



Stability, Protection and Control of Systems with High Penetration of Converter Interfaced Generation

Final Project Report

S-56

Power Systems Engineering Research Center

*Empowering Minds to Engineer
the Future Electric Energy System*



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Executive Summary

The goal of this project is to evaluate the stability, protection and control of converter-interfaced generation both at the converter level and in the bulk power system. With the increased penetration of renewable energy and decommissioning of aging thermal power plants, there is a renewed focus on converter-interfaced generation. As more of these sources appear in the transmission system, the control of converters and their representation in software have to be more accurate in order to make a reliable study of the system behavior.

This research proposes a new converter model for use in positive sequence transient stability software. The questions addressed include- Does this converter model accurately represent the electromagnetic transient operation of a power electronics converter? Does the model perform robustly in commercial positive sequence time domain software? With large system simulations, is there a significant increase in computation time with the use of this converter model? Can a large system handle an increased presence of converter-interfaced generation? Will the converter models be able to provide frequency response in the event of a contingency?

Part I: Stability, Protection and Control of Systems with High Penetration of Converter Interfaced Generation

Increasing penetration of generating units that are interfaced to power grid with power electronic devices create new challenges in the protection, control and operation of the power grid. These generating units are allowed to operate at variable or non-synchronous frequencies (e.g. wind turbines), or to operate without any rotating parts (e.g. photovoltaic cells) and they are synchronized to the power grid via power electronics. We refer to these units as Converter-Interfaced Generation (CIG). The power grid operates at a fixed frequency or a regulated frequency. The power system can easily cope with a small amount of CIGs. However, in some areas of the world, the percentage of CIGs versus synchronous machines has risen to high values and it is possible to reach 100%. High penetration levels bring serious challenges to the present protection, control and operation paradigm.

The conventional power system powered by synchronous generators has the following characteristics. (a) synchronous generators are driven by mechanical torque, so the control of the speed governor can maintain load/generation balance by controlling the frequency of the synchronous generator; (b) synchronous generators have high moment of inertia, so the oscillations of frequency and phase angle are small and slow, and transient stability of the power system can be ensured. These characteristics are absent in CIGs. In conventional systems, frequency constancy means generation/load balance. In systems with 100% CIGs this concept does not exist.

Compared to the conventional power system, a power system with high penetration of CIGs will confront the following challenges. (a) There exists no mechanical torque input to the DC link of a grid side converter, thus the control of the converter output frequency is irrelevant to load/generation balancing [2-3]. Traditional control schemes, such as area control error (ACE) become meaningless in systems with 100% CIGs. (b) CIGs do not have inertia [4-5], thus the frequency and phase angle may oscillate quickly after disturbances and in this case the operational constraints of the inverters may be exceeded to the point of damaging the inverters or causing the

shutdown of the inverters. Inverters can be protected with Low Voltage Ride Through (LVRT) function. However, in a system with high penetration of CIGs, the LVRT function practically removes a large percentage of generation for a short time (typically 0.15 to 0.2 seconds). It is not clear whether the system will gracefully recover from such an event.

One existing approach to deal with these issues is to control the converter interface such that the CIG systems behave similarly as synchronous machines with frequency responses and inertia [6-7]. However, this approach is not as good as expected because it is practically impossible to achieve high synchronizing torques due to current limitations of the inverter power electronics. For traditional power systems, synchronous machines can provide transient currents in the order of 500% to 1000% of load currents. On the contrary, the converters have to limit the transient currents to no more than approximately 170% of load currents for one or two cycles and further decrease this value as time evolves [8]. Consequently, the CIGs' imitation of synchronous machines is not quite effective.

The first important problem is the recognition that fault currents in a system with high penetration of CIGs will be much lower than conventional systems and many times may be comparable to load currents. The issue has been addressed in this project. The findings are summarized in reference [M1] listed in section 7. This reference shows the transformation of the fault currents as the penetration of CIGs goes from 0% to 100%. The reduced fault currents create protection gaps for these systems, in other words the system cannot depend on traditional protection schemes to reliably protect against all faults and abnormal conditions. We propose a new approach to protection based on dynamic state estimation.

The second important problem is the stabilization of CIGs with the power grid during disturbances. To control the CIGs such that the CIG smoothly follows the oscillations of the system and avoids excessive transients, a Dynamic State Estimation (DSE) enabled supplementary predictive inverter control (P-Q mode) scheme has been proposed, implemented and tested. The method is based on only local side information and therefore no telemetering is required and associated latencies. The method consists of the following two steps: **Step 1:** The power grid frequency as well as rate of frequency change is estimated using only local measurements and the model of the transmission circuit connecting a CIG to the power grid. **Step 2:** The power grid frequency as well as rate of frequency change are injected into the inverter controller to initiate supplementary control of the firing sequence. The supplementary control amounts to predictive control to synchronize the inverter with the motion of the power grid. Numerical experiments indicate that the supplementary control synchronizes CIGs with the power grid in a predictive manner, transients between CIGs and the power grid are minimized. One can deduce that the supplementary controls will minimize instances of LVRT logic activation.

The application of the proposed method requires an infrastructure that enables dynamic state estimation at each CIG. The technology exists today to provide the required measurements and at the required speeds to perform dynamic state estimation. In essence the method provides full state feedback for the control of the CIGs. While in this project we experimented with one type of supplementary control, the ability to provide full state feedback via the dynamic state estimation opens up the ability to use more sophisticated control methodologies. Future work should focus on utilizing the dynamic state estimation to provide full state feedback and investigate additional

control methods. The methods should be integrated with resource management, for example managing the available wind energy (in case of a WTS) or the PV energy, especially in cases that there is some amount of local storage. The dynamic state estimation based protection, should be integrated in such a system.

Part II: Development of Positive Sequence Converter Models and Demonstration of Approach on the WECC System

A voltage source representation of the converter-interfaced generation is proposed. The operation of a voltage source converter serves as a basis for the development of this model wherein the switching of the semiconductor devices controls the voltage developed on the ac side of the converter. However, the reference current determines the value of this voltage. With the voltage source representation, the filter inductance value plays an important role in providing a grounding connection at the point of coupling. A point on wave simulation served as a basis for the calibration of the proposed positive sequence model. Simulation of a simple two-machine test system and the three-machine nine-bus WSCC equivalent system validated the performance of the model with comparison against the existing boundary current injection models that are presently in use. In the existing models, the absence of the filter inductance causes significant voltage drops at the terminal bus upon the occurrence of a contingency and in a large system, it can lead to divergence of the network solution. It was found that the voltage source representation was a more realistic representation of the converter and was proposed to be used in all large-scale system studies.

The 2012 WECC 18205 bus system was used as a test system for large-scale system studies. Initially, converters replaced only the machines in the Arizona and Southern California area and the response to various system contingencies was analyzed. Carrying this forward, converters replaced all machines in the system resulting in a 100% converter-interfaced generation set. The performance of this system was found to be largely satisfactory. With the absence of rotating machines, a numerical differentiation of the bus voltage angle gave an approximate representation of the frequency. For the trip of two Palo Verde units, the frequency nadir was well above the under frequency trip setting of the WECC system and the recovery of the frequency was within 2-3 seconds enabled by the fast action of the converters. For other contingencies, the voltage response of the individual units reflected the fast control action with the achievement of steady state again within 2-3 seconds following the disturbance. Incorporation of overcurrent and overvoltage protection mechanisms ensured adherence to the converter device limits.

An induction motor drive model was also developed and tested in an independent C code written to perform a time domain positive sequence simulation. The performance of the nine bus system with and without induction motor drives was analyzed.

Project Publications:

1. Ramasubramanian, D.; Z. Yu, R. Ayyanar and Vijay Vittal. “Converter Control Models for Positive Sequence Time Domain Analysis of Converter Interfaced Generation,” submitted to the *IEEE Transactions* – under review.

2. Ramasubramanian, D.; and Vijay Vittal. "Transient Stability Analysis of an all Converter Interfaced Generation WECC System," Submitted to the *Power Systems Computation Conference 2016* – abstract accepted.
3. Liu, Yu; Sakis A.P. Sakis Meliopoulos, Rui Fan, and Liangyi Sun. "Dynamic State Estimation Based Protection of Microgrid Circuits," *Proceedings of the IEEE-PES 2015 General Meeting*, Denver, CO, July 26-30, 2015.
4. Liu, Yu; Sanghun Choi, A.P. Sakis Meliopoulos, Rui Fan, Liangyi Sun, and Zhenyu Tan. "Dynamic State Estimation Enabled Predictive Inverter Control," Accepted, *Proceedings of the IEEE-PES 2016 General Meeting*, Boston, MA, July 17-21, 2016.

Student Theses:

1. Ramasubramanian, D. "*Impact of Converter Interfaced Generation on Grid Performance*," Ph.D. Thesis, Arizona State University, Tempe, AZ, 2016.
2. Weldy, Christopher. "*Stability of a 24-Bus Power System with Converter Interfaced Generation*," Master Thesis, Georgia Institute of Technology, Atlanta, GA, 2015.