Format for uploading details of completed projects

1. **Project details**

   a. *Title*: Characterization and Detection of Power System Ambient, Transient and Forced Oscillations Based on Synchrophasor Data Analytics in Indian Context.

   b. *Institute*: Indian Institute of Technology Patna

2. **Aim / Objectives:**

- Analysis and Detection of oscillations from Synchrophasor data of ERLDC, POSOCO.
- Prediction of Instability using efficient methods (AI learning methods).
- To develop oscillation detector module (ODM) and oscillation source locator module (OSLM) for online application.

3. **Executive Summary (*One page*):**

Forced Oscillations (FOs) differ fundamentally from natural oscillations in power systems, particularly in their origins, behavior, and impact. Natural or modal oscillations arise from the system's internal dynamics, such as interactions between generators and network elements, and occur at characteristic frequencies determined by the system's structure. These oscillations are typically managed using traditional control mechanisms like power system stabilizers (PSSs) and wide-area damping controllers, which are designed to address intrinsic oscillatory modes. In contrast, FOs are caused by external, periodic disturbances from sources such as cyclic loads, turbine malfunctions, or renewable energy fluctuations. These disturbances occur at arbitrary frequencies and, when they align with the system's natural modes, can result in resonance, amplifying oscillations to dangerous levels and jeopardizing grid stability.

Unlike natural oscillations, FOs cannot be mitigated effectively through increased system damping or traditional control strategies, as these methods target internal dynamics rather than external disturbances. The most effective strategy for handling FOs is to detect and localize their sources accurately, allowing for targeted interventions to eliminate the disturbance. This research focuses on developing data-driven, machine learning-based algorithms for detecting and localizing FOs within the Eastern Regional Grid (ERG), a critical component of India's power network.

The study begins with the development of a dynamic model of the ERG, constructed using data provided by the system operator to simulate real-world grid conditions. Simulated data from this model will be used to analyze and characterize FOs, including the estimation of critical parameters such as oscillation frequency and damping ratio. Machine learning methods will then be developed to detect FOs and distinguish them from natural oscillations, ensuring accurate identification of external disturbances. Furthermore, advanced algorithms will be designed to pinpoint the sources of FOs within the grid, enabling precise and effective mitigation.

Additionally, the research will employ AI techniques to predict potential grid instability caused by FOs, facilitating proactive management of such events. The proposed detection and localization framework will be rigorously validated using the ERG model, ensuring its relevance and effectiveness in the Indian grid context. By transitioning from traditional damping approaches to source-specific intervention strategies, this study addresses the unique challenges posed by FOs in modern power systems with high renewable energy penetration and complex disturbance profiles.

4. Scope for further work

The outcomes of this research open several avenues for future exploration and development in the domain of power system stability and forced oscillation (FO) mitigation. While the current study has successfully developed machine learning-based methods for FO detection and source localization, as well as a web-based application for real-time monitoring, there remain opportunities to enhance these solutions further and address additional challenges in modern power systems.

1. **Extension to Multi-Regional Grids**: The current work focuses on the Eastern Regional Grid (ERG). Extending the methodologies to multi-regional or national grids, which have more complex interconnections and dynamics, would enhance the generalizability of the proposed solutions.
2. **Enhanced Predictive Capabilities**: Incorporating predictive analytics to forecast the onset of forced oscillations and identify potential resonance scenarios could provide grid operators with early warning systems. This would facilitate proactive mitigation strategies and further enhance grid resilience.
3. **Handling Renewable Energy Variability**: As renewable energy penetration increases, the variability and uncertainty associated with such sources pose additional challenges. Future research could explore the integration of renewable energy forecasting models with FO detection algorithms to improve accuracy in systems with high renewable energy contributions.
4. **Advanced Feature Engineering and Model Optimization**: While the current study employs machine learning methods, future work could explore advanced feature extraction techniques, such as those derived from deep learning and signal decomposition methods, to improve detection accuracy and robustness under various operational conditions.
5. **Cybersecurity Integration**: The increasing reliance on data-driven methods in power systems introduces vulnerabilities to cyber threats. Future efforts could focus on developing secure and robust frameworks to safeguard FO detection and localization systems against cyberattacks.
6. **Validation with Real-Time Data**: While the current framework is validated using simulated data, the use of real-time grid data for testing and refinement would enhance the reliability and practical applicability of the proposed methods.

By addressing these aspects, future work can further advance the capabilities of FO detection and mitigation, ensuring grid stability and reliability in the face of evolving power system dynamics. These developments will play a critical role in modernizing grid infrastructure and supporting the transition to sustainable and resilient energy systems.

5. Benefits visualized

The outcomes of this research present significant advancements in the field of power system stability, particularly in detecting and mitigating forced oscillations. Machine learning methodologies are developed that demonstrated high precision in detecting and distinguishing FOs from natural oscillations, ensuring reliable identification of disturbances. A user-friendly application was successfully developed, integrating ML models for real-time FO detection, localization, and monitoring, providing a valuable tool for grid operators. That and tools offer both theoretical insights and practical solutions, delivering tangible benefits to stakeholders such as operators of eastern regional grid. Below are the publications resulting from this project:

Publications

Journals

1. Kumar Abhinav, et al. "A data-driven online approach for detection and localization of forced oscillation in wind turbine integrated power system." Electric Power Systems Research 233 (2024): 110512.
2. Priya Singh, Abhineet Prakash, and S. K. Parida. "Neural network based pattern recognition for classification of the forced and natural oscillation." Electric Power Systems Research 224 (2023): 109706.
3. S. Murali, P. Saini, K. Abhinav, R. Shankar and S. K. Parida, "Improved LSTM-Based Load Forecasting Embedded 3DOF (FOPI)-FOPD Controller for Proactive Frequency Regulation in Power System," in IEEE Transactions on Industry Applications, vol. 60, no. 6, pp. 8213-8227, Nov.-Dec. 2024, doi: 10.1109/TIA.2024.3443243.
4. Kumar, Raushan, Shubham Anand, and S. K. Parida. "A protection approach of AC transmission lines utilizing positive-sequence fault components." Electric Power Systems Research 233 (2024): 110490.
5. K. Kumar, A. Prakash, S. K. Parida, S. Ghosh and C. Kumar, "A Novel Multi-Functional Observer Based Distributed WADC for Large Power System Using Modified Decoupled Control Approach," in IEEE Transactions on Power Systems, vol. 39, no. 5, pp. 6662-6674, Sept. 2024, doi: 10.1109/TPWRS.2024.3351369.

A. Prakash, K. Kumar and S. K. Parida, "A Modal Transformation Approach to Design Reduced Order Functional Observer-BasedWADC for Low-Frequency Oscillations," in IEEE Transactions on Power Systems, vol. 38, no. 4, pp. 3593-3604, July 2023, doi:10.1109/TPWRS.2022.3196787

6. M. K. Mishra and S. K. Parida, "A Game Theoretic Horizon Decomposition Approach for Real-Time Demand-Side Management," in IEEE Transactions on Smart Grid, vol. 13, no. 5, pp. 3532-3545, Sept. 2022, doi: 10.1109/TSG.2022.3173786.
7. A Prakash, R. K. Tiwari, K. Kumar and S. K. Parida, "Interacting Multiple Model Strategy Based Adaptive Wide-Area Damping Controller Design for Wind Farm Embedded Power System," in IEEE Transactions on Sustainable Energy, vol. 14, no. 2, pp. 962-973, April 2023, doi: 10.1109/TSTE.2022.3231647.

8. K. Kumar, A. Prakash, P. Singh and S. K. Parida, "Large-Scale Solar PV Converter Based Robust Wide-Area Damping Controller for Critical Low Frequency Oscillations in Power Systems," in IEEE Transactions on Industry Applications, vol. 59, no. 4, pp. 4868-4879, July-Aug. 2023, doi: 10.1109/TIA.2023.3268632.
9. Shubham Anand, Kaustav Kalita, and S. K. Parida. "A novel transmission system protection scheme using optimal wide-area measurements." Electric Power Systems Research 216 (2023): 108976.
10. Abhineet Prakash, Kumar Abhinav, Piyush Rai and S.K. Parida "Distributed Generation Based WADC for Inter-Area Oscillations Considering Unknown Inputs," in Electric Power Components and Systems 2023, doi: 10.1080/15325008.2023.2258503.
11. Abhineet Prakash, Kundan Kumar & S. K. Parida "Damping of Inter-Area Oscillations Using TCPS Based Delay Compensated Robust WADC," in Electric Power Components and Systems 2023 , 51:15, 1562-1575, DOI: 10.1080/15325008.2023.2200772.
12. Anand, Shubham, Kaustav Kalita, and S. K. Parida. "A modified mutual impedance based backup protection for series-compensated transmission lines." Electric Power Systems Research 224 (2023): 109719.

Conferences

1. Saini, Priyesh, Abhineet Prakash, and S. K. Parida. "Enhanced Short-Term Load Forecasting Using Facebook Prophet and Discrete Wavelet Transform." 2023 IEEE 3rd International Conference on Smart Technologies for Power, Energy and Control (STPEC). IEEE, 2023.
2. Prakash, Abhineet, Priyesh Saini, and S. K. Parida. "Distributed Generation Based Design of Prescribed Degree Robust Wide Area Damping Controller for Inter-Area Oscillations in Power Systems." 2023 IEEE 3rd International Conference on Smart Technologies for Power, Energy and Control (STPEC). IEEE, 2023.
3. Saini, Priyesh, Kumar Abhinav, and S. K. Parida. "Improved Facebook Prophet Model Using Singular Spectrum Analysis for Short-Term Load Forecasting." 2023 IEEE International Conference on Energy Technologies for Future Grids (ETFG). IEEE, 2023
4. P. Saini and S. K. Parida, "Inertia Estimation of Islanded Power System With Distributed Generation Using Long Short Term Memory Algorithm," 2023 IEEE IAS Global Conference on Renewable Energy and Hydrogen Technologies (GlobConHT), Male, Maldives, 2023, pp. 1-6, doi: 10.1109/GlobConHT56829.2023.10087690.
5. K. Abhinav, P. Rai, A. Prakash and S. K. Parida, "Comparative Assessment of Prony Analysis and Eigensystem Realization Algorithm for Forced Oscillation De-tection and Mode Estimation Considering PMU Noise," 2023 IEEE 3rd International Conference on Smart Technologies for Power, Energy and Control (STPEC),Bhubaneswar, India, 2023, pp. 1-6, doi: 10.1109/STPEC59253.2023.10430933.
6. K. Abhinav, P. Saini, P. Rai, A. Prakash and S. K. Parida, "A Data-Driven Forced Oscillation Detection Using Random Forest," 2023 IEEE International Conference on Energy Technologies for Future Grids (ETFG), Wollongong, Australia, 2023, pp.1-6, doi: 10.1109/ETFG55873.2023.10408579.
7. K. Kumar, A. Prakash and S. K. Parida, "Wide-Area Damping Controller Design with TCSC Using Active Disturbance Rejection Control," 2023 IEEE IAS Global Conference on Emerging Technologies (GlobConET), London, United Kingdom, 2023, pp. 1-5, doi: 10.1109/GlobConET56651

8. K. Abhinav, P. Rai, P. Saini, A. Prakash and S. K. Parida, "Forced Oscillation Source Location using System Oscillating Energy and Eigensystem Realization Algorithm," 2024 IEEE National Power System Conference (NPSC), IIT Indore

9. P. Rai, Kumar Abhinav, P. Saini, A. Prakash and S. K. Parida "Detection of Wind Turbine Induced Forced Oscillations using Periodogram and DEF Techniques", 2024 Joint International Conference on Power Electronics, Drives and Energy Systems (PEDES).