelity information to network apps.

Purpose of (3ϕ) LSE

LSE also has misconception of purpose

– "I already have a state estimator!!"
– "LSE won't give me a base case so its useless!!"

LSE provides a front end data conditioning for [certain classes of] synchrophasor network apps by:

1. **Reducing errors**
2. **Extending observability**
3. **Increasing signal availability**
4. **Network contextualization of PMU data**

Comparison at a Glance

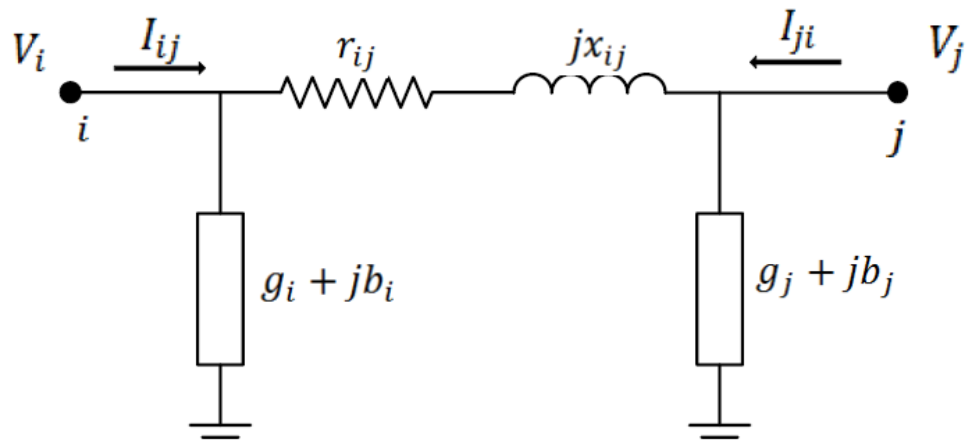
Traditional State Estimation

- Circa 1970
- Non-linear, iterative
- V_{mag}, I_{mag}, P, Q (scalars)
- Non-synchronized (SCADA)
- Solves (at best) in seconds
  - But minutes is more representative of the norm
- No dynamics
- Mainstream by 1990s
- **Feeds network apps**

(3ϕ) Linear State Estimation

- Circa 1980
- Linear
- **V**, **I**, (complex)
- GPS time synchronized
- Solves at frame rate
- Tracks dynamics
- Trending now
- **Feeds network apps**

LSE Problem Formulation



$$\begin{bmatrix} V_i \\ V_j \\ I_{ij} \\ I_{ji} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ y_{ij} + y_{i0} & -y_{ij} \\ -y_{ij} & y_{ij} + y_{j0} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix}$$

$$[\boldsymbol{x}] = \begin{bmatrix} V_i \\ V_j \end{bmatrix} \qquad [\boldsymbol{z}] = \begin{bmatrix} V_i \\ V_j \\ I_{ij} \\ I_{ji} \end{bmatrix}$$

$$[\boldsymbol{z}] = \begin{bmatrix} \boldsymbol{E} \\ \boldsymbol{I} \end{bmatrix} = \begin{bmatrix} \boldsymbol{II} \\ \boldsymbol{y}\boldsymbol{A} + \boldsymbol{y}_s \end{bmatrix} [\boldsymbol{x}] + [\boldsymbol{e}]$$

$$y_{ij} = \left(r_{ij} + jx_{ij}\right)^{-1}$$

$$[\boldsymbol{B}] = \begin{bmatrix} \boldsymbol{II} \\ \boldsymbol{y}\boldsymbol{A} + \boldsymbol{y}_s \end{bmatrix}$$

$$y_{i0} = g_i + jb_i$$

$$[\boldsymbol{x}] = [\left(\boldsymbol{B}^T \boldsymbol{W}^{-1} \boldsymbol{B}\right)^{-1} \boldsymbol{B}^T \boldsymbol{W}^{-1}][\boldsymbol{z}] = [\boldsymbol{H}][\boldsymbol{z}]$$

$$y_{j0} = g_j + jb_j$$

LSE Problem Formulation

$$\mathbf{W}(\phi)_{rect} = \begin{bmatrix} \cos\phi^2\sigma_M^2 + \sin\phi^2\sigma_A^2 & \cos\phi\sin\phi(\sigma_M^2 - \sigma_A^2) \\ \cos\phi\sin\phi(\sigma_M^2 - \sigma_A^2) & \cos\phi^2\sigma_A^2 + \sin\phi^2\sigma_M^2 \end{bmatrix}$$

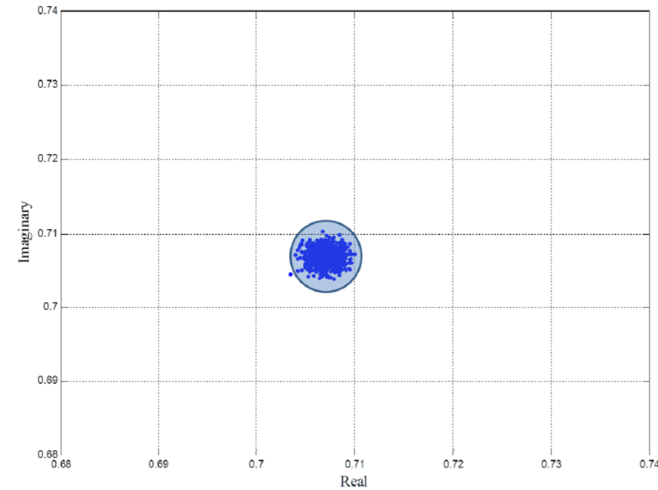
$$[\boldsymbol{v_r}] = real\{\boldsymbol{x}\}; \quad [\boldsymbol{v_x}] = imag\{\boldsymbol{x}\}$$

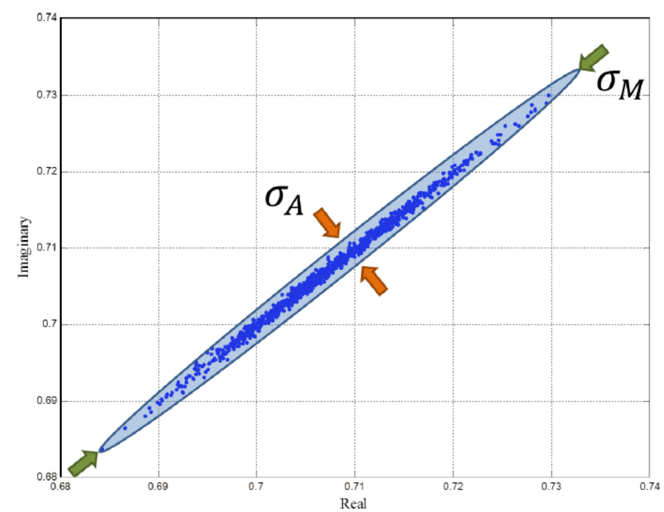
$$[\boldsymbol{z_r}] = real\{\boldsymbol{z}\}; \quad [\boldsymbol{z_x}] = imag\{\boldsymbol{z}\}$$

$$[\boldsymbol{bA} + \boldsymbol{b_s}] = imag\{\boldsymbol{yA} + \boldsymbol{y_s}\}$$

$$[\boldsymbol{gA} + \boldsymbol{g_s}] = real\{\boldsymbol{yA} + \boldsymbol{y_s}\}$$

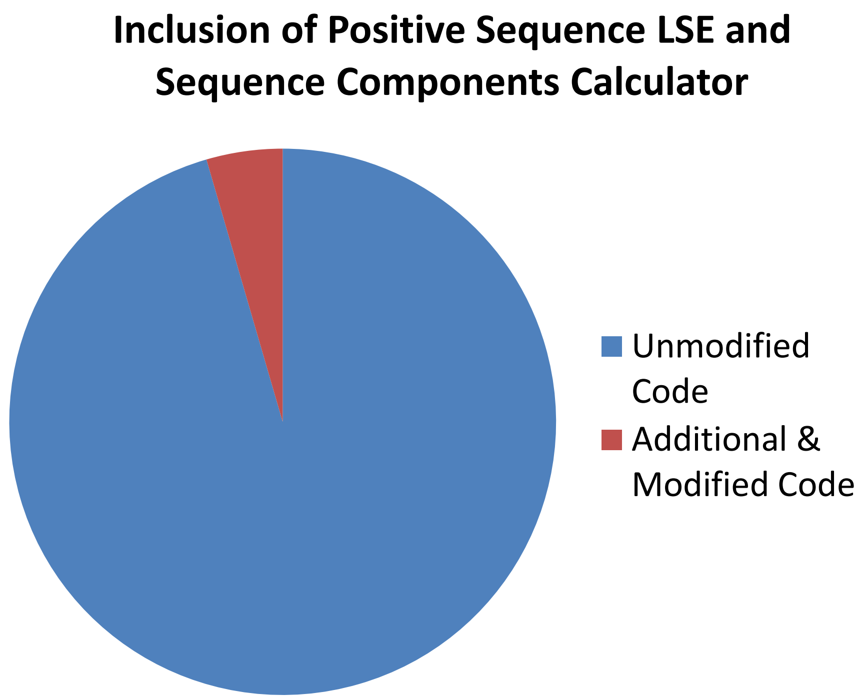
$$\begin{bmatrix} \boldsymbol{z_r} \\ \boldsymbol{z_x} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} \boldsymbol{II} \\ \boldsymbol{gA} + \boldsymbol{g_s} \end{bmatrix} & \begin{bmatrix} \boldsymbol{0} \\ -\boldsymbol{bA} - \boldsymbol{b_s} \end{bmatrix} \\ \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{bA} + \boldsymbol{b_s} \end{bmatrix} & \begin{bmatrix} \boldsymbol{II} \\ \boldsymbol{gA} + \boldsymbol{g_s} \end{bmatrix} \end{bmatrix} \begin{bmatrix} \boldsymbol{v_r} \\ \boldsymbol{v_x} \end{bmatrix} + [\mathcal{E}]$$





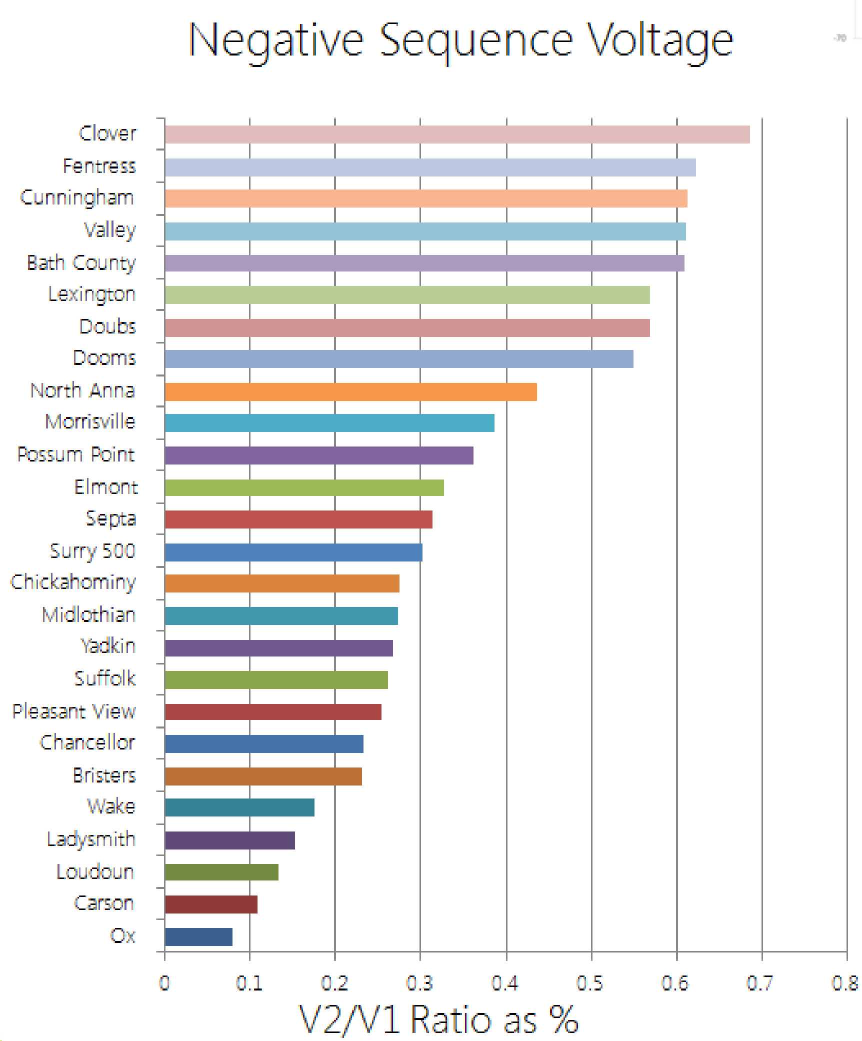
Three Phase vs. Positive Sequence

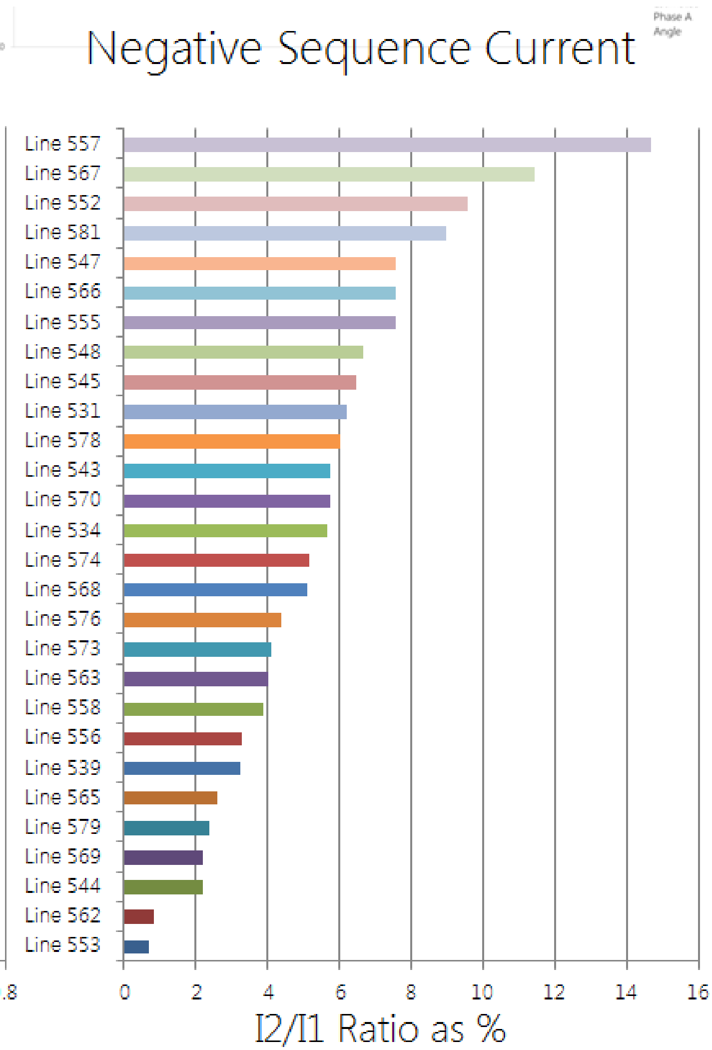
- 3ϕLSE is the only way to estimate sequence (+, -, 0) components
- At DVP, monitoring sequence components was valuable for power quality assessment and equipment health-monitoring
- Developing an LSE compatible with positive sequence as well as three phase was very straightforward



$$\begin{bmatrix} Z_D & Z_O & Z_O \\ Z_O & Z_D & Z_O \\ Z_O & Z_O & Z_D \end{bmatrix} \quad \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix}$$

Negative Sequence Component Monitoring





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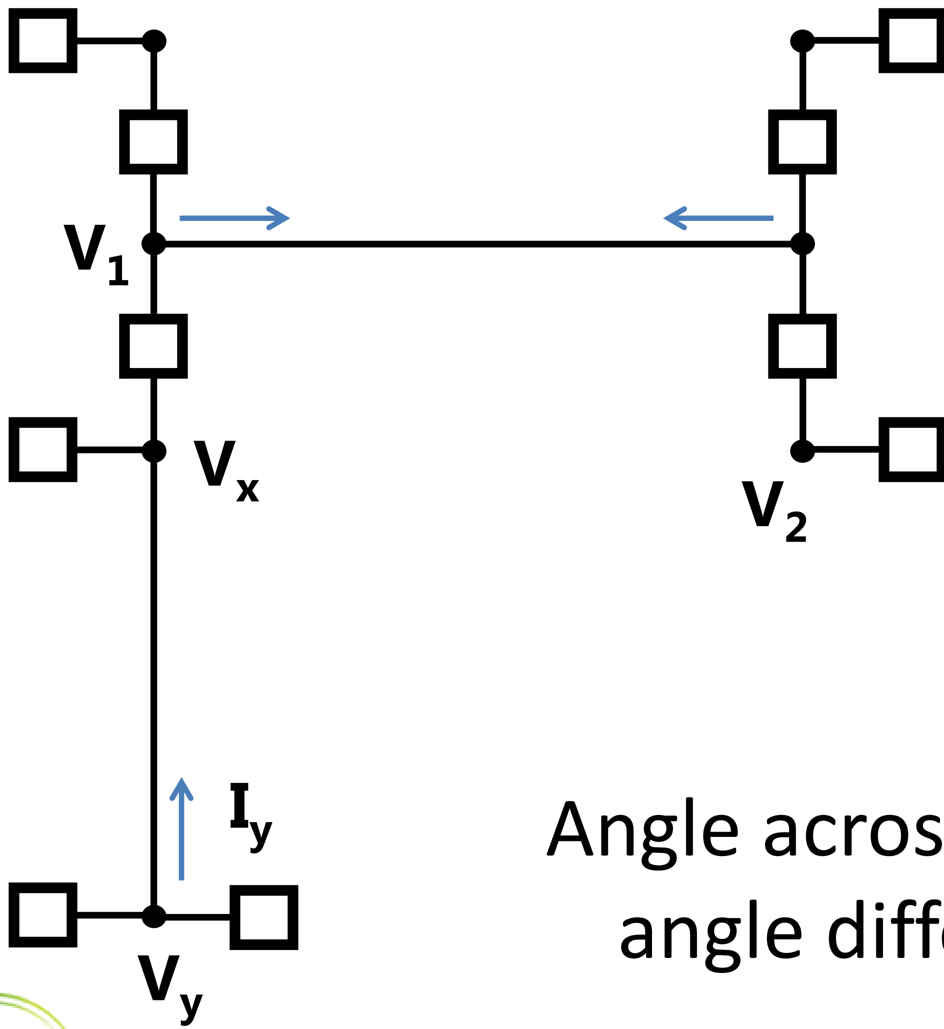
Example Network App



If **Line$_{1\text{-}2}$** is open, how to tell breaker closing angle?

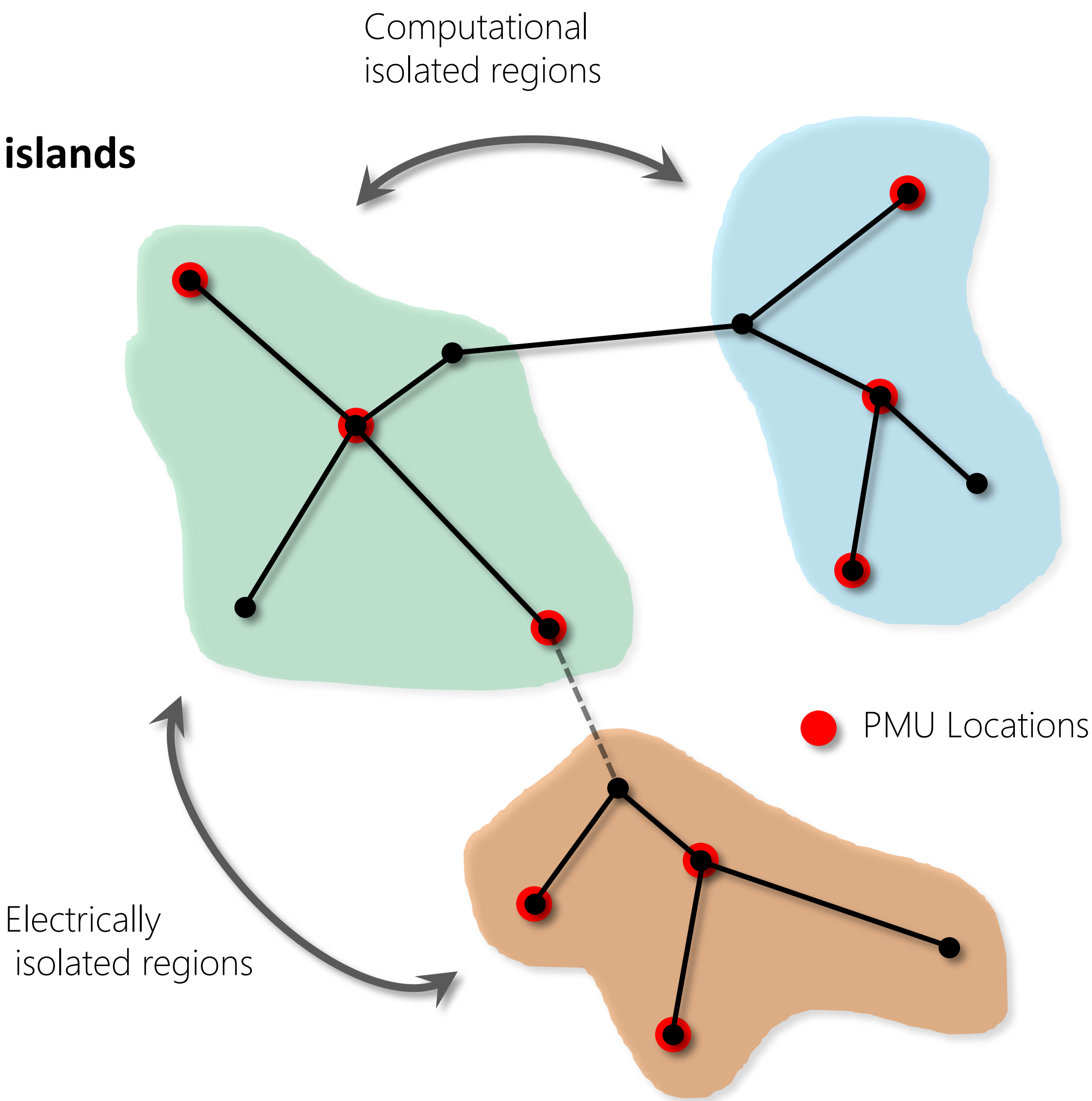
- Substitute $\mathbf{V_1}$ with $\mathbf{V_x}$
- Compute $\mathbf{V_x}$ with $\mathbf{V_y}$ & $\mathbf{I_y}$

Similar concept would apply to any two angle deltas across the transmission network.

Angle across breaker & angle differences

LSE can easily handle computational and physical islands

- PMU footprints are often sparse and non-uniform *(computational isolated measurement regions)*
- PMU monitoring of system restoration (black start) events would benefit from LSE *(electrically isolated measurement regions)*
- Synchronized monitoring of islands
- Could know voltage magnitude and angle on far end of line before connecting two islands

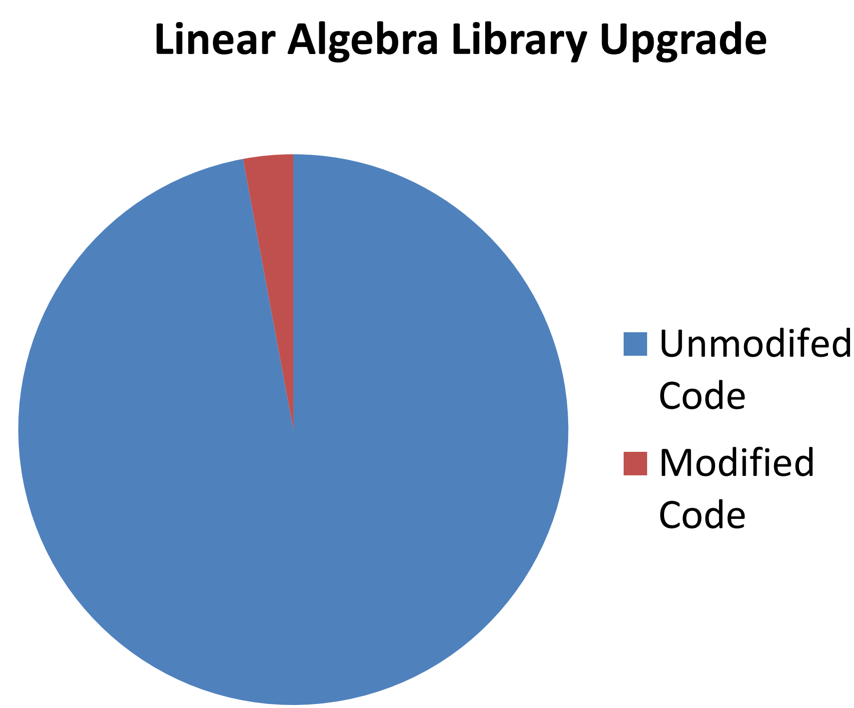


Modeling Considerations

- **Modeling is the most time consuming part of standing up the (3ϕ)LSE**
  - *Network Modeling*
    - At DVP, PMU footprint is small enough that as of today, all (3)LSE models are built manually
    - Automated process will be needed in the future
    - Use built-in topology processor to prune network model
  - *PDC Modeling*
    - Every estimated value has to be modeled in the central PDC as virtual measurement so that the LSE can send output as stream
- **CIM vs. Native format**
  - Purpose driven – native format is light(er)-weight and adds functionality
  - Can always build adapters!

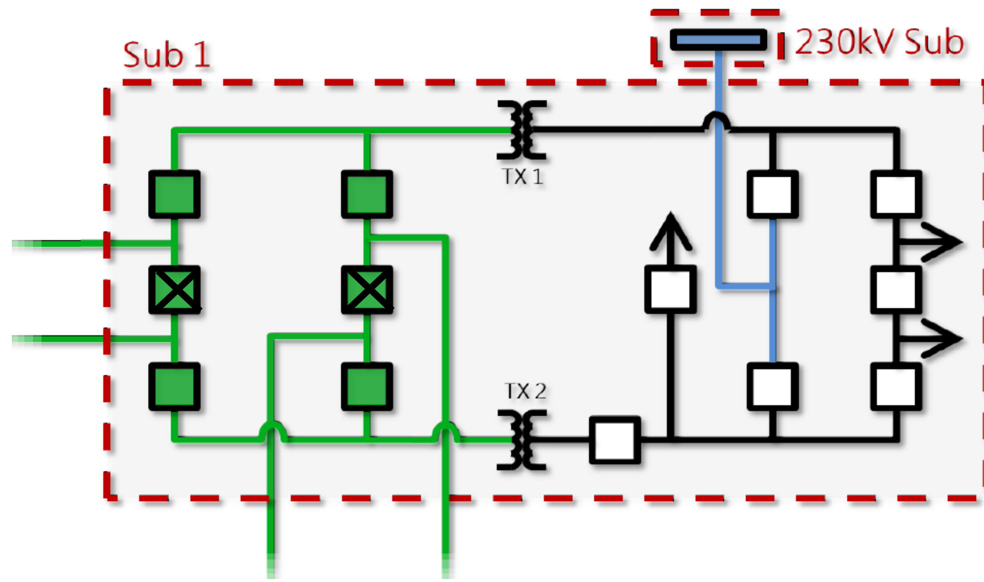
Addressing Computation Time

- Processing at frame rate can be CPU intensive
- Majority of CPU time is matrix multiplication
- Trying and migrating to different linear algebra packages to improve computation time
- Experience: migrated from **Extreme Optimizations** to **Math.NET** achieved orders of magnitude improvements to computation time.
- Very minor changes to code base and less than 1 working day of time



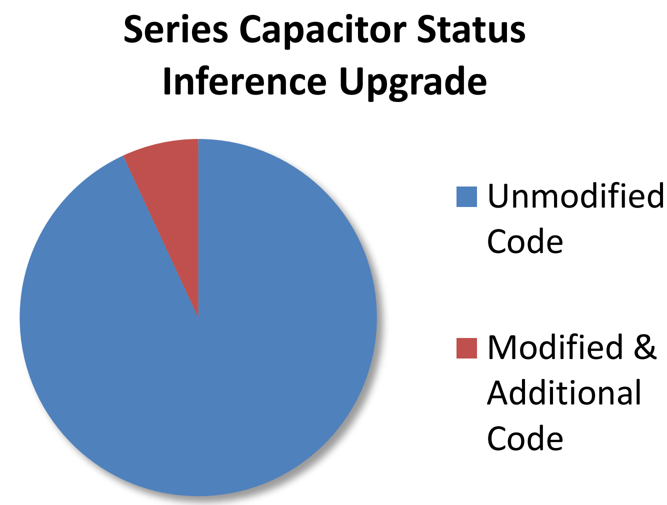
Lack of Breaker Status Telemetry

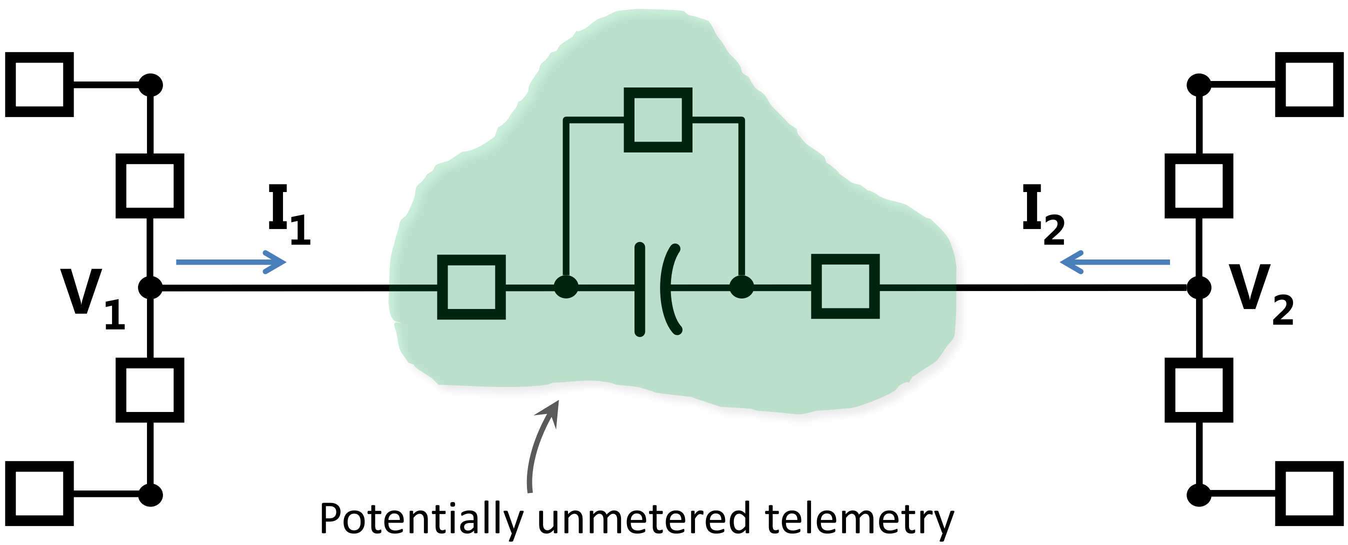
- Breaker statuses key for accurate topology processing, especially at frame rate.
- Breaker statuses can be brought in via a digital word in the C37.118 PMU stream. However, availability of this type of telemetry can be limited. Future PMU installations can be standardized to address this issue.
- LSE can be supplemented with breaker statuses from SCADA via ICCP. While signal availability is not an issue, these are not time synchronized and LSE output temporally close to breaker status change could have incorrect topology information.



Series Compensator Status Inference

- Total **Z** needed for LSE
  - Breaker telemetry and/or series compensator telemetry may not be available.
  - Can infer status of series compensators by calculating total line reactance





What's Next for the (3ϕ)LSE Project?

At DVP

- DVP is working on an historian modernization project. The LSE engine may be ported into our PI system
- State Estimation is 1 of 3 key components to control room integration of synchrophasors

As open source

- Synchrophasor Analytics Project
  http://phasoranalytics.codeplex.com
  – Documentation recommendations
  – Unit tests
- GPA's Project Alpha
  http://projectalpha.codeplex.com/

Summary & Conclusion

- (3ϕ)LSE is data conditioning for network apps
  - *Bias and noise reduction*
  - *Extended observability*
  - *Observation redundancy*
  - *Network model contextualization*
- LSE will be key, foundational component of future data systems and DVPs control room integration strategy
- Three phase monitoring for power quality and equipment health
- Practical considerations include modeling, computation time, and availability of telemetry
- Continuing forward with open source project

Questions?

- Contact Info

Kevin D. Jones, Ph.D.
Operations Planning – System Operations Center
Dominion Virginia Power
Personal Mobile: 304-767-4748
Office Mobile: 804-380-0658
Office: 804-273-3316
kevin.d.jones@dom.com
kevin.d.jones@outlook.com