Performance of Grid-forming Control of Grid-edge DERs in Distribution Grids

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***Abstract*—In order to maintain the resilience and stability of distribution grids with the integration of grid-edge distributed energy resources (DERs), the inverter control of DERs is required to have grid-forming (GFM) capabilities to provide effective frequency (f) and voltage (V) regulation. However, the existing GFM inverter control strategies are all designed based on a device perspective that treats the distribution grid as a passive load. In these studies, complex dynamics and characteristics of distribution grids with distributed generations and loads are ignored. These make the developed model based inverter control of DERs not be able to provide effective f and V regulation. This paper studies the performance of control strategies of the existing GFM inverter in a distribution grid that is modified based on a standard system, i.e., the IEEE 30 bus system. Two typical GFM control schemes, including the single-loop droop control and multi-loop droop control, are developed and applied in a DER that is connected to the modified standard distribution grid. The simulation results show that the f and V control of the GFM inverter is coupled associated with active power (P) and reactive power (Q) when the grid-forming DER is connected to the distribution grid. The existing grid-forming control strategies cannot provide effective and independent f and V regulation in realistic distribution grids.**

***Index Terms*—DERs, grid-forming inverter, droop control, distribution grid, frequency and voltage regulation.**

I. INTRODUCTION

To meet the rising demand for renewable energy in the United States, the next-generation distribution grids will incorporate a large scale of DERs, such as solar photovoltaic (PV), wind, and batteries [1]. These grid-edge DERs are usually integrated via inverters, which bring the power grid with numerous power electronic components that can greatly decrease the system inertia [2]. The low inertia can lead to frequency oscillations, device damages, or even widespread power outages, such as the South Australia blackout in 2016 [3] and the United Kingdom blackout in 2019 [4]. Therefore, the DERs, especially the utility-scale ones are required to provide f and V regulation services.

Currently, most DERs operate as grid following (GFL) sources that regulate their power output by measuring the angle of the grid voltage using a phase-locked loop. They merely follow the grid angle/frequency and do not actively control their frequency and voltage output. In contrast, the DERs adopting GFM control schemes act as GFM sources that can actively control their frequency and voltage output, thus providing f and V regulation services. The GFM DERs will be the inevitable trend as they can play a constructive role in improving the frequency dynamics and maintaining the stability of inverter-dominated distribution grids or microgrids by regulating the frequency and voltage of the connected electrical systems [5].

The existing GFM control strategies fall into three main categories: droop control [6-7], virtual synchronous generators (VSG) [8], and virtual oscillator control (VOC) [9], which are all droop based control and comply with the P-f and Q-V droop laws. The droop-based control enables DERs to control their output f and V based on the local measurements of the deviations of P and Q. Therefore, they do not rely on communication links between inverters, thus waiving the communication infrastructure costs and cybersecurity risks. The droop-based control methods usually include the outer droop loop and inner voltage control loop, which has two typical configurations, including the single-loop voltage control [6, 10] and multi-loop voltage & current control [11-12]. The single-loop voltage droop control directly regulates the magnitude and phase of the output voltage, while the multi-loop droop control has an additional inner current loop to improve the dynamic response [11]. These two schemes have their own advantages: the single-loop droop control can provide more damping and has a simpler control structure and larger stability regions [13], while the multi-loop droop control has faster responses and allows the implementation of the current limiter that can protect the inverter during contingencies [14].

However, all the existing GFM inverter control schemes are designed based on the model that treats the distribution grid as a passive load. This simple circuit cannot reflect the dynamics and characteristics of the future distribution grids that contain a large variety of dynamic components, such as inverter-based or synchronous distribution generations. However, there isn't existing literature on the inverter control that is based on a detailed distribution grid model and takes consideration of its dynamics. The inappropriate inverter control design of the DERs can induce instability issues, such as harmonics and frequency oscillations, when they are integrated with realistic distribution grids.

This paper aims to investigate the existing GFM inverter control strategies, including the widely used single-loop control and multi-loop droop control, and testify their performance in a distribution grid. Such a study has not yet been done in existing

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GFM control studies. Two cases are carried out by implementing the existing GFM control schemes in an inverter-based DER that is connected to a passive load (case 1) and a modified IEEE 30 bus system (case 2). The simulation results in MATLAB/Simulink show that the f and V regulation using both droop control methods are coupled as distribution grids are usually resistance-dominated and their f and V are associated with both P and Q. This indicates that the existing GFM control of DERs cannot provide effective and independent GFM f and V regulation.

II. System Configuration

This section introduces the development of a distribution grid benchmark and an inverter-based DER system. In addition, two widely used droop GFM control strategies, i.e., the single-loop and multi-loop droop control schemes, are discussed in detail.

A. Development of a distribution grid benchmark

To investigate the performance and feasibility of the existing GFM control schemes, a distribution grid benchmark is developed based on the IEEE 30 bus system. The original IEEE 30 bus system includes multiple voltage levels, such as 1 kV, 33 kV, and 132 kV. The parameters can be found in [15]. In the benchmark system, the grid connections at the voltage level of 132 kV and 1kV are removed and the grids of 33kV are remained, as shown in Fig. 1. In addition, a 2MVA, 33kV synchronous generator, and a 5MVA, 33kV synchronous generator are added and connected to buses 1 and 2 in the benchmark system, respectively. Bus 1 performs as the slack bus to provide the reference voltage in the system. Bus 2 performs as a PV bus, where the output active power P and voltage magnitude V are controlled by the generator. The inverter-based DER implemented with the GFM control strategies is connected to bus 15.

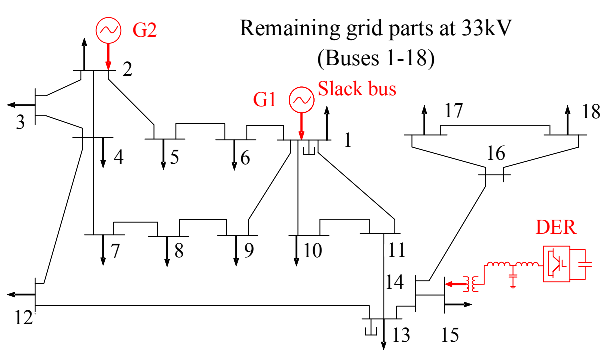

Figure 1. Benchmark system of the distribution grid

B. Inverter based DER system

The GFM inverter-based DER system is shown in Fig. 1. It consists of a dc source, an inverter, and an LCL filter. The inverter transforms the dc power to ac power and feeds it into the distribution grid. Applying the GFM control, the inverter-based DER system works as a controllable voltage source that is connected to the distribution system via a point of common coupling (PCC) bus.

In Fig. 2, E and ϕ represent the output magnitude and phase of the inverter voltage, respectively; V is the magnitude of PCC voltage, whose phase is 0; P and Q are the active power and reactive power transmitted from the inverter to the distribution grid; Z is the sum of the inverter output impedance and the outline impedance. The P and Q from the inverter can be usually represented by (1).

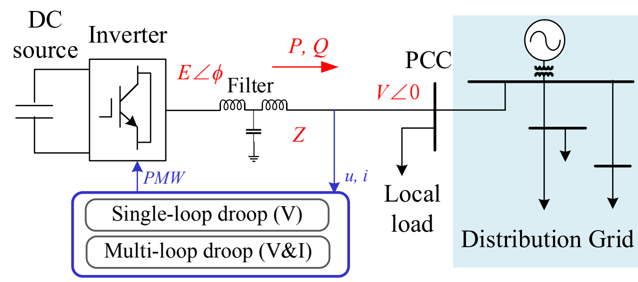

Figure 2. Structure of inverter-based DER system.

$$\begin{cases} P = VE\phi/Z \\ Q = V(E-V)/Z \end{cases} \tag{1}$$

It can be seen that the power angle ϕ is linear to the active power P, and the voltage magnitude V is linear to the reactive power Q. Notice that the P-f droop rather than P-ϕ droop scheme is used. The reason is that the initial phase value at the PCC cannot be known by the inverter, however, the f reference can be set as nominal values [16]. As a result, the f and V control can be achieved by implementing P-f and Q-V droop functions as shown in Fig. 3.

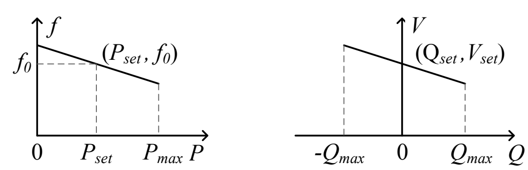

Figure 3. P-f and Q-V droop control

Specifically, f is the system frequency, f_0 is the rated frequency, and V_{set} is the voltage set point. P_{set} is the active power setpoint, and Q_{set} is the reactive power setpoint. P_{max} and Q_{max} are active and reactive power ratings of the inverter. The P-f droop coefficient m_p and Q-V droop coefficient m_q are determined by the frequency droop ratio m_pP_{max}/f_0 and voltage droop m_qQ_{max}/V_{set}. By properly designing the droop gain, the GFM inverter can control the output f and V based on P and Q deviations to achieve power-sharing and f and V regulation.

C. Single-loop and multi-loop droop control schemes

The droop control is applied to the outer loop of the inverter control. The inverter has two different inner voltage control configurations, i.e., the single-loop and multi-loop. Fig. 4 shows the single-loop droop control. The single-loop droop control has two control blocks, including the outer droop loop and inner voltage loop [6, 13]. P_f and Q_f are the measured and filtered output active and reactive power, respectively; m_p and m_q are droop coefficients, respectively; f_0 is the rated frequency; V_{magf} is the measured magnitude of the output voltage; E^*_{inv} is the magnitude reference and θ_{inv} is the phase reference of the

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inverter output voltage, which will be sent to the pulse width modulation (PMW) generator to generate the PWM signals for the inverter switches.

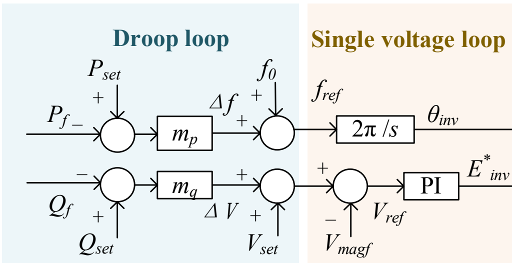

Figure 4. Single-loop droop control

Compared with the single-loop control, the multi-loop droop control has the same droop control loop that can achieve the P-f and Q-V droop function. However, it has different inner loop control consisting of the voltage and current control loops in the *d-q* frame. The voltage loop is used to control the output voltage of the inverter according to the voltage reference generated from the droop loop. The additional inner current loop is expected to improve the dynamic response speed and allow the implementation of the current limiters for protecting the switches during contingencies, such as faults and overloads.

The detailed circuit and control blocks are shown in Fig. 5 [11]. The structure of voltage and current loops is built based on the voltage and current models in the *d-q* frame. The v^*_{od} and v^*_{oq} are the d-axis and q-axis voltage references of the voltage loop in the *d-q* frame. Specifically, v^*_{od} is the voltage magnitude reference that is generated from the droop control, and the q-axis reference v^*_{oq} is set to zero. The v_{od} and v_{oq} are the corresponding feedbacks, which are generated from the voltage measurements via the *d-q* transformation. The outputs of the voltage loop, i.e., i^*_d and i^*_q are the current references in the *d-q* frame for the current loop; the feed-forward loop using the i_{od} and i_{oq} with a gain F is added to achieve low output impedance and improve the disturbance rejection of the inverter system; i_{od} and i_{oq} are the LC filtered current measurements in the *d-q* frame; i_{ld} and i_{lq} are the corresponding negative feedbacks that are generated from the current measurements via the *d-q* transformation.

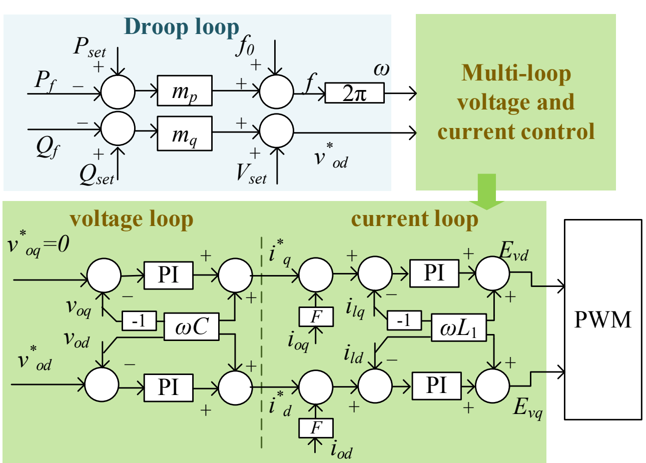

Figure 5. Multi-loop droop control.

These two control schemes are widely used for providing f and V regulation of the power system by actively controlling its output voltage and frequency. However, all the related studies [6-9] of their designs or dynamic investigations treat the distribution grid as a passive load, which ignores the impact of the complex dynamics in the distribution system on the control performance of the inverters. Since the dynamics in the inverter-based distribution grid are much more complicated, there is an urgent need to study the performance of these grid-edge inverter controls when they are connected to a distribution grid rather than a passive load.

III. Case Study

Two cases are developed to investigate the performance of both droop control schemes with different grid models, including a passive load grid model (case 1) and a modified IEEE 30 bus distribution grid benchmark (case 2).

A. *Case 1: Performance of droop control applied to passive load grid model*

Fig. 6 shows the system configuration that is widely used in the existing studies [9, 11, 13], consisting of two parallel-connected inverters and a passive load as the grid model. Two scenarios that implement the single-loop and multi-loop droop controls into the inverters respectively are developed to study their performances. The system parameters are shown in Table I in the appendix.

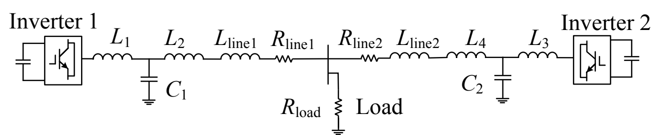

Figure 6. System configuration in case 1.

The performances of the single loop droop control (scenario 1) and the multi-loop (scenario 2) are evaluated by initiating an active power reference step change from 50 kW to 100 kW at 2 s. The simulation results of both scenarios are shown in Fig. 7 (a) and Fig. 7 (b) respectively. It can be seen that when the active power reference step change is initiated, the active power output P1 and P2 of both inverters reach steady states fast and smoothly. Specifically, the active power of inverter 1 increases and the active power of inverter 2 decreases due to the coordination of the droop control. The frequency increases and is stabilized fast by the P-f droop control, while the voltage remains the same. The simulation results show that both the control methods show good performance when they are applied on a passive load grid model on the power-sharing and primary frequency control.

B. *Case 2: Performance of droop control applied to benchmark system model*

In this case, an inverter-based DER is connected to the distribution grid benchmark system, as shown in Fig. 8. This system has a total load of 1.4 MW active power, and 0.76 Mvar reactive power. The governor of the 2MVA synchronous generator (G2 in Fig. 1) has a 5% P-f droop to coordinate with the inverter for load sharing and primary frequency control. Other parameters are shown in Table I.

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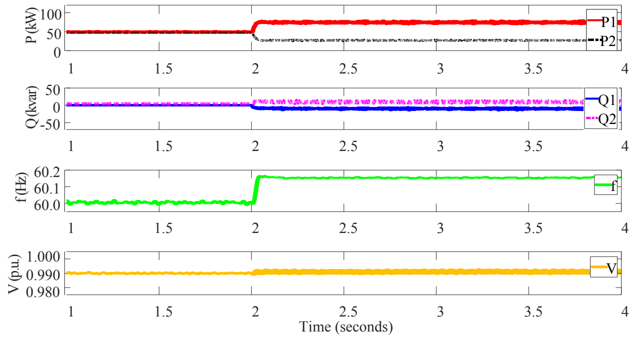
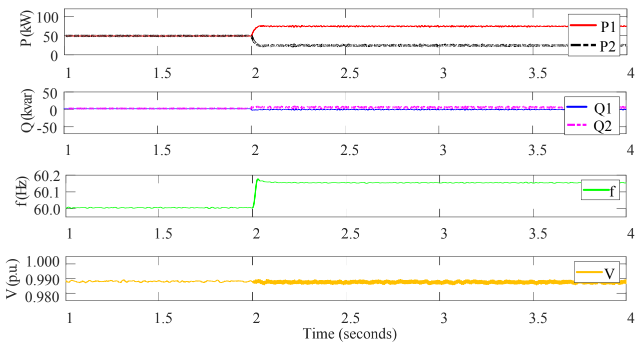
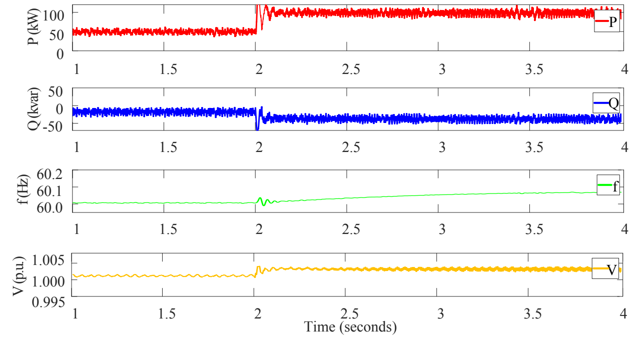


(a) Senario 1: single-loop droop control in case 1

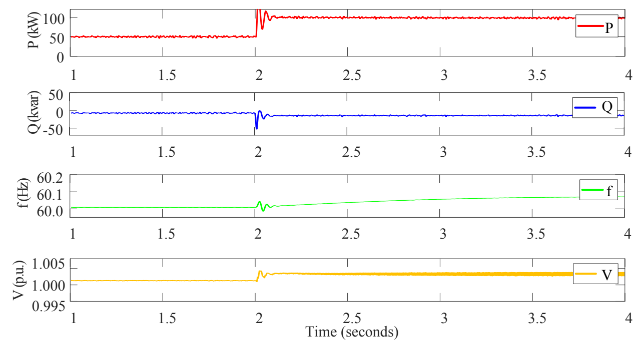


(b) Senario 2: multi-loop droop control in case 1

Figure. 7 Simulation results of control performances in case 1



(a) Senario 3: single-loop droop control in case 2



(b) Senario 4: multi-loop droop control in case 2

Figure. 9 Simulation results of control performances in case 2

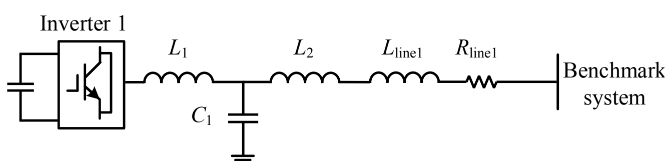


Figure. 8 System configuration in case 2

The simulation results of the control performances of the single-loop (scenario 3) control and multi-loop control (scenario 4) in case 2 are shown in Fig. 9(a) and Fig. 9(b) respectively. In Fig. 9(a), the P and Q have steady-state oscillations compared with Fig. 9(b), indicating that the multi-loop droop control has a better control performance in realistic distribution grids. When the active power reference step is initiated at 2 s, the output active power follows the reference from 50 kW to 100 kW. Complying with the P-f droop law, the frequency has a slow step response due to the inertia provided by the synchronous generators. However, it should be noted that the voltage also has an inappropriate step response. This indicates that the f and V control are coupled associated with P and Q. In addition, there are severe oscillations of the P, Q, f, and V during the transients. As a result, it can be concluded that when applied to a realistic distribution grid, the existing droop-based control methods show an inappropriate performance with the coupled f and V regulation and bad transient performances that are affected by complex dynamics of the distribution grid.

C. Discussion on the results

The performances of the f and V control using the droop control methods in both cases are discussed below. As discussed in section II, since the f is mainly correlated to the P and V is mainly correlated with Q, the droop control is designed according to the P-f and Q-V droop laws to control f by regulating P and control V by regulating the Q independently. Ideally, after a step change of P is imposed, only f should be affected and the V should maintain the same, such as in Fig. 7, indicating that the f and V regulations are independent and effective. In addition, it can also be seen in Fig. 7 that the P, Q, f, and V reach steady states fast and smoothly without significant oscillation during transients after the step change of the P reference. This shows that the existing droop control can achieve the expected performance in aspects of the independent f and V control and transient dynamics in case 2 which treats the distribution grid as a simple passive load. However, as shown in Fig. 9, the droop control has deteriorated performance when they are connected to the benchmark grid containing synchronous generators and loads with complex dynamics. Specifically, when the P reference has a step change, the f and V both have step responses in Fig. 9(a) and Fig. 9(b). This shows that the change of P affects f and V simultaneously. Therefore, the control of f and V are coupled associated with P and Q in distribution systems. In addition, it also can be seen that the P, Q, f, and V have large oscillations during transients, indicating the coupling issue severely impacts the performance of f and V control.

The reason for the coupling issue is that the existing droop-based schemes are all designed based on the P-f and Q-V droop laws, which are only valid in the highly inductive transmission system. In the distribution grid, the f and V controls become coupled with the P and Q due to the high R/X ratio. This can be derived from the relationships of the inverter output P, Q with the f and V at the grid connection point. In addition, the ratio is

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also undetermined due to the complex dynamics and changing operating conditions in the distribution grids. Therefore, the existing GFM control schemes cannot enable DERs to provide independent and effective f and V regulation in distribution grids and even threaten system stability, which can cause severe damages to the equipment or even wide-area outages.

IV. CONCLUSION

This paper systematically investigates and analyzes the feasibility of the existing GFM control on the DERs and reveals their critical issues when applied to the detailed distribution grid model. The presented study unveils the gap of the application of droop control in the distribution grids and provides insights for the future grid-edge inverter control study. This paper investigated the control performance of the existing droop control methods on a distribution grid model. The results show that the performances of the existing droop control methods deteriorated when they are applied on a distribution system model, inditing that their infeasibility on a realistic distribution grid with complex dynamics and characteristics. Therefore, it can be concluded that there is an urgent need to develop a new control strategy for GFM DERs to achieve independent and effective f and V regulation in the future DER-dominated distribution grids.

V. APPENDIX

TABLE I. PARAMETER SETTINGS

Control	Parameter	Symbol	Value
Single- & multi-loop control	Voltage setpoint	V_{set}	392 V
	Nominal frequency	f_0	60 Hz
	Active power setpoint	P_{set}	50 kW
	Reactive power set point	Q_{set}	0 kvar
	DC voltage of DER	V_{dc}	850 V

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