NERC Functional Testing of Grid-forming Inverter Models in PSCAD

EECE 567 Project
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***Abstract*—This report presents PSCAD simulation results evaluating virtual synchronous machine (VSM) and droop grid-forming (GFM) inverter control methodologies with respect to the proposed NERC GFM functional test. An additional functional test is presented to investigate the performance of grid-forming inverters when connected by a high-impedance line to a bus with a synchonous machine and load. While both VSM and droop control meet the passing criteria for the NERC functional test, results from this additional test highlight important differences between the two control methodologies, as the fast frequency drop produced by droop control causes it to lose synchronism with the second bus, while slow frequency drop achieved with VSM control allows synchronism to be maintained.**

I. Introduction

The ongoing push towards low-carbon electricity systems is resulting in large-scale deployment of inverter based resources (IBRs) including wind, solar photovoltaic, and battery energy storage systems (BESS). With total capacity of IBRs on the bulk power system undergoing rapid growth, full utilization of these low cost and low carbon generation sources will require operating the grid with instantaneous IBR penetration approaching 100% [1]. With the grid-following (GFL) control methodologies employed by existing IBRs connected to the bulk power system, these high levels of instantaneous IBR penetration would result in system-wide instability and are therefore not operationally feasible [2]. For this reason, the North American Electric Reliability Corporation (NERC) is recommending that all newly interconnecting BESS projects should be commissioned with the capability for grid-forming (GFM) control to provide system stability in support of the high-IBR future grid [3]. Furthermore, GFM inverters offer benefits even in systems comprised primarily of synchronous machines, including improved stability in low system strength areas and increased fault current contribution [4].

Although the emerging need for grid-forming control of IBRs is widely recognized, the exact control methodologies and functional specifications for GFM inverters are not yet settled. Proposed control methodologies include virtual synchronous machines (VSM) [5], droop control [6], and virtual oscillator control (VOC) [7]. In general, functional specifications do not specify the underlying control methodology, but instead describe the behaviour of the GFM inverter when connected to the bulk power system. For example, NERC has proposed a suite of three tests in a test system with two GFM BESS projects and one synchronous generator to verify GFM functionality [3]. However, other entities have proposed alternate functional specifications for GFM inverters, which may preclude control methodologies which are acceptable under the NERC functional specification. For example, the Australian Electricity Market Operator (AEMO) has issued a voluntary requirement for GFM inverters specifying that they should have "inertia-like" frequency response, implying that active power output should vary in proportion to rate of change of frequency (RoCoF) [8]. This requirement is not met by droop control or virtual oscillator control, where active power instead varies in proportion to deviation from the reference frequency. In contrast, a NREL technical report imposes a requirement for 1-second settling time, and finds that it is not possible to achieve this using methodologies which calculate power and frequency over multiple cycles before responding [9]. The report presents virtual oscillator control as preferable due to the instantaneous response offered by its time domain control strategy.

This report reviews three prominent categories of GFM control methodologies (VSM, droop, and VOC) as well as a generic primary-control model which has been proposed to unify all three [10]. A publicly-available PSCAD model implementing the generic primary-control scheme [11] is leveraged to evaluate the proposed control methodologies with respect to the NERC GFM functional test. As the NERC functional test does not evaluate interactions between GFM inverters and synchronous machines or the impact of the network, results are presented from an additional functional test in which a GFM IBR is connected to a synchronous generator by a high-impedance line. The results of these functional tests allow for comparison between GFM control methodologies, as well as comparison between GFM inverters and synchronous machines.

II. GFM Control Methodologies

VSM, droop, and VOC are three GFM control methodologies which have received widespread attention in recent literature [12]. The VSM control methodology seeks to approximate the frequency characteristics of conventional synchronous generators, where active power output increases in proportion to rate of change of frequency. In addition to this inertia-like response characteristic limiting RoCoF, VSM control may also include damping or frequency droop terms, causing output power to proportional to deviation from synchronous frequency. In contrast, droop control varies output power *only* in proportion to deviation from synchronous frequency, without any inertia-like response to limit RoCoF. VOC is similar to droop control in that power varies in proportion to frequency deviation, but the underlying dynamics causing this power-frequency control differ from droop control. Whereas droop control is a phasor-domain control strategy, VOC controls inverter terminal voltage in the time-domain by emulating the dynamics of a nonlinear oscillator. The key difference between droop control and VOC appears in the equilibrium $Q-V$ characteristics, as VOC results in a nonlinear steady-state $Q-V$ curve in contrast to the linear relationship between reactive power and voltage achieved by droop control.

It has been proposed in [10] that all three of these control methodologies can be unified into a single primary-control model, which under certain parameter settings reduces to the dynamics of VSM, droop, or VOC control. The full generic primary-control model is given by [10]:

$$\tau_f \dot{\omega} = -\omega + \omega_0 + k_d(k_P \dot{\eta} + \omega_0 k_I \eta) + k_f(p^\star - p_m), \tag{1a}$$

$$\tau_v \dot{e} = f_v(e) + k_v(q^\star - q_m), \tag{1b}$$

$$\frac{1}{\omega_0}\dot{\eta} = \mathbb{e}_2^{\mathrm{T}} T_2(\alpha) T_2(\delta) T_1(\omega_0 t) v, \tag{1c}$$

$$\frac{1}{\omega_0}\dot{\alpha} = \frac{k_P}{\omega_0}\dot{\eta} k_I \eta, \tag{1d}$$

$$\tau_p \begin{bmatrix} \dot{p}_m \\ \dot{q}_m \end{bmatrix} = -\begin{bmatrix} p_m \\ q_m \end{bmatrix} + \begin{bmatrix} p \\ q \end{bmatrix}. \tag{1e}$$

Here, the dynamics of the inverter reference frequency ω are influenced by the terminal frequency observed by a phase-locked loop (the expression proportional to k_d) as well as the difference between reference active power and measured active power output (the expression proportional to k_f). Meanwhile, the dynamics of the inverter reference voltage magnitude e are influenced by a (nonlinear, in the case of VOC) function $f(e)$ and a droop term reflecting the difference between reference reactive power and measured reactive power output (with proportionality constant k_v). Parameter definitions and parameter settings under which the generic primary-control model transforms into VSM, droop, and VOC can be found in [10].

This generic primary-control model was used within a configurable IBR PSCAD model developed by the UNIFI consortium [11]. This detailed EMT-domain model includes the power electronic circuitry of a three-phase IBR along with a control module which can be configured to implement VSM, droop, or VOC control.

III. GFM Functional Specifications

The GFM functional test proposed by NERC evaluates the ability of BESS systems equipped with GFM inverters to maintain stable operation following the loss of the last synchronous machine. The test system (shown in Fig. 1) consists of a synchronous machine model (including exciter and governor) connected via a circuit breaker to a bus with two GFM BESS systems and a 100MW load. After the simulation has achieved stable steady-state (flat-start condition), the breaker is tripped disconnecting the synchronous generator.

For success of the functional test, the GFM inverters must be able to achieve stable steady-state operation after the synchronous generator is disconnected, with final system frequency and bus voltage consistent with the inverter droop parameters. These criteria have been proposed by NERC primarily for the purposes of differentiating GFM inverters from GFL inverters, as a Project BESS emloying GFL control would not be able to achieve stable operation following the loss of the last synchronous machine [3].

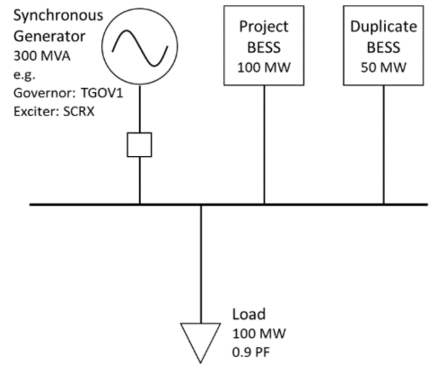

Fig. 1. NERC test system for GFM Functional Tests. The functional test consists of opening the breaker to disconnect the Synchronous Generator and validating that the two GFM BESS systems (Project BESS and Duplicate BESS) are able to achieve stable operation following the loss of the last synchronous machine [3].

IV. Simulation Results

This section presents results of PSCAD simulations using the IBR model published by the UNIFI consortium [11] to evaluate GFM control methodologies (VSM and droop) with respect to the NERC GFM functional test. Note that while the IBR model supports VOC operation, no model parameters were found to achieve pre-contingency steady-state operation and thus results for VOC are not presented here.

Synchronous machine models in PSCAD may be operated in 'source' mode to achieve flat-start conditions before switching to 'machine' mode. To synchronize the GFM inverters with the synchronous generator, both IBRs were enabled while the synchronous generator was still in 'source' mode. After all transients arising from the GFM IBRs had settled, the synchronous generator was switched to 'machine' mode and mechanical dynamics were enabled. The bus frequency following the loss of last synchronous machine contingency at $t = 3$s with Project IBRs controlled via VSM and droop control is shown in Fig. 2. Also shown for comparison is the bus frequency following the same contingency for a comparable system where the Project IBRs are replaced with synchronous generators, to contrast the GFM frequency response characteristics to those of conventional synchronous machines.

As shown in Fig 2, both droop and VSM control methodologies achieve a stable steady-state frequency following the loss of last synchronous machine contingency. After a brief subtransient, VSM control is able to successfully limit RoCoF as intended. In contrast, droop control drops rapidly to the post-contingency steady-state frequency, as droop control does not inherently limit RoCoF. It is also worth noting that both control methodologies settle to the post-contingency steady-state much faster than synchronous generators, and in doing so

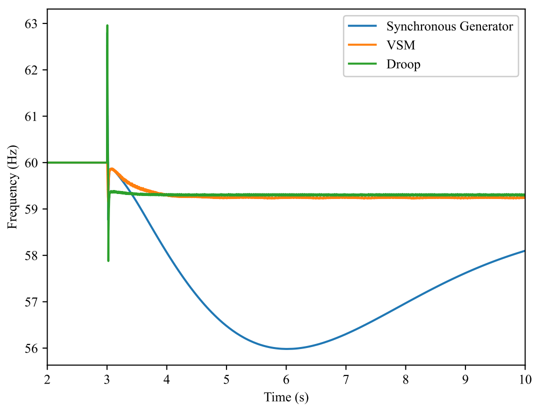

Fig. 2. Results of the NERC GFM functional test with VSM and droop control, implemented using the PSCAD IBR model released by the UNIFI consortium [11].

avoid the significant frequency nadir exhibited by synchronous generators before their inertial RoCoF is arrested by slow-acting governor response.

V. VSM vs. Droop with Weak Intertie

The NERC GFM functional test does not consider the impact of network power flow on GFM controllers, nor does it consider the interaction between GFM inverters and conventional synchronous machines. To address both of these limitations, this section presents simulation results of a test system consisting of a bus with a GFM IBR connected by a weak intertie (high-impededance line) to a bus with a conventional generator and a 180MW load. Similar to the NERC functional test, co-located with the IBR at Bus 1 is a 90MW load as well as a synchronous generator connected via a breaker, and the test consists of opening the breaker to disconnect the synchonous generator. This test system is shown in Fig. 3.

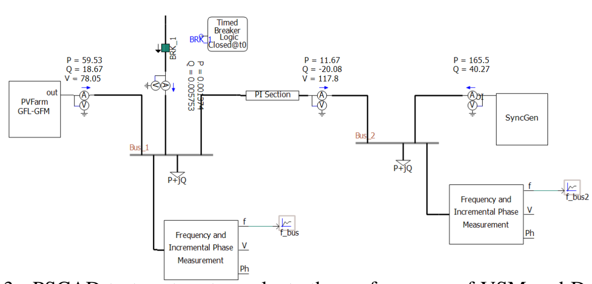

Fig. 3. PSCAD test system to evaluate the performance of VSM and Droop-controlled GFM inverters when connected to conventional resources via a weak intertie. A GFM IBR and a 90MW load are connected at Bus 1, alongside a synchronous generator connected via a breaker (BRK_1). Bus 1 is connected by a high-impedance line to Bus 2, where a second synchronous generator is situated alongside a 180MW load. The test consists of opening BRK_1 to disconnect the synchronous generator at Bus 1.

Results of this functional test conducted with both VSM and droop contol are shown in Fig. 4. Before the contingency is applied at $t = 3$s, the local generation and local load of the two buses are closely balanced, with only 1.7MW flowing through the intertie from Bus 1 to Bus 2. With the droop-controlled GFM, the power flowing through the intertie oscillates through the full range of the line's carrying capacity (between $\pm P^{\max} = 12.1$MW) immediately after the contingency is applied, as the sudden drop in frequency applied by droop control at bus 1 causes it to lose synchronism with bus 2. In contrast, with the GFM controlled in VSM mode, the same contingency does not result in loss of synchronism between the two buses. Instead, the flow on the intertie does reverse immediately after the contingency is applied, but the reverse flow never exceeds $P = -5.8$MW. Instead, the ability of the VSM IBR to limit RoCoF at Bus 1 allows the two buses to remain in synchronism, while the inertia of the synchronous generator at Bus 2 contributes to mitigating the power imbalance at Bus 1.

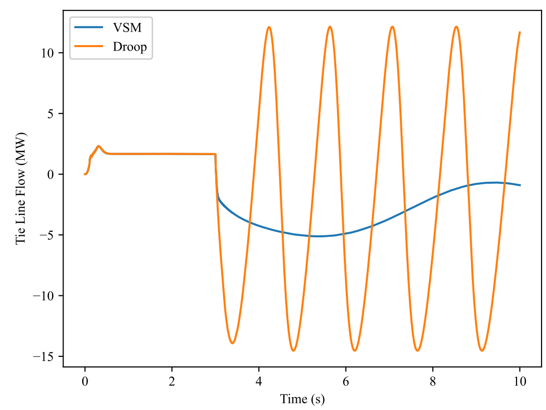

Fig. 4. Simulation results of VSM and droop controlled IBRs connected via a weak intertie to a bus with a synchronous machine and local load. After the contingency is applied at $t = 3$s, the fast drop in frequency by the droop controlled IBR results in a loss of synchronism between the two buses and large oscillations in intertie flow. In contrast, the VSM controlled IBR is able to maintain synchronism after the contingency is applied, resulting in reduced maximum tie-line flow.

From this example, it can be seen that the ability of VSM control to imitate the inertial response of synchronous generators and limit RoCoF has important implications on the interaction between GFM inverters and synchronous machines, especially when coupled by high-impedance lines. Scaling up from this example, one can consider a scenario where a balancing area dominated by GFM IBRs is weakly connected via tie-lines to a second balancing area dominated by conventional synchronous generators. In such a case, it would be important for the GFM IBRs in the first area to be controlled as VSMs to prevent fast frequency drop following a contingency in the IBR-dominated area (as would be exhibited by droop control) from causing it to lose synchronism with the second area. This is especially important when considering that unstable intertie flows may cause protection devices to trip on the tie-line, potentially islanding the two areas.

VI. Conclusion

This report presents simulation results evaluating VSM and droop GFM control methodologies with respect to the NERC functional specification. While both VSM and droop are able to pass the NERC functional specification test by achieving stable operation following the loss of the last synchronous machine, VSM limits RoCoF while settling to the new steady-state frequency, while droop control exhibits a rapid drop towards the new steady-state frequency without limiting RoCoF. The importance of this distinction is revealed by a supplemental functional test, where a bus with a GFM and a load is connected by a weak intertie to a bus with a synchronous machine and a load. In this case, the rapid frequency drop of the droop-controlled GFM causes it to lose synchronism with the synchronous machine bus, while the limited RoCoF achieved by the VSM-controlled GFM allows it to maintain synchronism over the course of the contingency. The difference in performance between VSM and droop control in this setting suggests that it may be advisable to require GFM inverters to have the capability to limit RoCoF with inertia-like response, as proposed by AEMO's voluntary specification for grid-forming inverters [8].

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