



Identification and Mitigation of T&D Operational Security Vulnerabilities in Inverter Dominated Power Systems

Final Project Report

T-65

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

This project focused on identifying operational security vulnerabilities in T&D assets that grid integration of massive amounts of inverter-based resources creates. The project focused on the following three main factors (1) Grid Synchronization Instability of Inverter Based Resources, (2) Protection Systems Response, (3) Load and Inverter Based Resources Dynamic Response Analysis which are explained as follows:

Part 1: Grid Synchronization Instability of Inverter Based Resources

Part I of this report was focused on the factors affecting grid synchronization stability of inverter base resources (IBRs). Impacts of different parameters of controllers on the grid synchronization stability were studied. Moreover, the impacts of the grid strength were studied and scenarios were created to show how the outages of lines may cause IBRs to lose grid synchronization stability. Accordingly, mitigative strategies were proposed. The main results of the projects are as follows:

- Different factors on the grid synchronization stability of IBRs were studied using Bode plots, Generalized Nyquist Criterion and time domain simulations.
- MIMO (multiple input, multiple output) transfer function of inverters was derived and using Bode plots the impacts of PLLs parameters on the grid synchronization stability were studied.
- The Generalized Nyquist Criterion was applied to the MIMO transfer function of inverters, and it was shown as the strength of the host power grid at the point of common coupling (PCC) reduces the inverter may face grid synchronization instability.
- Time domain simulations were performed, and it was also shown the decrease in the grid strength after outages of lines may lead to instability of inverters.
- It was shown reducing the bandwidth of PLLs may improve the grid synchronization stability of inverters. However, it may reduce the ability of PLLs to track fast changes in the system.
- To enhance the grid synchronization stability of inverters a supplementary controller structure was implemented that enhances the grid synchronization stability of inverters by adding supplementary signals to the main controllers of inverters to damp out power oscillations.

Part 2: Protection System Response

The increasing deployment of inverter interfaced resources in the modern power system changes the characteristics of the power grid. The new characteristics affect the performance of practically all subsystems of the power system. This project and in particular thrust 2 of the project focuses on the effects of inverters to the protection and control system. During faults, inverters may follow different control strategies such as suppression of fault current levels, suppression of negative and zero sequence current, suppression of active power fluctuations, or suppression of reactive power fluctuations. Certain protective relays depend on the presence of negative and zero sequence fault currents to determine fault direction as well as they depend on the level of fault current to determine the onset of faults. As a result, relays may mis-operate depending on the inverter control strategies.

This part of the report is focused on item 2. Based on the identified vulnerabilities, we propose mitigation strategies. Specifically, we propose new protection schemes that are immune to the characteristic of inverter dominated power systems.

Recent events of power system disturbances have identified the cause of these disturbances being the interactions of relays with inverters and in particular, inverter controls. These events have been reported by NERC and it appears that their frequency has increased. As the level of inverter penetration in power systems increases, these events will occur more often. We reviewed a number of events that resulted in major disturbances and blackouts due to the interaction of inverter based resources and the protection and control systems. In addition, we reviewed the literature and the research activities for the purpose of understanding and mitigating these complex interactions.

Early in the research it was recognized that the accuracy and fidelity of simulation models to reproduce the actual performance of the system is very important in assessing the new challenges and problems posed by the proliferation of inverters in the power system. Section 3 of the report describes the problem and provides an example to illustrate the issues.

The impact of inverters on the performance of the protection and control system depends on the specific protection function employed by it. This means the impact of inverters on the performance of protection and control systems must be assessed for each individual protection function. In order to provide the background, section 4 introduces the major protection functions that are of interest in this problem. Then, in section 5, the assessment of the effects of inverters on the protection system is performed by simulations of appropriate example test systems. Specifically, an example test system has been developed that consists of sections that are dominated by synchronous machines and sections that are dominated by inverters. Several contingencies have been utilized which represent systems that are well interconnected between synchronous machine dominated sections and inverter dominated sections or very loosely interconnected. The results indicate that the performance of the protection and control system deteriorates as the various parts of the system are loosely interconnected. Similarly, the level of inverters affects the performance of protection and control. This means as the systems move toward 100% inverter based systems, major deterioration of protection performance should be expected. These results make it clear that new approaches for protection and control are needed.

Section 7 presents new technology that provides reliable protection, immune to the new characteristics generated by inverters. The new technology is protection algorithms that are based on dynamic state estimation. The new protection function directly determines any abnormality in a protection zone, independently of fault current levels, components of fault currents, transients, harmonic content and other usual transients during faults. This technology provides a reliable answer to the challenges created by inverters.

For completeness, the report provides an approach for testing protection function in the laboratory with hardware in the loop. These methods have been implemented at the Georgia Tech laboratory. The methods support testing with hardware in the loop of legacy protective relays as well as newer technology of merging units and IEC 61850 approaches.

Finally, it is important to note that the subject of this project is very complex and the present report does not address all the issues. Research should continue to provide more understanding of the problems and issues as well as to improve new technologies.

Part III: Load and Inverter Based Resources Dynamic Response Analysis

Part III of this report focuses on the dynamic response analysis of load and inverter-based resources in distribution system. In particular, we develop a simplified model of the overall distribution system that captures the key responses of the distribution system to faults in the transmission system and identify the critical settings of inverter-based resources (IBRs) in distribution system for dynamic support.

Main results of this report include the following:

- We show that the aggregation of entire distribution system into a single composite load model (CLM) cannot accurately capture the dynamics of full distribution system. Especially when the significant fraction of single-phase induction motors is present in the distribution system with stalling behavior.
- We propose the reduced order distribution system models (RDSM) composed of sub-models that are analogous to the WECC CLM and aggregates the distribution system into load areas while ensuring the overall dynamics are retained. Full distribution system simulation data is employed to estimate the parameters of RDSM by matching the dynamics of the full DS model through the parameter optimization.
- Proposed RDSM models will facilitate the faster simulation of distribution system models integrated to transmission system for dynamic studies. Single phase models of RDSM can be easily integrated into any transmission system phasor simulation software such as PSS®E to further accelerate the co-simulation by eliminating the data exchange delays between the transmission and distribution system simulators.
- Critical parameters of the IBRs are identified through the global sensitivity analysis of grid forming inverter based solar photovoltaic (PV) generation. Real and reactive power control loop parameters of GFM inverter along with the maximum current rating are ranked according to their sensitivity on real and reactive power outputs of IBRs during the voltage disturbances.

Project Publications:

- [1] Hassan Yazdani, Saeed Lotfifard, “Parametric Study of Grid Synchronism Stability of Inverter Based Resources” to be submitted IEEE PES General Meeting, 2024.
- [2] Aditya Shankar Kar, Venkataramana Ajjarapu, “Robust Aggregated VAR Capability Curve of DER with Uncertain Renewable Generation” to be submitted IEEE PES General Meeting, 2024.
- [3] Amarsagar Reddy Ramapuram Matavalam, R. Venkatraman and V. Ajjarapu, “Accurate Representation of Distribution System Dynamics in Bulk System Studies by Clusters of Composite Load Models”, *accepted at IEEE Industry Applications Society Annual Meeting (IAS)*, 2023.

Student Theses:

- [1] Hassan Yazdani, Expected Ph.D thesis title “Grid Synchronization Stability Enhancement of Inverter Based Resources”, Washington State University.
- [2] *Aditya Shankar Kar*, “Quantification and Impact of Uncertainty for Voltage Stability Studies in Power System with High Penetration of Distributed Energy Resources” *Expected thesis.*