OPEN ACCESS INTERNATIONAL JOURNAL OF SCIENCE & ENGINEERING

Comparative Investigation of Grid-Forming and Grid-Following Control Strategies for Islanded PV-Battery Energy Storage Systems

Siddhant Verma, Divya Soni
Research scholar, Department of EXE, SVCE, Indore. (siddhantv256@gmail.com)
Assistant Professor, Department of EXE, SVCE, Indore. (divyasoni19y@gmail.com)

Abstract: The increasing integration of inverter-based renewable energy sources has considerably changed the behaviour of modern power systems, especially in weak grid and low-inertia operating conditions. Conventional grid-following inverters mainly depend on phase-locked loop (PLL) synchronisation and require the support of a strong utility grid for proper operation. Due to this dependency, their performance becomes limited during grid outage or islanding conditions. On the other hand, grid-forming inverters can independently establish and regulate system voltage and frequency, making them more suitable for stable islanded operation when combined with battery energy storage systems (BESS). This paper presents a comparative study of grid-forming and grid-following control techniques for a solar photovoltaic (PV) system integrated with battery energy storage under grid outage conditions. To ensure a fair comparison, both control strategies were implemented using the same system configuration and operating conditions in MATLAB/Simulink. The study mainly evaluates the performance of both approaches in terms of voltage and frequency regulation, active and reactive power response, and harmonic characteristics during the transition from grid-connected mode to islanded operation. Simulation results show that the grid-following inverter loses synchronisation and experiences deterioration in power quality after grid disconnection. In contrast, the grid-forming inverter successfully maintains stable voltage and frequency, enabling smooth and uninterrupted islanded operation. Additionally, the grid-forming approach achieves lower voltage and current total harmonic distortion (THD) compared to the grid-following method.

Keywords: Grid-Forming Inverter, Grid-Following Inverter, Battery Energy Storage System (BESS), Solar Photovoltaic System, Harmonic Distortion, Power Quality

---

I. Introduction

The growing integration of solar photovoltaic (PV) systems and other inverter-based renewable energy sources has significantly changed the operating behaviour of modern power systems. Traditionally, electrical power systems mainly depended on synchronous generators, which naturally provided inertia, voltage support, and frequency regulation. However, renewable energy systems connected through power electronic converters contribute very little physical inertia to the grid. As a result, modern power systems have become more sensitive to disturbances such as sudden load changes, fluctuations in renewable generation, and grid outage conditions [1], [2]. These issues become more severe in weak grid and distribution network conditions, where low short-circuit capacity and strong voltage–frequency interactions affect overall system stability.

At present, most grid-connected solar PV systems operate using grid-following inverter control. In this approach, the inverter synchronises with the utility grid through a phase-locked loop (PLL) and injects current according to the grid voltage and frequency reference. Although this method performs satisfactorily under strong grid conditions, it faces major limitations during abnormal operating situations. During grid outages or islanding conditions, the absence of a stable grid reference can cause the PLL to lose synchronisation, which may lead to instability, poor power quality, or complete inverter shutdown [3], [4]. With the continuous increase in inverter-based renewable penetration, these limitations have become a major concern for maintaining system reliability and secure operation.

To overcome these challenges, grid-forming inverters have emerged as an effective alternative. Unlike grid-following inverters, grid-forming inverters behave as controlled voltage sources that can independently regulate system voltage and frequency. By imitating the dynamic characteristics of synchronous generators using concepts such as virtual synchronous machines (VSMs), grid-forming inverters can provide synthetic inertia, rapid frequency response, and voltage support even under weak or islanded grid conditions [5], [6].

In recent years, several studies have explored different aspects of grid-forming inverter control, including stability enhancement in weak grids, interaction between multiple inverters, and power-sharing capability in microgrids [6]–[8]. However, limited work has been reported on the direct comparative analysis of grid-forming and grid-following control strategies specifically during grid outage conditions in utility-scale PV-BESS systems. In addition, although voltage and frequency stability have been widely investigated, comparatively less attention has been given to harmonic performance during islanded operation. Harmonic distortion becomes highly important during grid outages because the inverter acts as the primary voltage source supplying sensitive connected loads [9].

2. 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].

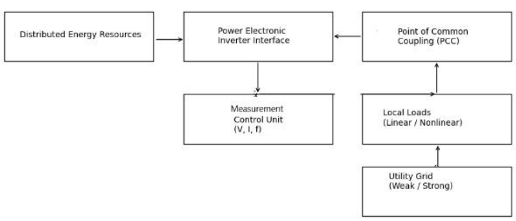

Figure 1. Overall system architecture of the inverter-based microgrid under study

Several studies have highlighted the limitations of grid-following inverter control during islanding and grid outage conditions. It has been reported that when the grid is disconnected, the absence of a strong and stable voltage reference causes instability in the phase-locked loop (PLL). As a result, the inverter may experience distorted current injection, increased harmonic distortion, and eventually complete shutdown or tripping [12]. These problems become more severe when multiple grid-following inverters operate simultaneously in parallel networks, where interactions among controllers and mismatched reference signals can lead to oscillations and improper power sharing [13]. Due to these limitations, grid-following inverters are generally not considered suitable for independent islanded operation unless additional supervisory controllers or grid-forming support mechanisms are provided.

To overcome these issues, grid-forming inverter control strategies have attracted significant research interest in recent years. Unlike grid-following control, grid-forming inverters operate as controlled voltage sources capable of independently establishing system voltage magnitude and frequency. Different grid-forming control approaches have been proposed in the literature, including virtual synchronous machine (VSM) control, synchronverter techniques, and matching control methods [8], [14].

Many researchers have demonstrated the capability of grid-forming inverters to improve overall system stability under weak grid conditions and transient disturbances. Previous studies have shown that grid-forming inverters can successfully maintain synchronisation, regulate voltage, and ensure proportional load sharing during islanded microgrid operation [6], [7]. In addition, the integration of battery energy storage systems with grid-forming inverters has been found to significantly improve transient response by supplying rapid active power support during sudden frequency deviations and voltage disturbances [15].

Although considerable progress has been made in grid-forming control research, comparatively limited work has focused on the harmonic performance of grid-forming and grid-following inverters during grid outage conditions. Most available studies mainly concentrate on voltage and frequency stability under grid-connected operation, while the influence of inverter control strategy on voltage and current total harmonic distortion (THD) during islanded operation remains insufficiently investigated [16].

3. System Description and Control Strategy

3.1 PV–BESS System Configuration

The system considered in this study consists of a utility-scale solar photovoltaic (PV) plant integrated with a battery energy storage system (BESS) and connected to a medium-voltage distribution network. The PV array is connected to the AC grid through a DC–DC converter followed by a voltage source inverter (VSI). In addition, the battery energy storage system is interfaced to the same AC bus using a bidirectional inverter, which allows the exchange of both active and reactive power with the grid depending on system requirements. To analyse the behaviour of the system under challenging operating conditions, the network is intentionally designed to represent a weak grid environment with a low short-circuit ratio at the POI. This setup makes it possible to clearly observe and compare the dynamic performance of grid-following and grid-forming control strategies during grid outage and islanding events. For a fair and unbiased comparison, all simulations are carried out using the same electrical parameters, inverter ratings, and network configuration for both control approaches. Therefore, any variation in system performance can be directly attributed to the inverter control strategy rather than differences in system structure or component sizing [17].

3.2 Grid-Following Control Strategy

In the grid-following control configuration, the battery inverter operates as a controlled current source and achieves synchronisation with the utility grid through a phase-locked loop (PLL). The PLL continuously measures the grid voltage angle and frequency, which are used for abc–dq reference frame transformation during inverter control.

However, this approach strongly depends on the presence of a stable grid voltage reference for proper operation. During a grid outage or islanding event, the voltage at the point of interconnection (POI) collapses or becomes unstable, which negatively affects PLL operation. This leads to loss of synchronisation, distorted current injection, and unstable inverter performance. Therefore, grid-following control alone cannot maintain stable voltage and frequency during islanded operation unless additional external support or grid-forming capability is available [3], [7].

3.3 Grid-Forming Control Strategy

In the grid-forming control configuration, the battery inverter operates as a controlled voltage source that can independently establish and regulate system voltage magnitude and frequency. The implemented control approach is based on the virtual synchronous machine (VSM) concept, where the inverter is designed to imitate the dynamic characteristics of a conventional synchronous generator. In this method, an internal oscillator generates the reference frequency and phase angle, thereby eliminating the requirement for a phase-locked loop (PLL) for synchronisation.

To improve dynamic performance during disturbances, virtual inertia and damping components are incorporated into the control strategy. These elements help in shaping the frequency response of the inverter and reducing oscillations during transient operating conditions. The battery energy storage system provides rapid active power support whenever required, enabling the grid-forming inverter to maintain stable voltage and frequency during grid disconnection and islanded operation [5], [8].

Unlike grid-following control, the grid-forming inverter does not depend on an external grid voltage reference for operation. Because of this autonomous capability, the inverter can smoothly transition from grid-connected mode to islanded mode without losing stability.

4. Results and Discussion

This section presents a detailed comparative analysis of grid-following and grid-forming control strategies for the PV-BESS system under grid outage conditions. The outage scenario is created by disconnecting the upstream utility grid at the point of interconnection (POI) while keeping the local load demand and renewable power generation active.

The comparative assessment mainly focuses on important performance parameters such as voltage and frequency stability, active and reactive power response, and harmonic characteristics during the transition from grid-connected operation to islanded mode. To ensure a fair and accurate comparison, both grid-following and grid-forming control strategies are tested using identical network parameters, inverter ratings, loading conditions, and operating scenarios. Therefore, any observed variation in system performance is directly related to the implemented control strategy rather than differences in system configuration.

4.1 Voltage and Frequency Response during Grid Outage

Figure 2 presents the variation in voltage magnitude and frequency at the point of interconnection (POI) after grid disconnection. In the case of grid-following control, the removal of the grid voltage reference causes significant deterioration in frequency regulation performance. Because the phase-locked loop (PLL) depends on a strong and stable grid for synchronisation, it becomes unable to maintain proper synchronism once the grid is disconnected. As a result, large frequency oscillations are observed, and the system is unable to maintain stable islanded operation.

In addition, the voltage magnitude shows noticeable fluctuations following the outage event, indicating poor voltage regulation capability under islanded conditions. These results highlight the limitations of grid-following control during grid disturbances and demonstrate its strong dependence on external grid support for stable operation.

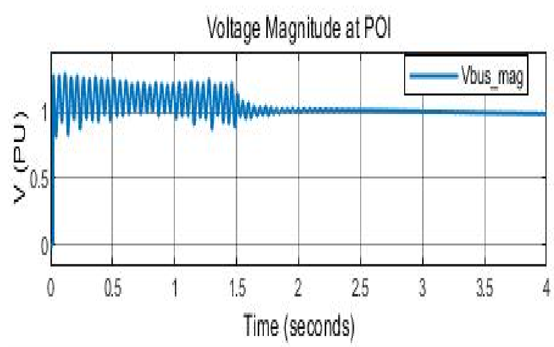

Figure 2: Voltage Magnitude

In contrast, the grid-forming control strategy is able to maintain stable voltage and frequency during the entire grid outage event. The inverter independently generates and regulates the system voltage and frequency through its internal oscillator-based control mechanism. During the transition to islanded operation, only small frequency deviations are observed, and these oscillations are quickly suppressed because of the implemented virtual inertia and damping characteristics.

This stable behaviour clearly demonstrates the capability of grid-forming inverters to operate autonomously during islanded conditions without depending on an external grid voltage reference. As a result, the grid-forming control strategy provides improved system stability, reliable operation, and better support for connected loads during grid outage events.

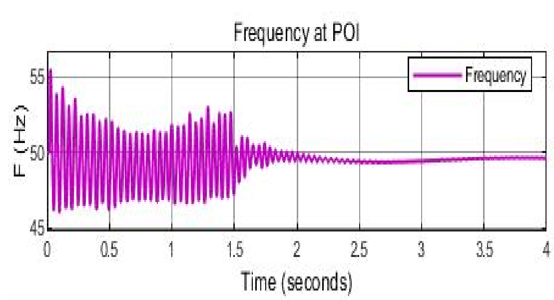

Figure 3: Frequency

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.

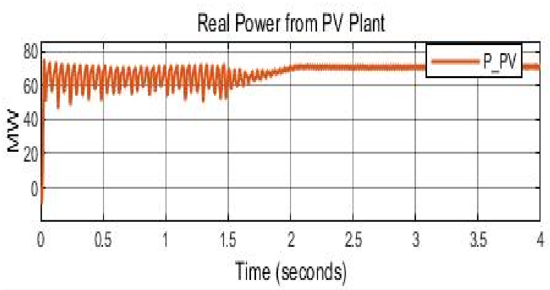

Figure 4: Active Power

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.

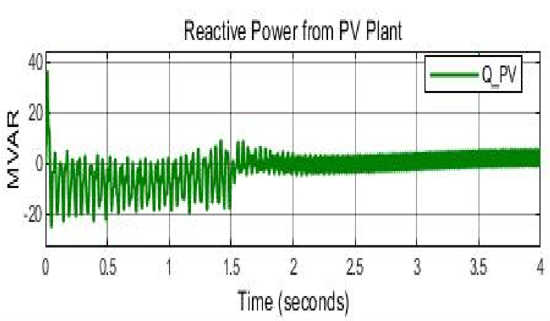

Figure 5: Reactive Power

4.3 Harmonic Performance during Islanded Operation

The harmonic performance of the PV-BESS system during grid outage conditions is evaluated by analysing the total harmonic distortion (THD) of voltage and current at the point of interconnection (POI). In the grid-following control case, the voltage and current THD values are observed to be nearly 0.88%, which indicates a noticeable increase in harmonic distortion during islanded operation. This deterioration in waveform quality mainly occurs because the phase-locked loop (PLL) loses stable synchronisation after the grid voltage reference is removed. As a result, reference frame misalignment takes place, leading to distorted modulation signals and higher harmonic injection into the system.

On the other hand, the grid-forming control strategy demonstrates considerably better harmonic performance under the same operating conditions. The measured voltage and current THD values are approximately 0.065% and 0.068%, respectively, which are significantly lower than those obtained with the grid-following approach. Since the grid-forming inverter independently generates and regulates system voltage and frequency, it is capable of maintaining a stable and nearly sinusoidal voltage waveform even during islanded operation. Consequently, harmonic distortion in both voltage and current is greatly reduced. The obtained THD values remain well within the acceptable limits specified by standard harmonic regulations, indicating superior power quality performance.

The significant reduction in harmonic distortion clearly highlights one of the major advantages of grid-forming control during grid outage conditions. This feature becomes particularly important in practical applications where sensitive electrical loads continue to operate in islanded mode and require stable, high-quality power supply.**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.

5. Conclusion

This paper presented a comparative analysis of grid-forming and grid-following control strategies for a solar photovoltaic (PV) system integrated with battery energy storage under grid outage conditions. The study was performed using a common simulation framework in which both control approaches were implemented using the same system configuration and operating conditions, ensuring a fair and reliable comparison between the two methods.

The simulation results showed that the grid-following inverter was unable to maintain stable operation after grid disconnection because of its dependence on phase-locked loop (PLL)-based synchronisation. Once the external grid voltage reference was removed, the system experienced deterioration in voltage and frequency regulation, unstable power response, and increased harmonic distortion during islanded operation. In contrast, the grid-forming control strategy successfully enabled a smooth transition from grid-connected mode to islanded operation by independently establishing and regulating system voltage and frequency.

A noticeable improvement in overall power quality was also achieved using grid-forming control. During islanded operation, the voltage and current total harmonic distortion (THD) values were found to be significantly lower compared to those obtained with the grid-following approach. This demonstrates the capability of grid-forming inverters to maintain stable and nearly sinusoidal voltage and current waveforms during grid outage events.

References:

[1] Muhammad Akbar Syahbani et al., "Performance enhancement of grid-forming inverter-controlled PV systems: A comparative study with and without battery energy storage under intermittent and unbalanced load conditions", Results in Engineering, Volume 27, 2025. https://doi.org/10.1016/j.rineng.2025.105980.

[2] Hossain, Md I., Hasanur Z. Anonto, Abu Shufian, Bishwajit B. Pathik, Mohammad A. Mannan, Abdur Rashid, and Parag Biswas. "Enhancing Microgrid Resilience through Integrated Grid-forming and Grid-following Inverter Strategies for Solar PV Battery Control and Fault Ride-through." Scientific Reports 15, no. 1 (2025): 40078. Accessed May 18, 2026. https://doi.org/10.1038/s41598-025-18767-4.

[3] Tina, G.M., Maione, G. & Ventura, C. Evaluation of the Impact of Grid Forming Inverter Penetration on Frequency Transients in Systems with a High Percentage of Renewables. Smart Grids and Energy 11, 1 (2026). https://doi.org/10.1007/s40866-025-00318-5.

[4] Evald, Paulo J. D. D. O., Lenon Schmitz, Jéssika M. De Andrade, Francisco J. Viglus, and Telles B. Lazzarin. "Towards the Future Low-inertia Power Systems: A Review on Grid-forming Inverter Control - Advances, Challenges, and Opportunities." Renewable and Sustainable Energy Reviews 235, (2026): 116948. Accessed May 18, 2026. https://doi.org/10.1016/j.rser.2026.116948.

[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.

[18] R. Parmar and D. K. Sakravdia, "Intelligent Learning Methods for Battery State of Charge Estimation for Electric Vehicles: a Review," 2025 2nd International Conference on Advanced Computing and Emerging Technologies (ACET), Ghaziabad, India, 2025, pp. 1-6, doi: 10.1109/ACET67282.2025.11430296.

[19] R. Parmar et al., "A Comparative study on Different ANN Techniques in Wind Speed Forecasting for Generation of Electricity", IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE), Volume 12, Issue 1 Ver. III (Jan. – Feb. 2017), PP 19-26. DOI: 10.9790/1676-1201031926

[20] 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

[21] 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