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A Droop Based Virtual Synchronous Generator in an Islanded Microgrid

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ABSTRACT

With the emergence of renewable energy sources and the decrease in system inertia, islanded microgrids face stability challenges. Grid-following inverters cannot control voltage and frequency independently in such circumstances. In this paper, a droop control based Virtual Synchronous Generators (VSGs) is proposed to simulate synchronous generator's behavior by offering virtual inertia and damping. For the regulation of a three-phase voltage source inverter with an output filter, a dq-frame voltage-current dual-loop controller is used in conjunction with P-f and Q-V droop loops. MATLAB/Simulink was used to assess the model's performance under islanded operation. The system demonstrates fast dynamic response with a frequency overshoot of less than 0.04% and rapid convergence to the nominal value of 50 Hz, ensuring stable and well-damped operation. A good damping in the power output characteristics, voltage regulation accuracy, and sinusoidal waveform balance are exhibited from the simulation outcomes. The suggested technique guarantees stable voltages and frequencies in applications with low inertia microgrids.

Keywords: Droop control, dq control, Grid-forming inverter, Islanded microgrid, Virtual Synchronous Generator.

I. INTRODUCTION

Because of the increasing deployment of unconventional renewable energy sources, including photovoltaics and wind energy, today's power generation systems have undergone several changes. Traditional synchronous machines with low installation and operational expenses have significantly lowered system inertia due to high levels of penetration of renewable energy sources into electrical networks. Due to the absence of built-in inertia, today's power systems can be less stable and are likely to face voltage disturbances, variations in frequency, and synchronization problems in the event of system failure. Therefore, renewable power systems require answers to these questions in order to work stably. [1].

Grid-forming inverters were invented to resolve the problems associated with typical grid-following inverters. Because of the disadvantages associated with conventional grid-following inverters, grid-forming inverters were invented. The synchronverter imitates swing dynamics, voltage regulation, and frequency response without using phase-locked loops. Apart from improving the system's stability, synchronverters promote smooth power sharing. Thus, these attributes make microgrids, weak grids, and renewable-rich systems ideal for synchronizers. [2].

There have been several researches made on synchronverter-based systems within the last decade. During the first stage of the system at emergency frequencies, basic theories were examined such as virtual inertia and damping properties. Next came other factors such as self-synchronization techniques, impedance characteristics, and one- or multi-phase converters. Some of the latest innovations include concepts such as fault ride-through, stability studies, parameter adaptation using artificial intelligence methods, and applications in hybrid AC/DC grids as well as intelligent energy systems. Despite these developments, recent reviews have mostly centered on the synchronverter concept while overlooking grid-forming inverters as another part of virtual synchronous machines. There is still a need for an in-depth study into synchronization and its progress in order to understand the development of the technology. [3],[4].

There are still many challenges to overcome when it comes to synchronverter-based Virtual Synchronous Generator (VSG) control. There is a major research gap in multi-VSG coordination and communication less power sharing, as most existing studies focus only on single VSG systems. Additionally, robust and adaptive control strategies are not sufficiently explored under ultra-low inertia conditions. It is also difficult to assess and compare different control approaches without standardized benchmark systems. The limitations of island microgrids highlight the need for improved grid-forming control techniques.

To address the stability issues of low-inertia power systems, we propose a grid-forming control technique that uses Virtual Synchronous Generators (VSGs) for inverter-interfaced renewable sources operating in isolated mode. Using the swing equation, the proposed model simulates the dynamics of synchronous generators in order to add virtual inertia and damping for better frequency stability. Dual-loop controllers with dq-frame voltages/currents ensure accurate voltage monitoring and dynamic response, while active and reactive power are controlled through a combination of P-f and Q-V control loops. When an output filter and load are attached, the controlled inverter functions as a steady voltage source suitable for island microgrid operation. Simulation results validate the importance of

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the suggested VSG-based control method in island-based microgrid operations. It ensures constant voltage and power output by ensuring that the inverter produces balanced sinusoidal waves as well as good damping.

This paper is organized as follows: Section II presents a system modeling and control design for proposed grid-forming inverter with VSG; Section III discusses the simulation results and discussion under islanded operation condition; and Section IV concludes the paper.

II. SYSTEM MODELING AND CONTROL STRATEGY

The grid-forming inverter is based on the virtual synchronized generator (VSG) concept as depicted in Fig. 1. It reflects the dynamic characteristics of a conventional synchronous generator in an islanded microgrid. The control framework includes measurement and transformation blocks, power computation, droop control, a DQ-frame dual-loop voltage-current controller, pulse-width modulation, and a three-phase inverter with an output filter. A major goal of the control scheme is to maintain steady voltage and frequency while ensuring reliable power delivery to the load [5].

First, accurate measurement and transformation of electrical quantities are needed to implement the proposed control strategy.

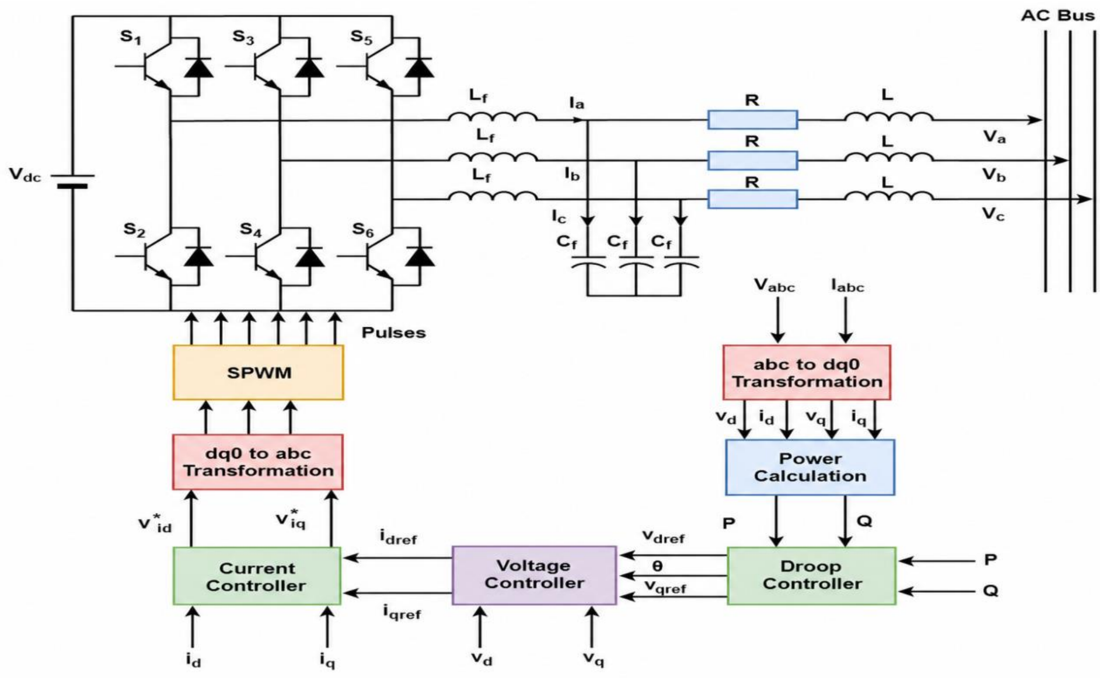

Fig. 1 Control architecture of the three-phase VSG-based grid-forming inverter.

A. abc–dq0 Transformation and Power Calculation

The Park Transformation is used to convert three-phase stationary AC signals (abc) into a two-axis rotating reference frame (dq0) [6], [7], [8]. Equation (1) illustrates the park transformation:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} cos\theta & cos\left(\theta-\frac{2\pi}{3}\right) & cos\left(\theta+\frac{2\pi}{3}\right) \\ -sin\theta & -sin\left(\theta-\frac{2\pi}{3}\right) & -sin\left(\theta+\frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

Inverters supply instantaneous active and reactive power in accordance with the dq-axis voltage and current components. Active power (P) and Reactive power (Q) are respectively calculated from equations (2) and (3).

$$P = \frac{3}{2}\left(v_d\, i_d + v_q i_q\right) \quad (2)$$

$$Q = \frac{3}{2}\left(v_q\, i_d - v_d i_q\right) \quad (3)$$

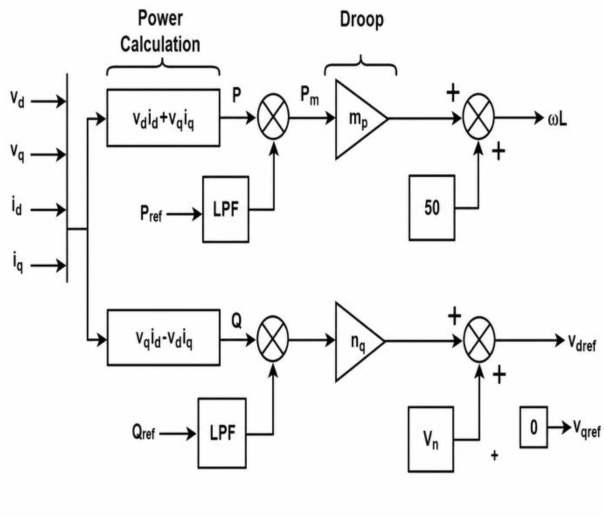

Fig. 2 Droop Control

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B. P–f and Q–V Droop Control

Using droop control, the proposed method mimics the behavior of a traditional synchronous generator. Droop control establishes a link between Reactive Power and Voltage (Q-V) as well as Active Power and Frequency (P-f).

The P-f droop control modifies the inverter frequency based on how much the active power differs from the reference value. Based on equation (4), a relationship exists between frequency and active power [9].

$$\omega = \omega_{ref} - k_p(P - P_{ref}) \quad (4)$$

where ω is the output angular frequency, ω_(ref)is the nominal system frequency, P is the measured active power, and k_p represents the frequency droop coefficient.

As a result of changes in reactive power, the Q-V droop control adjusts the inverter output voltage. In equation (5), voltage is expressed in terms of reactive power.

$$V = V_{ref} - k_q(Q - Q_{ref}) \quad (5)$$

Where V is the inverter output voltage, V_{ref} is the reference voltage, Q is the measured reactive power, and k_q represents the voltage droop coefficient.

Using the droop equations provided in equations (4) and (5), the inverter adjusts its operating point in response to change in load.

The voltage and current controller with two loops is employed to improve dynamic performance.

C. Voltage–Current Dual Loop Controller

Voltage and current controller with two loops is applied in the synchronous reference dq framework in order to achieve better dynamic performance. The structure presented in Fig. 3 is composed of inner current loop control and outer voltage loop control

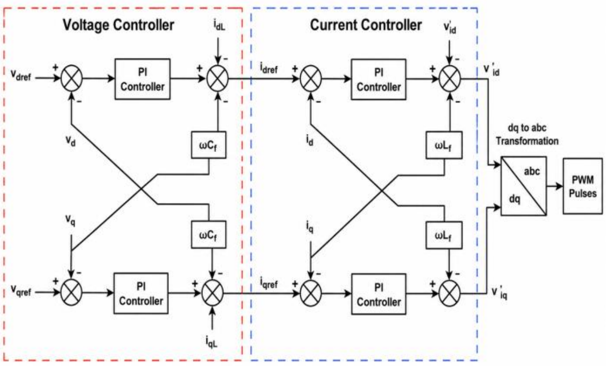

Fig. 3 Dual Loop VSG Control

As a result of the voltage difference between the reference voltage and the measured voltage, the outer voltage loop generates reference current components. In (6) and (7), proportional–integral (PI) control equations are presented for determining the reference currents (i_{dref}) and

$$(i_{dref}).\, i_{dref} = K_{pv}(V_{dref} - V_d) + K_{iv}\int(V_{dref} - V_d)dt - \omega C_f V_q - I_{dL} \quad (6)$$

$$i_{dref} = K_{pv}(V_{dref} - V_d) + K_{iv}\int(V_{dref} - V_d)dt - \omega C_f V_q - I_{dL} \quad (7)$$

where K_{pv} and K_{iv} represent the proportional and integral gains of the voltage controller.

The inner current loop tracks the voltage controller's reference current values from the inverter's currents. Reference voltage signals are derived using the PI current control equations in (8) and (9) [10].

$$V_{id}^* = K_{pi}(i_{dref} - i_d) + K_{ii}\int(i_{dref} - i_d)dt - \omega L_f I_q \quad (8)$$

$$V_{iq}^* = K_{pi}(i_{qref} - i_q) + K_{ii}\int(i_{qref} - i_d)dt - \omega L_f I_q \quad (9)$$

where K_{pi} and K_{ii} denote the proportional and integral gains of the current controller.

Equations (6)-(9) describe a dual-loop control that ensures precise voltage regulation and rapid current tracking.

Sinusoidal Pulse Width Modulation (SPWM) is used to convert the generated control signals (V_{id}^* *and* V_{iq}^*) into switching pulses.

D. SPWM Generation

As a result of inverse dq transformation, the voltage references (V_{id}^* , V_{iq}^*), generated by the current controller, are converted into three-phase quantities. As shown in (10), dq-axis voltage components are transformed into three-phase reference signals.

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta \\ cos\left(\theta - \frac{2\pi}{3}\right) & -sin\left(\theta - \frac{2\pi}{3}\right) \\ cos\left(\theta + \frac{2\pi}{3}\right) & -sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} \quad (10)$$

By using the three-phase reference signals generated by the SPWM block, switching pulses are generated for the inverter switches.

E. Three-Phase Inverter and Output Filter

As part of the power conversion stage, a three-phase voltage source inverter is powered by a DC voltage source. Inverters convert DC input voltages into three-phase AC voltages using the switching signals produced by SPWM controllers.

Equation (11) represents the reference three-phase voltage signals.

$$V_{abc} = \begin{bmatrix} V_a \\ V_a sin\left(\theta - \frac{2\pi}{3}\right) \\ V_a sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \quad (11)$$

An LC output filter is installed between the inverter and the load in order to ensure sinusoidal voltage and current waveforms. Through the coordinated operation of the control system and the inverter stage, the

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proposed system maintains steady voltage and frequency in island microgrid operation [2], [11].

III. RESULTS AND DISCUSSIONS

The schematic diagram of the developed inverter system is shown in Fig. 4. The system is supplied by a DC voltage source(V_{dc}), which feeds a three-phase inverter that converts the DC input into AC output using a PWM-controlled PWM unit to control the switching. In order to emulate the behavior of synchronous generators, the VSG control block generates reference voltages and currents based on measurements. Smoothing the output of the LCL filter ensures high-quality sinusoidal power is delivered to the load. The proposed Virtual Synchronous Generator (VSG)-based inverter system was constructed and simulated using MATLAB/Simulink's discrete-time framework. Table 1 shows the parameters of droop control.

TABLE I
DROOP CONTROL PARAMETERS

S.No	Parameter	Value
1.	DC Voltage (V_{dc})	800 V
2.	Inverter-side Filter Inductance (L_f)	9000 H
3.	Grid-side Inductance (L_g)	2.7 mH
4.	Active Power Reference (P_{ref})	10 kW
5.	Reactive Power Reference (Q_{ref})	0W
6.	Damping (D)	10^6 Kg/s
7.	Inertia (J)	10^3 Kg.m^2
8.	Switching Frequency (f_s)	10 kHz
9.	Nominal Voltage (V_n)	400V
10.	Load	10 kW
11.	Nominal Frequency (ω)	50 Hz

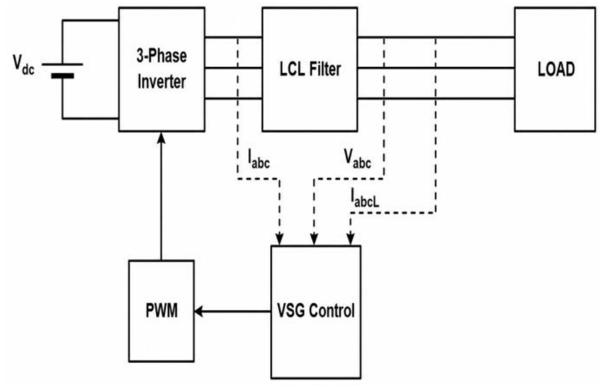

Fig. 4. Schematic diagram of a test system.

Simulation results are used in this section to evaluate the performance of the proposed VSG-based inverter under islanded operating conditions. The system consists of a DC source, a three-phase voltage source inverter (VSI), an output filter, and a three-phase load. Dynamic responses of voltage, current, and power under islanding conditions are used to assess the effectiveness of the control strategy.

A. Inverter Output Voltage and Current

In Fig. 5, the inverter output waveforms present the switching characteristics of the three-phase VSI. The corresponding current waveforms are filtered to be smooth and sinusoidal, while the voltage waveforms remain PWM with high switching frequencies. Three-phase current balance and 120° phase displacement confirm accurate modulation and correct inverter operation. In the islanded microgrid, the inverter functions as a grid-formation source and successfully convert DC to AC.

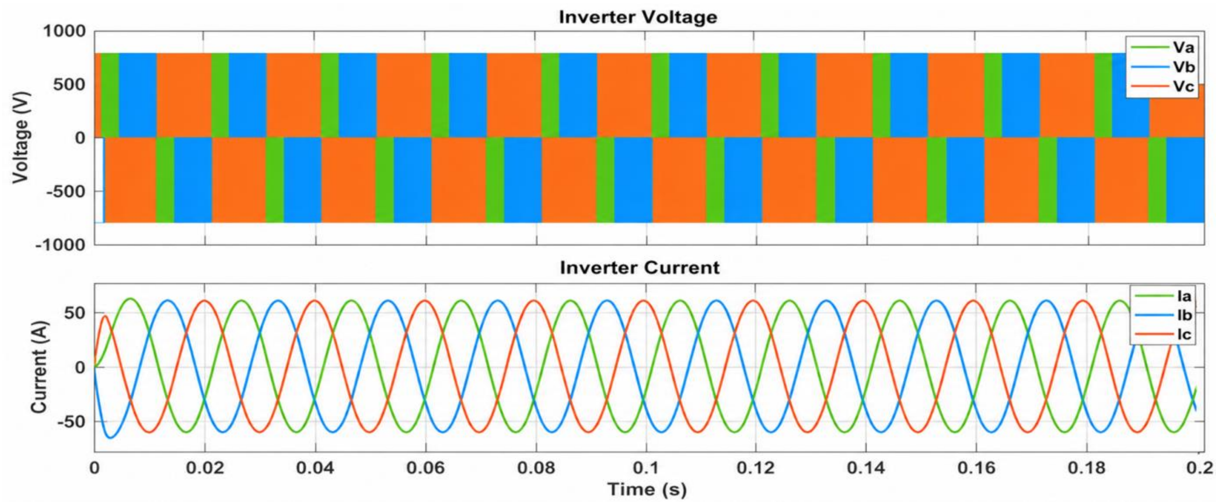

Fig. 5. Three-phase inverter output showing PWM voltage and filtered sinusoidal current, indicating successful DC–AC conversion.

B. Load Voltage and Current Response

As shown in Fig. 6, the load-side voltage and current waveforms are sinusoidal and balanced. As demonstrated by the lack of discernible distortion, the output filter successfully suppresses switching harmonics introduced by the inverter. In addition, the constant amplitude of the waveforms indicates the system's ability to maintain steady-state voltage levels. As a result, the suggested control method can guarantee high-quality power to the load.

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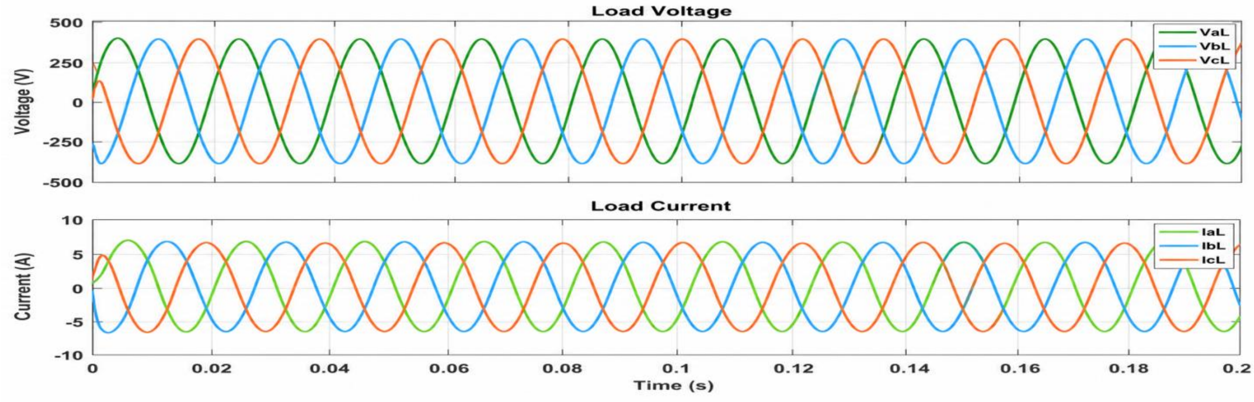

Fig. 6. Balanced and sinusoidal load voltage and current waveforms demonstrating stable power delivery and effective harmonic filtering.

C. Voltage Dynamics and dq Control Performance

As shown in Fig. 7 the d-axis voltage response accurately tracks the reference voltage. Within a short amount of time, the system stabilizes and the error converges to zero, despite a transient overshoot during the first startup. PI-based voltage controllers provide efficient regulation and a quick settling period, based on this behavior. The observed transient overshoot is primarily due to aggressive PI controller gains. In order to minimize this effect, controller parameters can be optimized, damping control can be introduced, or advanced tuning techniques like adaptive or fuzzy based controllers can be utilized. In the microgrid, the results confirm that the dq-frame control strategy provides accurate and steady voltage regulation.

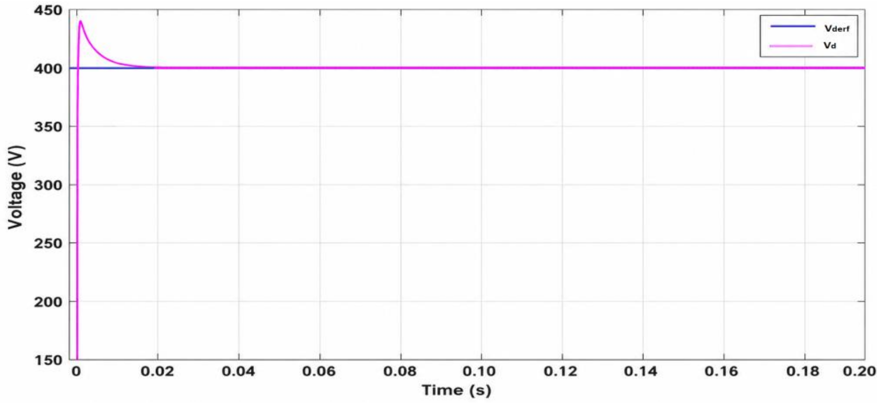

Fig. 7. d-axis voltage tracking response showing fast settling and accurate reference voltage regulation using PI control.

D. Active and Reactive Power Response

As shown in Fig. 8 during system initialization, active and reactive power exhibit a brief transient before quickly settling to steady state values. The oscillations are damped significantly, as the proposed VSG control mechanism provides the equivalent virtual inertia and damping. The controller can guarantee real-time power balance, and maintain stable frequency and voltage in the islanded condition with small deviations. Finally, all the simulation results show that the proposed VSG based control strategy can accomplish the smooth and steady operation of the inverter in an islanded microgrid.

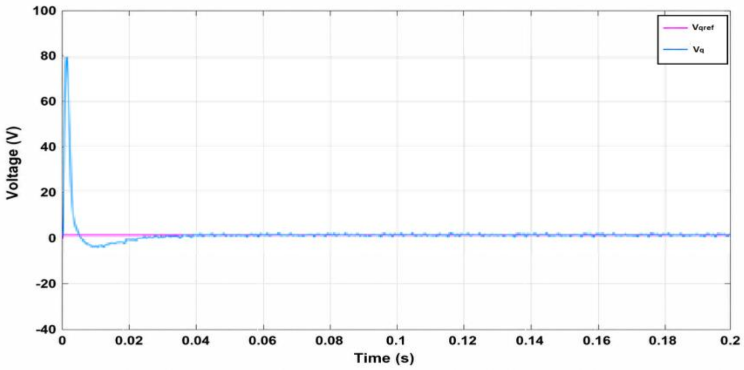

Fig. 8. Dynamic response of active and reactive power illustrating well-damped transients and stable steady-state operation.

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The system provides accurate voltage tracking, well-damped power dynamics, balanced sinusoidal voltage and current and efficient harmonic mitigation. These are characteristics which have similarities with traditional synchronous machines: thus, the effectiveness of VSG method in addressing low inertia problems in modern power systems is evident from such characteristics.

E. Droop Control Response

The droop control response of Fig. 9 represents the dynamic response of the system frequency, voltage reference, and power with the adopted VSG control approach. As it can be seen from the figure, P-f droop control has been successfully proven to provide good frequency regulation since a transient deviation in the initial phase of the simulation quickly stabilizes at its nominal level. From studying the Q-V droop behavior, the d-axis voltage reference (V_{dref}) exhibits a small settling phase and then remains constant, hence proving voltage regulation.

As per the adopted VSG technique, active power (P) approaches a steady state with very few fluctuations, whereas reactive power (Q) achieves a steady state under Droop control response.

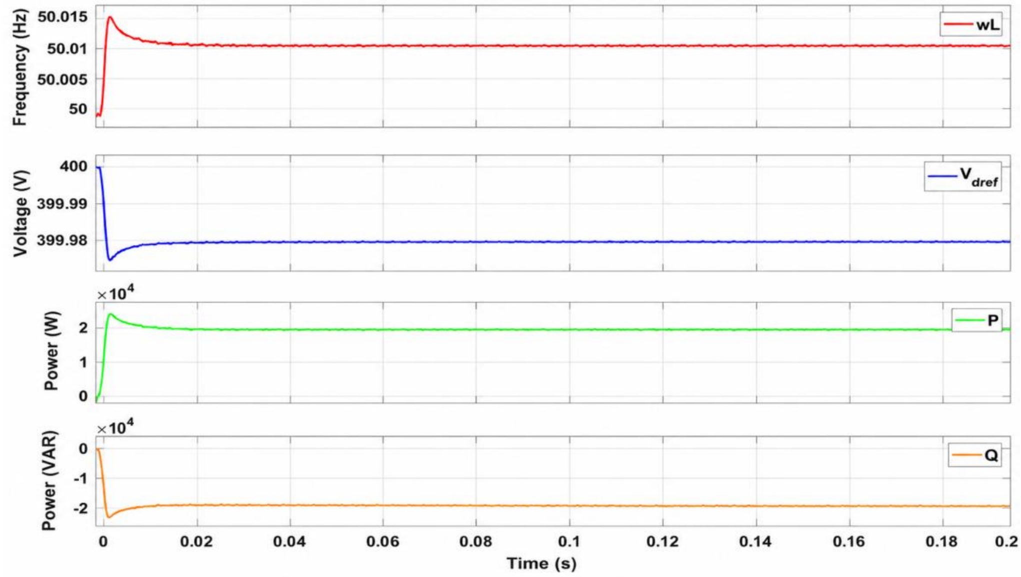

Fig. 9. (a) Droop Control Frequency (b) V_{dref} (c) Active Power (d) Reactive Power

Using droop control, the system sustains voltage-frequency stability along with equal distribution of power during steady state operation.

The simulation outcomes show that VSG control yields rapid dynamic performance, highly damped power behavior, and voltage-frequency stability in an isolated microgrid scenario.

Though the above results have been achieved through simulation, they fail to consider the practical issues associated with its implementation, including measurement noise, switching losses, and other constraints. Based on operational parameters, further tuning of controller settings may be required.

IV. CONCLUSION

In microgrid systems where grid tie is not possible, a virtual synchronous generator (VSG) control scheme is utilized to control the inverters. Using virtual circuit design concepts, the proposed scheme controls the voltage and frequency regulation process, dynamic study of inertia using swing equations, double loop control through dq-frames, P-f and Q-V droop control method, and double loop control through dq frames. Based on the simulation results, the output of the proposed inverter scheme includes sine wave formation, fast dynamics, and controlled power behavior. Thus, the proposed technique can be effective for improving the performance of low inertia power systems.

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