SIMULATION ANALYSIS TO IMPROVED INVERTER CONTROL TECHNIQUES IN TERMS OF HOSTING CAPACITY FOR SOLAR PHOTOVOLTAIC ENERGY WITH BATTERY ENERGY STORAGE SYSTEM

Ms. Domala Vennela, PG Scholar,
Dept of EEE,
Vaagdevi College of Engineering, Bollikunta, Warangal-506005
venneladomala@gmail.com
Mr. P. Purna Chander Rao
Associate Professor,
Dept of EEE,
Vaagdevi College of Engineering, Bollikunta, Warangal-506005
Email id :purnachanderrao_p@vaagdevi.edu.in

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ABSTRACT
The increasing penetration of solar photovoltaic (PV) systems into low-voltage distribution networks is limited by inverter-related constraints such as voltage rise, power quality degradation, and restricted hosting capacity. This work presents a simulation-based analysis of improved inverter control techniques aimed at enhancing the hosting capacity of grid-connected solar PV systems integrated with a Battery Energy Storage System (BESS). The proposed configuration consists of a PV array subjected to both steady-state and variable irradiance conditions to emulate realistic environmental variations. The variable PV output is processed through a DC–DC boost converter, whose output is stabilized using a DC-link capacitor. A bidirectional DC–DC converter interfaces the battery unit with the DC link, enabling controlled charging and discharging to mitigate PV intermittency. The inverter is connected to a single-phase 230 V grid through an LCL filter while simultaneously supplying local loads. Maximum Power Point Tracking (MPPT) is implemented for the PV-side DC–DC converter to ensure optimal energy extraction under varying irradiance. An Artificial Neural Network (ANN)-based controller is employed for inverter control to enhance dynamic response, voltage regulation, and power quality. Extensive MATLAB/Simulink simulations demonstrate that the proposed control strategy effectively improves power flow management, reduces grid stress, and increases PV hosting capacity under fluctuating generation conditions. The results validate the suitability of ANN-controlled inverters with BESS for future high-penetration PV-integrated distribution systems.

Keywords: Solar Photovoltaic System, Battery Energy Storage System, Inverter Control, Hosting Capacity, Artificial Neural Network, MPPT Algorithm, Grid-Connected PV.

I INTRODUCTION

The global transition towards sustainable and low-carbon energy systems has positioned solar photovoltaic (PV) technology as a pivotal contributor to modern power generation portfolios. Owing to its modularity, declining installation costs, and environmental benignity, solar PV has witnessed unprecedented deployment at both utility-scale and distributed levels across low-voltage distribution networks [1], [2]. Nevertheless, the escalating penetration of PV-based distributed generation has introduced a new set of operational and planning challenges for existing electrical infrastructures, particularly with respect to voltage regulation, power quality maintenance, system stability, and overall hosting capacity [3]–[5]. Hosting capacity, defined as the maximum level of distributed energy resources that can be accommodated within a distribution network without violating technical constraints or necessitating network reinforcements, has emerged as a critical performance metric for PV-integrated grids [6], [7]. Traditional distribution networks were originally designed for unidirectional power flow, wherein electrical energy is conveyed from centralised generating stations to passive consumers. The widespread integration of rooftop and small-scale PV systems disrupts this paradigm, resulting in bidirectional power flows, localised voltage rise, reverse power injection, and increased stress on grid-connected inverters [8]–[10].

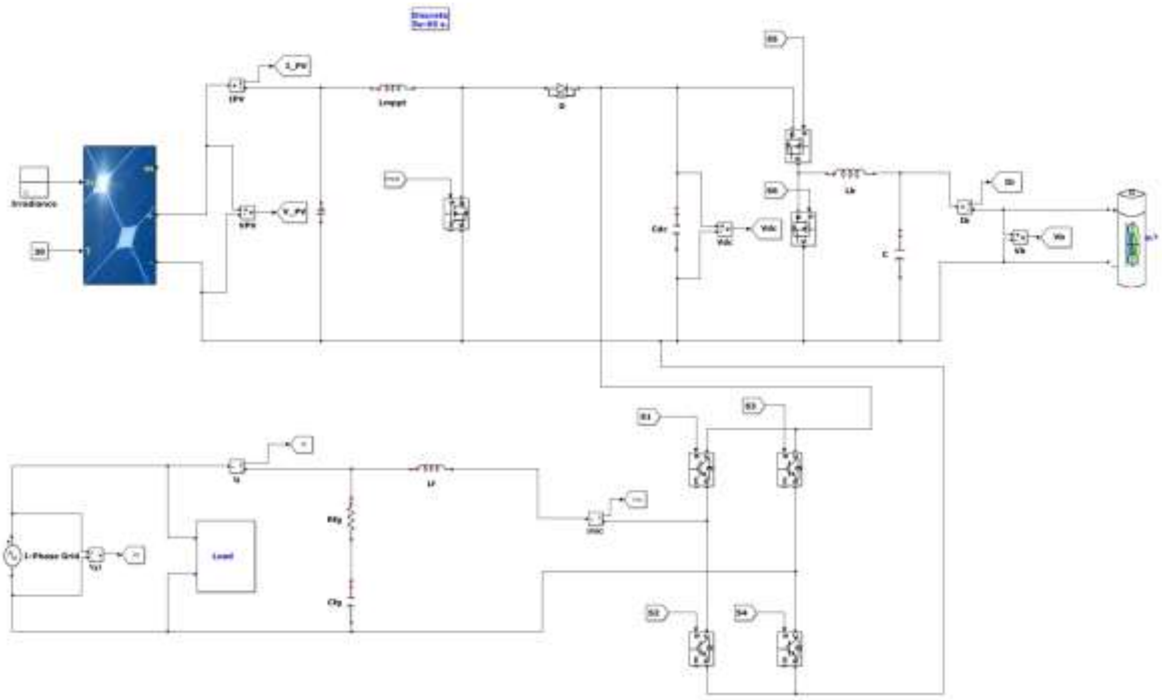


Fig. 1. MATLAB/SIMULINK circuit of the Proposed system

Among the various components in a grid-connected PV system, the power electronic inverter plays a decisive role in determining the interaction between renewable generation and the utility grid. Conventional inverter control strategies, typically based on proportional–integral (PI) regulators, often exhibit limited adaptability under rapidly varying irradiance and load conditions [11], [12]. Such limitations can exacerbate voltage fluctuations, harmonic distortion, and reduced power factor, thereby constraining the permissible PV penetration level within the network [13], [14]. Consequently, improving inverter control techniques has become a central research focus for enhancing PV hosting capacity without extensive grid reinforcements. The inherent intermittency of solar energy further compounds these challenges. Variations in solar irradiance due to cloud cover, seasonal changes, and atmospheric conditions lead to fluctuating PV output power, which directly impacts grid stability and power quality [15], [16]. These fluctuations are particularly problematic in weak or lightly regulated distribution networks, where even modest PV penetration can result in unacceptable voltage deviations and frequency disturbances [17]. To address this issue, Battery Energy Storage Systems (BESS) have been increasingly integrated with PV installations to provide buffering, energy balancing, and ancillary support functions [18], [19].
The integration of BESS with PV systems enables controlled energy exchange between the DC and AC domains, thereby mitigating the adverse effects of PV intermittency. Through appropriate control of bidirectional DC–DC converters, batteries can absorb excess energy during high irradiance periods and supply power during low generation intervals or peak demand conditions [20], [21]. This coordinated operation not only enhances self-consumption but also contributes to voltage

stabilisation, peak shaving, and improved grid compliance, all of which are essential for increasing hosting capacity [22]. In grid-connected PV–BESS architectures, the DC–DC boost converter and DC-link capacitor serve as vital interfacing elements between the PV array, battery system, and inverter. The boost converter ensures adequate voltage elevation from the PV array to the DC-link level, while the DC-link capacitor provides voltage stabilisation and decouples dynamic interactions between source and load [23], [24]. Effective control of these components is therefore indispensable for maintaining system stability under both steady-state and transient operating conditions.

Maximum Power Point Tracking (MPPT) algorithms are commonly employed to maximise energy extraction from PV arrays under varying irradiance levels. Classical MPPT techniques such as Perturb and Observe (P&O) and Incremental Conductance, although widely adopted, may exhibit oscillatory behaviour and reduced tracking accuracy during rapid irradiance changes [25], [26]. These shortcomings can propagate through the power conversion stages and adversely influence inverter performance and grid interaction, further limiting hosting capacity [27]. Recent advancements in intelligent control methodologies have introduced Artificial Neural Network (ANN)-based controllers as a promising alternative for power electronic applications. Owing to their non-linear mapping capability, adaptive learning characteristics, and robustness against parameter variations, ANN controllers have demonstrated superior performance over conventional linear controllers in complex, non-stationary environments [28], [29]. When applied to inverter control, ANN-based approaches can enhance dynamic response, improve voltage regulation, suppress harmonics, and ensure smoother power exchange with the grid [30].

In the context of PV-integrated distribution systems, ANN-controlled inverters offer a viable pathway to overcoming the inherent limitations of traditional control schemes. By intelligently regulating inverter output in response to real-time grid conditions, load demands, and energy storage states, such controllers can significantly reduce grid stress and enhance overall system hosting capacity. Furthermore, the synergistic coordination between ANN-based inverter control and MPPT-controlled DC–DC conversion enables optimal utilisation of available solar energy while maintaining stringent grid compliance requirements. Simulation-based analysis plays a crucial role in evaluating the effectiveness of advanced control strategies prior to practical deployment. MATLAB/Simulink provides a comprehensive platform for modelling complex PV–BESS–grid systems, allowing detailed assessment of dynamic behaviour, power quality indices, and control performance under diverse operating scenarios. Through systematic simulation studies, it is possible to quantify the impact of improved inverter control on voltage stability, power flow management, and hosting capacity enhancement. Against this backdrop, the present work focuses on the simulation analysis of an ANN-controlled grid-connected inverter integrated with a solar PV system and BESS. By subjecting the PV array to both steady-state and variable irradiance conditions, the proposed study aims to replicate realistic environmental variations and assess system performance accordingly. The adoption of intelligent inverter control, combined with energy storage support, is intended to demonstrate a practical and scalable solution for increasing PV hosting capacity in modern low-voltage distribution networks.

II LITERATURE SURVEY

The progressive integration of solar photovoltaic (PV) generation into electrical distribution networks has been the subject of extensive scholarly investigation over the past two decades. Early studies primarily focused upon the fundamental modelling and performance evaluation of grid-connected PV systems, highlighting their potential for decentralised energy production and emission reduction [1], [2]. However, as PV penetration levels increased, researchers began to observe significant technical challenges related to voltage regulation, reverse power flow, harmonic distortion, and protection coordination within low-voltage networks [3], [4]. These issues collectively contributed to limitations in PV hosting capacity, thereby constraining large-scale deployment. Several researchers have examined hosting capacity as a quantitative metric for assessing the maximum permissible level of distributed PV integration without violating statutory grid codes or operational constraints [5], [6]. It has been demonstrated that voltage rise at the point of common coupling is often the most restrictive limiting factor, particularly in radial distribution feeders with high R/X ratios [7]. Conventional mitigation approaches, such as network reinforcement and on-load tap changer adjustments, have been shown to be economically burdensome and operationally inflexible [8]. Consequently, attention has increasingly shifted towards inverter-based solutions as a more cost-effective and adaptive alternative.

The role of inverter control strategies in influencing grid performance has been widely documented. Traditional grid-following inverters employing proportional–integral (PI) controllers have been shown to provide acceptable steady-state operation under nominal conditions; nevertheless, their performance deteriorates under dynamic irradiance and load variations [9], [10]. Studies have reported that such controllers exhibit sluggish transient response, poor harmonic suppression, and limited robustness to parameter uncertainty, thereby aggravating voltage fluctuations and power quality issues [11]. These shortcomings directly impact the allowable PV penetration level within distribution systems [12]. To address these concerns, several authors have proposed enhanced inverter functionalities, including reactive power support, voltage droop control, and active power curtailment [13], [14]. Whilst these techniques have demonstrated partial success in extending hosting capacity, they often entail trade-offs in terms of reduced energy yield or increased control complexity [15]. Moreover, their effectiveness is highly dependent upon accurate system modelling and parameter tuning, which may not be feasible in heterogeneous distribution environments [16].

Parallel to inverter control advancements, the integration of Battery Energy Storage Systems (BESS) has gained considerable research attention as a means of mitigating PV intermittency and improving grid flexibility [17], [18]. Numerous studies have established that energy storage can effectively smooth PV output, reduce peak power injection, and provide ancillary services such as voltage support and frequency regulation [19]. The coordinated operation of PV and BESS has been identified as a key enabler for enhancing hosting capacity without resorting to infrastructure upgrades [20]. The interfacing of BESS with PV systems typically involves bidirectional DC–DC converters coupled through a common DC-link. Prior investigations have emphasised the importance of DC-link voltage regulation in ensuring stable power exchange between the PV array, battery unit, and inverter [21], [22]. Inadequate control of the DC-link has been shown to induce oscillations and degrade inverter performance, thereby adversely affecting grid interaction [23]. Hence, robust control of both unidirectional and bidirectional converters is deemed essential for reliable system operation.

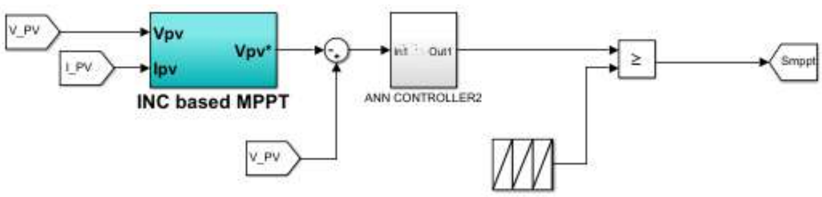
Maximum Power Point Tracking (MPPT) remains a cornerstone of PV system control, with extensive literature devoted to the development and refinement of MPPT algorithms. Classical techniques such as Perturb and Observe and Incremental Conductance have been widely implemented due to their simplicity and ease of realisation [24]. Nonetheless, several authors have highlighted their susceptibility to steady-state oscillations and mis-tracking during rapidly changing irradiance conditions [25]. Such deficiencies can propagate through the power conversion chain and exacerbate grid-side disturbances [26]. In recent years, intelligent and adaptive control methodologies have been proposed to overcome the inherent limitations of conventional control approaches. Artificial intelligence-based techniques, particularly Artificial Neural Networks (ANNs), have been successfully applied to PV modelling, MPPT, and inverter control applications [27]. The ability of ANNs to approximate non-linear functions and adapt to varying operating conditions has been shown to significantly enhance control accuracy and robustness [28].

Specific to inverter control, ANN-based strategies have demonstrated superior dynamic performance compared to PI-controlled counterparts. Studies have reported notable reductions in total harmonic distortion, improved voltage regulation, and faster transient response under fluctuating generation and load conditions [29]. These attributes are particularly advantageous in high PV penetration scenarios, where rapid system dynamics and uncertainty are prevalent. Furthermore, ANN controllers have been observed to reduce the need for precise system parameter identification, thereby enhancing practical applicability [30]. Simulation-based studies using platforms such as MATLAB/Simulink have played a pivotal role in validating these advanced control strategies. Through detailed modelling of PV arrays, power converters, storage systems, and grid interfaces, researchers have been able to systematically evaluate the impact of improved inverter control on hosting capacity enhancement. The consensus emerging from existing literature indicates that intelligent inverter control, when combined with BESS, constitutes a promising and scalable solution for addressing the technical challenges associated with high PV penetration.

Despite these advancements, the literature reveals that comprehensive studies explicitly linking ANN-based inverter control, coordinated BESS operation, and hosting capacity improvement remain relatively limited. Many existing works focus on isolated aspects such as power quality enhancement or energy management, without fully addressing hosting capacity as a holistic performance metric. This observation underscores the necessity for integrated simulation-based investigations that assess system-level impacts under realistic irradiance and load variations. In summary, the reviewed literature establishes a clear progression from conventional inverter control towards intelligent, adaptive strategies supported by energy storage integration. While significant progress has been achieved, further research is warranted to quantitatively demonstrate hosting capacity enhancement through coordinated ANN-controlled inverter operation in PV–BESS systems. Such investigations are essential for facilitating the large-scale deployment of solar PV within future low-voltage distribution networks.

III METHODOLOGY

The methodological framework adopted in this study is founded upon a detailed simulation-based representation of a grid-connected solar photovoltaic system integrated with a Battery Energy Storage System, implemented within the MATLAB/Simulink environment. The overall configuration comprises a photovoltaic array exposed to both steady-state and time-varying irradiance profiles in order to emulate realistic solar operating conditions. By introducing controlled variations in irradiance, the dynamic response of the system to fluctuating power generation is systematically examined. The electrical output of the PV array is interfaced through a DC–DC boost converter, whose primary function is to elevate the PV voltage to a level suitable for DC-link integration while ensuring continuous operation near the maximum power point. A suitably sized DC-link capacitor is employed to stabilise the intermediate DC voltage and to decouple the dynamic interactions between the source-side and grid-side converters, thereby enhancing system robustness under transient conditions.



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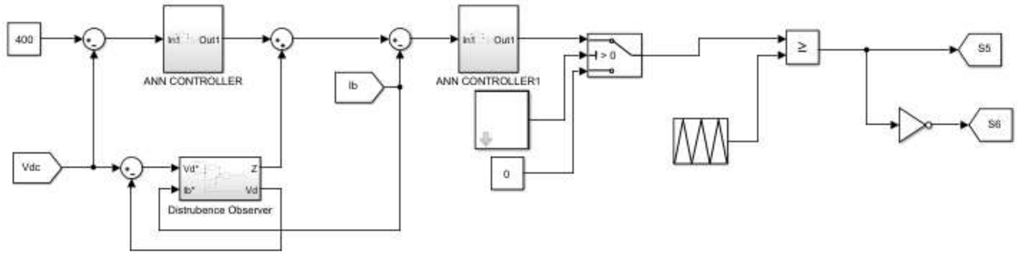

Fig.2 Control system for Boost and DC/DC Converter

The control of the PV-side DC–DC boost converter is achieved through the implementation of a Maximum Power Point Tracking algorithm, which continuously adjusts the converter duty cycle in response to variations in irradiance and temperature. This approach ensures optimal extraction of available solar energy while minimising steady-state oscillations around the operating point. Particular emphasis is placed upon maintaining stable converter operation during rapid irradiance transitions, as such conditions are known to induce power fluctuations that may propagate to the grid interface. The algorithmic parameters are carefully selected to balance tracking accuracy and dynamic response, thereby ensuring that the PV system contributes predictable and well-regulated power to the DC-link. The performance of the MPPT-controlled boost converter is evaluated under both uniform and non-uniform irradiance profiles to assess its effectiveness in mitigating the inherent intermittency of solar energy.

To address the variability of PV generation and enhance overall system flexibility, a Battery Energy Storage System is integrated via a bidirectional DC–DC converter connected to the common DC-link. This converter enables controlled charging and discharging of the battery in accordance with the instantaneous power balance between the PV source, grid, and local loads. During periods of excess solar generation, surplus energy is diverted to the battery, whereas during reduced irradiance or increased demand, stored energy is released to support the DC-link voltage. The bidirectional converter is governed by a control strategy that prioritises DC-link voltage regulation while respecting battery operational constraints such as state-of-charge limits and current ratings. This coordinated energy management mechanism serves to smooth power fluctuations and reduce stress on the grid-connected inverter, thereby contributing to improved hosting capacity.

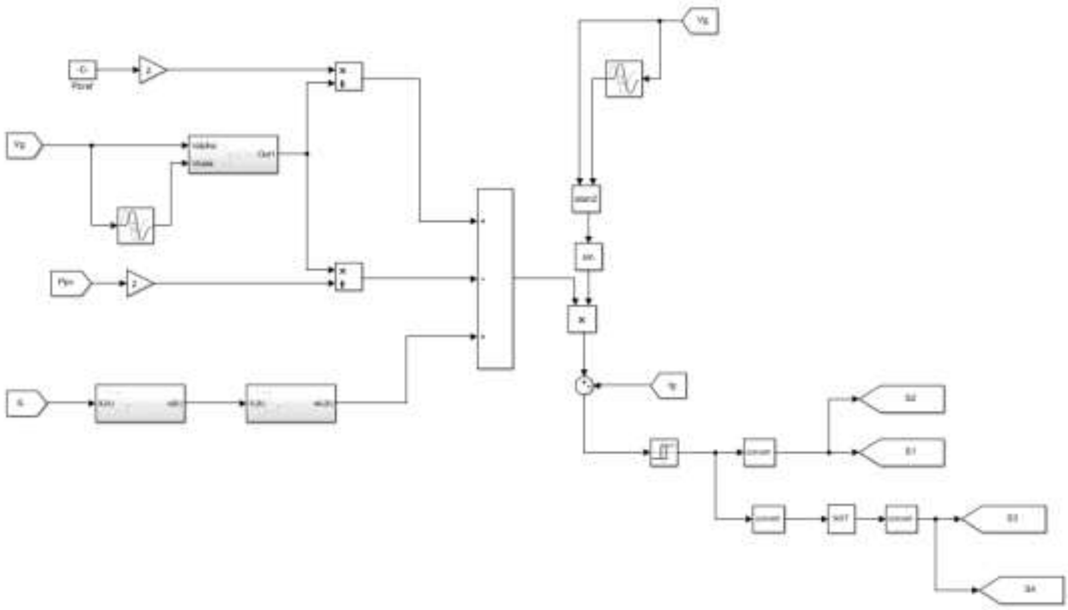

Fig.3 Control system for VSC

The grid-side power conversion stage consists of a single-phase voltage source inverter connected to a 230 V utility grid through an LCL filter. The inverter is responsible for converting the regulated DC-link power into high-quality alternating current suitable for grid injection and load supply. In this work, the inverter is controlled using an Artificial Neural Network-based controller, selected for its ability to handle non-linear system dynamics and adapt to varying operating conditions. The ANN controller is trained to generate appropriate gating signals that ensure precise regulation of output voltage and current while minimising harmonic distortion. By replacing conventional linear controllers, the ANN-based approach enhances dynamic performance during irradiance fluctuations, load changes, and battery charge–discharge transitions. The LCL filter is designed to attenuate high-frequency switching harmonics, ensuring compliance with grid power quality standards and reducing electromagnetic interference.

The effectiveness of the proposed methodology is evaluated through extensive time-domain simulations conducted under diverse operating scenarios. These include steady irradiance conditions, rapidly varying solar input, and combined PV–battery operation with simultaneous grid and load interaction. Key performance indicators such as DC-link voltage stability, inverter output quality, power flow balance, and grid current characteristics are closely monitored. Particular attention is devoted to assessing the system's ability to accommodate higher levels of PV power injection without violating voltage or power quality constraints, thereby providing an indirect measure of hosting capacity enhancement. Through comparative analysis of system behaviour under varying conditions, the methodology demonstrates the capability of intelligent inverter control combined with energy storage integration to achieve stable, efficient, and grid-compliant operation in high PV penetration environments.

IV PROPOSED SYSTEM

The proposed system operates as an integrated solar photovoltaic and battery-supported grid-connected power conversion arrangement, designed to accommodate variable renewable generation whilst maintaining stable interaction with the utility network. Electrical energy is initially harvested from the photovoltaic array, which is subjected to both steady and fluctuating irradiance conditions so as to reflect realistic environmental influences. Under constant irradiance, the PV array delivers a nearly uniform current and voltage output, whereas under variable irradiance, the generated current exhibits proportional fluctuations. These variations form the basis for evaluating the dynamic response of the system. The PV output is not directly connected to the grid but is first conditioned through appropriate power electronic stages, thereby ensuring that variations in solar input do not directly compromise grid stability or load performance.

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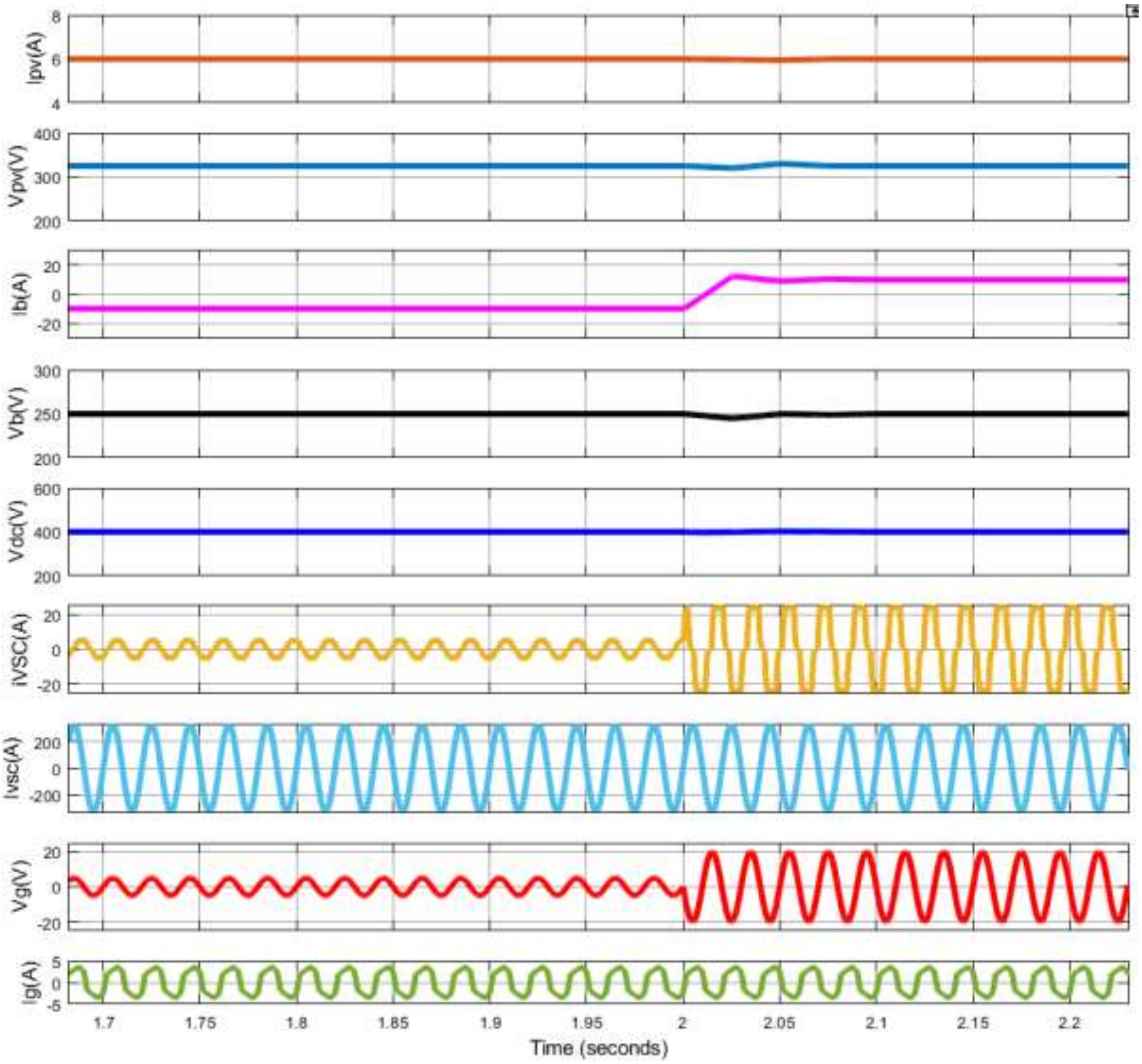

Fig. 4. Performance during the constant solar irradiance.

The direct current produced by the photovoltaic array is fed into a DC–DC boost converter, which performs voltage elevation and regulation to match the required DC-link level. The operation of this converter is governed by a Maximum Power Point Tracking mechanism, which continuously adjusts the switching duty ratio in accordance with changes in irradiance. Through this adaptive regulation, the PV array is maintained at its optimal operating point, allowing maximum extraction of available solar energy under all tested conditions. The boosted output is supplied to a DC-link capacitor, which functions as an energy buffer and voltage stabiliser. By absorbing transient fluctuations and smoothing the DC voltage, the DC-link capacitor decouples the source-side dynamics from the grid-side inverter operation, thereby ensuring uninterrupted and stable power transfer.

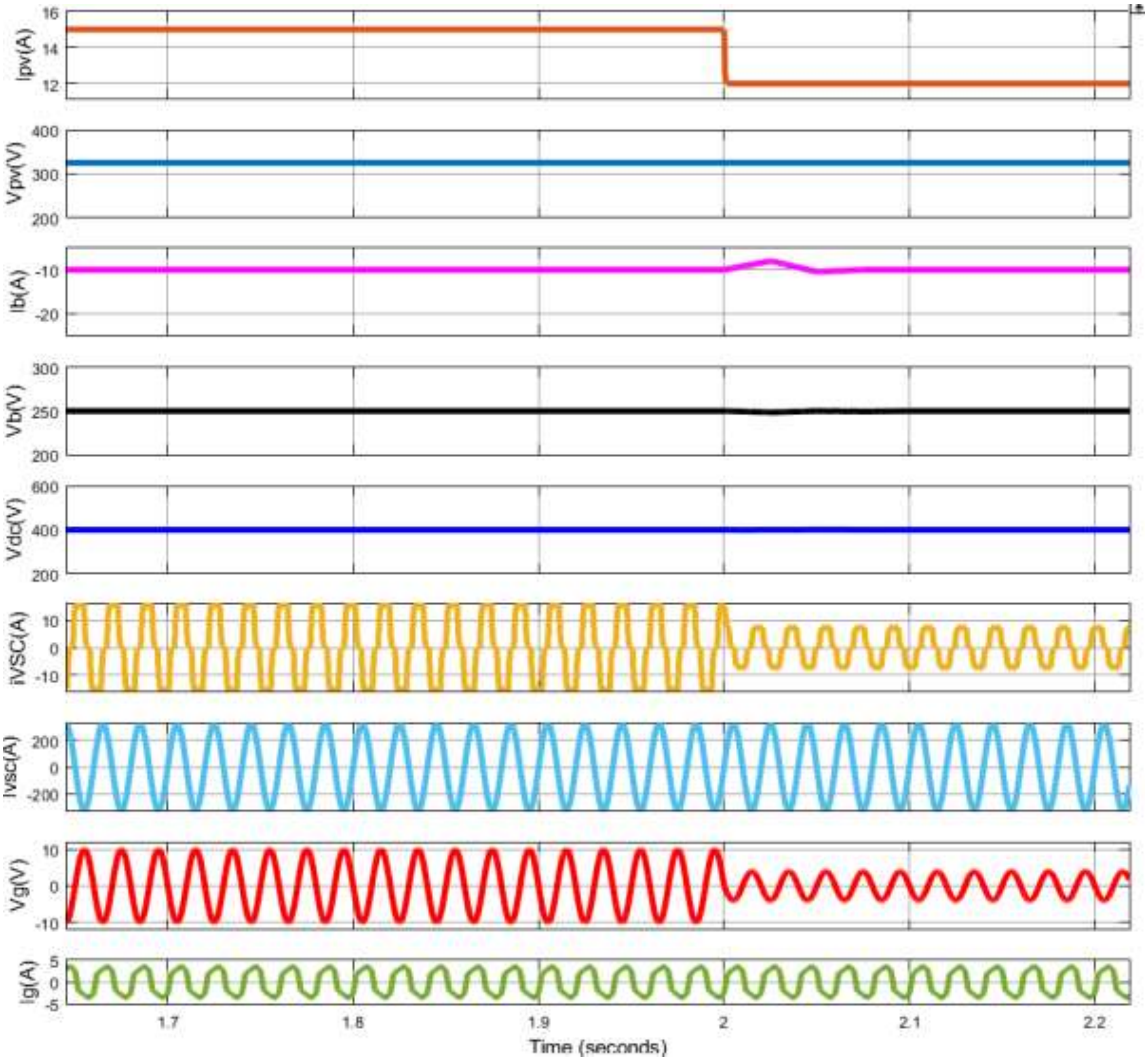

Fig. 5. Performance during the change of solar irradiance.

To further enhance system reliability and mitigate the inherent intermittency of solar generation, a Battery Energy Storage System is integrated at the DC-link through a bidirectional DC–DC converter. This converter facilitates controlled charging of the battery during periods of surplus PV generation and regulated discharging when solar power is insufficient or load demand increases. The bidirectional nature of the converter allows seamless transition between charging and discharging modes without interrupting inverter operation. By maintaining the DC-link voltage within prescribed limits, the battery system plays a crucial role in balancing power flow between the PV source, grid, and connected loads. This coordinated energy exchange reduces abrupt power variations and contributes to smoother grid interaction.

The inverter constitutes the principal interface between the DC subsystem and the single-phase 230 V utility grid. Its primary function is to convert the regulated DC-link power into alternating current that is synchronised with grid voltage and frequency. In the proposed system, the inverter is governed by an Artificial Neural Network-based controller, which dynamically adjusts switching signals in response to real-time system conditions. The ANN controller enables precise regulation of output current, effective suppression of harmonics, and improved transient response during irradiance fluctuations or battery charge–discharge events. An LCL filter is employed at the inverter output to attenuate high-frequency switching components, thereby ensuring that the injected current conforms to established power quality standards while simultaneously supplying local loads.

The coordinated operation of all subsystems enables the proposed configuration to enhance hosting capacity by reducing grid stress and improving power quality under high PV penetration scenarios. The PV array, MPPT-controlled boost converter, battery-supported DC-link, and ANN-controlled inverter function in unison to ensure balanced power flow and voltage stability across operating conditions. During periods of high solar availability, excess energy is either supplied to local loads or stored within the battery, thereby preventing overvoltage at the grid interface. Conversely, during reduced irradiance, stored energy supports inverter operation, maintaining continuity of supply. Through this integrated working principle, the proposed system demonstrates its capability to accommodate higher levels of solar PV integration whilst preserving grid reliability, operational stability, and compliance with distribution network constraints.

CONCLUSION

This work has presented a comprehensive simulation-based investigation into improved inverter control techniques aimed at enhancing the hosting capacity of grid-connected solar photovoltaic systems integrated with battery energy storage. By incorporating variable and steady irradiance conditions, the proposed system realistically captures the intermittent nature of solar energy and its influence on distribution network operation. The coordinated interaction between the MPPT-controlled DC–DC boost converter, the stabilised DC-link, the bidirectional battery interface, and the ANN-controlled inverter ensures effective power flow management under diverse operating scenarios. The inclusion of battery energy storage plays a decisive role in mitigating power fluctuations, supporting voltage regulation, and reducing grid stress during periods of excess or deficient solar generation. The application of an Artificial Neural Network-based inverter controller further improves dynamic response, harmonic suppression, and grid compliance when compared with conventional control approaches. Simulation results confirm that the proposed configuration enables higher levels of photovoltaic penetration without violating voltage or power quality constraints, thereby directly contributing to hosting capacity enhancement. Overall, the study demonstrates that intelligent inverter control combined with energy storage integration constitutes a viable and scalable solution for future low-voltage distribution networks with high renewable energy penetration.

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