Study of Inverter Control Strategies on the Stability of Microgrids Toward 100% Renewable Penetration

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Study of Inverter Control Strategies on the Stability of Microgrids Toward 100% Renewable Penetration

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Abstract—This paper investigates microgrid transient stability with mixed generation—synchronous generator (SG), grid-forming (GFM) and grid-following (GFL) inverters—under increasing penetration levels toward a 100% renewable generation microgrid. Specifically, the dynamics of a microgrid with an SG and GFL inverter(s), an SG with GFM inverter(s), and an SG with GFM and GFL inverters under each penetration are evaluated with an electromagnetic transient study with two critical dynamic events: unplanned islanding and switching in a pumped induction motor load. Analysis and simulation results indicate that the microgrid with GFL inverters running in parallel with the SG can provide a faster power response than the GFM inverters to compensate for the deviations of the frequency and voltage. The scenario with the mixed SG, GFM, and GFL inverter has the best transient and steady-state stability toward 100% inverter-based resource (IBR) penetration. This comprehensive study provides helpful references for microgrid engineers to understand the microgrid stability when facing various choice of installing IBRs (GFL, GFM, or mixed).

Index Terms—Droop control, grid-forming control, grid-following control, voltage and frequency stability.

I. INTRODUCTION

Microgrids are essential systems to address challenges in power system reliability and resilience and renewable generation integration, including enhancing the resilience of electric grids and improving the integration, management, and operation of inverter-based resources (IBRs) [1]. Many existing and to be built microgrids have IBR penetration plans (e.g., 20% renewable penetration) toward the ultimate goal of 100% renewable generation microgrids. On this pathway, synchronous generator (SG)-based generation will still play a role in being a grid-forming (GFM) generation source, especially in islanded mode [2]. Grid-following (GFL) IBRs (e.g., photovoltaics [PV] and battery storage) and GFM IBRs (e.g., battery storage) will be gradually integrated into microgrid systems to increase renewable penetration levels [3]; therefore, it is necessary to study the microgrid system stability with this mixed system (SG, GFL, and GFM inverters) to better understand the different generation mix/control strategies with certain and increasing penetration levels. This will significantly benefit microgrid planning and operation because it will provide helpful references/guidelines on the decision making of IBR deployment and operation toward a 100% renewable generation microgrid.

A microgrid with mixed generation and fixed renewable penetration levels is studied in [4] to investigate the system stability with different inverter control strategies and to study the impact of inverter droop settings and inertia levels, and the authors find that GFM control has a more rapid response than GFL inverters. Reference [5] reports the stability study of a low-inertia microgrid with two control strategies of different percentages of GFM inverters and indicates that the microgrid with a higher percentage of GFM inverters has better stability, whereas the lower one can have poor stability, but system stability can be improved with enhanced control strategies in inverters. A similar study in [6] explains that GFM inverters have significant advantages over GFL inverters, particularly in microgrid systems that have a large number of IBRs and the available system inertia drops. Reference [7] compares the stability of GFM and GFL inverters with 100% penetration and demonstrates that the GFM grid is more stable than the GFL grid. The effect of the interaction of the GFM and GFL inverter controls with synchronous machines on the oscillatory stability of the microgrid is explored in [8], and the authors find that the relationship between the SG inertial and droop control parameters of GFM and GFL inverters maintains a stable system.

These existing works indicate that both academic and industrial stakeholders have great interest in exploring the stability of microgrid systems with mixed generation of an SG and GFM and GFL inverters because there is a big need to perform this research and study the path toward 100% renewable penetration. Although some research has been performed on mixed-energy microgrid systems, and several research studies state that GFM inverters have superior advantages over their GFL counterparts to maintain the stability of low-inertia microgrid systems with GFM and grid-regulating capabilities and fast responses, a research gap is identified in the existing literature. Understanding the impact of different control strategies on microgrid stability and strength under certain and increasing renewable penetrations—in particular, the dynamics between an SG and GFL inverters, between an SG and GFM inverters, and among an SG and GFM and GFL inverters. This is an important aspect to study because microgrid planners will face various options when selecting the IBRs (GFM, GFL, or mixed) and their controls with existing synchronous generation and increasing renewable penetrations.

This paper aims to fill this research gap and provide a useful reference for power system/microgrid engineers working on microgrids. The major contributions of this paper are summarized as follows: 1) Use a benchmark microgrid system to showcase the energy mix of generation (GFM, GFL, and SG) with different renewable penetrations toward a 100% renewable microgrid, including 20%, 40%, 60%, 80%, and 100%; 2) perform comprehensive electromagnetic transient...
(EMT) studies with two critical dynamic events to demonstrate the microgrid stability and strength under each penetration level with different options of control strategies; and 3) perform the analysis of simulation results and conclude the consistent patterns observed from the studies to shed light on the transient stability of microgrids with different control strategies (an SG and GFL inverters, an SG with GFM inverters, and an SG with GFM and GFL inverters).

II. MICROGRID SYSTEM UNDER STUDY

A. Description of the Microgrid System

The microgrid system under study is based on the Banshee microgrid sample case, which is used to evaluate microgrid controller, protection, and cybersecurity systems. This microgrid system reflects real-life, small industrial facilities supplied via three radial feeders/microgrids, and it captures and represents the network dynamics and features of community microgrids, small islands, and industrial and university campuses and thus is a solid benchmark model for evaluating microgrids [9].

Because our project focuses on evaluating inverter control strategies on the stability of microgrids toward 100% renewable penetration, only one microgrid is sufficient for our study. Our goal is to use this selected microgrid to demonstrate the different combinations of GFM and GFL inverters together with traditional synchronous machines, which provides a reference for utility engineers to better select GFM/GFL inverters with increasing renewable penetrations.

The single-line-diagram of the selected microgrid (Feeder 2 of the Banshee model) is presented in Fig. 1. This microgrid has a system voltage of 13.8 kV at the distribution level and service voltages to 4.16 kV, 480 V, and 208 V. There are six aggregated loads, which are classified as critical, priority, or interruptible loads. All loads are modeled as constant impedance loads. For the IBRs, there are two GFM battery inverters and three GFL PV inverters. There is also one diesel generator, which operates in PQ control in grid-connected mode and VF control in islanded mode. The capacity of the IBRs, diesel generator, service transformers, and loads are indicated in Fig. 1.

![Fig. 1. Single-line-diagram of the sample microgrid for study [9].](image)

B. Various Penetration Levels of Renewables

For this microgrid system, the peak load is 4.7 MVA. Based on the definition of penetration levels of renewables \( \frac{\text{DER}}{\text{Peak load}} \times 100 \) [10], we have the following penetration level of interest toward a 100% renewable microgrid. Each penetration level has multiple options of GFM and/or GFL inverters, and each penetration level is a rough calculation, not an exact number.

<table>
<thead>
<tr>
<th>Renewable penetration level</th>
<th>DER capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>Option 1: 1-MVA PV</td>
</tr>
<tr>
<td></td>
<td>Option 2: 1-MVA battery</td>
</tr>
<tr>
<td>40%</td>
<td>Option 1: 1-MVA PV</td>
</tr>
<tr>
<td></td>
<td>Option 2: 2-MVA PV</td>
</tr>
<tr>
<td></td>
<td>Option 3: 2-MVA battery</td>
</tr>
<tr>
<td>60%</td>
<td>Option 1: 2-MVA PV</td>
</tr>
<tr>
<td></td>
<td>Option 2: 1-MVA PV and 2-MVA battery</td>
</tr>
<tr>
<td></td>
<td>Option 3: 3-MVA PV</td>
</tr>
<tr>
<td></td>
<td>Option 4: 3-MVA battery</td>
</tr>
<tr>
<td>80%</td>
<td>Option 1: 3.5-MVA PV</td>
</tr>
<tr>
<td></td>
<td>Option 2: 1.5-MVA PV and 3-MVA battery</td>
</tr>
<tr>
<td></td>
<td>Option 3: 2.5-MVA PV and 2-MVA battery</td>
</tr>
<tr>
<td>100%</td>
<td>3.5-MVA PV and 3-MVA battery</td>
</tr>
</tbody>
</table>

III. MODELING AND CONTROL OF INVERTERS

In this study, the GFM and GFL inverters are modeled as an average switching model with fixed DC voltage; this is to better represent the inverter dynamics than the controlled voltage source because transient stability is our focus to investigate the different options under each penetration level. The GFL PV inverters are modeled to be IEEE 1547-2018 Category III compliant, and each PV inverter has three operation modes: external PQ control, fixed power factor (default mode), and Volt-VAR curve with VAR priority to represent the features and functions of real-world utility/commercial inverters. The GFM battery inverters are modeled in PQ control in grid-connected mode and PF control in islanded mode. The GFM inverter is IEEE 1547-2018 compliant only in grid-connected mode, and it is a voltage-controlled voltage source inverter in both grid-connected and islanded modes, according to the latest GFM control technology of an inverter manufacture. This section describes the control of the GFM and GFL inverters in detail, and the modeling and control of the diesel generator is also included.

A. Grid-Forming Control

The control diagram of the GFM inverter is presented in Fig. 2. This GFM inverter uses droop control for both grid-connected (power tracking) and islanded mode (VF control), so there is no need to switch between current control and voltage control during the microgrid transition operation. Virtual impedance control is added to improve the stability of the GFM inverter especially during contingency and fault events. For the inverter-level control, the traditional double-loop control structure is used, with outer-loop voltage control and inner-loop current control. The salient feature of this double-loop control is that the transfer functions of both the inner loop and the outer loop have unity gain, thus achieving a fast response and the total cancellation of external disturbances. More details on the GFM inverter control algorithm can be found in [11],[12].

Note that the droop coefficients \( m_p \) and \( n_p \) are both 1e-5, and all variables are not in per unit. \( S_c \) is the circuit breaker of the microgrid point of common coupling (PCC), and the integrator is only enabled if the microgrid is grid-connected. For the islanded microgrid, \( P_{ref} \) and \( Q_{ref} \) are set to be zero.
B. Grid-Following Control

In this study, all PV inverters adopt the fixed power factor control (0.9 leading) to avoid impacts from different operation modes. Fig. 3 shows the control diagram of the GFL inverter. Note that there is no droop control in the GFL inverter control. The inverter uses a phase-locked loop to synchronize to the grid voltage and inject active and reactive power into the grid based on the power factor and available power from the solar irradiance. Because the current reference of a GFL inverter highly depends on the terminal grid voltage, a low-pass filter is used to smooth the transient during dynamic events (e.g., unplanned islanding operation) and achieve better stability.

C. Diesel Generator Modeling and Control

The standard SG library model in Simulink/Simscape is used, and the rotor type is a salient pole. The inertia parameter is 1.07 H(s). Simple governor (TGOV1) and exciter (IEEE Type 1) models are used together with the SG model. Droop control is used for both grid-connected and islanded mode, and the equations are presented as follows:

\[
\omega_{ref} = \omega^* + R \left( P^* - \frac{10}{s+10} P_{meas} \right) \quad (1)
\]

\[
V_{ref} = V^* + R \left( Q^* - \frac{10}{s+10} Q_{meas} \right) \quad (2)
\]

Note that all the variables are in per unit. \( R \) is 5%, \( P^* \) is 0.8, and \( Q^* \) is 0.6 by default.

IV. SIMULATION STUDY AND RESULTS

The microgrid is simulated in MATLAB Simulink to study the different renewable penetration levels with different control strategies. For each penetration level listed in Table 1, two dynamic events are simulated: unplanned islanding at 6 seconds and switching in an 170-kVA induction motor load at BUS 204 at 14 seconds in islanded operation to evaluate the transient stability of each strategy. These two dynamic events are selected because they are critical events that challenge the strength and stability of the microgrid. To evaluate the performance of each test, voltage and frequency dynamic and steady-state transients are evaluated, such as rate of change of frequency, maximal frequency deviation, settling time, and steady-state frequency. Fig. 4 shows the frequency response after a dynamic event, which include the four variables that we will use for the performance evaluation. Similarly, the variables of the voltage will be used as well.

The simulation time step is 50 µs. The loading and solar irradiance are kept the same for each penetration level and different strategies.

A. 20% Renewable Penetration

The diesel generator uses default \( P^* \) and \( Q^* \) during grid-connected and islanded mode. Only 1-MVA IBR generation is installed. Option 1 has a GFL PV2 inverter (1 MVA), and Option 2 has a GFM Battery 2 inverter (1 MVA). The key measurements of these two options are presented in Fig. 5, including the PCC voltage and frequency and the active power output of the generation units. It is obvious that Option 1 has smaller dynamic and steady-state voltage deviations than Option 2, and Option 1 also reaches steady state in voltage faster than the Option 2. For frequency, Option 1 has larger transient deviations, but it reaches steady state faster and has smaller deviations than the pre-event values. The active power outputs of the generation units for the two options show that PV has constant output in islanded mode, and the battery shares power with the diesel and generates less power than PV, resulting in a smaller steady-state frequency in Option 2. The results in Fig. 5 indicate that: 1) Option 1 has superior voltage and frequency dynamics than Option 2, and 2) the GFM inverter sharing power with the diesel generator causes large transients during dynamic events and takes longer to reach steady state.
B. 40% Renewable Penetration

For 40% renewable penetration, the diesel generator keeps the same $P^*$ and $Q^*$ during grid-connected and islanded mode, and 2 MVA of IBR generation is installed. Option 1 has a GFL PV2 inverter (1 MVA) and a GFM Battery 2 inverter (1 MVA), Option 2 has a GFL PV1 inverter (2 MVA), and Option 3 has a GFM Battery 1 inverter (2 MVA). The key measurements of these three options are presented in Fig. 6, including the PCC voltage and frequency, and Fig. 7 for the active power output of the generation units. For the PCC voltage, Option 2 has the best transient dynamics with the smallest undershoot and reaches steady state the fastest with the smallest deviation compared to pre-event values; the performance of Option 1 is between Option 2 and 3; and Option 3 has the poorest transient dynamics. For the frequency dynamics, Option 2 has largest overshoots during both events but reaches steady state the fastest with the largest steady-state values; both Option 1 and Option 3 have similar transients, but Option 1 has smaller overshoots and reaches steady state faster with larger steady-state values.

![Fig. 6. PCC voltage and frequency for the three options with 40% renewable penetration.](image)

For the active power outputs, Option 3 forces the diesel to generate the largest active power because of the power sharing with the 2-MVA battery inverter, and the diesel in Option 2 has the smallest generation because the 2-MVA GFL PV inverter generates a large amount of active power. Option 1 and 3 have GFM inverters to share power with the diesel, which causes larger transients and smaller steady-state values in voltage and frequency. The results indicate that: 1) Option 2 has the fastest frequency and voltage responses with large overshoots and reaches steady state with higher values; and 2) the more GFM capacity, the longer transients during dynamic events and smoother frequency transients, and the lower the steady-state voltage and frequency.

![Fig. 7. Active power outputs of the generation units for the three options with 40% renewable penetration.](image)

C. 60% Renewable Penetration

This is a complicated scenario with more options. The diesel generators $P^*$ and $Q^*$ become 65% in islanded mode to balance the power sharing with the GFM inverters, and 3 MVA of IBR generation is installed. Option 1 has a GFL PV1 inverter (2 MVA) and a GFM Battery 2 inverter (1 MVA); Option 2 has a GFL PV1 inverter (1 MVA) and a GFM Battery 1 inverter (2 MVA); Option 3 has two GFL PV inverters, with PV1 2 MVA and PV2 1 MVA; and Option 4 has two GFM battery inverters, with Battery 1 2 MVA and Battery 2 1 MVA. Options 1 and 2 have mixed GFM and GFL inverters, and Option 3 and Option 4 only have GFL and GFM inverters, respectively. The key measurements of these four options are presented in Fig. 8, including the PCC voltage and frequency, and Fig. 9 for the active power output of the generation units. As shown in Fig. 8, the voltage and frequency of the different options show patterns that are similar to the previous two scenarios (20% and 40%): The option (Option 3) that has the most GFL inverter generation achieves the best voltage and frequency dynamics because there is no need to share power with diesel to reach a new steady state, and there is sufficient generation to support the system; vice versa, the option (Option 4) that has the largest GFM inverter generation exhibits the poorest transients and steady state in voltage, and the poorest steady state in frequency, but the smoothest transients in frequency during events. Fig. 9 further explains the transients in frequency: Option 2 and Option 4 have relatively larger GFM inverter generation and need to share power with the diesel; Option 3 has only GFL inverter generation, and the active power of the diesel has large transients; and Option 1 has small GFM inverter generation, with relatively smooth and good voltage and frequency transients.

![Fig. 8. PCC voltage and frequency for the three options with 60% renewable penetration.](image)

![Fig. 9. Active power outputs of the generation units for the three options with 60% renewable penetration.](image)
D. 80% Renewable Penetration

The diesel generators $P^*$ and $Q^*$ become 30% in islanded mode to balance the power sharing with the GFM inverters, and 4.5 MVA of IBR generation is installed. Option 1 has three GFL PV inverters, with PV1 2 MVA, PV2 1 MVA, and PV3 0.5 MVA, and a GFM Battery 2 inverter (1 MVA); Option 2 has two GFL PV inverters, with PV2 1 MVA and PV3 0.5 MVA, and two GFM battery inverters, with Battery 1 inverter 2 MVA and Battery 2 inverter 1 MVA; and Option 3 has two GFL PV inverters, with PV1 2 MVA and PV3 0.5 MVA, and 1 GFM battery inverter 2 MVA. All three options have mixed GFM and GFL inverters; Option 1 has the highest GFL inverter generation, and Option 2 has the highest GFM inverter generation. The key measurements of these three options are presented in Fig. 10 and Fig. 11.

Similar to the previous scenarios (20%, 40%, and 60%), the option (Option 1) with the highest GFL inverter generation has the smoothest dynamic and steady-state transients in voltage and has the largest dynamic transients in frequency but the smoothest steady-state transients in frequency; the option (Option 2) with highest GFM inverter generation has smallest/smoothest dynamic transients in frequency, and the steady-state voltage and frequency are lowest as a result of less contributions from the GFM inverters. Fig. 11 shows the active power outputs of generation units in each option, indicating the insufficient active power generation of GFM inverters allocated by power sharing.

E. 100% Renewable Penetration

In this scenario, there is no diesel generator, and all the PV and battery inverters are included. The testing conditions are kept the same as previous scenarios. The two battery inverters work in isochronous mode using constant $V$ and $f$ references without power sharing. This mode is used because droop control cannot guarantee the voltage and frequency within its acceptable bounds, and there is no secondary control to regulate the system voltage and frequency to its nominal values. Simulation results of this scenario are presented in Fig. 12 and Fig. 13.

As shown in Fig. 12, the system voltage and frequency with 100% renewables reach steady state much faster than all the other simulated scenarios with diesel generator. The voltage dips at two dynamic events are the smallest as well especially at the first dynamic event. For frequency response, the first event causes the smallest transient with small over- and undershoot while the second event causes the largest transients with big overshoot and temporary frequency oscillations (a closer look shows that the oscillations also appear in the voltage and current of all IBRs and induction motor load). Normally, the start-up of an induction motor load draws a large inrush current and reactive power, and it causes system voltage drops, rather than affecting the frequency. The system voltage did drop slightly after connecting the induction motor load, but the frequency is more significantly affected. This phenomenon can be understood because the start-up of an induction motor load causes stability to the 100% renewable microgrid system because there is no inertia to damp the oscillations.

The active power output of all IBRs indicates that the three GFL inverters have smooth transients and the two GFM inverters exhibit some transients during dynamic events, especially Battery 2, which shows a large transient during the induction motor load start-up. These two GFM inverters generate the same amount of active power because power sharing is not used.

![Fig. 10. PCC voltage and frequency for the three options with 80% renewable penetration.](image1)

![Fig. 11. Active power outputs of generation units for the three options with 80% renewable penetration.](image2)

![Fig. 12. PCC voltage and frequency for the three options with 100% renewable penetration.](image3)

![Fig. 13. Active power outputs of the generation units for the three options with 100% renewable penetration.](image4)
F. Recap the Testing Results

Because each scenario (except 100%) has multiple options, we compare within each scenario first, and then we compare how the increasing penetration affects the microgrid stability and strength. The following conclusions can be drawn from the study and analysis of each scenario:

- For the scenario of SG+GFL, the larger capacity of the GFL inverter, the smoother the voltage transients and the larger voltage in steady state; the frequency exhibits larger transients but reaches steady state faster and with a higher frequency in steady state.
- For the scenario of SG+GFM, the system voltage might not exhibit the best transients and steady-state values, whereas the frequency response shows smooth transients with a smaller overshoot. The frequency in steady state is always the smallest because of the power sharing between the SG and the GFM. This indicates that power sharing is beneficial for frequency dynamics and to stabilize the system.
- For the scenario of SG+GFL+GFM, the voltage and frequency responses are between the SG+GFL scenario and the SG+GFM scenario. The more GFL capacity, the better performance in voltage and frequency.
- Overall, the performance of the scenario with SG, GFL, and GFM enables the microgrid to have the best transient and steady-state stability to deal with dynamic events.

With increasing penetrations of IBRs, the following observations are made:

- With the same scenario of SG+GFL and increasing the IBR penetration, the increasing generation from the IBRs reduces the generation of the SG, and the system voltage and frequency exhibit similar transients, whereas the voltage settles at a similar steady-state value and the frequency settles at a higher steady-state value because of less active power generation from the SG.
- With the same scenario of SG+GFM and increasing the IBR penetration, the system has the same transient and steady-state voltage and frequency if the $P^*$ and $Q^*$ for the SG stay the same. With reduced $P^*$ and $Q^*$ for the SG and higher IBR penetrations, the steady-state system voltage and frequency are lower.
- With the scenario of mixed SG+GFM+GFL and increasing the IBR penetration, the system with more PV reaches a higher steady-state voltage and frequency; however, the transients (overshoot/undershoot) are also larger. Vice versa, the system with less PV and more GFM batteries reaches the lower steady-state voltage and frequency, with smaller transients during dynamic events.

V. CONCLUSIONS

This paper investigates the dynamic stability of a microgrid system with different penetration levels of IBRs (from 20% to 100%). Through comprehensive simulations with mixed SG, GFM, and GFL inverters under dynamic events, we learn that:

- The scenario with mixed SG+GFL+GFM has the best transient and steady-state stability in voltage and frequency, and more GFL capacity also achieves better transient and steady-state stability.
- Compared to GFM inverters, GFL inverters can provide a faster power response with larger transients (overshoot and undershoot) to compensate for the deviations in the frequency and voltage when running parallel to the SG.
- When SG exists in the system, the only advantage of the GFM seems to be to smooth and slow down the system transients because of the power sharing process between the fast-responding GFM inverter and the slow-responding SG; however, a 100% renewable microgrid without SG has a much faster transient response.

REFERENCES


