



Smart Meter-Driven Distribution Grid Visibility and Control

Final Project Report

T-67

Power Systems Engineering Research Center

*Empowering Minds to Engineer
the Future Electric Energy System*



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Power Systems Engineering Research Center

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Executive Summary

Project Overview

This report presents the outcomes of PSERC Project T-67, Smart Meter-Driven Distribution Grid Visibility and Control. The project addresses an emerging challenge in modern power systems: improving real-time visibility and control in distribution grids with increasing penetration of distributed energy resources (DERs). The project develops new computational methods for achieving visibility and control while relying on existing smart meter infrastructure constrained by communication bandwidth.

While smart meters are ubiquitous and capable of recording accurate and frequent measurements of voltage, current, and power, their potential for real-time monitoring and control has been under-utilized. The main barrier is communication bandwidth: utilities can only retrieve a limited number of high-frequency data streams, far fewer than the total number of meters deployed. We consider a setting where the smart meter communication capabilities can be dynamically allocated such that the bandwidth is limited in aggregate across a fleet of smart meters. As Fig. 1 illustrates conceptually, this is analogous to shining flashlights around a dark room: more data from certain smart meters can be obtained at the cost of transmitting less data from other meters. Accordingly, this project develops new theoretical frameworks, optimization methods, and machine learning techniques to maximize the value of limited smart meter data streams, thereby transforming smart meters from billing devices into critical sensing infrastructure for future distribution grids.

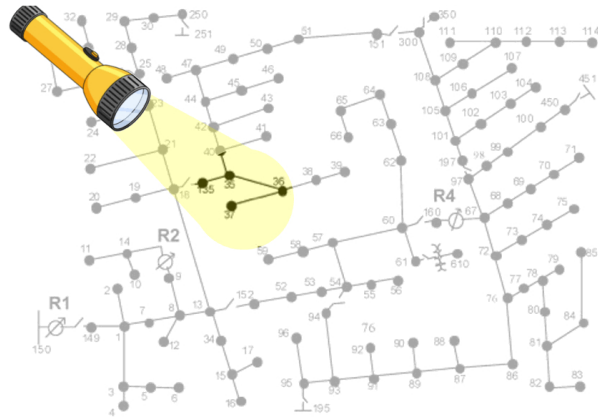


Figure 1: Conceptual illustration of dynamically using limited-bandwidth communication across a fleet of smart meters.

In this context, the project focuses on five particular topics: (1) online strategies for identifying worst-case violations of voltage magnitude limits in distribution networks, (2) machine learning methods for classifying the control laws of behind-the-meter solar inverters, (3) forecast-aided state estimation, (4) online identification of distribution network topologies using quantized measurements, and (5) information-theoretic approaches for managing bandwidth-limited smart meter data.

Online Strategies for Identifying Worst-Case Voltage Magnitude Violations

We developed two approaches for online sensor sampling to identify worst-case violations of voltage magnitude limits under bandwidth constraints. The first method builds on a stochastic lin-

earized power flow (LinDistFlow) model and casts the problem as a *spectral multi-armed bandit*. The algorithm iteratively selects subsets of smart meters in real time, guided by the graphical structure of distribution networks and sub-Gaussian bounds on voltage fluctuations. The second method is an iterative optimization algorithm that, at each step, identifies which buses may have the most significant voltage excursions given the measurements taken so far and known bounds on the power injections at each bus. The method updates the set of measurements to include voltages at unmeasured buses with the largest range of possible voltage magnitudes.

Simulations on benchmark feeders demonstrated that both measurement selection methods consistently outperform baseline algorithms, such as conventional linear bandit sampling. This work shows that limited communication capacity need not prevent effective monitoring of potential voltage limit violations. By exploiting the inherent network structure, utilities can adaptively reallocate bandwidth to measure critical buses, improving situational awareness without additional infrastructure investments.

Machine Learning for Classifying Control Laws of Behind-the-Meter Solar Inverters

Utility companies may not know the reactive power and voltage magnitude control laws of behind-the-meter solar inverters, but these control laws can have significant impacts on the behavior of distribution systems. Using a synthetic dataset of smart meter measurements reflecting different inverter control strategies (e.g., fixed power factor and volt-var controls), this work tested two methods for classifying inverter behavior: a nearest-centroid classifier and a neural network.

Both methods successfully identified inverter control laws, but the neural network substantially outperformed the simpler centroid approach, achieving higher accuracy and greater robustness to measurement noise. We also evaluated how measurement errors and data availability affect classification performance, identifying trade-offs between data quality and classifier reliability. The ability to infer control behaviors from smart meter data provides a low-cost means of improving grid models, forecasting, and operational decision-making.

Forecast-Aided State Estimation

State estimation is a key application for real-time visibility of power systems. Smart meter measurements can contribute to improving the accuracy of distribution system state estimation provided bandwidth limitations can be appropriately managed. Accordingly, we developed an algorithm for distribution system state estimation under bandwidth limitations using a hybrid approach that incorporates forecasting models. At unmeasured buses, a vector autoregressive (VAR) model with recursive least squares updates was used to forecast nodal power injections, providing priors for a state estimator. Real-time smart meter data were then incorporated to refine the estimates under bandwidth-limited conditions.

Case studies on unbalanced distribution feeders showed that forecast-aided distribution system state estimation achieved high accuracy even when only 10–20% of buses provided high-frequency measurements. The approach also adapted well under conditions with photovoltaic integration and vari-

able load demands. These results demonstrate that forecasting can compensate for measurement scarcity, enabling more accurate state estimation without deploying additional sensors beyond existing bandwidth-limited smart meters.

Online Identification of Distribution Network Topologies Using Quantized Measurements

In settings where the distribution network characteristics are unknown or rapidly changing (e.g., due to post-storm network restoration), it is valuable to infer the network topology and line parameters directly from measured voltages and power injections. We investigated the problem of learning radial distribution network topology and parameters from smart meter data subject to quantization (i.e., finite-resolution measurements). Building on the stochastic LinDistFlow power flow approximation, our method derives statistical error bounds for topology recovery when measurements are communicated at low precision due to bandwidth limitations.

Theoretical analysis established error bounds on topology estimation accuracy, quantifying how the number of samples and quantization levels affect recovery performance. Numerical experiments on test feeders confirmed that accurate topology learning is achievable even with coarse quantization, provided that sufficient time-series data are collected. By showing that reliable topology inference is possible from bandwidth-limited smart meter data, this research provides a pathway for enhancing grid visibility and data quality in regions where records are incomplete or outdated.

Information-Theoretic Approaches for Managing Bandwidth-Limited Smart Meter Data

Methods for managing limited communication capacity among a large number of sensors may be categorized into two groups: 1) sensor sampling or measurement selection, and 2) bit rate allocation. The online strategies for identifying worst-case voltage magnitude violations described above are a good example of the first approach. In contrast, we have also considered methods which continually acquire data from all the sensors in the network, but which allocate varying bit rates to each of the sensors based on the value of the data in a particular application such as state estimation. Well-known tools from information theory, including rate distortion theory and quantization, play a key role.

In order to determine the bit rate for a continuous random variable subject to quantization, knowledge of the prior probability distribution of that random variable is required. Hence, a probabilistic description of the underlying system from which the measurements are derived comes into play. We use a state variable description of the system, and a Kalman filter which gives the evolution of the state probability distribution functions based on the measurements. Our approach differs from conventional Kalman filtering in that we assume that the measurements are ideal, and that the measurement “error” is the result of the quantization which leads to finite bit rate communications.

Project Publications

- [1] S. Talkington, R. Gupta, R. Asiamah, P. Buason, and D.K. Molzahn, “Strategic Electric Distribution Network Sensing via Spectral Bandits,” *63rd IEEE Conference on Decision and Control (CDC)*, December 16-19, 2024.
- [2] J. Chen and L.A. Roald, “Real-time Assessment of Distribution Grid Security through Adaptive Smart Meter Measurements,” *63rd IEEE Conference on Decision and Control (CDC)*, December 16-19, 2024.
- [3] R. Asiamah, S. Talkington, M. Boateng, M. Vanin, F. Geth, and D.K. Molzahn, “Classifying Reactive Power Control Laws of Behind-the-Meter Solar Photovoltaic Inverters,” *6th Kansas Power and Energy Conference (KPEC)*, April 24-25, 2025.
- [4] A. Rangarajan, R.K. Gupta, D.K. Molzahn, and L.A. Roald, “Forecast-Aided State Estimation in Unbalanced Distribution Networks Using Smart Meter Data under Limited Communication Bandwidth,” *Sustainable Energy, Grids and Networks*, vol. 43, no. 101863, September 2025. Presented at the *12th IREP Bulk Power system Dynamics and Control Symposium*, June 22-27, 2025.
- [5] S. Talkington, A. Rangarajan, P.A. de Alcântara, L.A. Roald, D.K. Molzahn, and D.R. Fuhrmann, “Error Bounds for Radial Network Topology Learning from Quantized Measurements”, submitted, arXiv:2508.05620.
- [6] P. Aquino de Alcantara, F. Costa, and D. Fuhrmann, “One-Dimensional Kalman Filter with Measurement Noise Replaced by Quantization”, *59th Annual Conference on Information Science and Systems (CISS)*, March 2025.

Student Theses

- [1] Samuel Talkington, “Approximate and Differentiable Optimal Power Flow Models,” *PhD Dissertation, Georgia Institute of Technology, School of Electrical and Computer Engineering*, Spring 2026 (expected).
- [2] Richard Asiamah, “Development and Applications of Synthetic Electric Grid Models for Underrepresented Regions,” *PhD Dissertation, Georgia Institute of Technology, School of Electrical and Computer Engineering*, Fall 2026 (expected).
- [3] Jiaqi Chen, “Data-Driven Approaches for Distribution Grid Analysis,” *PhD Dissertation, University of Wisconsin–Madison, Department of Electrical and Computer Engineering*, July 2025.
- [4] Aditya Rangarajan, “Management of Renewable-rich Power Systems with Partial System Information,” *PhD Dissertation, University of Wisconsin–Madison, Department of Electrical and Computer Engineering*, Spring 2026 (expected).
- [5] Pedro Aquino de Alcantara, “Information-Theoretic Methods in Smart Meter Communication,” *PhD Dissertation, Michigan Technological University, Department of Electrical and Computer Engineering*, Spring 2027 (expected).