August 31, 2022
Webinar Questions and Answers

"Machine Learning Based State Estimation for Transmission and Distribution Grids"

with Evangelos Farantatos and Anamitra Pal

Question: I do not understand why PMUs offer measurements which are linear functions of the state, whereas that was not possible without PMUs?

Answer: *PMU measurements are phasors (magnitude and angle). If expressed in cartesian coordinates one gets a linear relationship between the measurement (voltage and current) and the state (voltage). There are many papers that have all the details about linear state estimation (LSE) formulation.*

Question: What deep learning framework was used, TensorFlow?

Answer: *We used TensorFlow, Keras.*

Question: What if the non-time-synchronized measurement set (SCADA) is different from the time-synchronized measurement set (PMUs)?

Answer: *The measurement sets are indeed different. For example, SCADA does not include phase angle measurements. However, the novelty of the proposed formulation is that SCADA and PMU datasets are not directly mixed to perform state estimation. Therefore, the differences in the SCADA and PMU datasets do not impact the performance of the proposed state estimator.*

Question: Some examples of on-line computation time?

Answer: *The online computation time was of the order of 10 milliseconds for each testing sample during real-time operation.*

Question: How was the DNN architecture (depth, width, activation function, optimizer, etc.) selected?

Answer: *The DNN architecture was selected using a platform called WANDB (https://wandb.ai/site). By employing this platform, one can find the best architecture using methods such as Random Search, Global Search, or Bayesian Optimization. We used Random Search.*

Question: For newer lines or buses or part of network, with no PMUs but only SCADA data, how much training data is needed for ML-based state estimation, and when can it be integrated?

Answer: *The size of the training database is a hyperparameter that must be determined during the DNN training which is performed offline.*
When new lines/buses are added, the relationship between the inputs and the outputs of the DNN change. Therefore, the offline training must be repeated whenever new lines/buses are added. Once the training is complete, the newly trained DNN should replace the older one.
Since the training database is created using knowledge gained from SCADA data only, even if the new parts of the network do not have PMUs, it will not be a concern for the proposed estimator.

Question: Are you saying that if angles are not available in measurements, then the relationship becomes non-linear? Does the state in your definition include voltage angles?

Answer: *Yes, the state is the voltage phasor, so it includes both voltage magnitude and voltage angle.*

Question: Why did you consider only the Magnitude and Angles alone? Can we consider the frequency variations?

Answer: *We are performing static state estimation. Frequency is not included in the static state estimation formulation. To consider frequency, we will have to do Dynamic State Estimation which is out of the scope of this work and presentation.*

Question: Wouldn't it help to select measurement locations with small correlations (rather than large correlations), to capture enough the possible spread in measurements?

Answer: *The purpose of looking at highly correlated measurements is to identify the smallest set of locations where high-speed sensors (e.g., micro-PMUs) must be placed in order to accurately track the variations occurring in the states. This is particularly important for the distribution system where it is cost-prohibitive to place large number of such sensors.*

Question: Typical distribution system is a very complex network with thousands of customers (AMI meters), many switches, voltage regulators, capacitor banks etc. How do you decide how many samples are appropriate for training the DNN model for such a complex network?

Answer: *The size of the training database is a hyperparameter that must be determined during the DNN training which is performed offline. For our simulations, for each topology, we created 10,000 samples for training and validation, and 2,500 samples for testing. The samples were generated by solving power flows in OpenDSS. While solving the power flows, we accounted for the presence of single/two-phase laterals, distributed loads, switches, on-load tap-changing transformers, voltage regulators, as well as capacitor banks.*

Question: In your work, you can use just 5 measurements to estimate the whole system?

Answer: *Yes, for the 240-node U.S. Midwest distribution system, micro-PMUs placed at 5 locations were sufficient to estimate the states (voltage phasors) of all the nodes. The reason why so few locations were adequate was because the states of this system were highly correlated, and therefore, by tracking the micro-PMU measurement variations in those strategic locations, a DNN could approximate all the states sufficiently well. Components, such as voltage regulators, and extremely long feeders can lower the correlations. This means that in systems in which these are present, more sensors will be needed.*

Question: What measurements are required from PMUs? Just voltage of all three phases? Or line current too. Injection currents?

Answer: *We used three-phase nodal voltage phasors and three-phase line current phasors.*

Question: For power systems of considerable size, shall we use the status of circuit breakers as the input to the DNN, or are there other approaches that be used to take care of topology changes, so that retraining is not necessary?

Answer: *We used Transfer Learning to quickly retrain the DNN for different topologies.*

Question: Can we share some papers related to the state-of-the-art of Linear state estimator and DNN estimator?

Answer: *Five papers are cited below. The first two papers were published by Prof. Pal's research group at ASU, while the third paper came out of Prof. Tong's research group at Cornell. These three papers are on distribution system state estimation using DNNs. The fourth paper is on the use of DNNs for transmission system state estimation. The last paper is on the topic of three-phase linear state estimation.*

[1] B. Azimian, R. S. Biswas, S. Moshtagh, A. Pal, L. Tong and G. Dasarathy, "State and Topology Estimation for Unobservable Distribution Systems Using Deep Neural Networks," in *IEEE Transactions on Instrumentation and Measurement*, vol. 71, pp. 1-14, 2022, Art no. 9003514. doi: 10.1109/TIM.2022.3167722

[2] B. Azimian, R. S. Biswas, A. Pal and L. Tong, "Time Synchronized State Estimation for Incompletely Observed Distribution Systems Using Deep Learning Considering Realistic Measurement Noise," *2021 IEEE Power & Energy Society General Meeting (PESGM)*, Washington, DC, USA, 2021, pp. 1-5. doi: 10.1109/PESGM46819.2021.9637858

[3] K. R. Mestav, J. Luengo-Rozas and L. Tong, "Bayesian State Estimation for Unobservable Distribution Systems via Deep Learning," in *IEEE Transactions on Power Systems*, vol. 34, no. 6, pp. 4910-4920, Nov. 2019. doi: 10.1109/TPWRS.2019.2919157

[4] G. Tian, Y. Gu, D. Shi, J. Fu, Z. Yu and Q. Zhou, "Neural-network-based Power System State Estimation with Extended Observability," in *Journal of Modern Power Systems and Clean Energy*, vol. 9, no. 5, pp. 1043-1053, September 2021. doi: 10.35833/MPCE.2020.000362

[5] K. D. Jones, J. S. Thorp and R. M. Gardner, "Three-phase linear state estimation using Phasor Measurements," *2013 IEEE Power & Energy Society General Meeting*, Vancouver, BC, Canada, 2013, pp. 1-5. doi: 10.1109/PESMG.2013.6672516

Question: Can we consider different KVA system variables to analyze like 765kV, 110kV, and 440kV?

Answer: *Yes.*

Question: Kindly share the referred papers too?

Answer: *The following six papers were referred in the presentation:*

[1] B. Azimian, R. S. Biswas, A. Pal and L. Tong, "Time Synchronized State Estimation for Incompletely Observed Distribution Systems Using Deep Learning Considering Realistic Measurement Noise," *2021 IEEE Power & Energy Society General Meeting (PESGM)*, Washington, DC, USA, 2021, pp. 1-5.
doi: 10.1109/PESGM46819.2021.9637858

[2] B. Azimian, R. S. Biswas, S. Moshtagh, A. Pal, L. Tong and G. Dasarathy, "State and Topology Estimation for Unobservable Distribution Systems Using Deep Neural Networks," in *IEEE Transactions on Instrumentation and Measurement*, vol. 71, pp. 1-14, 2022, Art no. 9003514.
doi: 10.1109/TIM.2022.3167722

[3] R. S. Biswas, B. Azimian and A. Pal, "A Micro-PMU Placement Scheme for Distribution Systems Considering Practical Constraints," *2020 IEEE Power & Energy Society General Meeting (PESGM)*, Montreal, QC, Canada, 2020, pp. 1-5.
doi: 10.1109/PESGM41954.2020.9282049

[4] F. Bu, Y. Yuan, Z. Wang, K. Dehghanpour and A. Kimber, "A Time-Series Distribution Test System Based on Real Utility Data," *2019 North American Power Symposium (NAPS)*, Wichita, KS, USA, 2019, pp. 1-6.
doi: 10.1109/NAPS46351.2019.8999982

[5] A. Pal, G. A. Sanchez-Ayala, V. A. Centeno and J. S. Thorp, "A PMU Placement Scheme Ensuring Real-Time Monitoring of Critical Buses of the Network," in *IEEE Transactions on Power Delivery*, vol. 29, no. 2, pp. 510-517, April 2014.
doi: 10.1109/TPWRD.2013.2279172

[6] K. R. Mestav, J. Luengo-Rozas and L. Tong, "Bayesian State Estimation for Unobservable Distribution Systems via Deep Learning," in *IEEE Transactions on Power Systems*, vol. 34, no. 6, pp. 4910-4920, Nov. 2019.
doi: 10.1109/TPWRS.2019.2919157

Question: Can you explain more about which all non-time synchronized measurements you used to train the DNN? How do these measurements correspond to the time synchronized measurements used during inference?

Answer: *For the 240-node distribution system, historical smart meter data is publicly available, and it was used directly. For the IEEE 118-bus transmission system, we only had information of a snap-shot in time. Therefore, historical SCADA data for the 2000-bus Synthetic Texas system[1] that is publicly available, was mapped on to the 118-bus system. Next, appropriate distributions were fit on to the historical data, and random sampling was performed from these distributions to solve power flows. The outputs of the power flows were used to create the time-synchronized measurements as well as the states, which were then employed to train and test the DNN. This procedure ensured that although slow timescale smart meter/SCADA data and fast timescale PMU/micro-PMU data were not directly mixed for performing state estimation, both the datasets corresponded to the same system and similar operating conditions.*

[1] A. B. Birchfield, T. Xu, K. M. Gegner, K. S. Shetye and T. J. Overbye, "Grid Structural Characteristics as Validation Criteria for Synthetic Networks," in *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 3258-3265, July 2017. doi: 10.1109/TPWRS.2016.2616385

Question: Interested in linearized SE logic used, measurement location selection. Could you please share the related paper for details?

Answer: *Some related papers are cited below. The first two papers are on the topic of linear state estimation, while the other four papers describe measurement location selection for attaining different objectives.*

[1] K. D. Jones, J. S. Thorp and R. M. Gardner, "Three-phase linear state estimation using Phasor Measurements," *2013 IEEE Power & Energy Society General Meeting*, Vancouver, BC, Canada, 2013, pp. 1-5.
doi: 10.1109/PESMG.2013.6672516

[2] P. Chatterjee, A. Pal, J. S. Thorp and J. De La Ree, "Partitioned linear state estimation," *2015 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC, USA, 2015, pp. 1-5.
doi: 10.1109/ISGT.2015.7131883

[3] A. Pal, G. A. Sanchez-Ayala, V. A. Centeno and J. S. Thorp, "A PMU Placement Scheme Ensuring Real-Time Monitoring of Critical Buses of the Network," in *IEEE Transactions on Power Delivery*, vol. 29, no. 2, pp. 510-517, April 2014.
doi: 10.1109/TPWRD.2013.2279172

[4] A. Pal, A. K. S. Vullikanti and S. S. Ravi, "A PMU Placement Scheme Considering Realistic Costs and Modern Trends in Relaying," in *IEEE Transactions on Power Systems*, vol. 32, no. 1, pp. 552-561, Jan. 2017.
doi: 10.1109/TPWRS.2016.2551320

[5] R. S. Biswas, B. Azimian and A. Pal, "A Micro-PMU Placement Scheme for Distribution Systems Considering Practical Constraints," *2020 IEEE Power & Energy Society General Meeting (PESGM)*, Montreal, QC, Canada, 2020, pp. 1-5.
doi: 10.1109/PESGM41954.2020.9282049

[6] B. Azimian, R. S. Biswas, S. Moshtagh, A. Pal, L. Tong and G. Dasarathy, "State and Topology Estimation for Unobservable Distribution Systems Using Deep Neural Networks," in *IEEE Transactions on Instrumentation and Measurement*, vol. 71, pp. 1-14, 2022, Art no. 9003514.
doi: 10.1109/TIM.2022.3167722

Question: How did you control that historical data also pertained to a base topology? Because actual historical data may be of different topology which may not be known.

Answer: *Since we had no prior information, we assumed that the historical data pertained to a single topology. In case this information is provided to us, we can treat the topology that occurs most often in the historical data as the base topology and employ Transfer Learning to update the DNN hyperparameters when the topology changes.*

Question: Is it done under OpenDSS tool?

Answer: *Yes, we used OpenDSS to model our distribution test systems.*

Question: I didn't quite catch how a topology change was detected. I will assume that you have a set of papers published about this work.

Answer: *The detection of topology change was treated as a supervised learning (classification) problem. Different topologies were created in the distribution system by opening/closing appropriate switches. You can find more information in the paper below:*

[1] B. Azimian, R. S. Biswas, S. Moshtagh, A. Pal, L. Tong and G. Dasarathy, "State and Topology Estimation for Unobservable Distribution Systems Using Deep Neural Networks," in *IEEE Transactions on Instrumentation and Measurement*, vol. 71, pp. 1-14, 2022, Art no. 9003514. doi: 10.1109/TIM.2022.3167722

Question: We can use MATLAB now? Can we have any sample DNN model?

Answer: *Please refer to our papers cited below to get more information about the DNN model and the software used.*

[1] B. Azimian, R. S. Biswas, S. Moshtagh, A. Pal, L. Tong and G. Dasarathy, "State and Topology Estimation for Unobservable Distribution Systems Using Deep Neural Networks," in *IEEE Transactions on Instrumentation and Measurement*, vol. 71, pp. 1-14, 2022, Art no. 9003514. doi: 10.1109/TIM.2022.3167722

[2] B. Azimian, R. S. Biswas, A. Pal and L. Tong, "Time Synchronized State Estimation for Incompletely Observed Distribution Systems Using Deep Learning Considering Realistic Measurement Noise," *2021 IEEE Power & Energy Society General Meeting (PESGM)*, Washington, DC, USA, 2021, pp. 1-5. doi: 10.1109/PESGM46819.2021.9637858

Question: Can you explain what "nearest operating condition" means?

Answer: *In the context of the proposed bad data replacement scheme, the "nearest operating condition" is that operating condition in the training database whose measurements are closest (in the L2 norm sense) to the corresponding good quality features of the testing sample.*

Question: Is network model required as an input to the proposed method? Or is it completely free of network model information?

Answer: *The network model is used for training. During the online execution, it is not needed.*