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Islanding Performance and Harmonic Analysis of Grid-Forming and Grid-Following PV–BESS Systems

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Abstract: The rapid integration of inverter-based renewable energy sources has significantly altered the dynamic behaviour of modern power systems, particularly under low-inertia and weak grid conditions. Conventional grid-following inverters rely on phase-locked loop–based synchronisation and are inherently dependent on the presence of a strong grid, which limits their ability to operate during grid outage events. In contrast, grid-forming inverters are capable of autonomously establishing voltage and frequency, enabling stable islanded operation when supported by battery energy storage systems.

This paper presents a comparative investigation of grid-forming and grid-following control strategies for a solar photovoltaic system integrated with battery energy storage under grid outage conditions. A detailed simulation model is developed using an identical system configuration for both control approaches, ensuring a fair and consistent comparison. The analysis focuses on voltage and frequency regulation, active and reactive power behaviour, and harmonic performance during the transition from grid-connected to islanded operation.

Simulation results demonstrate that the grid-following system experiences loss of synchronisation and degraded power quality following grid disconnection, whereas the grid-forming system maintains stable voltage and frequency with seamless islanded operation. Furthermore, the grid-forming control exhibits reduced voltage and current total harmonic distortion compared to the grid-following approach. These findings highlight the effectiveness of battery-supported grid-forming control in enhancing system stability and power quality during grid outage events in renewable-dominated power systems.

I. INTRODUCTION

The increasing penetration of solar photovoltaic (PV) generation and other inverter-based resources has fundamentally transformed the operational characteristics of modern power systems. Conventional power systems were dominated by synchronous generators that inherently provided inertia, voltage stiffness, and frequency regulation. In contrast, inverter-interfaced renewable sources contribute little or no physical inertia, leading to increased sensitivity of the grid to disturbances such as load variations, renewable intermittency, and grid outages [1], [2]. These challenges are particularly pronounced in distribution networks and weak grids, where the short-circuit ratio is low and voltage–frequency coupling is significant.

At present, most grid-connected PV systems employ grid-following inverter control strategies. In grid-following operation, the inverter synchronises with the grid using a phase-locked loop (PLL) and injects current based on externally imposed voltage and frequency references. While this approach is effective under strong grid conditions, it exhibits fundamental limitations during abnormal operating events. In particular, during grid outage or islanding conditions, the loss of a stable voltage reference causes the PLL to lose synchronisation, resulting in degraded power quality, instability, or inverter tripping [3], [4]. As power systems move towards higher shares of inverter-based generation, these limitations raise serious concerns regarding system reliability and resilience.

Grid-forming inverters have emerged as a promising alternative to address these challenges. Unlike grid-following inverters, grid-forming inverters operate as controlled voltage sources capable of autonomously establishing voltage magnitude and frequency. By emulating the dynamic behaviour of synchronous generators through techniques such as virtual synchronous machine (VSM) concepts, grid-forming inverters can provide synthetic inertia, fast frequency support, and voltage regulation even in the absence of a strong grid [5], [6]. When combined with battery energy storage systems (BESS), grid-forming control enables seamless transition between grid-connected and islanded operation, thereby enhancing system stability during grid outages.

Recent research has investigated various aspects of grid-forming control, including stability under weak grid conditions, interaction among multiple inverters, and power sharing in microgrids [6]–[8]. However, a focused comparative assessment of grid-forming and grid-following control strategies during grid outage events remains limited, particularly for utility-scale PV–BESS systems. Moreover, while several studies address voltage and frequency stability, the impact of control strategy on harmonic performance during islanded operation has received relatively less attention. Harmonic distortion becomes critical during grid outages, as sensitive loads remain connected and the inverter effectively becomes the sole voltage source [9].

In this context, this paper presents a detailed comparative study of grid-forming and grid-following control strategies for a solar PV system integrated with battery energy storage during grid outage conditions. A unified simulation framework is developed in which both control strategies are implemented on an identical system configuration, ensuring a fair and consistent comparison. The analysis focuses on voltage and frequency regulation, active and reactive power response, and total harmonic distortion (THD) during the transition from grid-connected to islanded operation. The results clearly demonstrate the superior performance of grid-forming control in maintaining system stability and power quality during grid outage events, highlighting its relevance for future low-inertia power systems.

II.RELATED WORK

The transition from synchronous machine–dominated power systems to inverter-dominated networks has motivated extensive research on advanced inverter control strategies. Early studies primarily focused on improving the performance of grid-following inverters, as this control paradigm has been widely adopted in commercial photovoltaic and wind energy systems. Grid-following inverters operate as controlled current sources and rely on phase-locked loop–based synchronisation to track grid voltage and frequency. While this approach ensures accurate power injection under strong grid conditions, several studies have reported degraded stability and loss of synchronisation when operating in weak grids or during grid disturbances [10], [11].

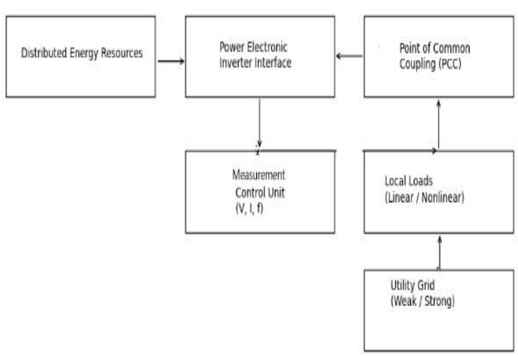

Figure 1. Overall system architecture of the inverter-based microgrid under study

The limitations of grid-following control during islanding and grid outage conditions have been highlighted in multiple works. It has been shown that the absence of a stiff voltage reference during grid disconnection leads to PLL instability, resulting in distorted current injection, increased harmonic content, and eventual inverter tripping [12]. These challenges are further aggravated when multiple grid-following inverters operate in parallel, as control interactions and reference misalignment may lead to oscillatory behaviour and poor power sharing [13]. Consequently, grid-following inverters are generally unsuitable for autonomous islanded operation without additional supervisory control or grid-forming support.

To address these challenges, grid-forming inverter control strategies have gained significant attention in recent years. Grid-forming inverters are designed to behave as voltage sources that can establish voltage magnitude and frequency independently of the grid. Various grid-forming approaches have been proposed, including virtual synchronous machine (VSM) control, synchronverter concepts, and matching control techniques [8], [14]. Among these, VSM-based methods are particularly attractive as they emulate the inertial and damping characteristics of synchronous generators, thereby providing synthetic inertia and improved frequency response in low-inertia systems.

Several studies have demonstrated the effectiveness of grid-forming control in improving system stability under weak grid conditions and during transient events. The ability of grid-forming inverters to maintain synchronism, regulate voltage, and share load proportionally in islanded microgrids has been reported in [6], [7]. Furthermore, the integration of battery energy storage with grid-forming inverters has been shown to enhance transient performance by enabling rapid active power support during frequency deviations and voltage disturbances [15]. These features make grid-forming PV–BESS systems well suited for applications requiring seamless transition between grid-connected and islanded operation.

Despite these advances, comparatively fewer works have focused on the harmonic performance of grid-forming and grid-following inverters during grid outage conditions. While some studies have analysed harmonic distortion under grid-connected operation, the impact of control strategy on voltage and current total harmonic distortion during islanded operation remains insufficiently explored [16]. In particular, the role of PLL dynamics in contributing to harmonic distortion during loss of grid reference has not been adequately quantified in existing literature.

Based on the above review, it is evident that although grid-forming control has been widely recognised for its advantages in voltage and frequency regulation, a focused comparative assessment of grid-forming and grid-following control during grid outage events, with explicit consideration of harmonic performance, is still lacking. This gap motivates the present work, which systematically evaluates the dynamic and harmonic behaviour of a PV–BESS system under grid outage conditions using both control strategies within a unified simulation framework.

III.SYSTEM DESCRIPTION AND CONTROL STRATEGY

3.1 PV–BESS System Configuration

The system under study consists of a utility-scale solar photovoltaic plant integrated with a battery energy storage system and connected to a medium-voltage distribution network. The PV array is interfaced to the AC system through a DC–DC conversion stage followed by a voltage source inverter. A battery energy storage system is connected to the same AC bus via a bidirectional inverter, enabling both active and reactive power exchange with the grid. The PV and battery inverters share a common point of interconnection (POI), from which the system is connected to the upstream transmission network through a distribution feeder and step-up transformers.

The network is intentionally configured to represent weak grid conditions, characterised by a low short-circuit ratio at the POI. This configuration allows the dynamic differences between grid-following and grid-forming control strategies to be clearly observed during grid outage events. All simulations are performed using identical electrical parameters, inverter ratings, and network topology for both control strategies, ensuring that observed performance differences arise solely from the control philosophy rather than from structural variations in the system [17].

3.2 Grid-Following Control Strategy

In the grid-following configuration, the battery inverter operates as a controlled current source and synchronises with the grid using a phase-locked loop. The PLL extracts the grid voltage angle and frequency, which are then used to perform abc–dq transformations for current control. Active and reactive power references are translated into d-axis and q-axis current commands, respectively, and inner current control loops regulate the inverter output to track these references.

During normal grid-connected operation, this control strategy ensures accurate power injection and compliance with grid codes. However, the grid-following inverter remains inherently dependent on the availability of a stable grid voltage reference. In the event of a grid outage, the loss of voltage at the POI leads to deterioration of PLL performance, resulting in loss of synchronisation and distorted inverter operation. As a consequence, grid-following control is unable to sustain stable voltage and frequency during islanded operation without additional external support [3], [7].

3.3 Grid-Forming Control Strategy

In the grid-forming configuration, the battery inverter operates as a controlled voltage source capable of autonomously establishing voltage magnitude and frequency. The implemented control strategy is based on the virtual synchronous machine concept, in which the inverter emulates the dynamic behaviour of a synchronous generator. An internal oscillator generates the reference frequency and phase angle, eliminating the need for a phase-locked loop.

Virtual inertia and damping terms are incorporated to shape the frequency response and suppress oscillations during transient events. The battery energy storage system provides the required fast active power support, allowing the grid-forming inverter to maintain stable operation during grid disconnection and islanded conditions [5], [8].

Unlike grid-following control, the grid-forming inverter does not rely on external voltage references and is therefore capable of seamless transition from grid-connected to islanded operation. This autonomous behaviour is particularly advantageous during grid outage scenarios, where the inverter becomes the sole source of voltage and frequency for connected loads.

3.4 Comparative Implementation Considerations

For a fair comparison, both grid-following and grid-forming control strategies are implemented on the same PV–BESS system using identical inverter hardware models, filter parameters, and network conditions. Control mode selection is realised through a variant-based framework, allowing only the control algorithm to change while preserving all other system parameters. This unified modelling approach ensures that the observed differences in voltage stability, frequency response, and harmonic performance during grid outage events can be directly attributed to the inherent characteristics of the respective control strategies [20].

IV.RESULT AND DISCUSSIN

This section presents a comparative evaluation of grid-following and grid-forming control strategies for the PV–BESS system under grid outage conditions. The grid outage event is initiated by disconnecting the upstream grid at the point of interconnection while maintaining the local load and renewable generation. The system response is analysed in terms of voltage and frequency stability, active and reactive power behaviour, and harmonic performance. Identical system parameters and operating conditions are maintained for both control strategies to ensure a fair comparison.

4.1 Voltage and Frequency Response during Grid Outage

Figure X illustrates the voltage magnitude and frequency response at the point of interconnection following grid disconnection. In the grid-following case, the loss of the grid voltage reference leads to rapid degradation of frequency regulation. Since the phase-locked loop is unable to maintain synchronisation in the absence of a stiff grid, frequency oscillations increase and the system fails to sustain stable operation. The voltage magnitude also exhibits noticeable fluctuations, indicating weak voltage regulation during islanded conditions.

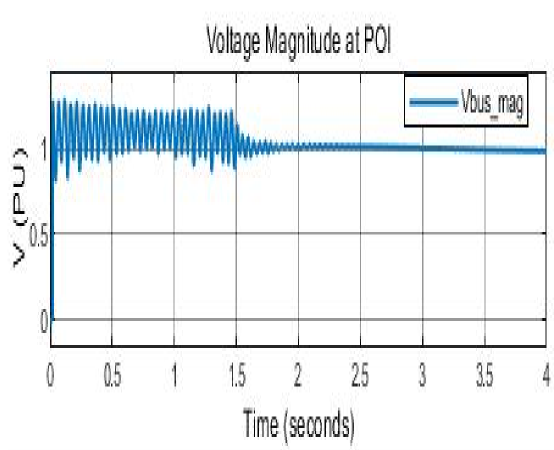

Figure 2: Voltage Magnitude

In contrast, the grid-forming control strategy maintains stable voltage and frequency throughout the grid outage event. The inverter autonomously establishes the reference voltage and frequency using its internal oscillator mechanism. Frequency deviations are limited and rapidly damped due to the presence of virtual inertia and damping, while the voltage magnitude remains close to its nominal value. This behaviour demonstrates the inherent capability of grid-forming inverters to support islanded operation without reliance on external grid references.

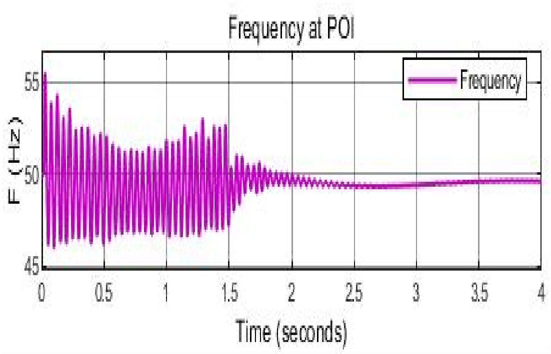

Figure 3: Frequency

These results confirm that grid-forming control significantly enhances system resilience during grid outages by ensuring continuous voltage and frequency support to connected loads.

4.2 Active and Reactive Power Behaviour

The active and reactive power responses of the battery energy storage system during the grid outage event are shown in Figure Y. In the grid-following configuration, the battery inverter exhibits limited and irregular power response following grid disconnection. The loss of synchronisation adversely affects power control, resulting in oscillatory active power injection and reduced reactive power support.

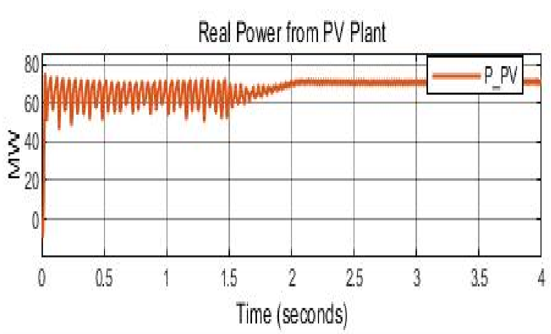

Figure 4: Active Power

On the other hand, the grid-forming battery inverter provides a well-regulated power response during islanded operation. Immediately after grid disconnection, the battery supplies the required active power to balance the local load demand, thereby preventing large frequency deviations. Reactive power is dynamically adjusted according to the voltage characteristics, contributing to stable voltage regulation at the point of interconnection.

The coordinated active and reactive power behaviour highlights the effectiveness of battery-supported grid-forming control in maintaining power balance during grid outage events.

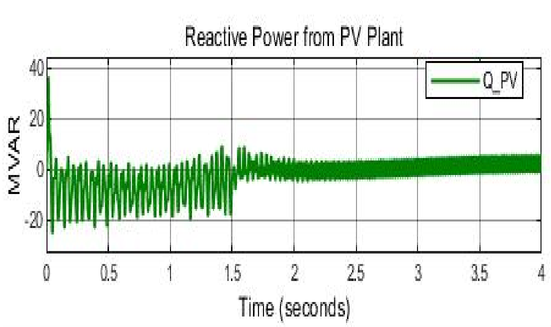

Figure 5: Reactive Power

4.3 Harmonic Performance during Islanded Operation

The harmonic performance of the system during grid outage is evaluated by analysing the total harmonic distortion of voltage and current at the point of interconnection. In the grid-following case, the measured voltage and current THD values are approximately 0.88%, indicating increased harmonic distortion during islanded operation. This degradation in waveform quality can be attributed to PLL instability and reference frame misalignment following the loss of grid voltage, which results in distorted modulation signals and increased harmonic injection.

In contrast, the grid-forming control strategy exhibits significantly lower harmonic distortion under identical operating conditions. The measured voltage and current THD values are approximately 0.065% and 0.068%, respectively. Since voltage and frequency are internally generated, the grid-forming inverter maintains a smooth and sinusoidal voltage waveform during islanded operation, thereby reducing harmonic content in both voltage and current. The observed THD levels are well within the limits specified by harmonic standards, demonstrating improved power quality performance compared to the grid-following approach .

The substantial reduction in harmonic distortion highlights an important advantage of grid-forming control during grid outage conditions, particularly in applications where sensitive loads remain connected to the islanded system.

4.4 Comparative Performance Summary

Table I summarises the key performance characteristics of grid-following and grid-forming control strategies during the grid outage scenario.

Table I
Comparative Performance during Grid Outage

Performance Metric	**Grid-Following Control**	**Grid-Forming Control**
Islanded operation capability	Not sustained	Fully sustained
Voltage regulation	Poor	Strong
Frequency stability	Degraded	Stable
Active power support	Limited	Fast and effective
Voltage THD (%)	≈ 0.88	≈ 0.065

The comparative analysis clearly indicates that grid-forming control provides superior performance across all evaluated metrics during grid outage conditions. The ability to autonomously regulate voltage and frequency, combined with improved harmonic performance, makes grid-forming PV–BESS systems a viable solution for enhancing the resilience of future low-inertia power systems.

V.CONCLUSION

This paper presented a comparative assessment of grid-forming and grid-following control strategies for a solar photovoltaic system integrated with battery energy storage under grid outage conditions. The analysis was carried out using a unified simulation framework in which both control strategies were implemented on an identical system configuration, ensuring a fair and consistent comparison.

Simulation results demonstrated that the grid-following inverter, due to its reliance on phase-locked loop–based synchronisation, was unable to sustain stable operation following grid disconnection. The loss of an external voltage reference resulted in degraded voltage and frequency regulation, irregular power response, and increased harmonic distortion during islanded operation. In contrast, the grid-forming control strategy enabled seamless transition to islanded mode by autonomously establishing voltage and frequency.

A significant improvement in power quality was also observed with grid-forming control. The measured voltage and current total harmonic distortion values during islanded operation were substantially lower compared to the grid-following case, highlighting the effectiveness of grid-forming inverters in maintaining sinusoidal waveforms during grid outage events. Overall, the results confirm that battery-supported grid-forming control offers a robust and practical solution for enhancing the resilience and power quality of inverter-dominated power systems under grid outage conditions.

VI.REFERENCES :

[1] F. Milano, F. Dörfler, G. Hug, D. J. Hill, and G. Verbič, “Foundations and challenges of low-inertia systems,” IEEE Transactions on Power Systems, vol. 33, no. 5, pp. 1–15, 2018.

doi: 10.1109/TPWRS.2018.2842700

[2] N. Hatziargyriou, Microgrids: Architectures and Control, 1st ed. Hoboken, NJ, USA: Wiley, 2014.

doi: 10.1002/9781118720677

[3] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodríguez, “Control of power converters in AC microgrids,” IEEE Transactions on Power Electronics, vol. 27, no. 11, pp. 4734–4749, 2012.

doi: 10.1109/TPEL.2012.2199334

[4] P. Rodríguez, J. Pou, J. Bergas, J. I. Candela, R. P. Burgos, and D. Boroyevich, “Decoupled double synchronous reference frame PLL for power converters,” IEEE Transactions on Power Electronics,

vol. 22, no. 2, pp. 584–592, 2007.

doi: 10.1109/TPEL.2006.890000

[5] Q.-C. Zhong and G. Weiss, “Synchronverters: Inverters that mimic synchronous generators,” IEEE Transactions on Industrial Electronics, vol. 58, no. 4, pp. 1259–1267, 2011.

doi: 10.1109/TIE.2010.2048839

[6] S. Li, Y. Zheng and Q. Xu, "Study on the Mechanism of the Influence of Grid-Forming Converters on Series-Compensated Grid Voltage Stability," 2024 6th International Conference on Power and Energy Technology (ICPET), Beijing, China, 2024, pp. 59-64, doi: 10.1109/ICPET62369.2024.10941051.

[7] U. Markovic, O. Stanojev, M. Aristidou, and G. Hug, “Understanding small-signal stability of low-inertia systems,” IEEE Transactions on Power Systems, vol. 35, no. 5, pp. 3997–4008, 2020.

doi: 10.1109/TPWRS.2020.2973676

[8] S. D’Arco and J. A. Suul, “Virtual synchronous machines—Classification of implementations and analysis of equivalence to droop controllers,” IEEE PES General Meeting, 2013.

doi: 10.1109/PESMG.2013.6672974

[9] IEEE Standard 1547-2018, “IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces,” IEEE, 2018.

doi: 10.1109/IEEESTD.2018.8332112

[10] J. Sun, “Impedance-based stability criterion for grid-connected inverters,” IEEE Transactions on Power Electronics, vol. 26, no. 11, pp. 3075–3078, 2011. doi: 10.1109/TPEL.2011.2168540

[11] X. Wang, F. Blaabjerg, and Z. Chen, “Synthesis of variable harmonic impedance in inverter-interfaced distributed generation unit for harmonic damping throughout a distribution network,” IEEE Transactions on Industry Applications,

vol. 48, no. 4, pp. 1407–1417, 2012.

doi: 10.1109/TIA.2012.2199951

[12] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuña, and M. Castilla, “Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization,” IEEE Transactions on Industrial Electronics, vol. 58, no. 1, pp. 158–172, 2011.

doi: 10.1109/TIE.2010.2066534

[13] T. L. Vandoorn, J. D. M. De Kooning, B. Meersman, and L. Vandevelde, “Review of primary control strategies for islanded microgrids with power-electronic interfaces,” Renewable and Sustainable Energy Reviews, vol. 19, pp. 613–628, 2013. doi: 10.1016/j.rser.2012.11.062

[14] Q.-C. Zhong, “Virtual synchronous machines: A unified interface for grid integration,” IEEE Power Electronics Magazine, vol. 3, no. 4, pp. 18–27, 2016. doi: 10.1109/MPEL.2016.2614906

[15] E. Avdiaj, J. A. Suul, S. D'Arco and L. Piegari, "A Virtual Synchronous Machine-based Control for Eliminating DC-side Power Oscillations of Three-Phase VSCs under Unbalanced Grid Voltages," 2021 IEEE 15th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Florence, Italy, 2021, pp. 1-6, doi: 10.1109/CPE-POWERENG50821.2021.9501184.

[16] IEEE Standard 519-2014, “IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems,” IEEE, 2014. doi: 10.1109/IEEESTD.2014.6826459

[17] N. Pogaku, M. Prodanovic, and T. C. Green, "Modeling, analysis and testing of autonomous operation of an inverter-based microgrid," IEEE Transactions on Power Electronics, vol. 22, no. 2, pp. 613–625, 2007.

doi: 10.1109/TPEL.2006.890003

[19] P. Rodríguez, A. Luna, I. Candela, R. Teodorescu, F. Blaabjerg, and A. Mujal, "Multiresonant frequency-locked loop for grid synchronization of power converters under distorted grid conditions," IEEE Transactions on Industrial Electronics, vol. 58, no. 1, pp. 127–138, 2011.

doi: 10.1109/TIE.2010.2042420

[20] U. Markovic, Z. Chu, P. Aristidou, and G. Hug, "LQR-based adaptive virtual synchronous machine for power systems with high inverter penetration," IEEE Transactions on Power Systems, vol. 34, no. 4, pp. 2691–2703, 2019.

doi: 10.1109/TPWRS.2019.2894719