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Integration and optimization of grid through ANN-based solar MPPT and battery

Kolli Sujran[1], Ankala Sirisha[1], Ganapaneni Swapna[1], Malligunta Kiran Kumar[1], Kambhampati Venkata Govardhan Rao[2]
[1]Department of Electrical and Electronics Engineering, Koneru Lakshmaiah Education Foundation, Vijayawada, India
[2]Department of Electrical and Electronics Engineering, St. Martin's Engineering College, Secunderabad, India

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ABSTRACT

Integration of solar energy into the grid is the most important aspect for achieving sustainable energy systems. This paper presents an artificial neural network-based maximum power point tracking (ANN-MPPT) system with battery storage to enhance grid efficiency. The proposed ANN-MPPT is dynamically adapted to the varying irradiance and temperature, hence ensuring optimal power extraction from the photovoltaic system. Excess energy is stored in batteries during high solar radiation and discharged when solar generation is low or grid demand is high, maintaining a stable power supply. This system enhances the grid performance in terms of supporting real-time energy exchange, load balancing, and grid stability. Efficient management of the energy fluctuations ensures reliability even at times of grid failures. Further, integration of ANN-based MPPT with battery storage reduces dependence on non-renewable sources and harmonizes solar energy utilization. It can be achieved through enabling smarter energy management and thus contributing to the resilience and efficiency of a grid for better integration of renewable energies. The proposed system can tolerate fluctuating grid demands apart from supporting the features of smart grid, hence viable for increasing stability and sustainability in the grid.

Corresponding Author:

Ganapaneni Swapna
Department of Electrical and Electronics Engineering, Koneru Lakshmaiah Education Foundation
Guntur, Vijayawada, Andhra Pradesh 522302, India
Email: ganapaneniswapna@gmail.com

1. INTRODUCTION

Fast growth in global energy demand, coupled with the concern over environmental pollution, quickened the pace toward renewable energy sources. Solar photovoltaic (PV) systems among these have gathered increasing attention, being sustainable, along with decreased costs of installations. However, the big challenges among the solar PV systems still are their dependability on the environment, considering that solar irradiance and ambient temperature directly affects their efficiency. The main intent in implementing maximum power point tracking (MPPT) techniques was, therefore, to enable one to harvest the maximum possible energy from PV arrays [1]. Traditional MPPT techniques, namely, perturb and observe (P&O) and incremental conductance, are usually not able to adapt quickly enough to the fast-changing environmental conditions, which results in power losses. Recent development in artificial intelligence, especially in artificial neural networks (ANN), has shown promising results in the improvement of MPPT efficiency, optimization of battery energy storage, and stable integration into the grid [2]. Sandeep and Mohanty [3] provided an ANN-trained energy management system for PV-powered EV charging with battery storage and grid integration. Results obtained show that the ANN-based control enhances the efficiency of the power flow between renewable sources and the grid significantly. A review by Villegas-Mier *et al.* [4] has highlighted the benefits of ANN-based MPPT in the optimization of the PV power system, mainly because it can adapt to real changes produced in the environment. Jyothy and Sindhu [5] developed the ANN-based MPPT algorithm for PV systems, showing improved tracking accuracy under fluctuating irradiance conditions. Rai *et al.* [6] have worked on ANN-based control schemes for power quality improvement in grid-connected PV systems, reducing voltage fluctuations and enhancing stability. In another study, Divyasharon *et al*. [7] optimized ANN-based MPPT models, achieving higher efficiency compared with conventional techniques. Mohammad [8] applied neural network controllers with direct current converters for the optimization of solar energy efficiency and showed good results on the reduction in power conversion losses. Khan and Mathew [9] designed an ANN-based MPPT controller for hybrid renewable energy systems to improve real-time power tracking significantly.

The rapid global rise in energy demand, coupled with environmental concerns over fossil fuel usage, has intensified the transition toward renewable energy systems. Among these, solar photovoltaic (PV) energy stands out due to its sustainability and declining installation costs. However, solar PV systems are inherently intermittent and heavily influenced by environmental factors such as irradiance and temperature, which leads to inconsistent power output and reduced efficiency. These limitations pose serious challenges in achieving stable power generation and reliable grid integration.

To address these issues, MPPT techniques have been developed to continuously adjust the PV operating point to maximize energy extraction. Conventional MPPT algorithms, such as P&O and incremental conductance, are widely used but suffer from slower response and tracking errors under rapidly changing conditions. Recent advancements in intelligent control have introduced ANNs as a viable alternative. ANNs offer adaptive learning capabilities, enabling more accurate and dynamic tracking of the maximum power point under varying conditions.

Apart from MPPT, ANN has also been applied in grid integration and V2G systems. Hakam *et al*. [10] analyzed PWM generator techniques for DC-AC conversion, an essential step in integrating the power generated by PV into the grid. Senapati *et al*. [11] proposed a hybrid control strategy of ANN and PID controllers for V2G systems, and better energy management was achieved. Nagendar and Raju [12] explored ANN-based battery management in V2G applications and showed improved grid reliability. Rao *et al*. [13] used ANN and PID control techniques in optimization for EV battery management in V2G applications, improving the life span and efficiency of the battery. MathWorks [14] reported the usage of MATLAB Simulink for modeling of power electronics and provided wide tools for simulation of ANN-based control systems. He *et al*. [15] had analyzed ANN-based control strategies for grid integration of EVs, referring to the potential of intelligent control techniques in renewable energy systems. Manousakis *et al*. [16] have simulated a V2G system using ANN and PID controllers in order to prove the effectiveness of the system during real-time grid interactions. Harshitha and Sujatha [17] worked on ANN-based fault diagnosis for smart grids with integrated solar power for ensuring reliable grid performance. The authors in [18] compared ANN and fuzzy logic-based MPPT techniques for solar grid applications where ANN shows superior tracking accuracy. Finally, Naveen and Manisha [19] addressed next-generation MPPT algorithms using neural networks, with the potential to enhance the efficiency of solar PV even more. The system has tackled some of the critical challenges pertaining to the utilization of renewable energy, such as intermittency, power stability, and grid reliability [20], for its viability in modern smart grids. To address the challenges of efficient solar energy integration, this paper presents a novel ANN-based MPPT system combined with battery storage [21]-[23]. The approach dynamically adapts to changing environmental conditions, enabling optimal energy extraction and utilization [24]-[26]. By improving grid reliability and supporting smart grid features, the proposed system offers a practical solution for enhancing renewable energy integration and long-term grid sustainability [27]. Table 1 will summarize the relevant literature.

The remainder of this manuscript is organized to clearly demonstrate the development, implementation, and relevance of the proposed ANN-based solar MPPT and battery-integrated grid system. Section 2: Methodology: This section presents the detailed design of the proposed system, including the solar PV setup, boost converter, battery energy storage system (BESS), and universal bridge inverter. It explains how the ANN-based MPPT algorithm was modeled and integrated to enable intelligent, real-time control of energy flow. Technical specifications and component parameters are also provided to establish the simulation environment and hardware configuration.

Section 3: Results and Discussion: Simulation results are presented to validate the system's performance under dynamic operating conditions. This section demonstrates how the ANN-based MPPT achieves stable DC voltage regulation, efficient battery charging behavior, and low-distortion AC output. Waveform analyses for voltage, current, and state of charge (SOC) support the claims of improved tracking speed, energy stability, and grid compatibility. These results directly confirm the practical effectiveness and superiority of the proposed solution.

Section 4: Conclusion: The key outcomes are summarized to highlight how the system meets the objectives defined in the introduction—optimal energy harvesting, reliable power storage, and seamless grid interaction. It also discusses potential future enhancements, such as hybrid renewable integration and AI-driven optimization, reinforcing the long-term relevance of this work. Each section builds upon the last to present a complete picture of the proposed system's design, operation, and advantages, clearly demonstrating its value in advancing intelligent renewable energy integration.

Table 1. Summary of relevant literature

Ref	Main contribution	Key findings
[1]	Evaluated ANN algorithm performance for MPPT in solar PV systems.	ANN provided faster and more accurate tracking than conventional MPPT under dynamic conditions.
[2]	Designed ANN-based MPPT in integrated PV system for EV charging and wireless transfer.	Showed improved power generation and efficient battery energy management.
[3]	Proposed ANN-trained energy management for PV-powered EV charging with grid link.	ANN control significantly improved power flow efficiency and responsiveness.
[4]	Reviewed ANN-based MPPT methods for PV optimization.	Confirmed ANN's superiority in real-time adaptation over traditional MPPT techniques.
[5]	Developed ANN-based MPPT for solar PV systems.	Demonstrated improved energy harvesting under fluctuating solar irradiance.
[6]	Used ANN-based control for power quality enhancement in grid-connected PV.	Reduced voltage fluctuation and enhanced grid stability.
[7]	Optimized ANN architecture for improved MPPT tracking efficiency.	Achieved higher MPPT efficiency than conventional methods.
[12]	Applied ANN for battery management in V2G systems.	Improved reliability and performance of grid-interactive battery storage.
[13]	Used ANN and PID controllers for EV battery optimization in V2G.	Enhanced battery lifespan and energy efficiency in smart grid applications.

2. METHOD

Despite significant advancements in solar PV systems and energy management strategies, several key challenges remain unresolved. Traditional MPPT techniques such as P&O and incremental conductance lack the adaptability needed to respond quickly to rapid fluctuations in solar irradiance and temperature, leading to suboptimal power extraction. Moreover, efficient coordination between MPPT control, battery energy storage, and grid integration is still a complex issue due to variable load demands and inconsistent solar generation. Existing systems often suffer from voltage instability, poor tracking efficiency, and high harmonic distortion in power conversion stages.

Another critical gap is the lack of a unified, intelligent control framework capable of dynamically managing energy flow across the solar array, battery, and grid in real time. Most conventional systems are not equipped to handle fast-changing environmental or grid conditions without performance degradation. Furthermore, ensuring grid compatibility with low total harmonic distortion (THD), maintaining power quality, and providing uninterrupted supply during grid failures remain important but under-addressed issues.

This manuscript addresses these challenges by proposing an integrated system using an ANN-based MPPT algorithm combined with battery storage and a universal bridge inverter. The system is designed to enhance real-time energy tracking, stabilize voltage, minimize THD, and improve overall reliability and grid performance. To address the aforementioned challenges, this work introduces several novel contributions that distinguish it from existing research. Firstly, we implement an ANN-based MPPT algorithm specifically trained to handle rapidly changing solar irradiance and temperature conditions, enabling faster and more accurate maximum power point tracking than conventional methods. Secondly, we integrate this intelligent MPPT approach with a BESS and a universal bridge inverter within a unified control framework—an area that remains underexplored in prior studies.

Unlike earlier works that focus on isolated components (e.g., MPPT or storage alone), our model ensures coordinated operation among the solar PV array, battery system, and the power grid. This integration allows for stable energy flow, dynamic power balancing, and reduced dependence on non-renewable sources. Moreover, we simulate and validate the system in MATLAB/Simulink under various operating conditions, demonstrating low total harmonic distortion (THD <2%), fast response time, and reliable grid synchronization—performance metrics not comprehensively addressed in previous literature. Overall, this study provides a scalable, intelligent energy management solution that not only enhances renewable energy utilization but also supports modern smart grid features and future-ready applications like EV charging and V2G integration.

2.1. Design of the system

The system shown in Figure 1 will be capable of efficiently integrating solar power generation, energy storage, and grid interaction. The model is created with MATLAB Simulink for real-time simulation and performance evaluation. The system can dynamically regulate the power flow between the solar array, battery storage, and grid to maintain stability and efficiency. It uses intelligent control algorithms to maximize energy harvest and distribution while responding to environmental variables and grid needs.

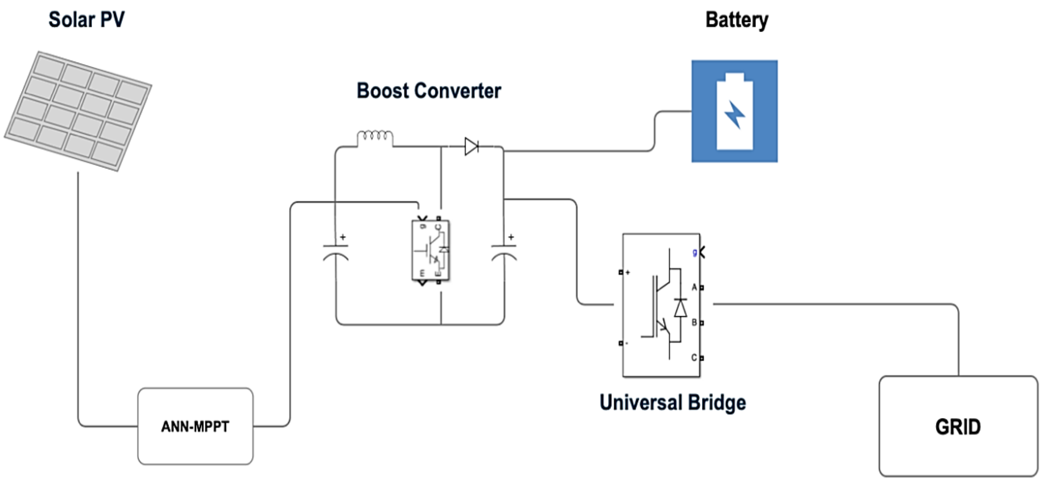

Figure 1. Architecture of the ANN-based PV solar MPPT system

2.2. System description

2.2.1. Solar PV system

A reliable and environmentally beneficial power source, solar energy is converted into electrical power through the use of photovoltaic systems in semiconductor-based solar cell technology. Among other factors, sun irradiation, temperature, and shade all affect how efficiently power is generated. Table 2 provides an overview of the solar PV system's primary design parameters. PV systems require very little maintenance and may be utilized in two ways: either stand-alone with related battery storage or integrated into the grid to guarantee energy supply reliability.

2.2.2. Boost converter

For renewable energy systems to maintain steady voltage levels, efficient power conversion is crucial. The main design parameters of a boost converter, a DC-DC converter that raises the input voltage while guaranteeing little power loss, are given in Table 3. It works by storing energy in an inductor while the switch is turned on, then releasing that energy to increase the output voltage when the switch is disabled. Factors that affect efficiency and voltage regulation, such as duty cycle, switching frequency, and component values, affect how well the converter performs.

2.2.3. Universal bridge

Smooth power conversion is vital for incorporating renewable energy into the system. A universal bridge, which uses semiconductor switches such as IGBTs or MOSFETs in an H-bridge topology, allows for efficient DC-AC or AC-DC conversion. It achieves steady voltage regulation and continuous power flow by carefully managing the switching process. Switching frequency, modulation techniques, and load circumstances all have an impact on power quality and system stability, determining the bridge's efficiency and performance.

Table 2. Design parameters of solar PV

Parameter	Value
Parallel strings	1
Series connected modules per string	15
Maximum power	250 W
Cells per module (Ncell)	60
Voltage at max power point Vmp	31.2 V
Current at max power point Imp	8.03 A

Table 3. Design parameters of boost converter

Parameter	Value
Inductor value	0.15636 mH
Input capacitor value	0.0397 F
Output capacitor value	0.0397 F

2.2.4. ANN-based MPPT

To deal with fluctuations in irradiance and temperature, improved tracking algorithms are required for efficient power extraction in solar PV systems. MPPT based on ANNs uses machine learning to dynamically adapt to changing environmental conditions, resulting in faster and more accurate power optimization than older approaches. The ANN-MPPT system uses many network layers to interpret real-time input data and provide optimal control signals, which improves energy efficiency and system performance. Its success is determined by elements like as training data quality, network architecture, and computing performance.

2.2.5. Battery energy storage system

Reliable energy management is critical for guaranteeing a consistent and dependable power supply in renewable energy systems. An energy storage system, with essential design parameters provided in Table 4, serves to regulate power variations by storing extra energy and releasing it when demand rises or generation falls. Its performance is determined by elements such as capacity, SOC, and nominal voltage, which all have an impact on reliability, longevity, and overall system efficiency.

Table 4. Design parameters of battery

Parameter	Value
Initial SOC	30%
Nominal voltage	24 V
Rated capacity	10 Ah
Cut-off voltage	18 V
Battery response time	2 s
Fully charged voltage	27.9357

2.2.6. Power distribution and stability

A well-balanced power distribution system is critical for ensuring a consistent and dependable electricity supply. Efficient energy management promotes smooth power flow by controlling voltage, frequency, and load distribution. To preserve synchronization and stability during power generation fluctuations, complex control techniques are required. Power quality, voltage regulation, and frequency control are critical components in ensuring seamless energy transfer and integration.

2.2.7. Model's operational workflow

Renewable energy systems rely on excellent energy management to offer steady power distribution. This article covers all aspects of solar power generation, energy storage, and grid connectivity. First and foremost, sunlight must be converted into DC energy using a solar photovoltaic array; the power produced is determined by solar irradiance and temperature. The ANN-based MPPT controller maximizes energy extraction by continuously adjusting the PV system's operating point. The boost converter regulates and boosts DC voltage to ensure effective power transfer, while its duty cycle is constantly modified in response to MPPT signals. Excess energy is stored in BESS, which balances supply and demand while optimizing charge-discharge cycles to maximize battery life. A universal bridge-based inverter converts regulated DC power to alternating current for grid integration; a PWM generator ensures smooth AC output. The system continuously monitors grid conditions and sends power to the grid or the connected loads as needed. If solar generation is insufficient, the stored battery energy meets the requirement. In the event of a grid outage, the technology ensures that power remains uninterrupted. The model will increase power reliability, grid stability, and renewable energy use, leading to an efficient and sustainable power network with dynamic energy flow control.

3. RESULTS AND DISCUSSION

3.1. PV system voltage regulation using ANN-based MPPT algorithm

Stable voltage regulation is critical to maximizing solar energy consumption in PV systems. In this system, a boost converter is employed to boost the voltage from the solar PV array, resulting in efficient power transmission. The ANN-based MPPT algorithm allows the system to respond fast to changing environmental factors such as sun irradiation and temperature. Initially, the voltage rises swiftly, reaching a high of nearly 2,800 V in 0.02 seconds, exhibiting the MPPT algorithm's rapid responsiveness. Following this peak, the voltage stabilizes at approximately 850 V, ensuring a consistent and optimal power output. This behavior demonstrates the effectiveness of the ANN-based MPPT in properly tracking the maximum power point and maintaining stable voltage regulation, while the boost converter plays an important role in increasing output voltage. Figure 2 shows the system's DC voltage output performance.

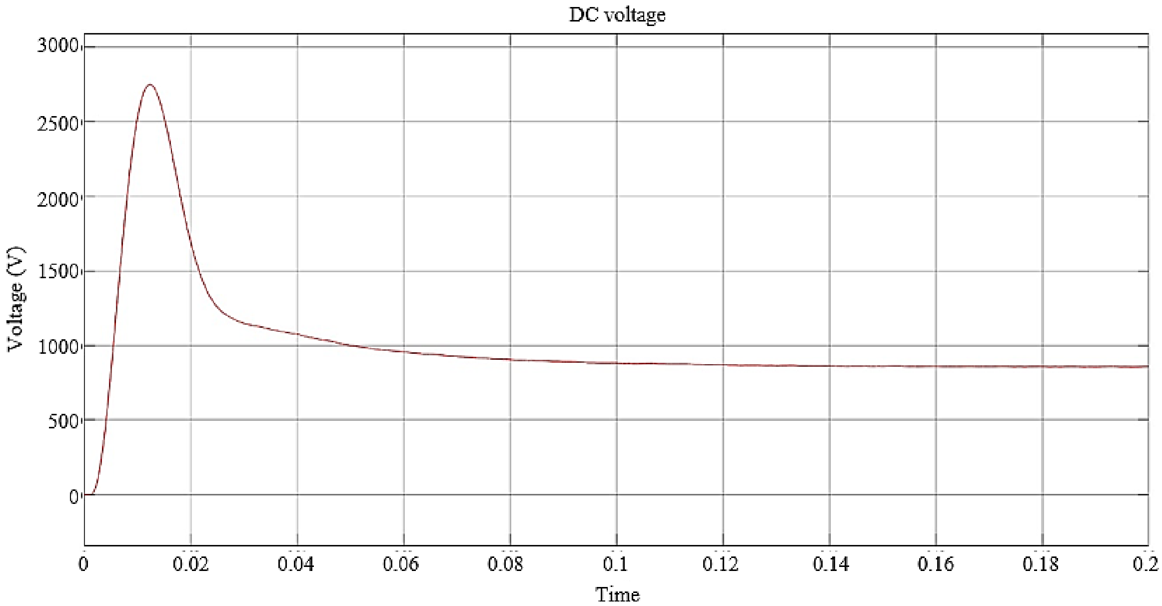

Figure 2. DC voltage characteristics

3.2. Battery parameters monitoring during PV-based charging

Reliable energy storage is critical to guaranteeing a stable power supply in renewable energy systems. In this system, the solar PV system's boosted DC voltage is used to charge the BESS, assuring smooth and reliable operation. The performance measurements are displayed as time-domain waveforms, which demonstrate how battery parameters change over time. As the charging process advances, the battery's SOC constantly climbs, generating a smooth, linear curve that suggests a continuous and efficient energy storage system. The battery voltage remains constant at roughly 200 V, while the current remains steady at around 10 A, as shown in Figure 3 with little variation. This stability maintains peak performance, allowing the battery to efficiently store surplus energy and release it when needed. The steady charging trend confirms the efficacy of the intelligent battery management system, which contributes to improved energy storage and grid integration.

3.3. Sinusoidal grid waveforms ensuring power quality and stability

To ensure effective grid integration, power delivery must be steady and of good quality. Figure 4 depicts the grid voltage and current waveforms, which are sinusoidal and well-regulated to ensure smooth power flow. The grid voltage remains consistent at around 230 V per phase, with no substantial changes like sags or swells, which is crucial for grid stability and the reliable operation of linked equipment. The grid current waveform has a balanced sinusoidal pattern with peak values of roughly 15,000 A and minimal harmonic distortion, reducing possible difficulties such as energy losses, equipment overheating, and interference with communication systems. These waveforms are smooth and distortion-free, confirming the proposed system's efficiency in integrating renewable energy and battery storage with the grid. During normal operation, the solar PV system provides power, while the battery supports the grid during peak demand or when solar generation is insufficient. The system maintains sinusoidal voltage and current waveforms, ensuring excellent power quality, grid stability, and effective energy use, making it a dependable solution for sustainable energy integration.

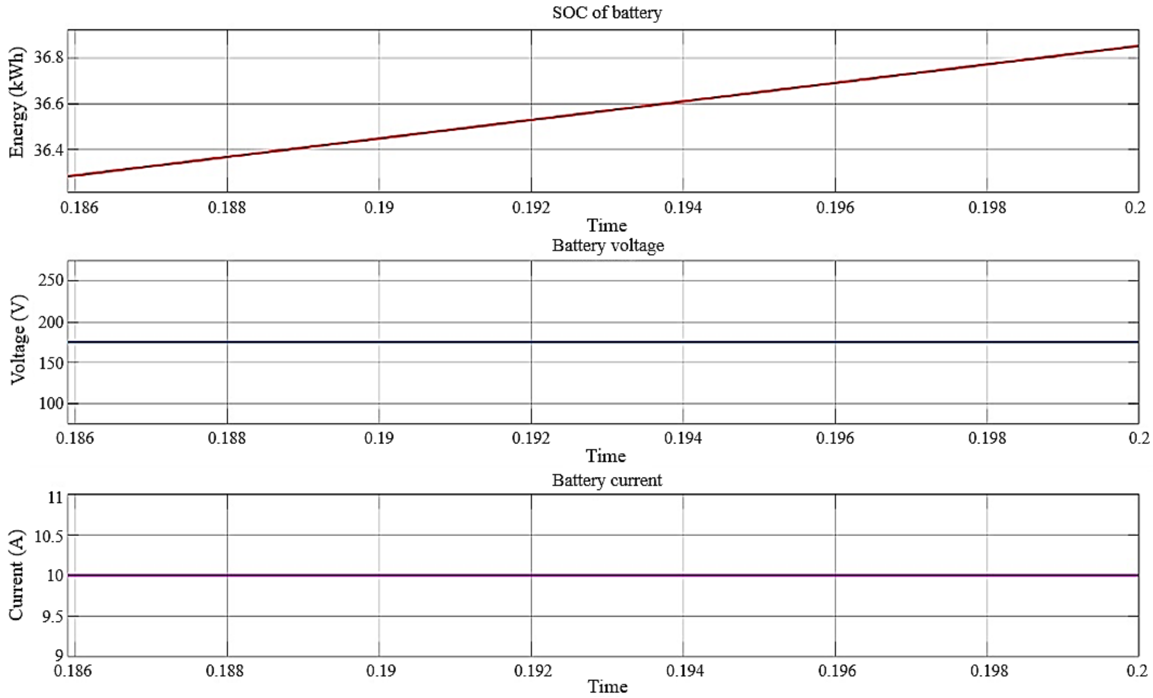

Figure 3. Battery characteristics

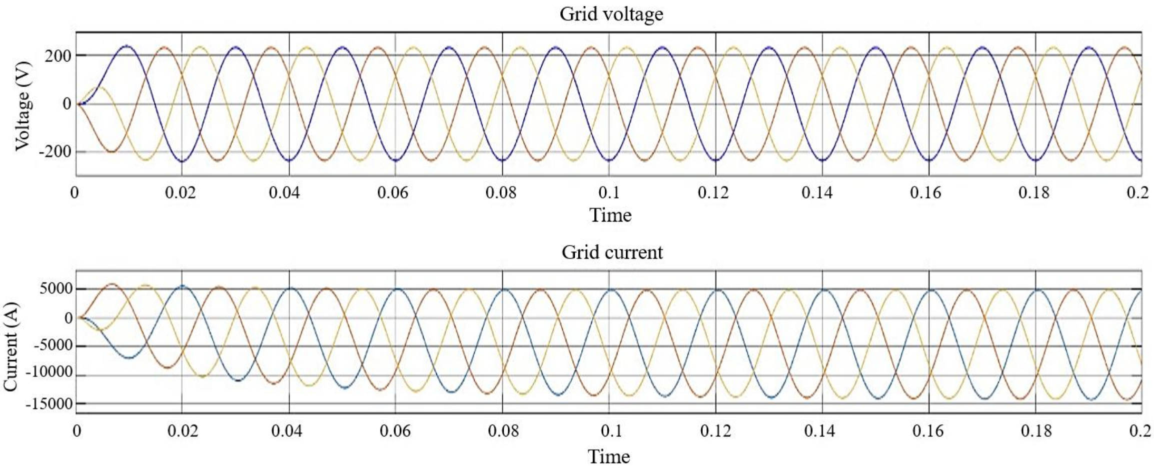

Figure 4. Three-phase grid voltage and current waveforms

3.4. Sinusoidal inverter waveforms ensuring grid compatibility

Effective power conversion is critical for integrating renewable energy into the grid while ensuring stability and efficiency. In this system, the inverter converts the solar PV and battery's enhanced DC voltage of around 850 V into an AC voltage of about 230 V per phase, assuring grid compatibility. The output voltage remains sinusoidal and stable, with total harmonic distortion less than 2%, preventing voltage fluctuations. In Figure 5, high power levels are used during testing and development of EV charging systems.

The inverter current waveform is balanced and sinusoidal, with peak values of 15,000 A, ensuring smooth power delivery. Furthermore, the inverter current helps to stabilize grid frequency during high demand periods, which improves overall reliability. The technology minimizes electromagnetic interference, lowers energy losses, and avoids electrical components from overheating, resulting in efficient power distribution and seamless renewable energy integration.

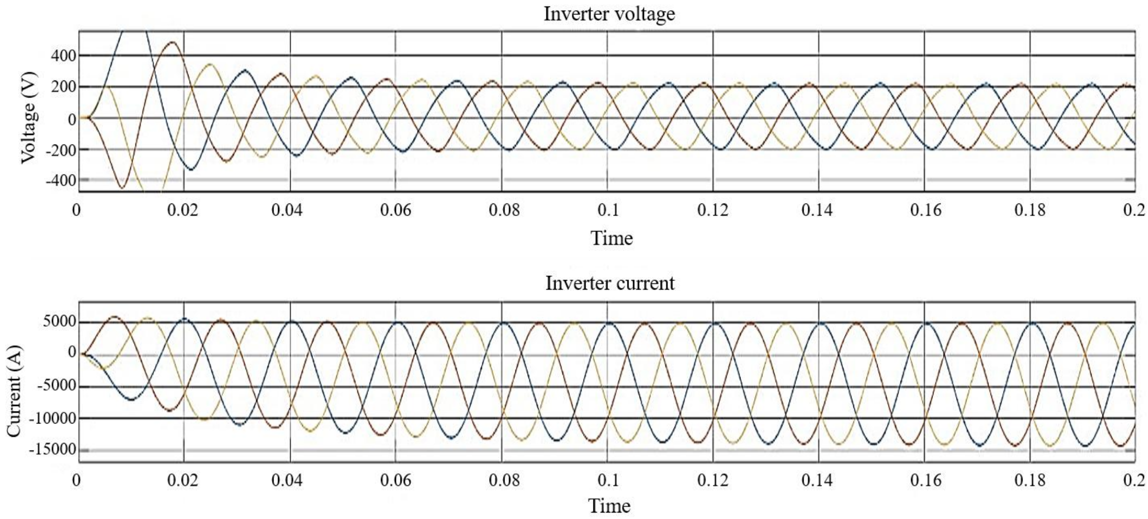

Figure 5. DC-AC conversion: voltage and current waveforms

The findings of this study have several important implications for the design and deployment of intelligent renewable energy systems. The successful implementation of an ANN-based MPPT algorithm demonstrates that machine learning can significantly enhance real-time energy tracking, outperforming traditional methods in both speed and stability. The integrated system—combining PV generation, battery storage, and grid interfacing—achieves low total harmonic distortion (THD <2%), efficient energy utilization, and consistent voltage regulation. These outcomes indicate that such intelligent control strategies can substantially improve power quality and reliability in grid-connected renewable systems. In the future, this framework can be extended to include hybrid renewable sources (e.g., wind or fuel cells), and integrated into electric vehicle (EV) charging infrastructure, smart microgrids, and V2G applications. Moreover, the modular nature of the proposed design allows for easy adaptation to larger-scale smart grid deployments, making it a valuable foundation for next-generation sustainable energy solutions.

3.5. Performance comparison of ANN-MPPT with conventional MPPT algorithms

To validate the effectiveness of the proposed ANN-based MPPT algorithm, a performance comparison was conducted against two widely used conventional techniques: perturb and observe (P&O) and incremental conductance (IC). All three algorithms were implemented and tested under identical environmental conditions in MATLAB/Simulink, with solar irradiance fluctuating between 600 W/m² and 1000 W/m², and ambient temperature varying from 25 °C to 40 °C. The comparison focused on key performance indicators, including response time to track maximum power point, steady-state oscillations, power extraction efficiency, and voltage stability. The results are summarized in the following Table 5.

As shown in Table 5, the ANN-MPPT algorithm outperformed both P&O and IC in every evaluated aspect. It achieved the fastest convergence to the maximum power point (within 0.02 seconds), while also minimizing oscillations during steady-state operation. The ANN-based system consistently maintained higher output power and demonstrated superior voltage stability, especially during abrupt irradiance changes.

These results highlight the superior adaptability of ANN in learning nonlinear relationships between environmental inputs and optimal operating conditions. Unlike traditional algorithms that rely on iterative logic and can struggle under rapid environmental shifts, the ANN model responds proactively by generating accurate control signals in real time. This ensures maximum energy harvesting and improved system reliability.

Table 5. Comparison of MPPT algorithms

Criteria	P&O	Incremental conductance	Proposed ANN-MPPT
Tracking speed (s)	0.06	0.045	0.02
Steady-state oscillations	Moderate	Low	Very low/negligible
Power extraction efficiency (%)	93.2	95.5	98.7
Voltage stability	Average	Good	Excellent
Adaptability to irradiance change	Moderate	Moderate	High

4. CONCLUSION

Integration of solar PV, battery storage, and grid interaction using an ANN-based MPPT algorithm, resulting in optimal energy use and system stability. The system meets its intended goals, as stated in the introduction, by effectively increasing DC voltage, controlling battery storage, and delivering high-quality AC power to the grid. The resulting waveforms of DC voltage, battery SOC, grid voltage, and inverter output confirm the system's efficiency, demonstrating stable operation, little harmonic distortion, and smooth power flow under different situations. The findings show that the ANN-based MPPT algorithm improves power tracking by responding dynamically to environmental changes to maximize energy extraction. The battery storage system is critical in balancing supply and demand, providing continuous power delivery even when solar is unavailable or during peak demand. The inverter output remains well-regulated, with sinusoidal voltage and current waveforms that promote power quality and stable grid operation. Future improvements could look at advanced AI-driven optimization approaches for better real-time decision-making, the integration of hybrid renewable sources to improve reliability, and the usage of next-generation battery technology for longer lifespans and higher efficiency. Furthermore, the system can be enhanced for real-world applications such as EV charging infrastructure and smart grid developments, resulting in a more sustainable and intelligent energy system.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Kolli Sujran	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓			
Ankala Sirisha	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓			
Ganapaneni Swapna	✓	✓			✓		✓	✓		✓		✓	✓	
Malligunta Kiran Kumar	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓			
Kambhampati Venkata Govardhan Rao	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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BIOGRAPHIES OF AUTHORS

Kolli Sujran is a final-year student pursuing a bachelor's degree in electrical and electronics engineering at KL University. Passionate about sustainable energy and smart technologies, she has actively contributed to research project focused on implementing integration and optimization of grid through ANN-based solar MPPT and battery. Her work reflects a keen interest in integrating AI with power systems to enhance grid efficiency and battery performance. Backed by solid technical skills and a deep curiosity for emerging technologies, she aims to advance clean energy solutions and pursue higher studies in the field. She can be contacted at email: sujran13@gmail.com.

Ankala Sirisha is a final-year student pursuing a bachelor's degree in electrical and electronics engineering at KL University. She holds a diploma in electrical and electronics engineering from MBTS Government Polytechnic. Throughout her academic journey, she has actively engaged in technical projects, notably working on the integration and optimization of grid through ANN-based solar MPPT and battery. With a strong foundation in electrical systems and a passion for innovation, she aspires to contribute to the advancement of sustainable energy technologies. She can be contacted at email: sirishaankala123@gmail.com.

Ganapaneni Swapna completed her M.Tech. from JNTU Kakinada. She has completed her Ph.D. from KL Deemed to be University. Her research interests encompass power systems, with a particular focus on the energy management of electric vehicles within smart grid environments. She is also actively engaged in exploring the optimization of distribution systems, aiming to enhance grid reliability and efficiency. She has published research papers in various international journals. Now, she is working as assistant professor in EEE Department, KL University, Guntur, Andhra Pradesh, India. She can be contacted at email: ganapaneniswapna@gmail.com.

Malligunta Kiran Kumar is working as an associate professor in the Department of Electrical and Electronics Engineering, Koneru Lakshmaiah Education Foundation (KL Deemed to be University) College of Engineering, has about 16 years of teaching experience. He received his B.Tech. degree in electrical and electronics engineering with distinction from JNTU Hyderabad and M.E. degree in power electronics and drives with distinction from Anna University, Chennai. He received Ph.D. degree in electrical and electronics engineering from KL Deemed to be University, Guntur, Andhra Pradesh. He has published more than 70 Scopus, SCI, and ESCI research papers in refereed international journals and 16 research papers in the proceedings of various international conferences and three patents in his credit. He received the best teacher award five times, and his research interest includes switched reluctance machines, power electronics, electric vehicles, and control systems. He is an active member of SIEEE, MISTE, and IEI. He can be contacted at email: kiran.malligunta@gmail.com.

Kambhampati Venkata Govardhan Rao is currently working as assistant professor in Electrical and Electronics Engineering Department, St. Martin's Engineering College, Dhulapally, Secunderabad, Telangana. He holds Doctor of Philosophy degree from Koneru Laxmaiah Educational Foundation (KL Deemed to be University), Vijayawada Campus. He completed his Master of Technology at Abdul Kalam Institute of Technological Sciences, Vepalagadda, Kothagudem affiliated to JNTU Hyderabad and Bachelor of Technology at Abdul Kalam Institute of Technological Sciences, Vepalagadda, Kothagudem affiliated to JNTU Hyderabad. He has more than 09 years of teaching experience. He published over 25 papers in various reputed journals, attended 10 conferences with ISBN number along with 04 best paper awards, and published 06 Indian Patent. He guides 05 M.Tech. students and 18 B.Tech. students. He is also a life member in Indian Society for Technical Education and Indian Association for Engineers. His areas of research include power electronics, power systems, converters, and electric vehicles. He can be contacted at email: kv.govardhanrao@gmail.com.