PowerSINDy: Identifying Nonlinear Time-Dependent Dynamics in Power Grid Frequency

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System identification plays a crucial role in physics and machine learning for discovering governing equations directly from data. A powerful approach is the Sparse Identification of Nonlinear Dynamics (SINDy) method, which assumes that only a few dominant terms drive the essential behavior of a nonlinear dynamical system. While SINDy methods have shown excellent results, they are most often illustrated on synthetic or simulated systems, leaving open the question of how well they perform on complex, noisy, real-world data. Power grid frequency dynamics provide a highly relevant and challenging environment for advancing system identification methods. In this work, we propose PowerSINDy as a framework for empirical power system data. We apply this framework to empirical frequency data from the Continental Europe (CE) and South Korea (SK) synchronous grids, two major power systems with distinct dynamical characteristics. PowerSINDy, which also includes time-dependent terms, can identify the dynamics of these complex real-world systems. Furthermore, we benchmark three sparsity-promoting regression strategies: Sequentially Thresholded Least Squares (STLSQ), Least Absolute Shrinkage and Selection Operator (LASSO), and Sparse Relaxed Regularized Regression (SR3) to evaluate trade-offs between accuracy, sparsity, and robustness. Results show that LASSO consistently achieves the lowest stable RMSEs, reaching 0.0101 for the CE, while STLSQ provides the best balance between accuracy and stability. SR3 exhibits higher variability and sensitivity to regularization, with L0 and L1 producing nearly indistinguishable outcomes.