



Reliable fault-ride through and protection of converter-dominated power systems under unbalanced conditions

Final Project Report

S-95

Power Systems Engineering Research Center
*Empowering Minds to Engineer
the Future Electric Energy System*



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PSERC Publication 23-04

November 2023

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Power Systems Engineering Research Center

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Acknowledgments

This is the final report for the Power Systems Engineering Research Center (PSERC) research project titled “Reliable fault-ride through and protection of converter-dominated power systems under unbalanced conditions” (project S-95).

The authors wish to thank the industry advisors: David Till (NERC), Hongtao Ma (NERC), Ben Kroposki (NREL), Kumaraguru Prabakar (NREL), Hung-Ming Chou (Dominion Energy), Aditya Jayam Prabhakar (MISO), Akshay Korad (MISO), Evangelos Farantatos (EPRI), Deepak Ramasubramanian (EPRI), Wenzong Wang (EPRI), Aboutaleb Haddadi (EPRI), Thibault Prevost (RTE), Carmen Cardozo (RTE), Harvey Scribner (SPP).

Executive Summary

At the heart of the transition towards a more sustainable electric power system is a paradigm shift from conventional bulk generation using synchronous machines to decentralized renewable generation integrated through power electronic converters. Control strategies for grid-connected power converters can be broadly categorized into (i) grid-following strategies that may provide grid-supporting services but require other devices to form a stable ac voltage waveform, and (ii) grid-forming strategies that impose a stable ac voltage waveform at their point of connection and are commonly envisioned to replace synchronous machines as the cornerstone of tomorrow's power system. Due to their comparatively low current limits, power converters cannot emulate the fault response of synchronous machines and the resulting fault-response strongly depends on the converter control and protection.

In this context, this research focuses on control and protection of grid-forming converters under unbalanced faults and load(s), the interaction of grid-forming converters with system protection, and distributed cold-start methods for unbalanced distribution feeders.

Notably, state-of-the-art grid-forming control provides a balanced voltage reference (i.e., angle and magnitude) to the converters' inner voltage and current control. However, under unbalanced conditions (i.e., faults or loading), the inner control loops cannot track a balanced voltage reference at the converter terminal. Moreover, for common converter topologies such as two-level voltage source converters, the current limits need to be enforced for every phase. However, state-of-the-art controls do not have this capability. To address this challenge and fully leverage the degrees of freedom of grid-forming converters, this project developed a generalized three-phase grid-forming control. The developed control combines a signal processing algorithm that extracts phasors for every phase signal of a three-phase converter with a generalized control architecture that applies state-of-the-art grid-forming controls and current limiting separately to every phase. In addition, a phase-balancing feedback is developed to synchronize the controls of every phase and adjust tradeoffs between voltage unbalance, power unbalance as well as the sharing of unbalanced load by multiple converters.

A steady-state analysis reveals how the tuning parameters of the generalized three-phase grid-forming control can be used to adjust tradeoffs between voltage unbalance and power unbalance, as well as how much load unbalance is picked up by a grid-forming converter. Moreover, we will briefly review results of an analytical small-signal stability analysis that highlights that small-signal frequency stability of the generalized three-phase droop control can be ensured under mild conditions that are comparable to those required to ensure small-signal stability of standard (positive sequence) grid-forming controls.

This approach also allows us to apply standard current limiting methods to each phase. We first investigate applying two widely used methods (i.e., reference current saturation and threshold virtual impedance) to every phase of a grid-forming converter. Notably, both approaches inherit well-known advantages and disadvantages from their balanced implementation. In particular, reference current saturation limits the current exactly and is easy to tune but suffers from a loss of synchronism for prolonged faults (i.e., short critical clearing time). In contrast, threshold virtual impedance largely avoids the loss of synchronism (i.e., long critical clearing time) but is ineffective if the difference between the converter phase angle and phase angle the point of interconnection is

large (i.e., after clearing a fault or tripping a line). To address this challenge, we developed a hybrid threshold virtual impedance method that can effectively limit the converter current under large phase angle jumps.

Finally, we developed an initial method for distributed cold-start methods for unbalanced distribution feeders that do not require centralized coordination and leverage the capabilities of distribution connected grid-forming converters and advanced load relays. Instead of energizing an entire distribution feeder at once, this approach relies on autonomously sequencing the energization of loads at a more granular level during a cold-start process initiated by grid-forming converters.

The effectiveness of the control algorithms developed in this project and study the interactions of grid-forming converters with the system protection, we developed two benchmark systems. The first benchmark system models a segment of a system consisting of a medium voltage feeder and a high voltage double circuit transmission line and is used to study transmission faults and interactions of the converter control and protection with distance relays. The second benchmark model is based on the IEEE 13-bus feeder and is used to study (i) the impact of loads (i.e., unbalanced loads, induction machine startup) on grid-forming converters and current limiting, (ii) interactions of grid-forming converters with protection (i.e., inverse time relays), and (iii) cold-start of unbalanced distribution systems.

Project Publications:

- [1] P. Bhagwat, D. Groß, “Three-phase grid-forming droop control for unbalanced systems and fault ride through,” IEEE Power & Energy Society General Meeting, 2023
- [2] Z. Zeng, P. Bhagwat, M. Saeedifard, D. Groß, “Hybrid Threshold Virtual Impedance for Fault Current Limiting in Grid-Forming Converters,” IEEE Energy Conversion Congress & Exposition, 2023
- [3] S. Nudahi, D. Groß, “Grid-forming control of three-phase and single-phase converters across unbalanced transmission and distribution systems”, IEEE Transactions on Power Systems, to appear
- [4] Z. Zeng, P. Bhagwat, M. Saeedifard, D. Groß, “Black Start Operation of Grid-Forming Converters Based on Generalized Three-Phase Droop Control Under Unbalanced Conditions,” Submitted to CIGRE Session, Paris, 2024.

Student Theses:

- [1] P. Bhagwat, Three-phase grid-forming droop control for unbalanced systems and fault ride through, MS thesis, 2023
- [2] P. Bhagwat, Constrained grid-forming control, PhD, in progress
- [3] Z. Zeng, Control of Multi-terminal HVDC Grids for Integration of Offshore Wind Farms, PhD, in progress