Outlook

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Dear organizing committee of the Postgraduate Research Colloquium,

I have attached the revised version of the accepted manuscript in Word and PDF files. Please note that registration with payment has been completed.

Kind Regards,
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5 November 2024

Dear Mr Yiizzan Suffian,

Thank you for submitting a manuscript to 1st Konsortium Universiti Universitas Borneo (KUUB) Postgraduate by Research Colloquium 2024 to be held in Miri, Sarawak, Malaysia from 3 – 5 December 2024.

RE: Integrated Control of Grid-Forming and Following in Low-Inertia Environments

Paper ID number: KUUB2024 - 0035

We are pleased to inform you that your manuscript has been accepted for an oral presentation. For your perusal, the reviewers' reports are also enclosed. Your abstract will be included in our book of abstract and your manuscript will be published in our conference proceeding. Therefore, please do make necessary amendments (if there are any from the reviewers), and get back to us with the revised manuscript by 10 November 2024.

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On behalf of the 1st Konsortium Universiti Universitas Borneo (KUUB) Postgraduate by Research Colloquium 2024 Organising Committee, we would like to thank you for your active participation in our conference and look forward to seeing you in Miri.

Warmest regards,

Professor Agus Saptoro
Organising Committee Chairman

Integrated Control of Grid-Forming and Grid-Following in Low-Inertia Environments

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Abstract. The growing integration of inverter-based resources (IBRs) such as solar photovoltaic (PV) systems and energy storage systems (ESS) is changing the dynamics of modern power grids. As renewable energy resources (RERs), such as solar PV systems, become more widespread, traditional power grids with mechanical inertia are being replaced, leading to significant challenges in maintaining grid stability due to reduced inertia. Despite various research on integrating microgrid technologies, there is still a lack of studies that look at the grid performance during a disturbance in a weak grid environment. To address such challenges, this paper proposes a hybrid technique that integrates grid-forming (GFM) and grid-following (GFL) inverter control within solar-powered microgrid systems in grid-connected and islanded modes. The proposed approach allows the inverter-based islanded microgrid to operate effectively during the absence of support from the utility grid. Thereby stabilizing frequency and voltage under disturbances even during low-inertia conditions. Simulation studies have been carried out to evaluate the capability of the integrated GFM and GFL in maintaining grid performance and enhancing the system during different conditions. The results highlight the potential of the hybrid GFM-GFL control system in reducing frequency deviations and voltage fluctuation.

1. Introduction

The grid-integrated systems evolved towards the interest in renewable generation, particularly solar power, which has become a significant player in global electricity generation due to its sustainability and abundance. However, such renewable resources introduce additional complexity and significant challenges in maintaining voltage and frequency stability due to the reduction of mechanical inertia [1], [2]. Therefore, the growing importance of smart grids underscores the need for advanced control strategies that allow prosumers to participate in real-time energy management including the balance of supply and demand. In this regard, efficient inverter control algorithms are essential for managing IBRs, ensuring consistent and reliable energy exchange between microgrids. Inverter-based microgrid systems differ fundamentally from traditional synchronous generators, which provide rotational inertia. Without this inertia, microgrids powered by solar PV systems become more vulnerable to frequency deviations during disturbances. It has been proven [1] – [4] that the emergence of GFM and GFL inverters is crucial for maintaining grid-integrated stability. GFM inverters emulate the behavior of traditional generators, allowing them to operate independently and provide fast frequency response and voltage regulation, especially in off-grid or weak-grid scenarios. On the other hand, GFL inverters are used to synchronize with the power grid via a phase-locked loop (PLL). Various control techniques have been proposed to improve the system stability and reliability of microgrids considering the impact of high penetration of renewable generation. Some of them focused on energy management of hybrid renewable systems using fuzzy logic [5] and Artificial intelligence [6]. The smooth switching control strategy developed in [2] for photovoltaic grid-connected converters considers high renewable energy penetration. The authors in [7] investigated the challenges associated with the intermittent nature of solar PV generation and the lack of inertia that can cause frequent and wide fluctuations in system strength, posing operational and technical challenges. Power generation or demand changes can lead to frequency and voltage fluctuations that the grid infrastructure may struggle to manage, especially in low-inertia scenarios and high renewable energy integration. The energy router concept based on the fuzzy approach proposed in [8] can make PV sets reliable for power grid support using efficient decentralized energy management. Although numerous studies were carried out toward developing control strategies for GFM and GFL, the adaptability of these techniques, particularly in addressing the dynamic nature of renewable energy generation, has not been fully developed. There remains a gap in the seamless integration of energy storage, inverter control, and uncertain or real-time nature of RERs in low-inertia environment. Addressing this gap is crucial for ensuring reliable and efficient grid performance in the evolving energy landscape. Accordingly, this paper proposes a hybrid control strategy that leverages the benefits of both GFM and GFL inverters in maintaining the quality and reliability of the grid performance, even during low inertia conditions.

2. Dynamic framework of integrated inverter-based resources

The voltage sourced converters are usually used with isolated transformers to integrate renewable generation into the power grid. Regarding the control approach, three types of power converters are used to connect distributed generation units. In the first type phase angle and current are controlled while in the second type the frequency and voltage magnitude are controlled. The third type is the grid supporting inverter in which active and reactive power is controlled [8]. The GFM microgrid operates in off-grid mode, functioning independently without support from the utility grid, whereas the GFL microgrid remains connected to the utility grid, as its control approach relies on grid stability for maintaining frequency and voltage. The analysis of the simultaneous operation of two microgrids GFM and GFL is well documented in the literature. Generally, the GFM inverter control shows the ability to stabilize the microgrid independently in off-grid scenarios, making it operate sustainably identical to the operation of a microgrid in grid-connected mode when using GFL inverter control. The structure of an inverter-based grid-connected microgrid typically consists of solar PV, ESS, and inverters as shown in Fig. 1. The following subsection briefly discusses microgrid operation in different schemes, mainly GFM (off-grid), GFL (grid-connected), and hybrid GFM-GFL.

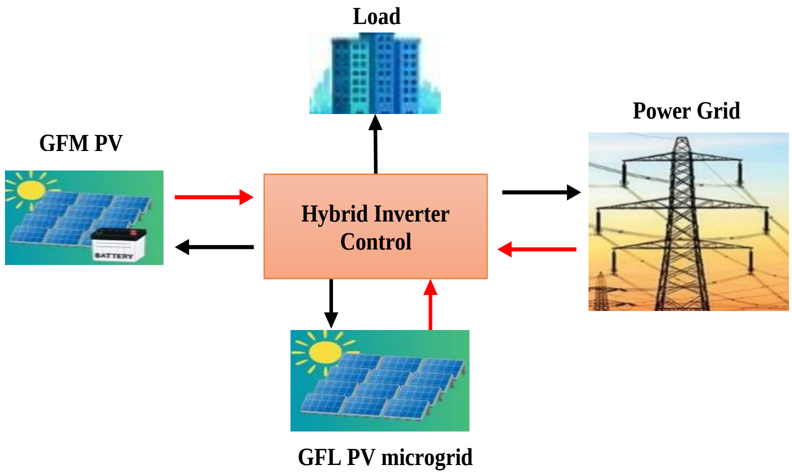

Figure 1: Structure of hybrid GFM-GFL for integrated inverter-based resources

2.1. *Microgrid operation based on hybrid GFM-GFL*

This study enhances the operation of inverter-based resources (Fig. 1) for GFL and GFM systems in grid-connected and islanded modes. Traditional control strategies, as outlined in subsections (2.2 and 2.3), are applied to assess their effectiveness under different operational conditions. Further, the integrated control of grid-forming and grid-following (GFM-GFL) in low-inertia environments is proposed to improve the system performance mainly during disturbances. With this aim, the hybrid control of GFM-GFL is introduced to allow the GFL microgrid to rely on the GFM microgrid as a source of the reference parameters such as the traditional utility grid during off-grid mode. The proposed approach has been investigated to ensure that the power balance in Eq. (1) can be maintained during steady and unsteady state circumstances, which is a benchmark to measure the proposed scheme's robustness. $P_{Grid}(t)$ represents the power from the utility grid at time (t). $P_{RER}(t)$ is the generated power from renewables such as solar PV and $P_{ESS}(t)$ is the power from energy storage.

$$P_{Grid}(t) + P_{RER}(t) + P_{ESS}(t) = P_{Load}(t) + P_{Loss}(t) \tag{1}$$

2.2. *Grid-forming architecture*

GFM inverters emulate the behavior of synchronous generators, providing frequency and voltage support. Fig. 2 illustrates the microgrid structure with grid-forming based on the droop control mechanism. The most common GFM control method is droop control in which the inverter regulates frequency and voltage based on the change in power imbalances. Droop control allows GFM inverters to operate autonomously in off-grid or weak-grid conditions by mimicking the behavior of conventional synchronous generators. It adjusts system frequency and voltage in response to changes in active and reactive power, as shown in Eqs. (2) and (3) [7], [9]. In these equations, ω and ω^* represent the actual and nominal frequencies, while V_i *and* V_i^* represent actual and nominal voltages. The control is further influenced by the system's active and reactive power outputs, P_i and Q_i.

$$\omega = \omega^* - m_i\,(P_i - P_i^*) \tag{2}$$

$$V_i = V_i^* - n_i\,(Q_i - Q_i^*) \tag{3}$$

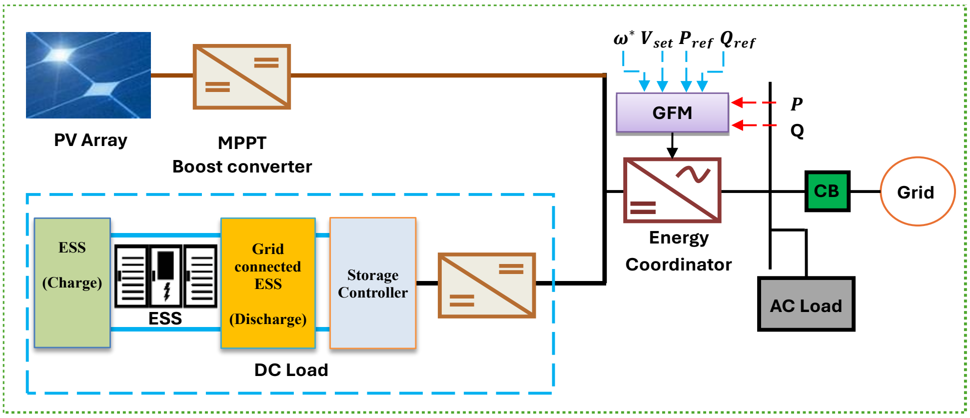

Figure 2: Microgrid structure with grid-forming

2.3. *Grid-following architecture*

GFL inverters operate differently from generator control and GFM inverters, they normally rely on PLL to detect the grid voltage angle and adjust the phase shift of inverter currents to deliver the desired active and reactive power [10]. This ensures that the inverter can follow the grid's frequency and voltage in grid-connected scenarios. In this sense, the current vector control (CVC) is a key strategy for PV inverters, managing current and frequency [2]. This technique uses the PQ control for the outer loop to regulate the active and reactive power injected into the grid as depicted in Fig. 3 [3], [11], [12]. The measured voltage and frequency of the grid side are fed as inputs to the GFL-based inverter control algorithm. The active and reactive power control can be expressed by Eqs. (4) – (7) [2], [11].

$$P = P_{ref} + k\,(\omega_0 - \omega) \tag{4}$$

$$Q = Q_{ref} + k\,(V_0 - V_{Grid}) \tag{5}$$

$$i_{dref} = \frac{P}{V_{Grid}} \tag{6}$$

$$i_{qref} = \frac{Q}{V_{Grid}} \tag{7}$$

where, k is the droop coefficient of the GFL controller, P_{ref} and Q_{ref} are the reference active and reactive power, representing the reserve operating point, ω_0 and ω are the angular nominal and actual frequencies, V_0 and V_{Grid} are the nominal and actual voltage values measured at the point of common coupling (PCC). P and Q are active and reactive power references formed by the CVC, i_{dref} and i_{qref} are the output currents to be injected into the inner current loop [1], [3], [7].

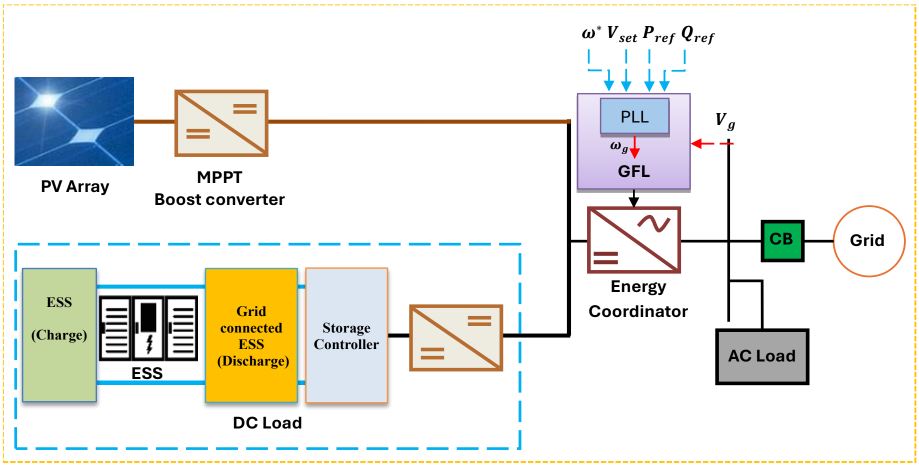

Figure 3: Microgrid structure with grid-following

2.4. Hybrid GFM-GFL architecture

In the hybrid GFM-GFL configuration, the microgrid operates independently without relying on the utility grid's mechanical inertia. This hybrid approach leverages the strengths of both GFM and Grid-Following (GFL) inverters. Here, the GFM inverter control in a microgrid regulates frequency and voltage autonomously in off-grid mode, ensuring stability during islanding mode as mentioned in subsection 2.2. The GFL inverter, which depends on the grid for stability, operates efficiently in grid-connected mode but struggles when islanded. In the hybrid GFM-GFL, the GFM control method remains the same. However, the GFL control technique is modified as in the set of equations presented in Eqs. (8) – (11) to follow the pre-disturbance reference parameters of GFM rather than the parameters of GFL control, that can be obtained from the power grid. The hybrid design provides reliable microgrid operation in the islanding mode, making the system resilient to outages and grid instability.

$$P_{GFL} = P^*_{GFL} + k\,(\omega_0 - \omega_{GFM}) \tag{8}$$

$$Q_{GFL} = Q^*_{GFL} + k\,(V_0 - V_{GFM}) \tag{9}$$

$$i_{dref} = \frac{P_{GFL}}{V_{GFM}} \tag{10}$$

$$i_{qref} = \frac{Q_{GFL}}{V_{GFM}} \tag{11}$$

3. Results and discussion

The microgrid was evaluated during steady state and load disturbance to analyze the behaviors of GFM and GFL inverter capabilities and demonstrate the effectiveness of the hybrid GFM-GFL scheme. Fig. 4a shows that GFM converter control can regulate frequency around 50Hz independently without relying on the utility grid. In addition, the voltage profile shown in Fig. 4b indicates that GFM and GFL microgrid keep the voltage stable (around 240V) with minimal deviation even under off-grid mode. Further, to observe how the control of microgrids respond during abnormal conditions, load disturbance was introduced by adding and removing 50kW at 6s and 8s respectively. The reaction of GFM and GFL control under sudden load disturbances is depicted in Fig. 4c and Fig. 4d. As seen in Fig. 4c, the GFM inverter control can maintain a stable frequency (around 50Hz) without grid support. Likewise, the voltage profile in Fig. 4d shows that both GFM and GFL maintain voltage in the range of 240V with minimal deviation. This reveals that GFM can maintain a steady voltage even under off-grid mode, highlighting a robust performance autonomously.

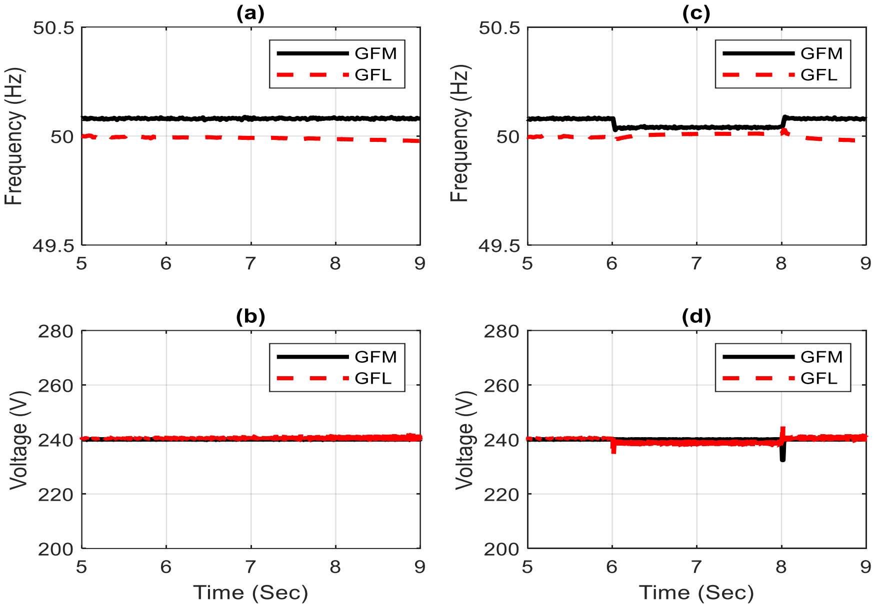

Figure 4: Microgrids operation during (a & b) Steady state; (c & d) Disturbances

Fig. 5a and Fig. 5b present the results of the hybrid GFM-GFL control under two scenarios. At 2-Sec, a 50-kW load was injected into the microgrid and then removed at 3-Sec. The results demonstrate that the GFM inverter quickly stabilized both frequency and voltage, despite the abrupt load changes, highlighting its effectiveness in maintaining system stability. During such disturbances, the GFM microgrid supports the GFL microgrid, ensuring system resilience and maintaining voltage and frequency with acceptable levels across the hybrid system without grid support.

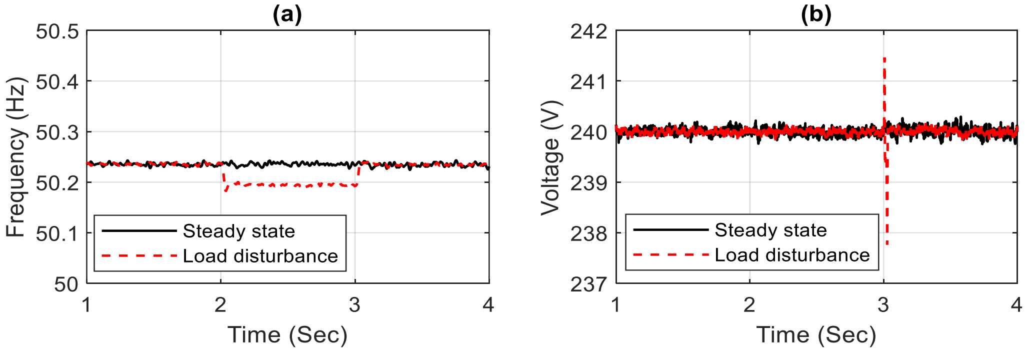

Figure 5: Hybrid GFM-GFL performance (a) Frequency; (b) Voltage

4. Conclusions

This paper has analyzed the performance of microgrids with GFM, GFL and hybrid GFM-GFL under both steady-state conditions, and load disturbances. The GFM control technique, even in off-grid mode, demonstrated its ability to independently regulate frequency and maintain voltage stability comparable to the GFL microgrid, which relies on utility grid support. Both systems maintained a stable frequency and voltage (around 50 Hz and 240 V), indicating effective control strategies for each microgrid control scheme. The hybrid GFM-GFL configuration demonstrated the ability to limit frequency deviations to within 5% and voltage fluctuations to just 0.63% during load disturbances, even without utility grid support. Future research will explore real-time energy management solutions and the integration of intelligent control mechanisms in microgrids, leveraging cloud computing to manage the variability and uncertainty inherent in renewable energy generation. This approach aims to enhance decision-making capabilities and improve system resilience in dynamically changing grid environments.

Acknowledgements

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