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Assessing the critical inertial energy based on a frequency indicator with the inertia reinforcement using grid-forming inverter-based renewables

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ABSTRACT

This paper aims to introduce a method for calculating the critical inertial energy of a power system operator, as well as to analyse the impact of incorporating grid-forming inverter-based renewable energy sources (RESs) on the frequency stability of the power grid. Critical inertial energy is defined as the minimum level of inertial energy needed to keep the power system stable during disturbances. The research employs a dynamic simulation method to assess the critical inertial energy of a reference system and the impact of grid-forming inverter-based sources on frequency stability. The findings indicate that grid-forming technology can mimic synchronous generators regarding the frequency response during contingency scenarios. The technique introduced in this study can serve as an approximation method to calculate the inertial energy requirements for other nations' power systems. The outcomes of this paper could assist in establishing a Net-Zero power grid with a high proportion of grid-forming renewable energy sources.

KEYWORDS Critical inertia; kinetic energy; frequency response; frequency stability; grid forming; inertia constant
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1. Introduction

Frequency is an important factor in maintaining system stability. To ensure the stable operation of the power grid, the system frequency must be kept within a specific range, typically around 60 ± 0.2Hz (Arina et al., 2022). In cases of imbalance between the power supply and demand, the frequency may drop, and recovery can be achieved through frequency regulator operation. However, if the rate of change of frequency (RoCoF) is excessively high, the regulator equipment may struggle to restore it, potentially leading to load shedding or, in severe cases, a blackout. Each country's system operators establish their own requirements for frequency nadir and RoCoF, employing various methods of critical initial energy calculation. This paper examines the method from the Electric Reliability Council of Texas (ERCOT).

Synchronous machines have inertia characteristics that counteract load imbalance and maintain frequency changes within an acceptable range. Conversely, grid-following (GFL) inverter-based connected sources lack a rotating component and cannot provide inertia to the grid. In contrast, a grid-forming (GFM) inverter has the capacity to emulate a synchronous generator by providing inertia to maintain the frequency, with the virtual synchronous machine (VSM) control method and droop control method (Bojana Barać et al., 2021).

This paper analyses the effect of the grid-forming inverter-based connected renewable energy sources on system frequency stability. To conduct this analysis, dynamic simulations were performed using the IEEE 118-bus system as the basis for the study cases. The paper is organised into four sections. Section 1 is the introduction of the article. Section 2 discusses the background of the frequency characteristics and GFM control. Section 3 introduces the benchmarking system used for analysing the critical initial energy. Finally, Section 4 presents the simulation results and analysis.

2. Background

2.1. The frequency characteristics of synchronous generator and power systems

The synchronous generator, characterised by the mass of its rotor, possesses inertia as a fundamental physical attribute. This property is quantified by an inertia constant (H), serving as a measure of the generator's capability to maintain system frequency within a power network. Essentially, the inertia constant indicates the time required for the transmission of stored energy within the rotor to a similarly rated power load. The kinetic energy (Ek) stored within the rotor at synchronous speed can be mathematically expressed as an equation (Arina et al., 2022).

$$E_{\mathrm{k}} = \frac{1}{2} J\omega_{\mathrm{n}}^{2}(\mathrm{s}) , \tag{1}$$

$$H = \frac{1}{2} \frac{J\omega_{\mathrm{n}}^{2}(\mathrm{s})}{S_{\mathrm{n}}} , \tag{2}$$

where E_{k} is the generator's kinetic energy in joules, J(kg-m^2) is the total moment of inertia, ω_{n} is the nominal angular speed of the rotor in rad/s, H is the inertia constant (MWs), and Sn is the rated power (MVA).

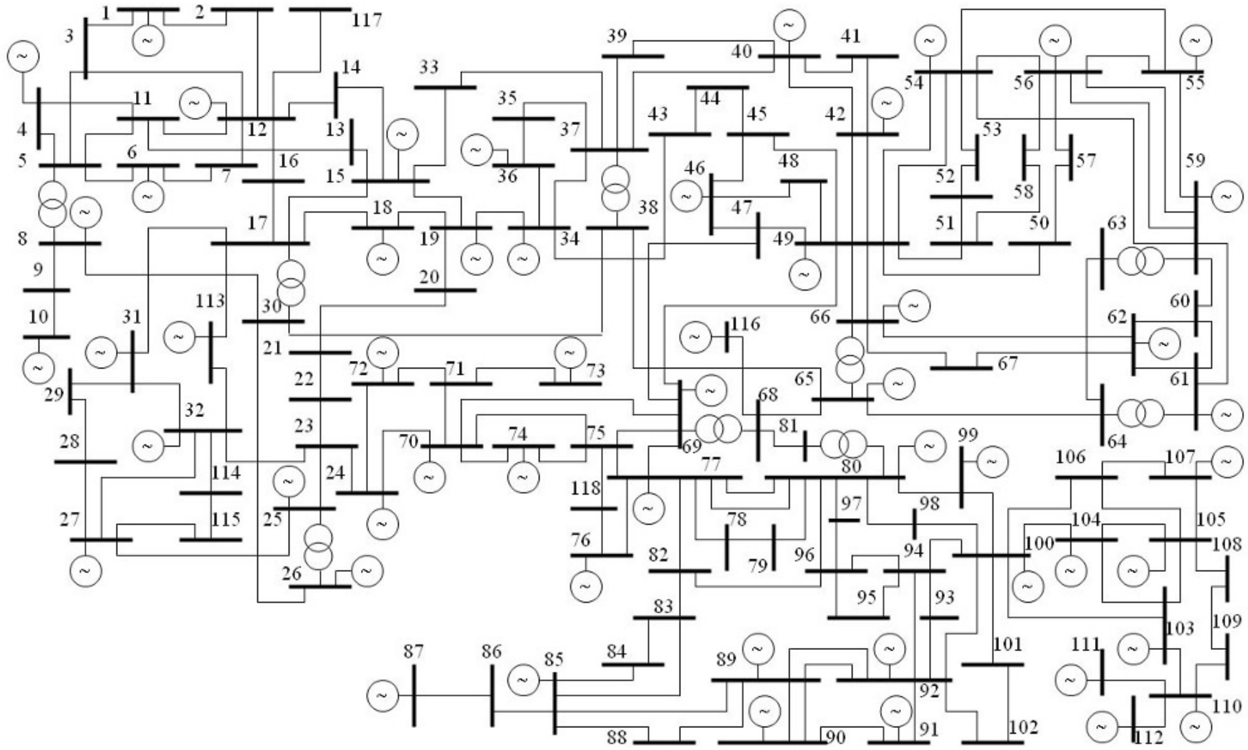

Figure 1. IEEE-118 bus single line diagram (Alexander et al., 2020).

The equivalent inertia constant for the entire system can be calculated as:

$$H_{\mathrm{sys}}=\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} S_{\mathrm{i}} H_{\mathrm{i}}}{\sum_{\mathrm{i}=1}^{\mathrm{n}} S_{\mathrm{i}}}\ \mathrm{s}\,, \tag{3}$$

where H_{sys} is the equivalent inertia constant, H_{i} is the inertia constant of synchronous generator i, and S_{i} is the rated power of generator i.

The synchronous generator's dynamic characteristics can be expressed by the swing equation, which shows the correlation between the imbalance power between mechanical power and electrical power and the frequency deviation:

$$H_{\mathrm{i}}\frac{df_{\mathrm{i}}}{dt}=\frac{f_{\mathrm{n}}^{2}}{2S_{\mathrm{i}}f_{\mathrm{i}}}\ P_{\mathrm{mi}}-P_{\mathrm{ei}}\,, \tag{4}$$

where f_{i} and H_{i} are the frequency and inertia constant of generator i, respectively, f_{n} is the rated frequency of the power system, P_{ei} is the electrical power, and P_{mi} is the mechanical power.

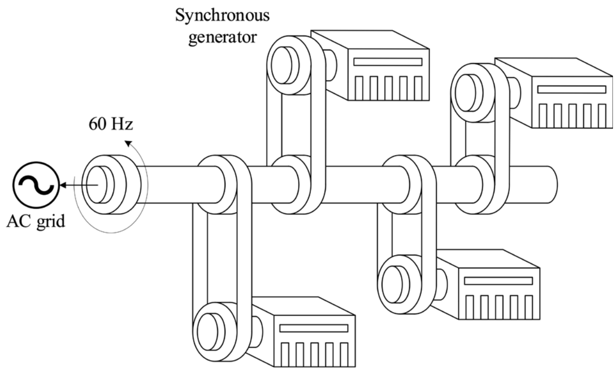

Figure 2. Synchronous generators in the power system.

2.2. GFM control methods

To furnish an inertial response as a synchronous generator, the GFM inverter needs to operate through both droop control and virtual synchronous machine (VSM) control. Droop control is used for power sharing amidst the various generators within the power system.

With the droop relationship between active power and frequency, the droop control can support GFM to generate the power based on the deviation of rotation velocity.

$$\Delta P=P_{GFM}-P^{*}=k_{\mathrm{d\text{-}P}}\cdot\ \omega_{GFM}-\omega^{*}\,, \tag{5}$$

$$\Delta Q=Q_{GFM}-Q^{*}=k_{\mathrm{d\text{-}Q}}\cdot\ v_{GFM}-v^{*}\,, \tag{6}$$

where P_{GFM} and Q_{GFM} are the active power and reactive power calculated from the GFM output, P^* and Q^* are the reference active and reactive power (the active and reactive power of the GFM-connected inverter source when the frequency and voltage of the PCC point is the nominal value), $k_{\text{d-P}}$ is the *P-f* droop coefficient, $k_{\text{d-Q}}$ is the *Q-v* droop coefficient, ω^* and v^* are the reference angular velocity and voltage, respectively, and ω_{GFM} is the angular velocity of the voltage at GFM inverter's PCC point.

The droop control can support frequency stability by fast reacting to power system changes such as load fluctuations or faults. However, GFM with only droop control does not provide inertia to the power system.

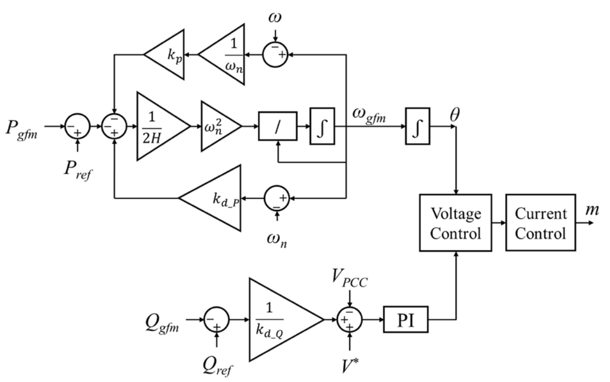

Figure 3. VSM control block diagram (Lim, 2024).

VSM control is based on the swing equation, and with the VSM control, GFM can provide inertia and react to the frequency change the same as the inertia characteristic of a synchronous generator.

$$P_{\text{ref}} - P_{gfm} + \Delta P_{droop} = \frac{2H}{\omega_n^2} \cdot \omega_{gfm} \cdot \frac{d\omega_{gfm}}{dt} + k_p \frac{\omega_{gfm} - \omega}{\omega_n}, \quad (7)$$

where ΔP_{droop} is the different power obtained from the droop equation with the reference angular velocity equal to the nominal value of angular velocity:

$$\Delta P_{\text{droop}} = k_{d\_P} \left(\omega_{gfm} - \omega_n \right), \quad (8)$$

where P_{ref}, Q_{ref} is the reference active power and reactive power, P_{gfm}, Q_{gfm} is the output active power and reactive power of GFM in pu, ω_{gfm} is the angular velocity of GFM, ω_{n} is the nominal value of angular velocity, ω is the measured angular velocity, H is the equivalent inertia constant, k_{p} is the damping term coefficient, and $k_{\text{d\_P}}$ is the *P-f* coefficients. V^* is the voltage reference, V_{PCC} is the voltage measured at the PCC point, and m is the modulation index that will be applied to the PWM.

3. Benchmarking system

In the pursuit of simulating and computing the critical initial energy, this manuscript will employ the IEEE 118-bus system. The IEEE 118-bus system is a portion of the American power system (in the Midwestern US). The test case consists of 118 buses, 19 generators, 91 loads, 177 lines, 35 synchronous condensers, and nine transformers. Figure 5 visualises the single-line diagram of the utilised system.

In this paper, the IEEE 118-bus system will be utilised to simulate the critical inertia calculation method from ERCOT. The information about the generators' power is given in Table 1.

Table 1. Generator of the IEEE 118-bus system.

Zone 1					
Bus	12	25	31	113	26
Rated power [MVA]	100	500	100	100	500
Rated voltage [L-L kV]	138	138	138	138	345
Bus	10				
Rated power [MVA]	500				
Rated Voltage [L-L kV]	345				
Zone 2					
Bus	59	54	49	69	65
Rated power [MVA]	500	100	500	1000	500
Rated voltage [L-L kV]	138	138	138	138	345
Bus	46	61	66	80	
Rated power [MVA]	100	500	500	500	
Rated voltage [L-L kV]	138	138	345	138	
Zone 3					
Bus	87	89	100	103	111
Rated power [MVA]	100	1000	500	100	100
Rated voltage [L-L kV]	161	138	138	138	138

To analyse the contribution of the GFM inverter to the frequency stability, we will replace four synchronous generators in zone 3 with four GFMs and simulate three cases with different amounts of the GFM inverter.

4. Simulation results

4.1. Critical inertia calculation

ERCOT defined the critical inertia as the minimum system inertia that is necessary to ensure that ERCOT's fast frequency response (FFR) resources can be effectively deployed before the frequency drops below 59.3 Hz (the trigger point of under frequency load shedding [UFLS]) (Matevosyan, 2021). The load resources provide responsive reserve service (RRS) in about 25 cycles (approximately 0.416 seconds) after the frequency drops below 59.7 Hz.

A range of dynamic simulations is carried out with support from PSS@E software to identify the time taken by the frequency to decrease from 59.7 Hz to 59.3 Hz.

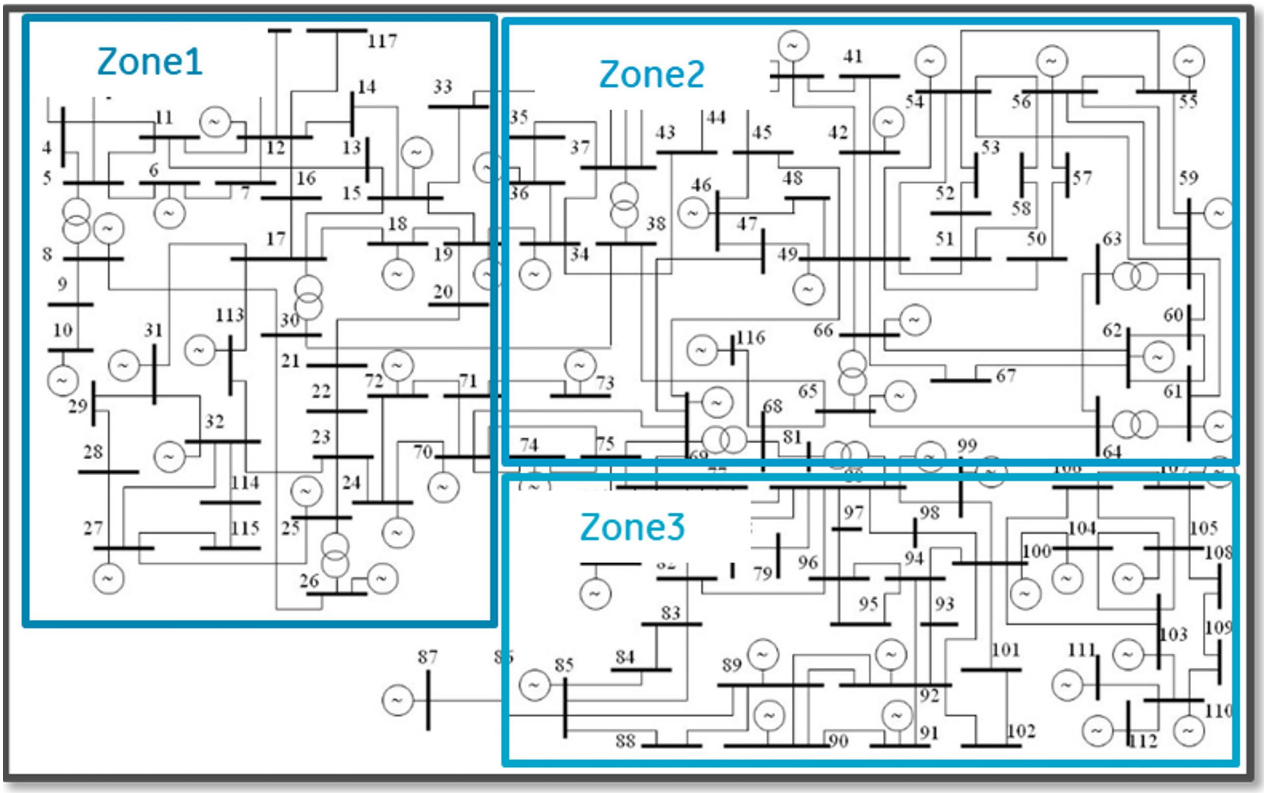

Figure 4. Divided IEEE 118-bus system.

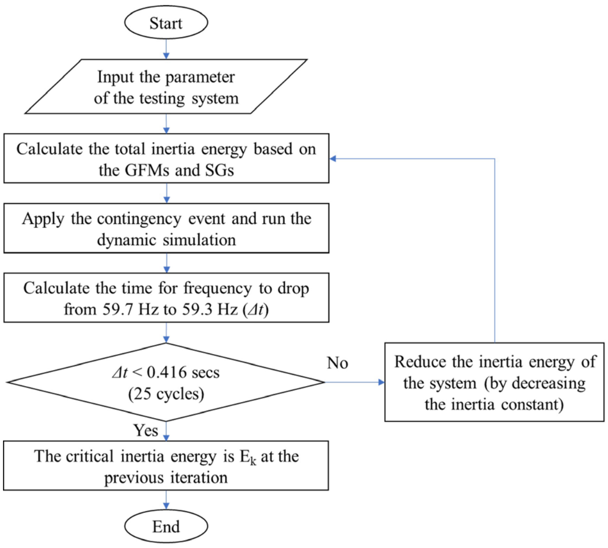

Figure 5. Critical inertial energy calculation flow chart.

In the IEEE 118-bus system, the contingency event of 2382 MW generators is tripped. Then, the inertia constant of the remaining generator is decreased to observe the frequency change and estimate the time needed for the frequency to decrease from 59.7 Hz to 59.3 Hz. Figure 6 and 7 show the results.

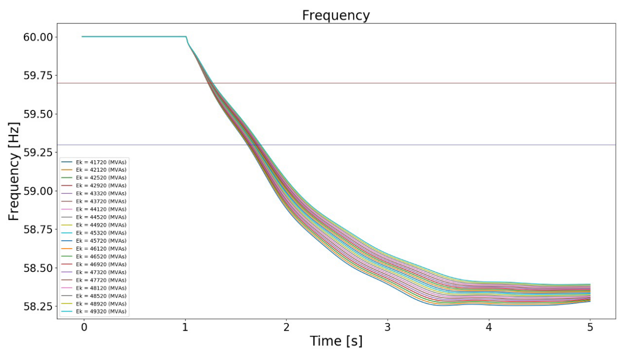

Figure 6. Frequency of the IEEE 118-bus system: After the event happens, the frequency drops to a certain value. Based on the inertial energy, they will have different nadir and dropping velocities.

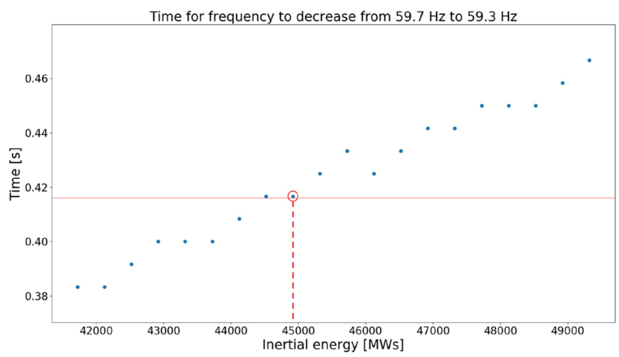

Figure 7. Critical inertial energy calculation.

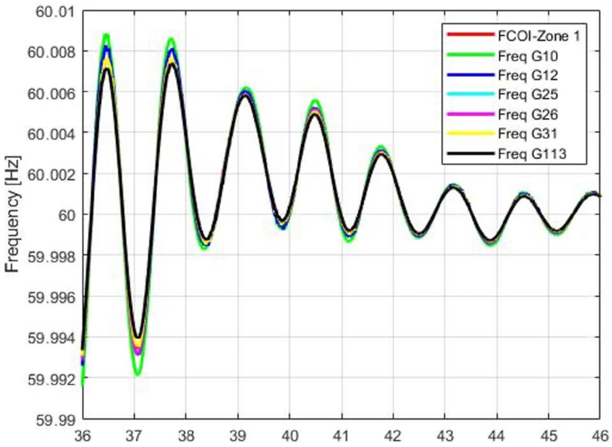

Figure 8. Frequencies in Zone 1: The frequency of the centre of inertia presents the average value of the generators' frequencies when considering the relationship inertia constant of each generator.

Figure 8 shows the relationship between the time when the frequency is 59.7 Hz to when it reaches 59.3 Hz and the inertial energy of the IEEE 118-bus system. The horizontal red continuous line illustrates the minimum time required by the system before the load resources provide a responsive reserve service, then it can be concluded that 45 GWs is the lowest inertia acceptable for the IEEE 118-bus system based on ERCOT's method. The simulation shows a method of critical inertia calculation from ERCOT which can be applied in other systems.

4.2. Replacing synchronous generators with GFM inverters

To evaluate the impact of a GFM inverter-based connected RES, the frequency of centre of inertia (COI) in each area is calculated.

$$f_{\mathrm{COI}} = \frac{\sum_{\mathrm{j=1}}^{\mathrm{m}} f_{\mathrm{j}} H_{\mathrm{j}} n_{\mathrm{j}} \frac{S_{\mathrm{j}}}{S_{\mathrm{base}}}}{\sum_{\mathrm{j=1}}^{\mathrm{m}} H_{\mathrm{j}} n_{\mathrm{j}} \frac{S_{\mathrm{j}}}{S_{\mathrm{base}}}}, \tag{9}$$

where S_{base} is the system power base, f_{COI} is the frequency of COI, f_{j} is the frequency, and H_{j} is the inertia constant of the j^{th} group, respectively. m is the number of generator groups in the coherent area, n_{j} denotes the number of generators within the j^{th} group. S_{j} is the rating of the j^{th} group.

To show the frequency response of the benchmarking system when replacing synchronous generators with GFM inverters, a 3 MW load is connected to bus 102 at 35 seconds and disconnected after 0.1 seconds.

In Figure 8, FCOI-Zone 1 indicates the frequency of COI for Zone 1, while Freq G10 to Freq G113 denote the frequencies of the bus from 10 to 113, respectively. Those buses are the location of the generators in Zone 1.

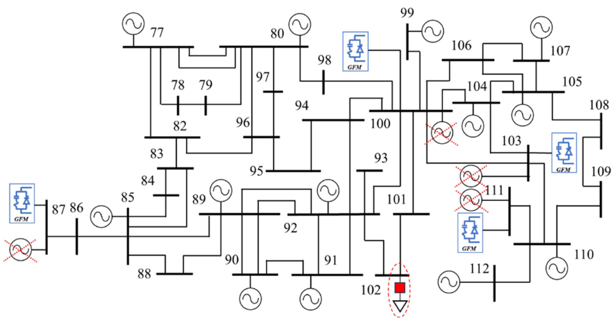

Figure 9. Replacing the synchronous generators with a GFM inverter.

Three cases were applied. Case 1: the event is applied to the conventional 118-bus system. Case 2: the synchronous generator connected to bus 111 is replaced with a GFM inverter with a similar voltage and rated power. For the last case, four generators connected to buses 87, 100, 103, and 111 were replaced with GFM inverters.

The rated voltage and power of the GFM inverters are given in Table 2 below:

Table 2. GFM voltage and power.

	Bus	Rated voltage	Rated power
GFM1	87	161 kV	100 MW
GFM2	103	138 kV	100 MW
GFM3	111	138 kV	100 MW
GFM4	100	138 kV	500 MW

The portion of the GFMs is given in Table 3 below:

Table 3. The portion of GFMs in the case studies.

Case	Number of GFM	Total power of GFM	Portion of GFM
1	0	0	0.00%
2	1	100	7.69%
3	4	800	61.54%

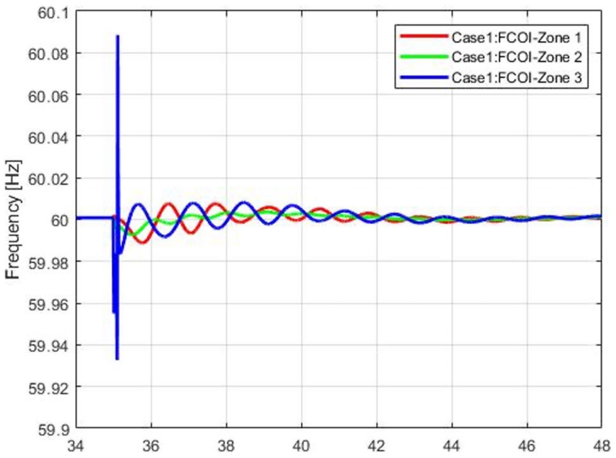

Figure 10. Frequency of COI in case 1: After the event happens, the frequency will undergo deviation. Because of the inertia characteristic of the synchronous generator, the frequency will return to a steady state after a period of fluctuation.

For a more detailed visualisation, the zoomed-in results are shown in Figure 11 to 13 below.

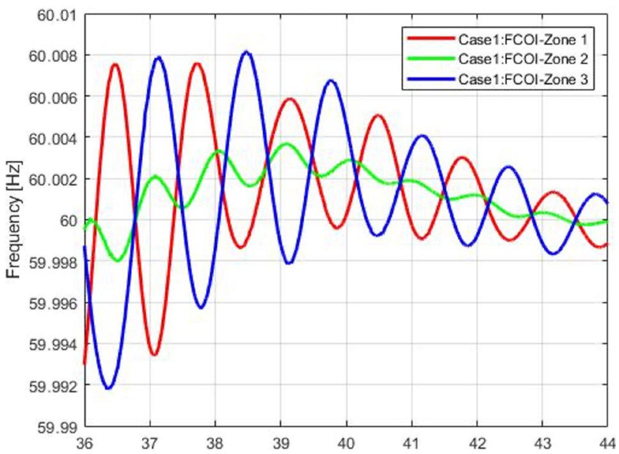

Figure 11. Frequency of COI in case 1: zoom into the recovery period of frequency in case 1.

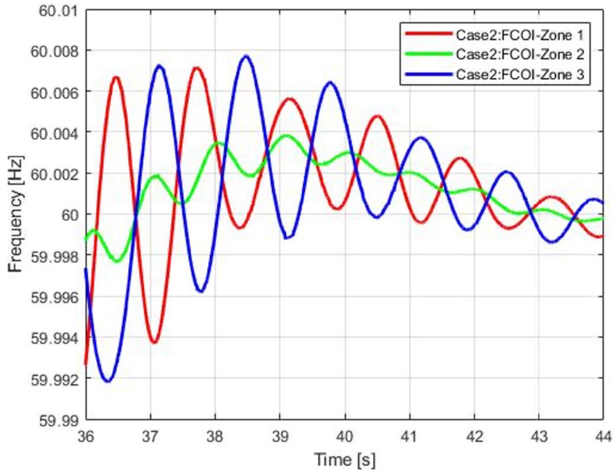

Figure 12. Frequency of COI in case 2: when replacing one generator with one GFM inverter, the tendency of frequency will be almost similar to case 1.

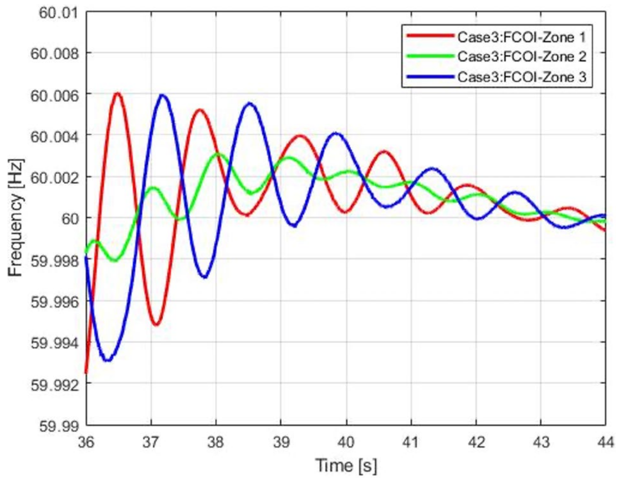

Figure 13. Frequency of COI in case 3: when replacing four generators with four GFM inverters in bus 87, 100, 103, and 111.

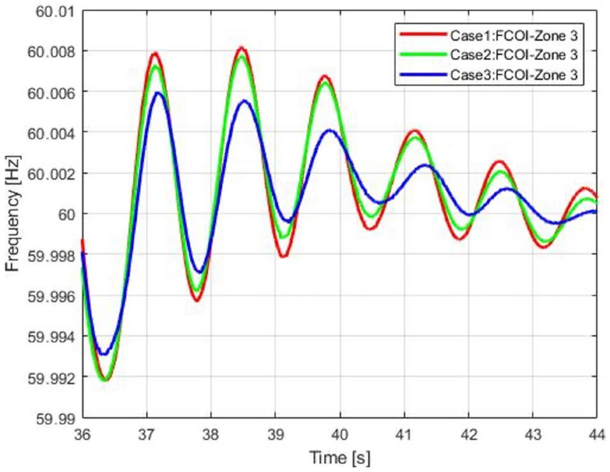

Figure 14. Comparison of the frequencies of COI for Zone 3 in three cases: the peak value of frequency fluctuations and the period to reach the nominal frequency when replacing the synchronous generators by GFMs are approximately similar.

Table 4. Maximum value of frequency of COI.

	Zone 1	Zone 2	Zone 3
Case 1	60.00761	60.00368	60.00817
Case 2	60.00715	60.00384	60.00773
Case 3	60.00605	60.00311	60.00595

The results show that the frequency response is almost similar when replacing synchronous generators with GFM inverters in terms of the frequency deviation and the time needed to reach the steady state after a contingency event. When replacing one generator with one GFM, the peak value of frequency deviation in zone 3 is 0.0129% of the nominal frequency, compared to the conventional case (0.0136%), and when replacing four generators with GFMs, it is 0.0099%. From the results, it can be concluded that GFM inverters can replace synchronous generators to reinforce the system frequency stability and the effect of them does not depend on how many generators were replaced as well as the location of those generators. For future research, it is expected to replace all the generators with the GFM inverters to express that the grid-forming technology can effectively support the inertia in the power system with a high penetration of RES.

4. Conclusion

In summary, this paper has introduced a method for identifying the critical inertial energy of a power system operator and evaluating the impact of grid-forming inverter-based renewable energy sources on frequency stability. The research has shown that grid-forming technology can effectively replace synchronous generators in terms of frequency response during contingencies, leading to greater resilience and stability in the power grid. In addition, the proposed methodology can be globally used in other power systems to estimate their inertial energy requirements. The findings of this study could help facilitate the transition towards a Net-Zero power grid with a significant proportion of renewable energy sources. For future research, it is suggested to apply more grid-forming modules to larger systems and calculate the critical inertia for other countries with varying frequency stability requirements.

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