Passivity-Based Grid Forming Control for DERs

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***Abstract*—This paper uses a passivity-based control method for grid-forming control-based distributed energy resources (DERs). A port-controlled Hamiltonian form is used to guarantee the passivity property. In addition, different passivity-based control methods are applied to different DERs in a microgrid, where an energy storage system, wind turbine, and solar-based DERs are considered. Since all the operating DERs can guarantee the passivity property, the stable operation of the microgrid is guaranteed. The simulation results demonstrate that the proposed control method effectively manages the microgrid, ensuring stable operation.**

***Index Terms*—Distributed energy resources, microgrid, passivity-based control, port-controlled Hamiltonian.**

I. INTRODUCTION

Nowadays, more and more distributed energy resources (DERs) are integrated into the grid due to the increase in the penetration level of renewable energy sources. DERs such as wind turbines (WTs) and photovoltaics (PVs) are normally operated in grid-following mode, synchronizing with the grid via a phase lock loop (PLL) mechanism [1], [2]. However, the stability of grid-following converters in weak grids, particularly with high grid impedance, is challenging due to potential instability issues caused by injected current and PLL dynamics. To solve this issue, grid-forming (GFM) controls [3] such as virtual synchronous generators, droop controls, virtual oscillators, and robust approaches are gaining attention because of their synchronous machine-like qualities and capacity to function in weak grid settings or as a standalone grid [4]–[9]. GFMs are advantageous in microgrid development because they can operate in grid-tied and off-grid modes, supporting weak grids while maintaining acceptable voltage and frequency range [10]. However, due to the inverter-grid interaction, stability analysis of the GFM-DERs becomes more complex [11].

The eigenvalue-based analysis approach is used for stability prediction, but it's difficult to model complex grid impedance conditions [12]. The impedance-based approach predicts stability from the ratio of inverter output impedance to grid impedance, however, it requires repeatedly assessing the stability when the grid impedance varies [13]. A large signal stability analysis method based on Lyapunov stability theory [14], [15], singular perturbation [16], and La Salle's Invariance Principle [17] can aid in the determination of stability bounds for certain operating locations. Though the local stability can be guaranteed, analyzing the overall system stability becomes difficult as more voltage source converters (VSCs) are added to the grid. To solve this issue, one of the possible solutions is to use the passivity principle, where if the passive sub-systems in the grid are integrated into parallel or feedback, the entire grid is also passive and stable [10], [18], [19]. The passivity-based approach is more promising under varying grid impedance and uncertain grid conditions [20] and based on this principle, the stability of the whole grid can be guaranteed [21].

Although the passivity-based analysis approach, used for conventional GFL inverters [22], [23], has shown promise, its application to GFM inverters remains insufficient. Recently, several passivity-based control methods have been designed for GFM-DERs to get a passive behavior of closed-loop output impedance of DERs [24], improve synchronization stability [8], provide provides passive output impedance [25], etc. One of the popular passivity-based control methods is using the port-controlled Hamiltonian (PCH) form, which is widely applied in various applications to guarantee passivity property [26]–[29]. In this paper, we consider a small microgrid grid, which consists of three DERs such as energy storage system (ESS), WT, and PV. Furthermore, we consider the different controllers applied to different DERs. At first, an ESS-based DER uses the method designed in [20] to ensure the passivity property. For WT-based DER, we propose a novel passivity-

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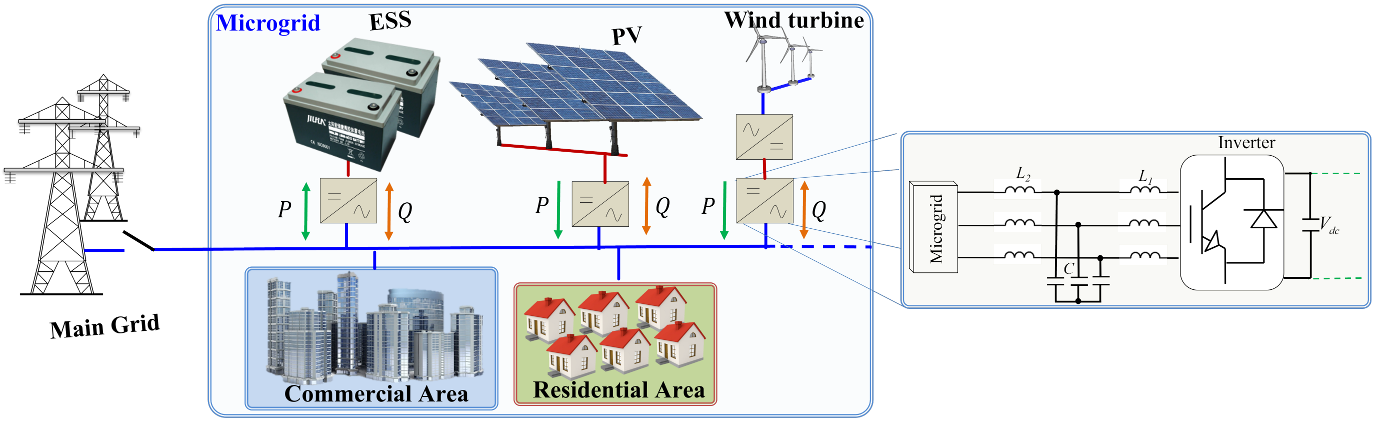

Fig. 1. Grid architecture with energy storage system, renewable energy sources (PV and wind turbine), and loads.

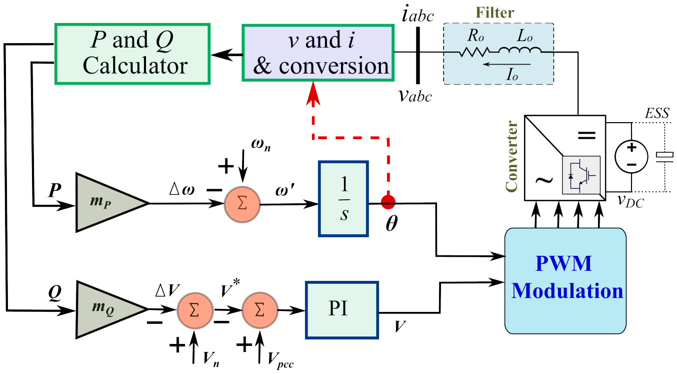

Fig. 2. Basic droop control scheme for GFM-DER (ESS).

based GFM control method by using the PCH form. In addition, a PV-based DER uses a passivity-based GFL control method. Although three different methods are used in the three DERs, the stable operation of the microgrid can be guaranteed since all the DERs are operating with the passivity property. Simulation results show that the proposed control methods manage the microgrid very well.

The rest of the paper is organized as follows. Section II presents the basics of control used for the DERs such as ESS and WT. In Section III, the simulation model under study is presented and the results are presented. Finally, Section IV concludes the study with future directions.

II. CONTROL OF INVERTER BASED RESOURCES

In this study, it is assumed that the GFM-DER is to provide the voltage and frequency of the microgrid, and the GFL-DERs is to regulate their MPPT references in the microgrid.

A. Grid Forming Control of Inverter Based Resource: ESS

With the increasing deployment of WT and PV, the GFM ESS has recently emerged as an attractive solution to improve the dynamic performances or DERs. For the GFM-DER of ESS, we design the outer-loop controller using voltage and frequency as references to generate the inner-loop reference.

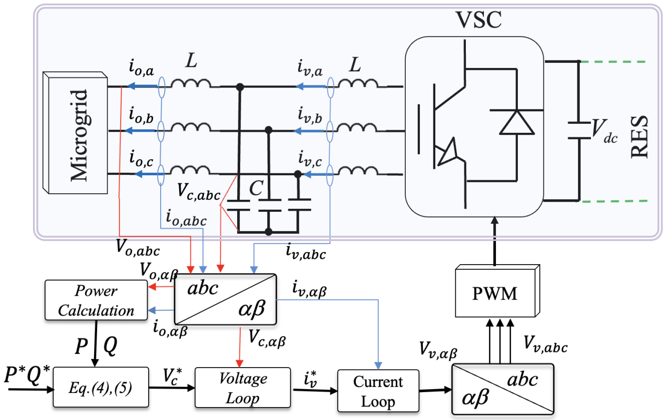

Fig. 3. Proposed control scheme for GFM-DER (WT).

A basic GFM inverter with $P - f$ and $Q - V$ droop controllers is shown in Fig. 2. The inverter uses voltage and current sensors to measure line-line voltages v_{abc} and currents i_{abc}, and then calculates active P and reactive power Q. The controller generates phase-angle θ and voltage V references for PWM generation, obtaining the appropriate frequency and voltage amplitude from the $(P - f)$ and $(Q - V)$ droops in order to establish power-sharing. This procedure is critical for grid-forming inverters in pulse load and plug-in situations.

B. Grid Forming Control of Inverter Based Resource: WT

For the sake of simplicity, a balanced grid voltage condition is considered in this case. We consider a DER with an LCL-filter as shown in Fig. 1. Based on the dynamics of the grid-connected converter with an LCL-filter, the dynamics of the output real and reactive powers in the output L could be obtained using the grid voltage variations as

$$\begin{aligned}\frac{dP_o}{dt} &= -\frac{R_2}{L_2}P_o - \omega Q_o + \frac{3}{2L_2}(v_{o,\alpha}v_{c,\alpha} + v_{o,\beta}v_{c,\beta} - V_g^2),\\ \frac{dQ_o}{dt} &= \omega P_o - \frac{R_2}{L_2}Q_o + \frac{3}{2L_2}(v_{o,\beta}v_{c,\alpha} - v_{o,\alpha}v_{c,\beta}),\end{aligned} \tag{1}$$

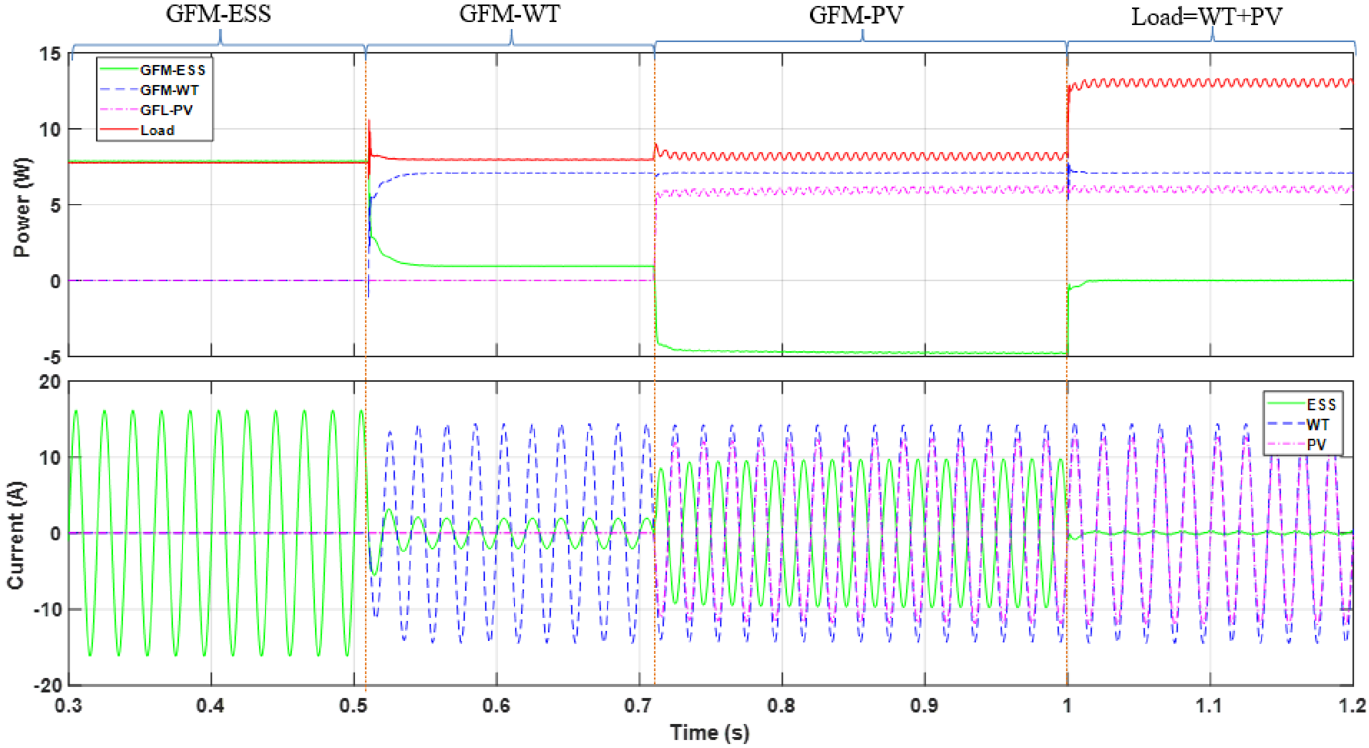

Fig. 4. Simulation results of active power (top) of ESS, WT, PV, and load and phase 'a' current (bottom) of ESS, WT, and PV.

where $V_g = \sqrt{v_{o,\alpha}^2 + v_{o,\beta}^2}$. In (1), ω is the angular velocity of the microgrid voltage. $v_{c,\alpha}$ and $v_{c,\beta}$ are the capacitor voltages in α–β reference frame, respectively. L_2 and R_2 are the inductance and resistance value of the output L, respectively. A new variable can be defined and used to replace terms in (1) to get a simpler model. Then, the dynamics in (1) is rewritten as

$$\begin{aligned} \frac{dP_o}{dt} &= -\frac{R_2}{2}P_o - \omega Q_o + \frac{3}{2L_2}u_{P_o}, \\ \frac{dQ_o}{dt} &= \omega P_o - \frac{R_2}{L_2}Q_o + \frac{3}{2L_2}u_{Q_o}, \end{aligned} \tag{2}$$

where u_{P_o} and u_{Q_o} are the new control inputs. To use the PCH system, taking a Hamiltonian function such as $H(x) = \frac{1}{2}x^T Sx$, where S is a 2 by 2 identity matrix. Then, the dynamics in (2) can be represented in the following PCH form:

$$\dot{x} = (\mathfrak{R} + \mathfrak{J})\frac{\partial H(x)}{\partial x} + G(u) \tag{3}$$

where

$$\mathfrak{R} = \mathfrak{R}^T = \begin{bmatrix} -\frac{R_2}{L_2} & 0 \\ 0 & -\frac{R_2}{L_2} \end{bmatrix} \prec 0,$$

$$\mathfrak{J} = -\mathfrak{J}^T = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}, \; G(u) = \frac{3}{2L_2}\begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} P \\ Q \end{bmatrix}, \; u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} u_P \\ u_Q \end{bmatrix}.$$

We assume that there always exists a desired dynamics that satisfies PCH form in (3), the error dynamics also satisfies the PCH form. If we design a controller as follows:

$$u = u^d + e^T K \tag{4}$$

where $e = x^d - x$, then the closed-loop system is exponentially stable if K is designed as a positive definite matrix by using the PCH method. Furthermore, K can be tuned for the convergence rate of the system. Consequently, the desired control input u^d can be designed by using the flatness property [30] from the output references (P_o^* and Q_o^*). Hence, the original capacitor voltage reference is calculated as

$$\begin{bmatrix} v_{c,\alpha}^* \\ v_{c,\beta} \end{bmatrix} = \begin{bmatrix} \frac{v_{o,\alpha}u_1 + v_{o,\beta}u_2}{V_g^2} + v_{o,\alpha} \\ \frac{v_{o,\beta}u_1 - v_{o,\alpha}u_2}{V_g^2} + v_{o,\beta} \end{bmatrix}. \tag{5}$$

The designed $v_{c,\alpha}^*$ and $v_{c,\beta}^*$ are the references used for the voltage inner loop control loop, which will be shown in the full paper. Then, from the inner loop controller, $v_{i,\alpha}^*$ and $v_{i,\beta}^*$ will be generated, which will be used for the PWM that creates the signal of the inverter. Based on the proposed method, it can guarantee the passivity of the GFM-DER. The control stature is illustrated shown in Fig. 3

III. PERFORMANCE VALIDATION

The proposed method is validated through Matlab/Simulink. The detailed parameters used in the simulation are listed in the Table. I. The proposed method is validated in a microgrid, where an ESS, WT, PV, and two loads are considered as

TABLE I
SYSTEM PARAMETERS IN THE CASE STUDY

Parameter	Symbol	Value
Microgrid voltage	V_{rms}^{*}	230 V
Microgrid frequency	f^{*}	50 Hz
LCL filter inductance of WT	$L_{in,WT}$	1.8 mH
Output LCL filter inductance of WT	$L_{o,WT}$	1.8 mH
LCL filter capacitor of WT	C_{WT}	27 μF
LCL filter inductance of ESS	$L_{in,ESS}$	1.8 mH
Output LCL filter inductance of ESS	$L_{o,ESS}$	1.8 mH
LCL filter capacitor of ESS	C_{ESS}	27 μF
L filter inductance of PV	L_{pv}	6 mH
Switching frequency of DERs	f_{sw}	10 kHz
Loads 1	P_{l1}	8 kW
Load 2	P_{l2}	5 kW

TABLE II
CONTROL PARAMETERS IN THE CASE STUDY

Symbol	Value	Symbol	Value
$K_{P,WT}$	10	$K_{I,WT}$	500
$K_{P,PV}$	100	$K_{I,PV}$	1000
$K_{P,V}$	1	$K_{I,V}$	100
$K_{P,I}$	100	$K_{I,I}$	1000

shown in Fig. 1. The system parameters used in the simulation are given in Table. I and the control parameters are given in Table. II. Fig. 4 shows the power of each DER and the total load and phase current of each DER. At first, the GFM-DER (ESS) provides the voltage and frequency of the microgrid when there is an 8kW load. Then, a GFM-DER (WT) is connected and injects its 7 kW power into the microgrid. The ESS reduces its output based on the regulation of the frequency in the microgrid shown in Fig. 5. The WT connects to the microgrid without any overshoot as shown in Fig. 6. At this time, the voltage of the microgrid has a small overshoot as shown in Fig. 7. In addition, when a GFL-DER (PV) injects 6 kW more power to the grid, the ESS starts charging the surplus power based on the frequency. Finally, a 5 kW load is connected and the generation from PV and WT are the same as the total load. Hence, the ESS regulates zero output automatically. In summary, the voltage and frequency of the microgrid are controlled without losing stability. It can be concluded that the proposed method can manage the microgrid effectively.

IV. CONCLUSIONS AND FUTURE WORKS

The stability of GFL on weak grids, particularly with high grid impedance, can be challenging due to potential instability issues caused by injected current and PLL dynamics. To solve this issue, this paper proposed a passivity-based control of GFM-DER. Moreover, different passivity-based control methods for GFM-DERs and GFL-DERs in a microgrid were presented. It has been shown that GFM-DER (ESS) supports voltage and frequency in the microgrid. The proposed solution has the advantage of ensuring the overall stability of the microgrid using the passivity principle. From the simulation results, it can be guaranteed that the proposed control schemes can manage the microgrid with different DERs efficiently.

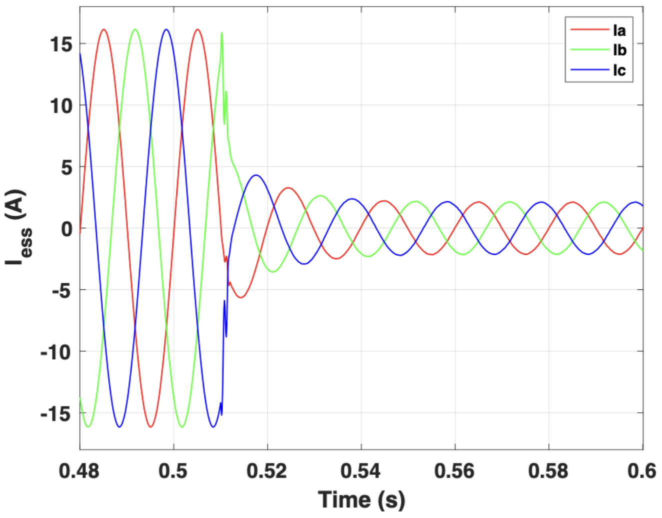

Fig. 5. Currents of WT when the GFM-WT is connected to the grid.

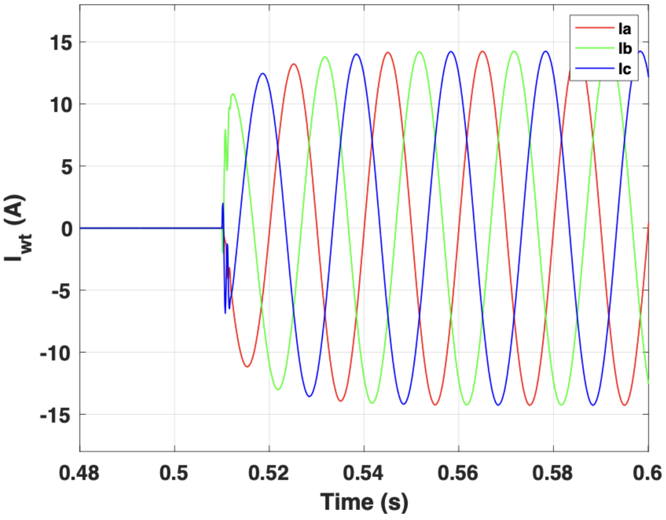

Fig. 6. Currents of WT when the GFM-WT is connected to the grid.

In the future, the proposed technology will be applied to all power electronics grids to ensure overall grid stability.

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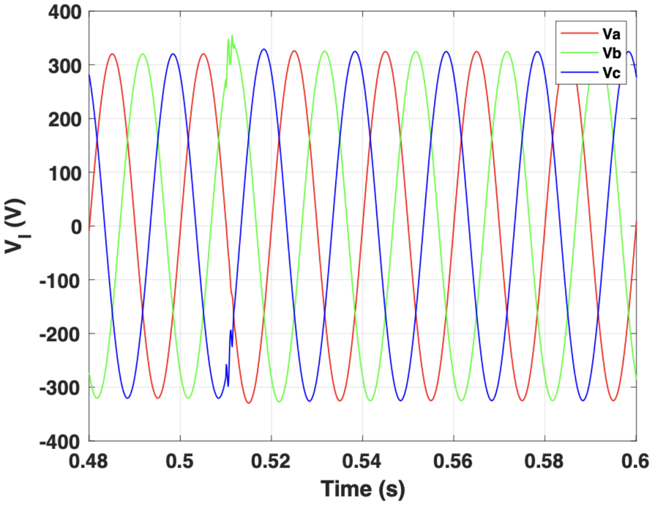

Fig. 7. Microgrid voltage when the GFM-WT is connected to the grid.

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