



Grid Supporting Controllers for Enabling 100% Penetration of Inverter-Based Resources

Final Project Report

S-90

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

Amid the optimism surrounding the benefits of massive integration of renewables, incidents such as loss of a large amount of PV generation in Southern California in 2016 due to faults on transmission lines have raised concerns over resiliency of the future power system grid with 100% renewables. Renewable energy sources are typically the so-called Inverter-Based Resources (IBRs), meaning that they are interfaced to the grid through power converters, whose fault characteristics are influenced by control strategies. In addition, control system of an inverter is sensitive to grid disturbances such as unbalanced faults. In summary, operation and control of power systems with 100% IBRs pose a number of technical challenges, which are mainly due to: i) lack of a set of reliable methods to achieve desired voltage and frequency supports of the future grid by introducing synthetic inertia to the future grid, ii) insufficient investigation of comprehensive methods enabling the stability analysis of a system with high penetration level of IBRs, and iii) insufficient investigation of fault-ride-through capability and post-fault recovery control strategies to avoid massive dropouts of renewables following a disturbance. The goal of this proposal is to address the aforementioned challenges. This research focuses on three core areas: (1) development of small-signal models for stability analysis of Grid-Forming (GFM) and Grid Following (GFL) inverters, (2) development of supplementary predictive inverter control to ensure robust operation of GFM inverters during disturbances, and (3) studying the influential factors on fault-ride-through and post-fault recovery of grid connected inverters. The report is presented in three parts.

Part I: Parametric Small-Signal Modeling of Grid Forming and Grid Following Inverters in 100% Renewable-Based Grids

Part I of this report is focused on small-signal models for the latest inverter control strategies including the GFM and GFL. This involves constructing a parametric model for the inverter by utilizing matrix formulations and linearizing specific blocks in the small-signal domain through the application of computational algebraic equation solvers. Various GFM and GFL control strategies are encompassed within this modeling approach. To this end, the matrix formulation for inverter modeling is detailed, with theoretical derivations of small-signal equations for each inverter control function and circuit component. These blocks are solved computationally and the resulting equivalent impedance/admittance transfer functions are deduced and presented. Then, a comparison of various GFM and GFL controls is undertaken in terms of the number of poles (eigenvalues analysis) and frequency responses. The eigenvalue analysis results show that certain GFM control methods present the highest level of complexity while the GFL represents the minimum number of poles. Another note-worthy point is that the number of poles exhibits notable variation across control strategies, frequently featuring diverse matrix elements with varying degrees of complexity. The frequency-domain analyses show that, depending on the adopted GFM control, the Bode diagram may show pronounced magnitude and/or phase angle shift within a specific frequency range, signifying an oscillatory behavior in response to disturbances. Since the developed models and analysis method are parametric, they can be expanded to multi-inverter systems with a blend of GFL and GFM and used as a basis for inter-area oscillation damping for future work.

Project Publications:

Student Theses:

- [1] Araz Bagherzadeh Karimi. Parametric Small-Signal Modeling of Grid Forming and Grid Following Inverters in 100% Renewable-Based Grids, Master's thesis, Georgia Institute of Technology, December 2022.

Part II: Grid Forming Inverters

As the number of Distributed Energy Resources (DERs) connected to the power system has been increasing rapidly, the power systems are now operating at a higher penetration level of Inverter-Based Resources (IBRs). In the foreseeable future, states like California and Minnesota have more ambitious plans of fully renewable power supply. Currently, the reliability and stability of the power system still relies on the conventional synchronous generators in the system. Due to the high mechanical inertia nature of the rotating machinery-based synchronous generators, the system dynamic changes at a lower speed, which allows the GFL inverters to track the phase angle and voltages using phase-locked loop (PLL). However, at high penetration levels of IBRs, the rate of change of frequency (RoCoF) increases significantly and makes it difficult for the PLL to track the system dynamics. Therefore, new challenges emerge as the instantaneous penetration of IBRs in the power system increases with forecast of 100% penetration. While the trend is obvious, it is also important to recognize that even at lower penetration levels in terms of installed capacities, operationally, the system may move into operating points that most of the produced electricity is coming from IBRs. It has happened already in the US that for certain periods of time, the system was operating at 100% of IBR generation. We can refer to this as operational penetration level. The reality is that for periods of time the present system operates at 100% IBR penetration level. The trend is that these periods of time will be increasing as we move into the future.

In inverter-dominated power systems, GFM inverters are considered a necessity to ensure synchronous operation of the system, control of frequency and voltages, and avoid disturbances. The alternative to keep using GFL inverters will not work well in a IBR dominated power system, as GFL cannot guarantee frequency and voltage control in these systems; in addition, their design is to drop out when a disturbance occurs.

There is a plethora of information and research on GFM inverters. We have performed a literature survey and reported the work of other researchers in this important issue of designing and controlling grid forming inverters. The literature discussion is provided in Section 3. The literature is rich. Yet, much work remains to be done.

The shortcomings of present inverter designs as far as grid forming is concerned, have been taken into account in the design of the proposed GFM inverters. The proposed design is provided in Section 4 in terms of the model of GFM inverters. We propose an inverter model that is quadratized to facilitate robust simulation and allow flexible control strategies. Example results are provided to compare the proposed GFM with other software, in this case PSCAD. This comparison was focused on systems with smooth transitions from one operating condition to another. At times of fast transients and/or system oscillations, additional controls must be added to ensure the proper

operation of the GFM inverters. For this purpose, we propose supplementary predictive inverter control to ensure robust operation of GFM inverters during disturbances. This work is described in Section 5.

In Section 6 we provide performance results of GFM operating in a hybrid system. The hybrid system is defined as one that has sections of synchronous machine-based systems and inverter based system. The example test system has been designed to operate as a hybrid system or it can island into two subsystems, (a) a 100% IBR system, and (b) a 100% synchronous machine system. The results demonstrate that GFM inverters provide good performance for 100% IBR power systems.

Finally, in Section 7, we performed a comparison of the proposed modeling and design of GFM inverter systems to the analysis results using industry accepted software, in this particular case, PSCAD. An identical test system was constructed and presented in Appendix B to validate the results obtained with the proposed modeling of GFM inverters. The model in Appendix B has been developed for PSCAD so that the proposed models can be compared with PSCAD. The simulation results from the model of Appendix B matches the results from the model of Appendix A (proposed GFM inverter models) despite minor differences in the RMS value of the current and voltage at the load caused by the different parameter settings. At this point in time, we have not identified the root cause of the differences between the described simulation results, i.e. between the proposed models and methods and the industry established PSCAD. We plan to continue this work.

The design and modeling of GFM inverters and the impact of these designs on the performance of the power system of the future is a very complex issue. Research work in this area will continue, so that the challenges generated by IBR dominated power systems can be addressed. This project addressed only a small part of the overall problem.

Project Publications:

[1] Yu Liu, Abhinav Kumar Singh, Junbo Zhao, A. P. Meliopoulos, Bikash Pal, M. A. M. Ariff, Thierry Van Cutsem, Mevludin Glavic, Zhenyu Huang, Innocent Kamwa, Lamine Mili, Saleem Mir, Ahmad Taha, Vladimir Terzija, and Shenglong Yu, "Dynamic State Estimation for Power System Control and Protection," IEEE Transactions on Power Systems, volume: 36, issue: 6, pp. 5909-5921, Nov. 2021, DOI: 10.1109/TPWRS.2021.3079395.

[2] Thomas E. McDermott, Sakis Meliopoulos, M. Ramesh, G. Cokkinides, J. Doty, J. Kolln, N. Shepard, G. Kou, F. Velez, R. Johnson, D. Duke, J. Hambrick and R. Fan, "Protection of Radial Circuits with High Penetration Distributed Photovoltaics", *Proceedings of the 2021 Georgia Tech Protective Relaying Conference*, Atlanta, Georgia, April 28-30, 2021..

Student Theses:

[1] **Liu Kaiyu**: Spring 2022, Thesis Title: "Dynamic State Estimation Based protection of power electronic systems"

Part III: Fault Ride Through and Post-Fault Recovery of Inverter Based Resources

A key grid code requirement for IBRs such as PV power plants is low voltage ride through capability. Based on the grid code, PV plants should remain connected during voltage sags and inject reactive power to the grid to support the voltage of the grid. In this project we focused on studying the influential factors on fault ride through and post fault recovery of grid connected inverter. The main results of the projects are as follows:

- We studied the impacts of different PLLs and control structures on the response of inverters during different types of faults. The simulation results show that decoupled double synchronous reference frame-PLL (DDSRF PLL) and dual current controller provide desirable results during balanced and unbalanced faults as they can handle unsymmetrical components in the voltage and current signals and can eliminate the output power oscillations during unbalanced faults.
- The results show that addressing the saturation of the controllers is essential to enable seamless transition from the during fault condition to the post-fault condition.
- We demonstrated the saturation of the PI controller of DC capacitor voltage of the inverter is influential on the overall response of the inverter during transitioning to the post-fault condition.
- We simulated different anti-windup controllers as well as a controller called proxy based sliding mode controller (PBSMC). The results show the effectiveness of anti-windup methods in enhancing the transitioning to the post-fault condition. However, the tuning of anti-windup methods is heuristic and may not provide desirable results under certain conditions.
- PBSMC combines nonlinear controller, sliding mode control, and conventional PID controllers. It provides accurate and fast tracking feature during normal condition similar to PID controllers and smooth resuming to the desired reference value after large disturbances that may lead the saturation of the controller. The simulation results demonstrated PBSMC is a promising method with desirable performance and systematic tuning of the control parameters.

Project Publications:

- [1] Ali Maleki, Saeed Lotfifard, “Impact analysis of controller saturations on post fault recovery of PV power plants” to be submitted IEEE PES General Meeting, 2024.

Student Theses:

- [1] Ali Maleki, Expected Ph.D thesis title “Fault Resilience Enhancement of Inverter Based Resources”, Washington State University.