# A FUZZY LOGIC-BASED HYBRID ENERGY STORAGE CONTROL STRATEGY FOR ENHANCING STABILITY IN PHOTOVOLTAIC GRID-CONNECTED SYSTEMS

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**ABSTRACT**
The increasing penetration of photovoltaic (PV) systems into modern power grids has introduced significant challenges related to voltage instability, power fluctuations, and reduced grid reliability due to the intermittent nature of solar energy. To address these issues, this paper presents a fuzzy logic-based hybrid energy storage control strategy aimed at enhancing the operational stability of grid-connected photovoltaic systems. The proposed framework integrates a hybrid energy storage system composed of batteries and supercapacitors, enabling effective management of both long-term energy balancing and short-term power transients. A fuzzy logic controller (FLC) is employed to intelligently regulate the charging and discharging operations of the hybrid storage system based on key system parameters such as photovoltaic power variation, grid voltage deviation, and load demand dynamics. Unlike conventional linear control methods, the fuzzy logic approach does not rely on an accurate mathematical model, making it highly suitable for handling nonlinearities and uncertainties inherent in renewable energy systems. The control strategy ensures smooth power injection into the grid, mitigates voltage fluctuations, and improves overall system stability under varying irradiance and load conditions. Simulation studies carried out in MATLAB/Simulink demonstrate that the proposed control scheme significantly enhances voltage regulation, reduces power oscillations, and improves dynamic response compared to traditional control techniques. The results confirm that the fuzzy logic-based hybrid energy storage system provides a robust and efficient solution for stabilising grid-connected PV systems, thereby supporting higher renewable energy penetration and improved grid resilience.

**Keywords:** Photovoltaic systems, Hybrid energy storage, Fuzzy logic controller, Grid-connected inverters, Voltage stability, Renewable energy integration, Power quality enhancement.



## INTRODUCTION

The rapid growth of global energy demand, coupled with increasing environmental concerns and the depletion of fossil fuel resources, has accelerated the large-scale integration of renewable energy sources into modern power systems. Among the various renewable technologies, photovoltaic (PV) energy has emerged as one of the most promising solutions due to its clean nature, modularity, and declining installation costs. Grid-connected PV systems are increasingly deployed in both urban and rural power networks to support sustainable electricity generation. However, the inherent intermittency and variability of solar irradiance introduce significant operational challenges to power system stability. Sudden changes in irradiance caused by cloud cover, temperature variations, and atmospheric conditions result in fluctuating PV output power, which can adversely affect grid voltage profiles, frequency regulation, and overall power quality. As the penetration level of PV systems continues to rise, maintaining grid stability and reliability has become a critical concern for utilities and system operators. Conventional grid infrastructure, originally designed for unidirectional power flow from centralized generation units, is often ill-equipped to accommodate such dynamic and distributed energy sources without advanced control and energy management strategies.

To mitigate the adverse impacts of PV intermittency, energy storage systems have been widely recognised as an essential component in grid-connected renewable energy applications. Energy storage provides the ability to decouple generation from consumption, thereby enabling smoother power injection, load balancing, and enhanced system flexibility. Battery energy storage systems (BESS) are commonly employed due to their high energy density and suitability for long-duration energy support. Nevertheless, batteries alone suffer from limitations such as limited power density, slower response to rapid transients, thermal stress, and reduced lifespan under frequent charge–discharge cycles. On the other hand, supercapacitors exhibit excellent power density, rapid response characteristics, and high cycle life, making them ideal for handling short-term power fluctuations. These complementary characteristics have motivated the development of hybrid energy storage systems (HESS), which combine batteries and supercapacitors to exploit the advantages of both technologies. By appropriately coordinating the operation of each storage component, a hybrid configuration can simultaneously address long-term energy management and short-term power stabilisation requirements, thereby improving the overall performance and longevity of the storage system in grid-connected PV applications.

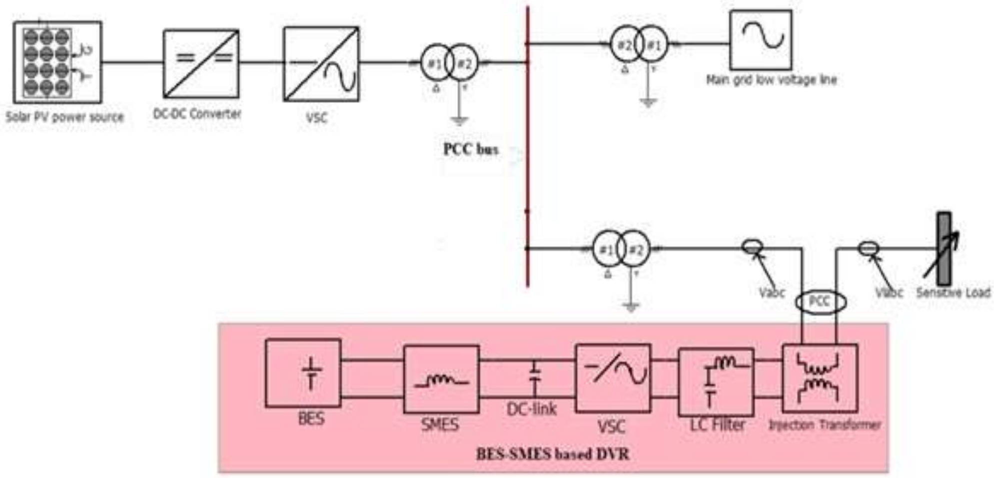


**Fig 1.proposed system configuration**

Despite the benefits of hybrid energy storage systems, their effective operation heavily depends on the design of an intelligent and adaptive control strategy. Traditional control approaches, such as proportional–integral (PI) and proportional–integral–derivative (PID) controllers, are widely used due to their simplicity and ease of implementation. However, these linear controllers require accurate system modelling and parameter tuning, which becomes increasingly challenging in renewable energy systems characterised by nonlinear dynamics, parameter uncertainties, and rapidly changing operating conditions. Moreover, conventional controllers often exhibit degraded performance when subjected to abrupt disturbances, fluctuating irradiance, and varying load demands. As a result, advanced control techniques capable of handling system nonlinearities and uncertainties are essential for ensuring stable and reliable operation of PV grid-connected systems with hybrid energy storage. Intelligent control methods, including fuzzy logic control, neural networks, and adaptive control strategies, have gained considerable attention as viable alternatives to conventional approaches.

Fuzzy logic control has emerged as a particularly attractive solution for renewable energy applications due to its ability to incorporate human-like reasoning and heuristic knowledge without relying on an explicit mathematical model. A fuzzy logic controller (FLC) utilises linguistic variables, membership functions, and a rule-based inference mechanism to map system inputs to appropriate control actions. This feature makes FLCs highly robust in dealing with uncertainties, nonlinearities, and imprecise system information. In the context of grid-connected PV systems, fuzzy logic control enables intelligent decision-making based on real-time system conditions such as PV power variation, state of charge of energy storage elements, grid voltage deviation, and load dynamics. By dynamically adjusting the charging and discharging behaviour of the hybrid energy storage system, an FLC can effectively suppress power oscillations, mitigate voltage fluctuations, and enhance dynamic response during transient events. Furthermore, fuzzy logic controllers offer flexibility in controller design, ease of modification, and improved robustness compared to classical control methods, making them well-suited for complex energy management tasks in modern power networks.

In light of the above considerations, this work focuses on the development of a fuzzy logic-based hybrid energy storage control strategy aimed at enhancing stability in photovoltaic grid-connected systems. The proposed approach integrates a PV generation unit with a battery–supercapacitor hybrid energy storage system interfaced to the utility grid through power electronic converters. The fuzzy logic controller is designed to intelligently coordinate power sharing between the battery and the supercapacitor based on system operating conditions, thereby ensuring stable grid interaction and improved power quality. By addressing both short-term power transients and long-term energy balancing, the proposed strategy enhances voltage regulation, reduces stress on storage components, and improves overall system reliability. Through comprehensive simulation studies, the effectiveness of the proposed control framework is evaluated under varying irradiance levels, load disturbances, and grid conditions. The outcomes of this research contribute to the advancement of intelligent energy management solutions and support the reliable integration of high-penetration photovoltaic systems into future smart grids.

## LITERATURE SURVEY

Extensive research efforts have been directed towards improving the stability and power quality of grid-connected photovoltaic (PV) systems as renewable energy penetration continues to increase worldwide. Early studies primarily focused on the modelling and control of grid-connected PV inverters to ensure compliant operation with grid codes and standards. Researchers highlighted that PV output variability caused by intermittent solar irradiance leads to voltage fluctuations, frequency deviations, and harmonic distortion in distribution networks [1]–[3]. Conventional control strategies, such as voltage-oriented control and current control methods using proportional–integral (PI) controllers, were initially adopted due to their simplicity and ease of implementation [4]. However, several authors reported that these linear controllers exhibit performance degradation under rapidly changing environmental conditions and grid disturbances [5]. Investigations into low-voltage ride-through capability and reactive power support further revealed the limitations of classical controllers when dealing with nonlinear dynamics and parameter uncertainties inherent in PV systems [6], [7]. Consequently, the literature gradually shifted towards advanced control frameworks capable of enhancing system robustness and dynamic response in grid-connected PV installations.

To address PV intermittency and grid instability issues, the integration of energy storage systems into PV-based power generation has been widely explored. Battery energy storage systems (BESS) have been extensively studied for applications such as peak shaving, load levelling, and frequency regulation in grid-connected environments [8]–[10]. Studies demonstrated that batteries effectively smooth PV power output and enhance grid support during generation deficits. Nevertheless, multiple researchers reported critical limitations associated with battery-only storage systems, including limited power density, slow transient response, ageing effects, and reduced lifetime under frequent cycling conditions [11], [12]. In response to these challenges, alternative storage technologies such as supercapacitors and flywheels were investigated for short-term power compensation [13]. Supercapacitors, in particular, attracted significant attention due to their fast charging capability, high power density, and long cycle life. However, their low energy density restricts their suitability for long-duration energy support. These findings motivated the emergence of hybrid energy storage systems (HESS), which combine batteries with supercapacitors to leverage the advantages of both technologies [14]–[16].

Numerous studies have examined different hybrid energy storage architectures and power management strategies for grid-connected PV systems. Researchers proposed various topologies employing bidirectional DC–DC converters to coordinate power flow between the battery, supercapacitor, and DC-link of the inverter system [17]. Energy management strategies based on frequency separation techniques were introduced, where low-frequency power components were assigned to batteries and high-frequency transients were handled by supercapacitors [18]. Other works employed rule-based control strategies that allocate power according to predefined thresholds of state-of-charge and load variation [19]. While these approaches demonstrated improved performance compared to single-storage systems, their effectiveness heavily depended on accurate parameter tuning and system modelling. Furthermore, deterministic rule-based strategies were found to lack adaptability under unforeseen operating conditions such as sudden irradiance drops or grid faults [20]. These limitations underscored the necessity for intelligent and adaptive control techniques capable of handling uncertainty and nonlinearity in hybrid PV-energy storage systems.

In recent years, intelligent control methods have gained prominence in the literature for managing hybrid energy storage systems in grid-connected PV applications. Artificial intelligence-based approaches, including neural networks, model predictive control, and fuzzy logic control, have been investigated to enhance system stability and decision-making capability [21]–[23]. Among these techniques, fuzzy logic control has emerged as a preferred solution due to its model-free nature and ability to incorporate heuristic knowledge. Several researchers demonstrated that fuzzy logic controllers (FLCs) outperform conventional PI controllers in mitigating voltage fluctuations, suppressing power oscillations, and improving transient response in PV systems [24]. FLC-based strategies were also applied to manage battery charging and discharging while maintaining state-of-charge within safe operating limits [25]. Studies further revealed that fuzzy logic control enables smooth power sharing between batteries and supercapacitors in hybrid configurations, thereby reducing stress on individual storage elements and extending their operational lifespan [26], [27]. Comparative analyses reported superior robustness of FLC-based hybrid storage control under variable irradiance, load disturbances, and grid voltage variations [28].

Despite the substantial progress achieved in fuzzy logic-controlled hybrid energy storage systems, several research gaps remain evident in the existing literature. Many reported works focus on specific operating scenarios and lack comprehensive evaluation under diverse grid disturbances and high PV penetration levels [29]. In addition, the coordination between hybrid storage components and grid-support functionalities such as voltage regulation and power quality enhancement is often treated independently rather than within a unified control framework. Some studies employ complex fuzzy rule bases that increase computational burden and limit real-time applicability in practical systems [30]. Furthermore, limited attention has been given to optimising fuzzy membership functions for enhanced stability performance under dynamic grid conditions. These observations indicate the need for a systematic fuzzy logic-based hybrid energy storage control strategy that simultaneously addresses PV intermittency, grid stability, and storage longevity. The present work aims to bridge these gaps by proposing an adaptive fuzzy logic control framework that intelligently manages hybrid energy storage operation to enhance stability and reliability in photovoltaic grid-connected systems.

## METHODOLOGY

The proposed methodology is structured to achieve enhanced stability in a photovoltaic grid-connected system through the coordinated control of a hybrid energy storage system using fuzzy logic. The overall system consists of a photovoltaic generation unit, a battery storage unit, a supercapacitor module, bidirectional power electronic converters, a grid-tied inverter, and a fuzzy logic controller. The photovoltaic array serves as the primary renewable energy source and is subjected to continuously varying irradiance and temperature conditions, which lead to fluctuations in output power. These variations are interfaced to a common DC link through appropriate power conditioning stages. The hybrid energy storage system is connected to the DC link via bidirectional converters, enabling both charging and discharging operations depending on system conditions. The grid interface ensures regulated power exchange between the DC side and the utility grid, maintaining compliance with grid voltage and frequency requirements.

The first stage of the methodology focuses on photovoltaic power extraction and DC-link regulation. The PV array output is continuously monitored, and maximum power point tracking is employed to ensure optimal energy extraction under varying irradiance conditions. The DC-link voltage acts as a critical indicator of system balance, reflecting the instantaneous mismatch between generation and demand. Any sudden change in solar irradiance causes deviations in DC-link voltage, which must be compensated rapidly to prevent instability in the grid-connected inverter. Maintaining a stable DC-link voltage is therefore a primary control objective, as it directly influences inverter performance, grid current quality, and overall system reliability.

The second stage involves the coordinated operation of the hybrid energy storage system. The battery unit is designated to handle low-frequency and long-duration power variations, such as sustained changes in irradiance or load demand. In contrast, the supercapacitor is responsible for mitigating high-frequency power fluctuations caused by rapid irradiance changes, load transients, or grid disturbances. Bidirectional DC–DC converters enable independent control of each storage element, allowing flexible power sharing based on system requirements. This division of responsibility reduces stress on the battery, improves its lifespan, and ensures faster dynamic response during transient events. The hybrid configuration thus enables both energy buffering and power smoothing within a unified framework.

The fuzzy logic controller forms the core of the proposed methodology and governs the energy management process of the hybrid storage system. Key input variables to the fuzzy controller include photovoltaic power variation, DC-link voltage deviation, and state-of-charge levels of the battery and supercapacitor. These inputs are fuzzified using suitable membership functions representing linguistic terms such as low, medium, and high. A rule base is formulated based on expert knowledge and system behaviour, defining appropriate control actions for different operating scenarios. The inference mechanism processes the rules to determine the required charging or discharging commands for the battery and supercapacitor. The defuzzification stage converts the fuzzy output into crisp control signals that regulate the duty cycles of the bidirectional converters.

The final stage of the methodology involves grid interaction and performance evaluation. The grid-tied inverter ensures synchronised power injection into the utility grid with controlled active and reactive power flow. The effectiveness of the proposed control strategy is evaluated through extensive simulation studies conducted in MATLAB/Simulink under varying irradiance levels, load disturbances, and grid conditions. Key performance metrics such as DC-link voltage stability, grid voltage regulation, power fluctuation suppression, and dynamic response are analysed. Comparative studies with conventional control methods demonstrate the superiority of the fuzzy logic-based hybrid energy storage control strategy in enhancing system stability and power quality.

## PROPOSED SYSTEM

The proposed system is designed to enhance the stability of a grid-connected photovoltaic system through intelligent hybrid energy storage control. It integrates renewable energy generation, energy storage technologies, and advanced control techniques into a unified architecture. The photovoltaic array serves as the primary energy source and is interfaced with the utility grid through a power electronic inverter. Due to the intermittent nature of solar energy, the PV output is inherently unstable and subject to rapid fluctuations. To mitigate these effects, a hybrid energy storage system composed of a battery and a supercapacitor is incorporated at the DC-link level. This configuration enables effective energy management while maintaining grid stability and power quality.

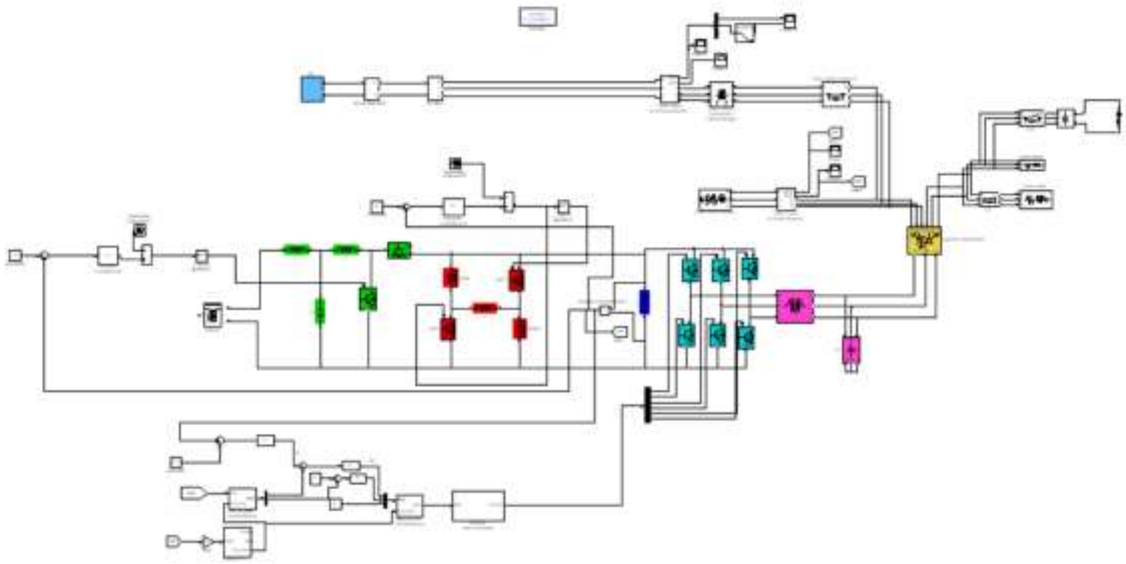

**Fig 2. Proposed circuit configuration**

At the core of the proposed system lies the hybrid energy storage unit, which combines the complementary characteristics of batteries and supercapacitors. The battery provides high energy density and is suitable for long-term energy balancing, whereas the supercapacitor offers high power density and rapid response capability. Both storage elements are interfaced with the DC-link through independent bidirectional DC–DC converters, allowing precise control of charging and discharging operations. This structural arrangement ensures that slow and sustained power variations are handled by the battery, while fast transient disturbances are absorbed by the supercapacitor. As a result, the system achieves improved dynamic performance and reduced stress on individual storage components.

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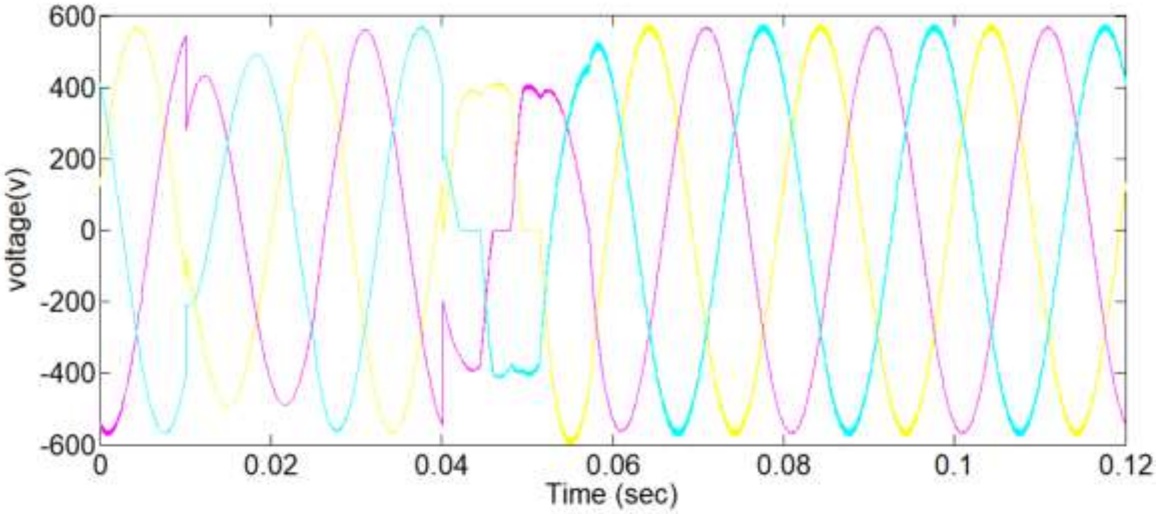


Fig 3. Proposed system voltage without DVR

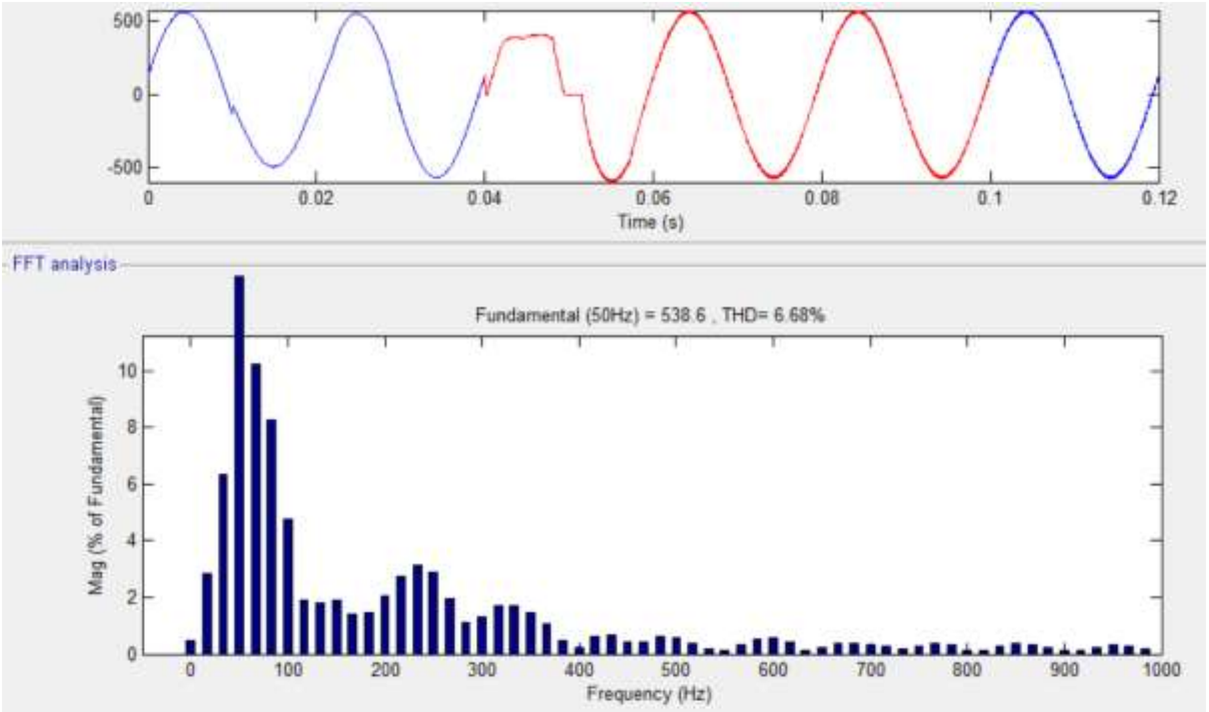


Fig 4. Proposed system voltage THD without DVR

The fuzzy logic controller plays a pivotal role in the proposed system by enabling adaptive and intelligent decision-making. Unlike conventional controllers that require accurate mathematical models, the fuzzy controller operates based on linguistic rules and expert knowledge. It continuously monitors system variables such as PV power fluctuation, DC-link voltage deviation, and storage state-of-charge levels. Based on these inputs, the controller determines the optimal power sharing between the battery and the supercapacitor. This adaptive behaviour allows the system to respond effectively to unpredictable operating conditions, including sudden irradiance changes, load variations, and grid disturbances.

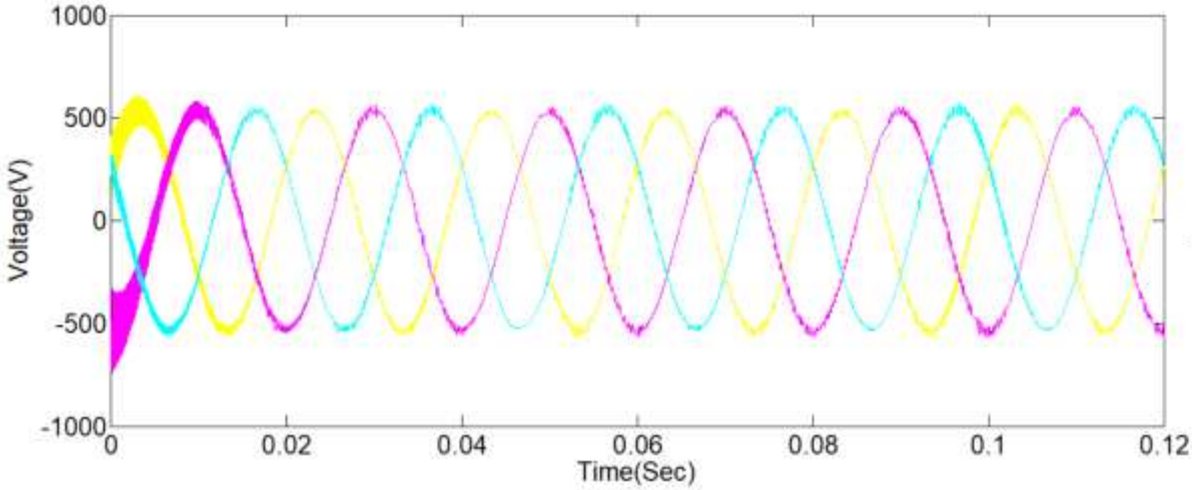


Fig 5. Proposed system voltage with DVR

The grid-connected inverter ensures seamless power exchange between the DC-link and the utility grid. It is designed to maintain synchronisation with grid voltage and frequency while injecting controlled current into the grid. The inverter operation is influenced indirectly by the hybrid energy storage system, which stabilises the DC-link voltage and ensures smooth power delivery. By minimising voltage oscillations and power ripples at the DC-link, the inverter produces high-quality AC output with reduced harmonic distortion. This contributes to improved grid compliance and enhanced reliability of the photovoltaic system.

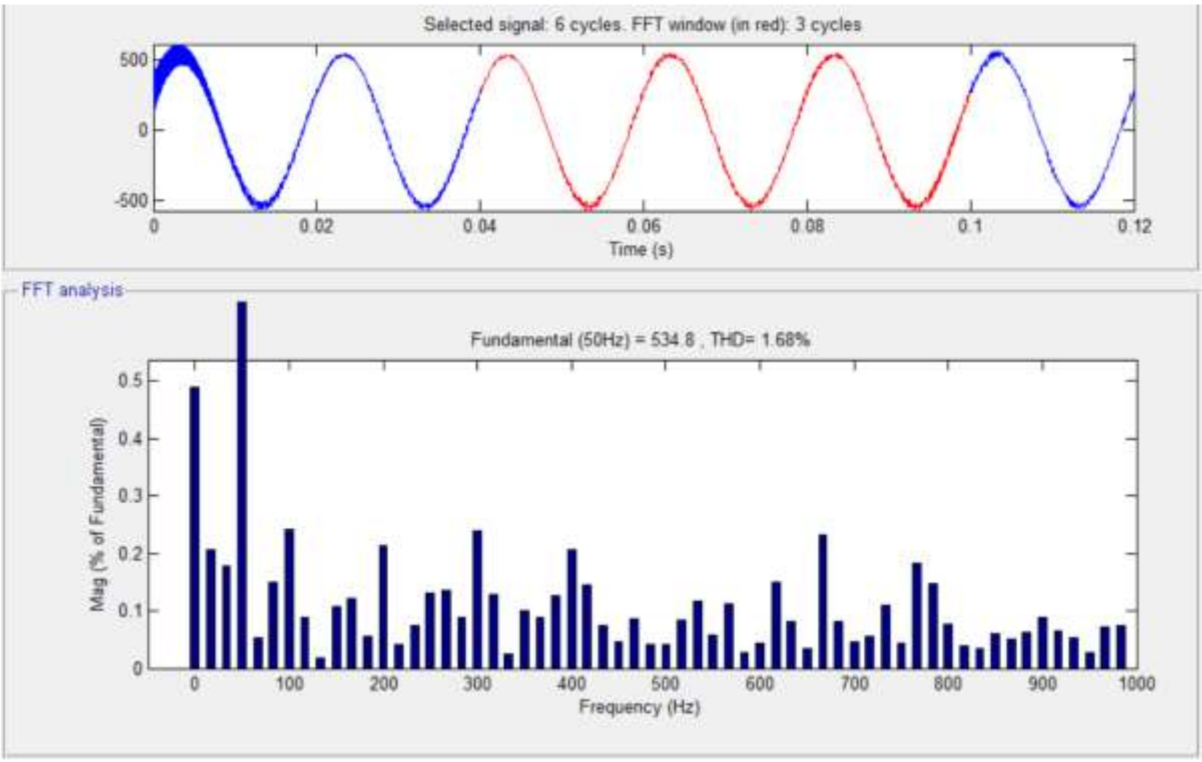


Fig 6. Proposed system voltage THD with DVR

Overall, the proposed system offers a robust and scalable solution for stabilising grid-connected photovoltaic installations. The integration of hybrid energy storage with fuzzy logic-based control enables effective handling of both short-term and long-term power variations. Simulation results confirm that the proposed architecture significantly improves voltage stability, suppresses power fluctuations, and enhances system resilience under dynamic operating conditions. The proposed system is therefore well-suited for modern power networks with high renewable energy penetration and supports the transition towards smarter and more sustainable grids.

## CONCLUSION

This work presented a fuzzy logic-based hybrid energy storage control strategy aimed at enhancing stability in photovoltaic grid-connected systems. By integrating a battery and supercapacitor within a hybrid energy storage framework, the proposed system effectively addressed both long-term energy balancing and short-term power fluctuations arising from photovoltaic intermittency. The fuzzy logic controller enabled intelligent and adaptive power management without relying on an accurate mathematical model, making it particularly suitable for handling nonlinearities and uncertainties in renewable energy systems. Simulation studies demonstrated that the proposed approach significantly improved DC-link voltage stability, reduced power oscillations, and enhanced dynamic response under varying irradiance and load conditions when compared with conventional control strategies. The coordinated operation of hybrid energy storage components reduced stress on the battery, thereby improving system reliability and extending storage lifespan. Overall, the proposed control strategy offers a robust and efficient solution for improving grid stability and power quality in high-penetration photovoltaic systems, supporting the reliable integration of renewable energy into modern power grids.

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