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Online Inertia Estimation of Droop Control-Based Grid-Forming Inverters in Islanded Microgrid

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Abstract. Inertia estimation of the droop control-based grid-forming (GFM) inverters has not been performed in an islanded microgrid by using an online method with low computational cost. This paper deals with this issue by considering the relationship between the active power-angular frequency droop equation and the conventional swing equation. As a solution, a first-order differential equation in the time domain is extracted from the active power-angular frequency droop equation in the Laplace domain to estimate the inertia constant of the GFM inverter. The simulation results conducted in the MATLAB/SIMULINK environment confirm the accuracy of the proposed inertia estimation method with different angular frequency droop gains as well as under load variation conditions.

Key words. Angular Frequency Droop Gain, Grid-Forming Inverter, Inertia Estimation, Islanded Microgrid

1. Introduction

The inertia of a synchronous generator is defined as the ratio of its kinetic energy to its rated power [1]. Therefore, the inertia of the power system is inherently provided by turbines and generators that store kinetic energy in their rotating part [2]. In recent decades, renewable energy resources, such as photovoltaic and wind systems, have increasingly been integrated into power systems to replace traditional synchronous generators [3]. Power electronic converters enable the electrical communication between these resources and power systems. This means that these converters are responsible for transferring electrical energy from DC or AC resources to the power grid in a suitable and regulated manner. These converters significantly reduce system inertia, as more synchronous generators are substituted, posing a great challenge to maintain system stability [1]. The researchers have shown that frequency droop control, angle droop control, and virtual impedance play important roles in load sharing among these distributed energy resources (DERs) in microgrids and maintaining system stability [4], [5].

To address the problems caused by the low inertia of the grid, accurate inertia estimation is required so that it can be used in applications such as virtual inertia control. Most proposed inertia estimation methods in the literature are offline (post-event) and developed for large interconnected power systems [6]. In these methods, the data of large disturbances in the power system are logged and, after significant signal processing, used to estimate the inertia constant. For instance, the inertia constant has been estimated in [7] by solving the swing equation based on the frequency transient measurements. The authors of [8] have proposed an online identification algorithm for the equivalent inertia of the entire power system by analyzing its dynamic response to a designed micro-perturbation. Since the micro-perturbation signal affects the frequency response of the system, it may lead to operation of protective relays, thus increasing the potential risk of the power system's stability. The same limit also exists for the perturbation needed inertia estimation method proposed in [9]. In [10], the inertia of the synchronous generator has been estimated in the grid-connected mode based on the swing equation. The second-order derivative has appeared in this method. Hence, a proportional-integral (PI) filter has been used instead of the second-order derivative to eliminate the effect of measurement noise, complicating the inertia estimation procedure. Authors in [11] have presented a disturbance-induced inertia estimation method for islanded microgrids comprising DERs with droop control based on choosing proper time intervals for the Rate of Change of Frequency (RoCoF) curve. However, this method computes the power change in response to a disturbance in the system.
This paper focuses on proposing a new inertia estimation method for droop control-based grid-forming (GFM) inverter in an islanded microgrid, in such a way that it does not have the problems of existing methods and can be used online. The inertia of the droop control-based GFM inverter is estimated based on the fact that the droop control method with low-pass filter is equivalent to a virtual synchronous generator (VSG) control method [12],

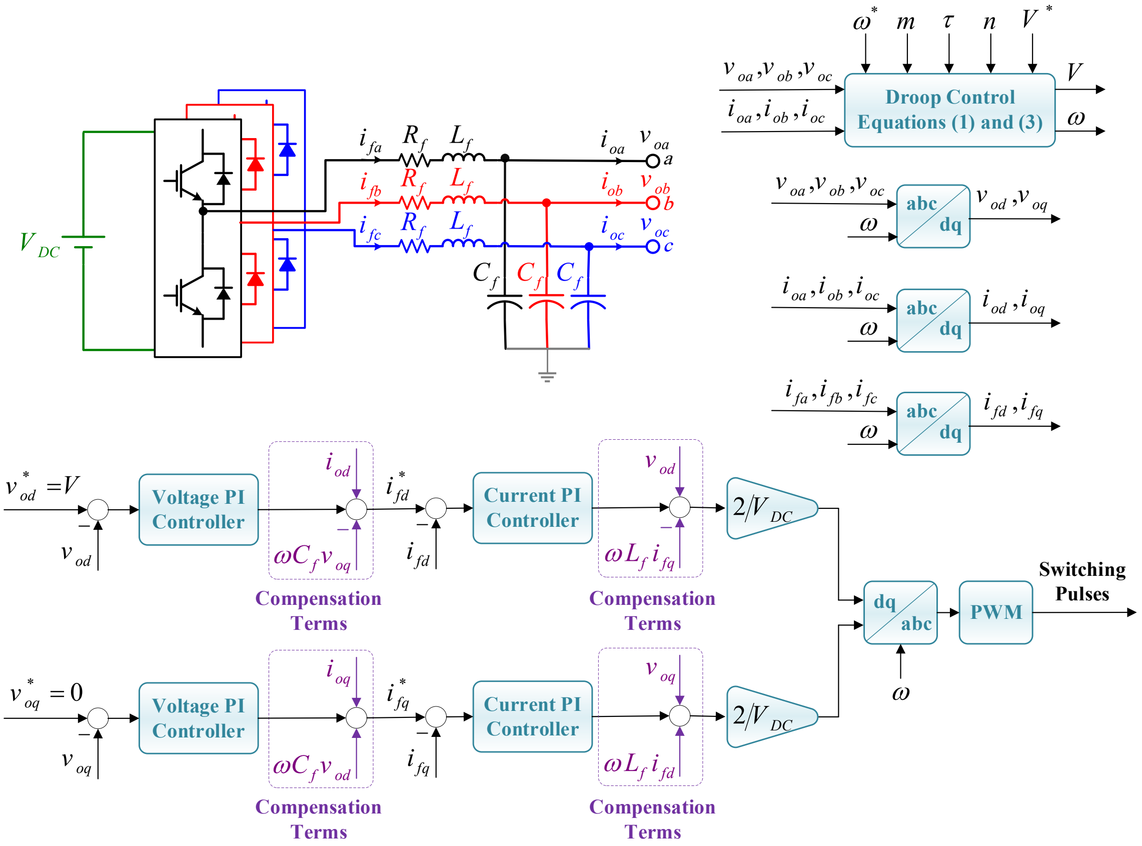


Fig. 1. Schematic diagram of droop control-based GFM inverter.

[13]. It should be mentioned that the proposed inertia estimation method in this paper does not require parameter tuning and complex computation.

In the remaining sections of this paper: the droop control-based GFM inverter is described in Section 2; the proposed online inertia estimation method is explained in Section 3; the simulation results are represented in Section 4, and the conclusion of this paper is drawn in the last Section.

2. Droop Control-Based GFM Inverter

Fig. 1 illustrates the schematic diagram of the droop control-based GFM inverter. The droop control method has been proposed to regulate the voltage amplitude and frequency of islanded microgrids as well as to achieve power sharing in parallel GFM inverters without communication links [12]. The basic idea of this control approach is to imitate the behavior of synchronous generators [14]. The active power-angular frequency ($P-\omega$) droop equation in an islanded microgrid is, as follows:

$$\omega = \omega^* - m\left(\frac{1}{\tau s + 1}\right)p \qquad (1)$$

$$\frac{1}{m}\left(\omega-\omega^*\right)\left(\tau s+1\right) = -p \xrightarrow{\text{time domain}} \frac{\tau}{m}\dot{\omega} = -p - \frac{1}{m}\left(\omega-\omega^*\right) \qquad (2)$$

where, m, ω, ω^*, $\frac{1}{\tau s+1}$, τ, and p are angular frequency droop gain, angular frequency, nominal value of ω, low-pass filter transfer function, time constant of the low-pass filter, and instantaneous active power of the GFM inverter, respectively. Also, the reactive power-voltage amplitude ($Q-V$) droop control equation is presented by the following equation.

$$V = V^* - n\left(\frac{1}{\tau s + 1}\right)q \qquad (3)$$

where, n, V, V^*, and q are voltage amplitude droop gain, voltage amplitude, nominal values of V, and instantaneous reactive power of the GFM inverter, respectively. It should be noted that large values for droop gains improve power sharing accuracy, but increase the deviation of voltage amplitude and frequency from their normal values, resulting in a tradeoff need [5].

3. Proposed Online Inertia Estimation Method

In the time domain, (2) is similar to the conventional swing equation in the VSG control method, as follows:

$$J\dot{\omega} = T_m - T_e \qquad (4)$$

where, T_e, T_m, and J are the electrical torque, mechanical torque, and virtual inertia, respectively. In (4), T_m in the islanded microgrid is equal to:

$$T_m = k_d\left(\omega^* - \omega\right) \qquad (5)$$

where, k_d is the angular frequency droop coefficient. By defining $M = \frac{1}{m}$, (2) in the time domain can be written, as follows:

$$\tau M\dot{\omega} = -p - M\left(\omega - \omega^*\right) \qquad (6)$$

To make (6) compatible with the conventional swing equation (i.e., (4)), which is in terms of torque, both sides of equation (6) are divided by ω^*, as follows:

$$\frac{\tau M}{\omega^*}\dot{\omega} = -\frac{p}{\omega^*} - \frac{M}{\omega^*}\left(\omega - \omega^*\right) \qquad (7)$$

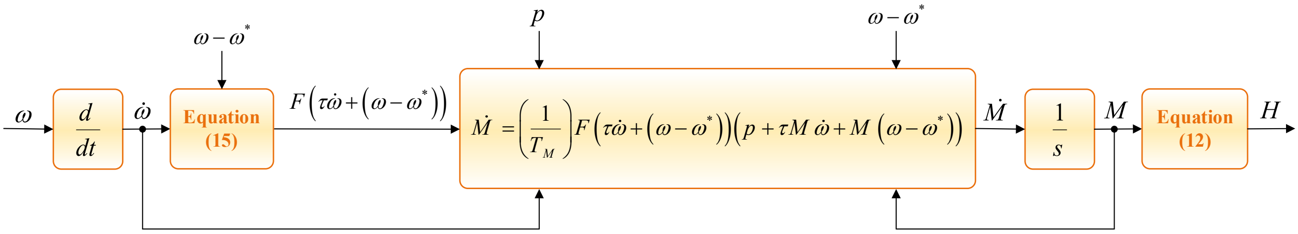


Fig. 2. Block diagram of the proposed online inertia estimation method for the droop control-based GFM inverter.

By comparing (7) with (4), the following equations can be written.

$$T_e = \frac{p}{\omega^*} \tag{8}$$

$$T_m = \frac{M}{\omega^*}\left(\omega^* - \omega\right) \tag{9}$$

$$J = \frac{\tau M}{\omega^*} \tag{10}$$

By comparing (9) with (5), the following equation is obtained.

$$k_d = \frac{M}{\omega^*} \tag{11}$$

According to (10) and the definition of the inertia constant, (12) can be written.

$$H = \frac{\frac{1}{2}J\omega^{*2}}{S_n} = \frac{\frac{1}{2}\tau M\omega^*}{S_n} \tag{12}$$

where, S_n is the rated apparent power of the GFM inverter. After estimating M, the GFM inverter's inertia constant is calculated according to (12).

According to (6), M can be calculated, as follows:

$$M = -\frac{p}{\tau\dot{\omega} + \left(\omega - \omega^*\right)} \tag{13}$$

However, calculating the value of M using equation (13) has numerical calculation problems due to division by the derivative ω. This means that in the inertia estimation process using (13), many spikes can be observed, the filtering of which causes singularity error. Therefore, based on the idea of [10] and using (6), a first-order differential equation is implemented as the following equation to calculate and estimate M:

$$T_M\dot{M} = F\left(\tau\dot{\omega} + \left(\omega - \omega^*\right)\right)\left(p + \tau M\dot{\omega} + M\left(\omega - \omega^*\right)\right) \tag{14}$$

$$F\left(\tau\dot{\omega} + \left(\omega - \omega^*\right)\right) = \begin{cases} -1 & \tau\dot{\omega} + \left(\omega - \omega^*\right) \geq \varepsilon \\ 0 & -\varepsilon < \tau\dot{\omega} + \left(\omega - \omega^*\right) < \varepsilon \\ 1 & \tau\dot{\omega} + \left(\omega - \omega^*\right) \leq -\varepsilon \end{cases} \tag{15}$$

In (14), T_M is the time constant of the rate of change of M, which is considered equal to 0.001 in this paper. The use of the Sign function in (14) is due to the possibility of changing the sign of the derivative of ω. The use of this function results in operation always near the equilibrium point and the estimated value of M using (14) will be equal to the desired value of M. In (15), ε is considered a small deadband to avoid the chattering phenomenon around the equilibrium point. In this paper, ε is taken to be equal to 10^{-6}.

Fig. 2 shows the block diagram of the proposed online inertia estimation method for the droop control-based GFM inverter in the islanded microgrid.

4. Simulation Results

To investigate the efficiency of the proposed online inertia estimation method for the droop control-based GFM inverter in an islanded microgrid, the microgrid under study in [15] consisting of one GFM inverter and three grid-following inverters has been implemented in the MATLAB/SIMULINK software [16]. The single-line diagram of this microgrid is illustrated in Fig. 3. The simulation studies are examined in two cases. In Case I, the angular frequency droop gain is changed. A new local load, next to the GFM inverter, is added to the microgrid and then removed in Case II.

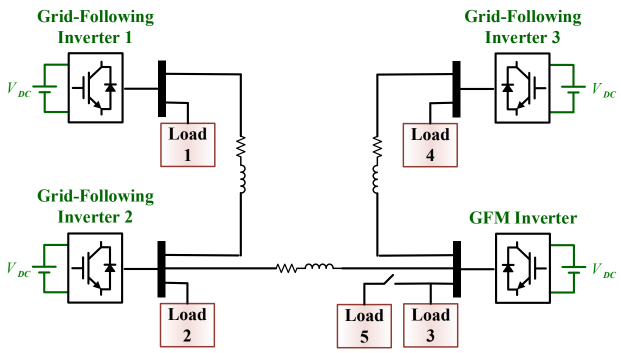


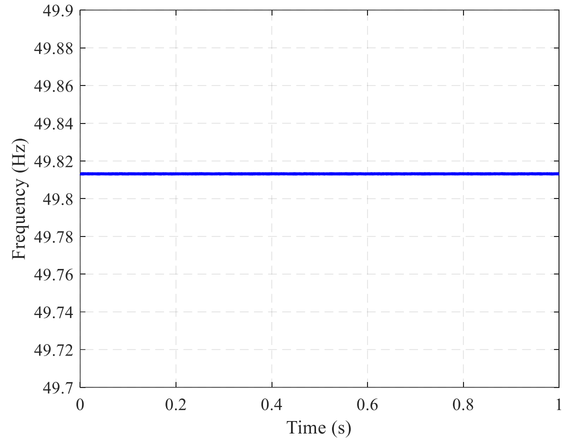
Fig. 3. Schematic diagram of the islanded microgrid under study [15].

A. Case I: Angular Frequency Droop Gain Change

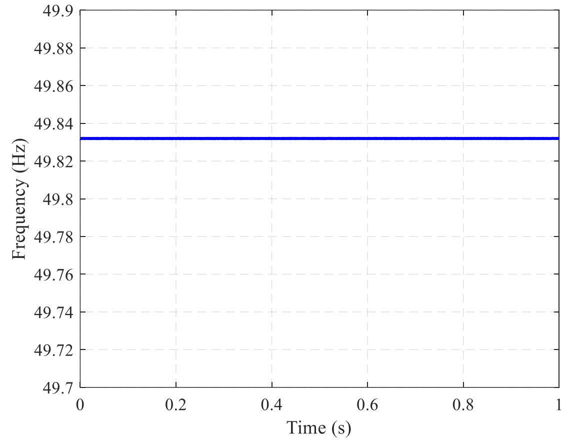
In this case, the angular frequency droop gain is decreased to 0.9 times its initial value given in [15]. The frequency of the microgrid regulated by the $P-\omega$ droop control of the GFM inverter, presented in Fig. 4, shows the effect of decreasing the angular frequency droop gain on the frequency regulation. Since the power demanded by the loads in the microgrid under study has not been changed in this case, the output active power of the droop control-based GFM inverter demonstrated in Fig. 5, has not been changed. Fig. 6 illustrates the change in the estimated inertia constant of the GFM inverter due to the angular frequency droop gain change.

B. Case II: Load Change

In this case, load 5 with active and reactive powers equal to half of the active and reactive powers of the local load 3, is added to the microgrid at t = 1 s, and then, removed at t = 2 s. The purpose of this case study is to examine the behavior of the microgrid when the load enters and leaves (see Figs. 7 and 8). As can be seen in Fig. 9, the load change does not affect the inertia of the droop control-based GFM inverter in general.

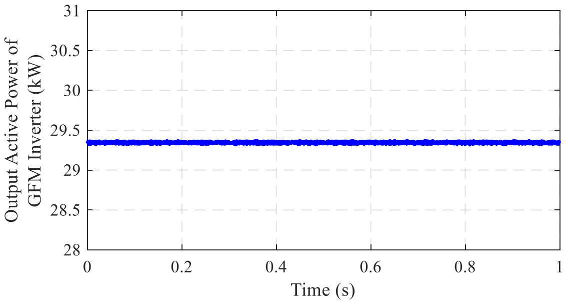


(a)

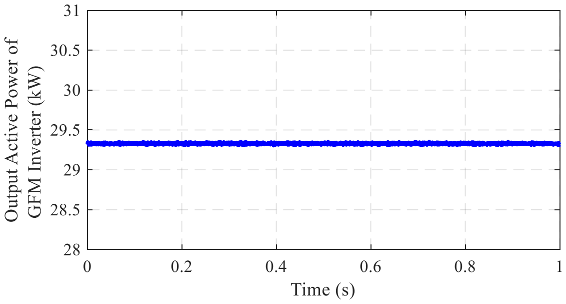


(b)

Fig. 4. Frequency of the microgrid regulated by the $P-\omega$ droop control of the GFM inverter in Case I; (a) considering initial m , and (b) 0.9 m .

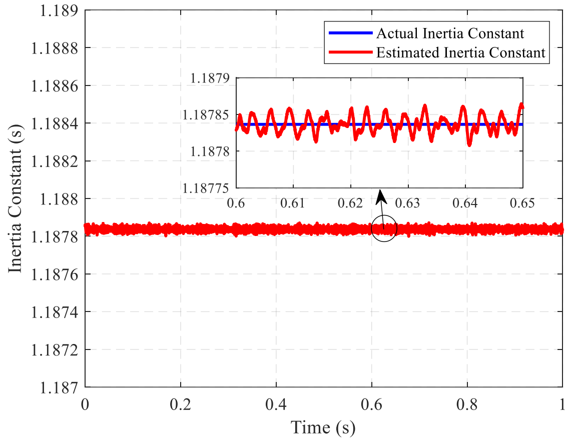


(a)

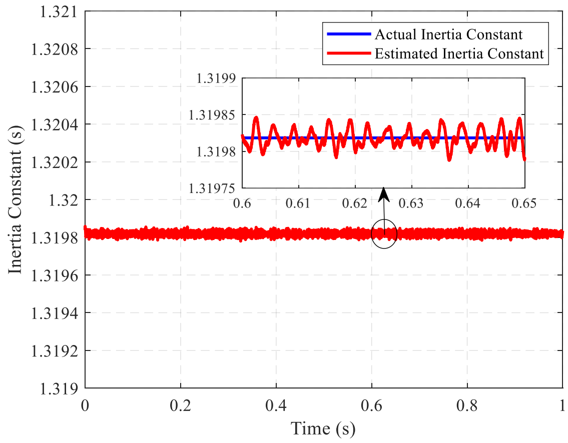


(b)

Fig. 5. Output active power of the GFM inverter in Case I; (a) considering initial m , and (b) 0.9 m .



(a)



(b)

Fig. 6. Estimated inertia constant of the GFM inverter in Case I; (a) considering initial m , and (b) 0.9 m .

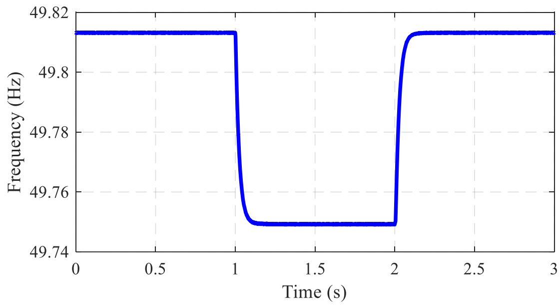


Fig. 7. Frequency of the microgrid regulated by the $P-\omega$ droop control of the GFM inverter in Case II.

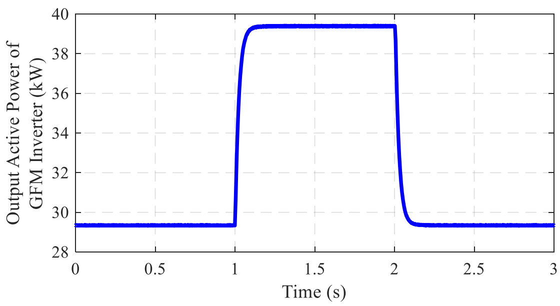


Fig. 8. Output active power of the GFM inverter in Case II.

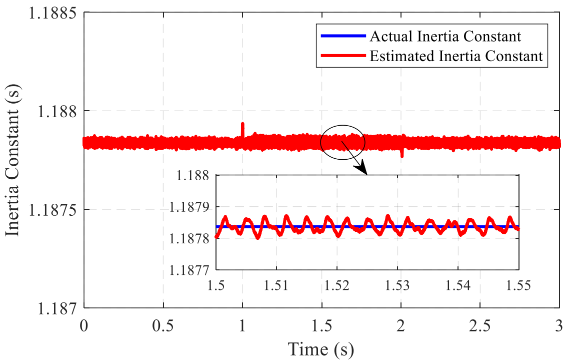


Fig. 9. Estimated inertia constant of the GFM inverter in Case II.

5. Conclusion

In this paper, an online inertia estimation method for the droop control-based GFM inverter in the islanded microgrid was proposed based on the description of the active power-angular frequency droop equation in the form of the conventional swing equation. It should be noted that when the angular frequency droop gain changes, the GFM inverter's inertia constant changes. This fact was verified in the simulation results, which confirms the accuracy of the proposed inertia estimation method. Simulation studies also demonstrated that the estimated inertia constant by the online proposed method does not change with the change of load powers in the islanded microgrid, as expected.

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