



Data Driven Control of DERs & Hybrid PV Plants for Enhancing Voltage Stability with TSO-DSO Interactions Over Multiple Timescales

Final Project Report

S-96

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

There is increasing pressure on power system operators and electric utilities to utilize the existing grid infrastructure to the maximum extent possible. This mode of operation leads the system to operate close to its limits and can lead to instability problems. There are several forms of voltage instability, and each type requires different techniques to monitor and control.

According to MISO's Renewable Integration Impact Assessment (RIIA) Report, as the penetration of Inverter-based Resources (IBRs) approaches greater than 30%, voltage and converter-driven stability concerns arise in the system. Fault-induced delayed voltage recovery (FIDVR) occurs when the post-fault voltage recovers to a pre-fault voltage very slowly. If left untreated, FIDVR can lead to a complete voltage collapse. Inverter-based resources (IBRs) have the potential to improve delayed voltage recovery by providing dynamic reactive power support. This work investigates the potential of IBRs to enhance power system voltage performance.

This project is divided into three major research thrusts:

Thrust 1: (V. Ajjarapu, Iowa State University)

- Thrust-1 focuses mainly on identifying control set-points for the hybrid-PV plants and DERs. It deals with the questions:
 - How do we coordinate hybrid PV plants and DERs with load control for the optimal voltage response?
 - How to properly exploit the capability of several inverters within a single hybrid power plant (PV + battery)?
 - How do we measure the effect of GFL/GFM inverter controls on the FIDVR performance?

Thrust 2: (Hugo Villegas, Iowa State University)

- Grid forming inverter controls to improve FIDVR while respecting inverter current limitation.

Thrust 3: (Sanjeev Pannala, Washington State University)

- Validation utilizing realistic T&D co-simulation testbed using RTDS and Opal-RT

Part I: Data-driven Hybrid PV Plant Control for mitigation of short-term voltage instability

As the bulk electric system operation is moving into an operation regime where the economics are more important than in the past, the system operates close to the operating points with more chance of voltage instability. An essential type of voltage instability is the short-term large disturbance voltage instability that is caused by increasing penetration of the induction motor and electronic loads.

The problem of monitoring and mitigating Fault-Induced Delayed Voltage Recovery (FIDVR) is addressed by utilizing the high sampling rate of PMUs and using data-driven control techniques to orchestrate hybrid PV plants to provide optimal dynamic var support to the system.

To find the optimal control settings of IBRs for dynamic reactive power support, the problem can be formulated as an optimal control problem. Due to the high dimensionality and high non-linearity in power systems, optimal control problems are computationally expensive to solve. So, a data-driven approach that only depends on the sensor measurements can overcome the curse of dimensionality. The data-driven agent can be trained in offline simulation and then can operate and control the system online.

To improve short-term voltage stability, deep RL-based control is used to train on the synthetic PMU measurements from the system. A deep RL agent requires an observations tuple, an action tuple, and a scalar reward function to evaluate each action. For voltage stability improvement, the observations are voltage measurements at specific buses. Control actions are real and reactive power setpoints for IBRs and the amount of flexible load to be controlled.

The key takeaway from this part is that utilizing PMU measurements and offline training of the deep RL agent will enable the utilities to detect the FIDVR phenomenon and automatically compute the control setpoints for hybrid PV plants to mitigate delayed voltage recovery. This capability, combined with flexible load control of the single-phase induction motors, can ensure that the FIDVR recovery meets the transient voltage criterion set by the reliability coordinators.

Part II: Grid forming Inverter Controls to Improve FIDVR While respecting Inverter Current Limitations

At present, grid-forming (GFM) inverter-based resources (IBRs), such as wind and solar, are expected to power the U.S. grid-like synchronous machines. However, one problem with this transition is that GFM IBRs powered by hybrid resources are still under research. Further, a major concern is that GFM IBRs cannot source over-rated currents, jeopardizing the starting up of SPIMs and the riding through of FIDVR events. Grid-forming inverters must optimally transfer power from dc-coupled photovoltaic arrays and batteries into an ac grid. Further, they must be able to restore single-phase induction motors (SPIMs) and withstand fault-induced delayed-voltage-recovery (FIDVR) events.

These resilience and reliability challenges are addressed here by:

- (i) engineering a controller to operate dc-coupled hybrid resources optimally.
- (ii) modeling residential air-conditioning compressors for restoration/FIDVR studies; and
- (iii) analyzing SPIM thermal-relay performance under limited inverter currents and designing an electronic protection for stalled SPIMs.

These contributions are demonstrated via electromagnetic-transient simulations to satisfy recommendations by the North American Electric Reliability Corporation.

Part III: Real-Time Synchrophasor Measurements Based Long Term Voltage Stability Monitoring and Control

The WSU team worked on three topics under this task to validate the system using a real-time simulation testbed. The first task considered the ZIP load estimation from the distribution system to produce the aggregated load models to reflect accurate models at bulk power system levels

considering DERs. Solar PV and Battery energy storage systems are considered within the distribution system and created an equivalent simulation model for different operating conditions. Besides, the team also worked on network-level aggregation to complement different feeder levels to generate a single equivalent network.

T&D co-simulation analysis was performed using benchmark systems from transmission and distribution sectors and applied different testing conditions from a distribution systems perspective to understand how noisy DER control impacts power system behavior.

Finally, the IEEE 9 bus system replicates the typical fault-induced delayed voltage recovery (FIDVR) from single-phase induction motors with and without a Hybrid Solar PV system. A detailed discussion with results is included in the report under specific sections.

Project Publications:

- [1] M. Sarwar, A. R. R. Matavalam and V. Ajjarapu, “*Deep Reinforcement Learning Framework for Short-Term Voltage Stability Improvement*,” 2023 IEEE Texas Power and Energy Conference (TPEC), College Station, TX, USA, 2023, pp. 1-6, doi: 10.1109/TPEC56611.2023.10078572.
- [2] M. Sarwar, A. Reddy Ramapuram Matavalam and V. Ajjarapu, “*Characterization and Mitigation of Fault Induced Delayed Voltage Recovery with Dynamic Voltage Support by Hybrid PV Plants*,” 2022 North American Power Symposium (NAPS), Salt Lake City, UT, USA, 2022, pp. 1-6, doi: 10.1109/NAPS56150.2022.10012146.
- [3] Abdel Mannan, Hugo Pico, “*FIDVR Capability of Hybrid Grid-Forming PV Power Plants During Feeder Restoration*”, submitted to IEEE Transactions on Energy Conversion
- [4] Muhammad Sarwar and V. Ajjarapu, “*Deep Reinforcement Learning based Control of Inverter Based Resources for Voltage Stability Improvement*”, To be submitted for publication, submitted to arXiv repository.
- [5] S. M. H. Rizvi and A. K. Srivastava, “*Integrated T&D Voltage Stability Assessment Considering Impact of DERs and Distribution Network Topology*,” in IEEE Access, vol. 11, pp. 14702-14714, 2023, doi: 10.1109/ACCESS.2023.3243100.
- [6] N.Patari, S.Rizvi ,S.Pannala and A. Srivastava “*Aggregated ZIP Load Estimation Method for DER Integrated Distribution Systems*”, submitted to IEEE PES Transaction.

Student Theses:

- [1] Muhammad Sarwar, *Data Driven Control of Inverter Based Resources to Enhance Power System Voltage Performance*, PhD dissertation, Iowa State University, Ames IA, (In Progress).
- [2] Abdelrehman Mannan, *Investigating the Performance of Grid-forming Hybrid Photovoltaic Systems in Residential A/C Dominated Networks: An analysis during distribution feeder restoration and FIDVR*, master’s thesis, Iowa State University, Ames IA, (submitted).
- [3] Qin, C. (2022). *Data-driven situational awareness for distribution system resiliency* (Order No. 29326873). Available from Dissertations & Theses @ Washington State University WCLP