Smart hybrid power management system in electric vehicle for efficient resource utilization with ANN

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ABSTRACT

The novel hybrid power system integrating energy storage, electric vehicle (EV) charging infrastructure and renewable energy sources improve sustainability and resilience. This work proposes a power management system controlled by artificial intelligence for EV charging infrastructure. The battery's state of charge (SoC) is continuously monitored by artificial neural network (ANN) algorithm improves the health of the battery and efficient operation of the system. The buck boost DC-DC converter performs dynamic switching mechanism, which adjusts to changing solar conditions and energy demands, guarantees a steady power supply. Depending on the situation, the ANN algorithm used in the battery's SoC control mechanism decides whether to priorities the EV charging or the inverter to supply the grid. The work is evaluated with the MATLAB simulation for different conditions and results are compared with different controllers such as PI, PID, and ANN. The experiment performed uses internet of things (IoT) for transferring the data from the EV motor, acts as an input for the controller to perform the novel hybrid power management operation with cloud technology. The experimental prototype evaluates the results connected to the photovoltaic (PV) system and battery management system (BMS) which lowers reliance on non-renewable resources, increases overall energy efficiency, and ensures a steady supply of power under a various condition.

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1. INTRODUCTION

An ecologically friendly and sustainable transportation system is one that is largely dependent on electric vehicles (EV). Their significance goes beyond the automobile sector; they have a worldwide impact on energy policy, urban development, and technological innovation [1]-[5]. EVs that have the capacity to charge in both directions that can be used as portable energy storage devices. EV batteries have the capacity to store extra energy from the source when connected to the renewable energy sources. The stored can be utilized during times of low energy demand or when the production of renewable energy surpasses the usage. When the EVs are connected to the grid system they can also the release stored energy back into the grid to enhance the supply during periods of high demand or grid instability [6]-[8]. Vehicle to home (V2H) and vehicle to grid (V2G) have enormous potential to improve the electrical grid's resilience, sustainability, and flexibility [4]. However, V2G capabilities are anticipated to become more significant in the future energy environment as the technology advances and EV penetration rises [9]-[12]. To optimise charging schedules depending on variables including energy pricing, grid circumstances, and customer preferences, intelligent charging infrastructure interfaces with EVs and the grid is needed [13]-[16]. By doing this, it is ensured that EV charging is synchronised to minimise expenses, lessen grid load, and optimise the utilisation of renewable energy sources [17]-[20].

Cutting-edge surveillance systems optimise charging and discharging schedules to extend battery lifespan by continuously evaluating the efficacy and overall wellness of EV batteries [21]. The integration of the ANFIS controller-based cascaded bidirectional DC-DC converter with the drive system allows for efficient energy conversion and precise speed control in applications such as EVs, renewable energy integration, or industrial automation. ANFIS controller calculates the appropriate control signals to adjust the motor drive system, ensuring precise speed control and dynamic response [22]. The need of predictive control, optimised resource allocation, fault detection, adaptive control, and integration with IoT and smart grid technologies offered by the artificial neural networks (ANN), improve system intelligence, resilience and efficiency. Real-time such as demand-side control devices, energy storage systems, renewable energy generators and grid conditions can be analysed by ANN algorithms [23]-[26]. The ANN-based control optimizes the charging and discharging of batteries based on, load requirements and grid conditions to minimize costs and maximize self-consumption of solar energy [27]. This work also optimizes resource utilization by implementing an intelligent algorithm to select the condition to operate the EV charging or to supply the grid and dynamically manage power distribution, ensuring efficient energy utilization and resilience with the bidirectional DC-DC converter. The literature survey from the previous work mentions that, despite of advancements in EVs and their integration with renewable energy, still several research gaps remain. The work investigates the hybrid power management system is capable of seamlessly transitioning between renewable energy sources and mains power, guaranteeing a reliable energy supply under varying conditions. The work is evaluated with the MATLAB simulation for different conditions and results are compared with different controllers such as PI, PID, and ANN. The experiment performed uses IoT for transferring the data from the EV motor to an input for controller to perform the novel hybrid power management operation with cloud technology. The proposed work is categorising; (i) introduction, (ii) proposed system design, (iii) experimental analysis of the proposed system with PI, PID controller, (iv) experimental analysis of the proposed system with ANN controller, (v) experimental analysis of the proposed system with prototype, and (vi) conclusion.

2. RESEARCH METHOD

The significant progress in EV technology and their integration with renewable energy systems, several critical research gaps persist. One key area that requires further investigation is the scalability of V2G and V2H systems, particularly concerning their long-term effects on EV battery health. The frequent bidirectional charging and discharging impact battery lifespan and performance is essential for the widespread adoption of these technologies. Additionally, there is a need to optimize intelligent charging infrastructure to adapt to real-time grid dynamics, ensuring that EVs can seamlessly interact with the grid and renewable energy sources. Furthermore, the practical implementation of advanced control systems like adaptive neuro-fuzzy inference system (ANFIS) and ANN in real-world scenarios is still underexplored. Research is needed to refine these systems for effective fault detection, adaptive control, and seamless energy management.

2.1. System design and setup

The Figure 1 shows the flow of the system and the initial phase encompasses the installation and configuration of the photovoltaic (PV) source, establishing a robust framework for harnessing solar energy. This involves selecting suitable PV panels, DC-DC converter circuit, inverters, and associated components to maximize efficiency and output. The PV panels connected to charge the battery system. A maximum power point tracking (MPPT) algorithm was incorporated into the system to maximize the energy harvested under varying solar irradiance conditions to ensure the PV system operated at its peak efficiency. The DC-DC converter used here is buck converter used to reduce the voltage at working conditions between battery connected to the PV system and EV battery. A buck converter was implemented to regulate the voltage between the PV panels and the battery system. The converter design includes a pulse width modulation (PWM) controlled switching circuit, and feedback control to maintain stable voltage reduction across different load and irradiance conditions. The selection of appropriate battery technologies, such as lithium-ion or advanced lead-acid batteries, is crucial to ensuring efficient energy storage. This phase involves detailed considerations of battery capacity, voltage, and charging characteristics, aligning with the system's overall energy needs. Lithium-ion batteries were chosen due to their high energy density, efficiency, and long cycle life. The battery bank was sized to match the system's energy requirements, taking into account load demands, solar generation capacity, and desired autonomy. The detailed considerations of battery charging and discharging characteristics need to be analyzed, including incorporating a battery management system (BMS) to monitor the state of charge (SoC) and ensure safe operation.

A bi-directional grid-tied inverter is used to convert stored DC energy from the batteries into AC for household use or to feed back into the grid in case of VV2G and V2H. The inverter was selected based on its compatibility with the PV system, battery storage, and grid connection. The inverter also supported seamless switching between grid and off-grid modes to ensure uninterrupted power supply. The control circuit, including microcontrollers and relays, was designed to manage power flow between different sources. The relays were programmed to execute switching commands based on signals from the microcontroller, which monitored real-time data such as solar output, battery SoC, and load demand.

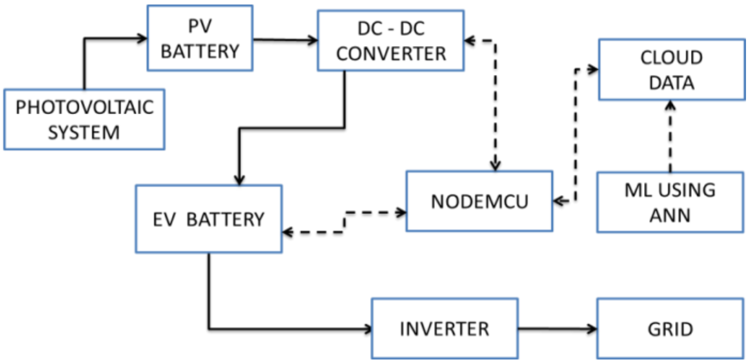

Figure 1. Proposed block diagram

2.2. ANN algorithm, control implementation, and system integration

An ANN algorithm was developed and trained using historical data, including solar irradiance patterns, load demands, and battery SoC levels. The ANN was designed to predict energy generation and consumption patterns, allowing it to make real-time decisions on power distribution. The control logic was implemented on a microcontroller, which interfaced with sensors and relays. The microcontroller used inputs such as PV output, battery SoC, and grid status to execute the ANN's decisions. It adjusted the power flow in real time, ensuring a seamless transition between energy sources while minimizing losses. The relays used in the system ensure smooth transitions and controls the prioritization of power outputs by effectively operating with commands from controller circuit. Throughout the implementation, rigorous testing and validation procedures are conducted to assess the system's performance under different scenarios, including varying solar conditions, fluctuating energy demands, and charging patterns for EVs. Continuous monitoring and adjustments are made to refine the algorithm and optimize the overall system efficiency. This iterative process allows for the identification and resolution of any technical challenges, ensuring the proposed hybrid power system operates seamlessly and effectively in real-world conditions. The hardware setup includes sensors for monitoring parameters like solar output, battery voltage, and current flows, all interfaced with the microcontroller for real-time data acquisition. The ANN-based control algorithm was embedded into the microcontroller, and a user interface was developed for system monitoring and manual control. This interface provided live feedback on system performance and allowed for manual override in case of emergencies.

2.3. Analysis, testing, and validation

The testing isconducted using MATLAB/Simulink to simulate various operational scenarios. The simulations tested the system's response to varying solar conditions, load changes, and EV charging patterns. Key performance indicators such as energy efficiency, SoC stability, and power quality were evaluated to ensure the system met design specifications. After successful simulations, the system was deployed in a controlled environment for real-world testing. The system's performance is monitored under different weather conditions, varying load demands, and fluctuating EV charging requirements. The data on energy generation, storage efficiency, and the effectiveness of the ANN in managing power flow are collected. The data is analyzed to assess the ANN's performance in optimizing energy distribution and maintaining system stability. Statistical analysis is conducted to evaluate the system's reliability and identify areas for further refinement.

3. EXPERIMENTAL ANALYSIS

This study investigated the implementation of a hybrid power system integrating PV panels, battery storage, and EV charging with an ANN-based energy management algorithm. While previous research has explored hybrid power systems and their control strategies, there is a gap in understanding how intelligent energy management can optimize power distribution between PV, batteries, and the grid in real-world dynamic conditions. In this section, it is explained the results of research and at the same time is given the comprehensive discussion. The dynamics of the system, including the behaviour of batteries, PV system connected and their interaction is analysed.

- Proposed system with PI, PID controller, and ANN

This simulation shown in Figure 2, aimed to determine the optimal mode of operation of the system with PI, PID algorithm, represents an intelligent approach to optimize energy utilization by dynamically determining whether to operate from a battery or the main power supply. This system utilizes real-time data and feedback mechanisms to make decisions that enhance efficiency and sustainability. This simulation of proposed system shown in Figure 3, determines the optimal mode of operation between battery and main power supply. This advanced system employs AI algorithms here used is ANN to continuously analyze various factors, such as electricity demand, battery SoC. The ANN algorithms continuously learn and adapt to changing usage and make the power management system more responsive and efficient over time. The large dataset such as containing various battery parameters such as voltage, current, temperature, SoC are analysed with the ANN. The effectiveness of the ANN algorithm for battery management depends on factors such as the quality of the dataset, the design of the neural network architecture, and the suitability of the chosen performance metrics.

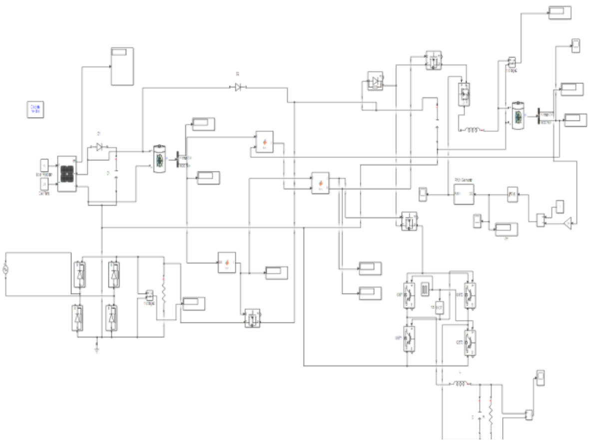

Figure 2. PI, PID based simulation of the proposed system

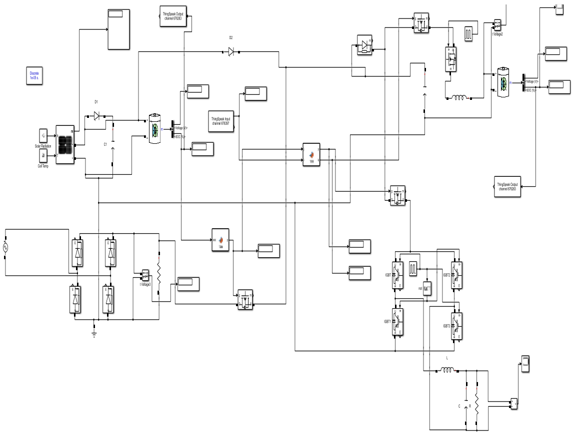

Figure 3. ANN based simulation of the proposed system

The output voltage from the main supply range fluctuates between 230 V to -230 V which indicates that the electrical supply is derived from the open loop connection. EV battery is in the process of charging and the Figure 4 indicates that the EV battery is less than 50%, it suggests that the SoC of the battery is below half of its full capacity. From the Figure 5 it is noted that output voltage range fluctuating between 20 V to -20 V indicates that the electrical supply is derived from the battery connection using PI and PID controller. EV battery is in the process of discharging and the Figure 6 indicates that the EV battery is greater than 50%, it suggests that the SoC of the battery is above half of its full capacity using PI and PID controller.

ANN has been employed to determine the mode of operation, and it outputs a voltage range fluctuating between 20V to -20V, it suggests that the electrical supply is originating from the battery connection and the Figure 7, indicates that the EV battery is less than 50%. From the Figure 7, observed that the ANN controller response of proposed controller is settled at 0.01 sec without any overshoot. The ANN response is made up with a fine response and without any oscillations compared with the PI PID controller responses. The Table 1 illustrates the performance evaluation of DC-DC converter using MATLAB with the PI, PID, and ANN. The result shows that ANN operated with the short duration to perform the task.

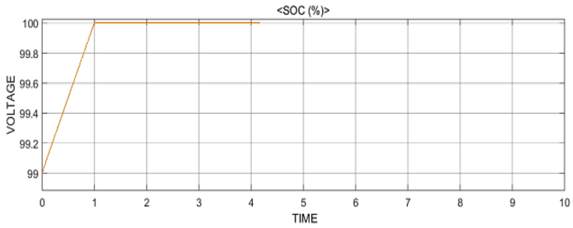

Figure 4. Battery state-of-charging

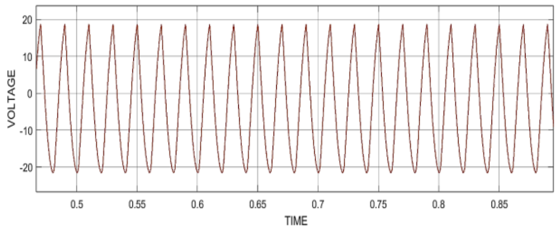

Figure 5. Inverter output

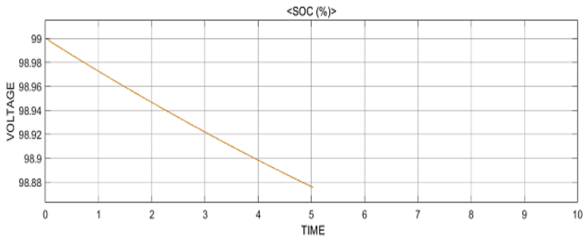

Figure 6. Battery state-of-charging

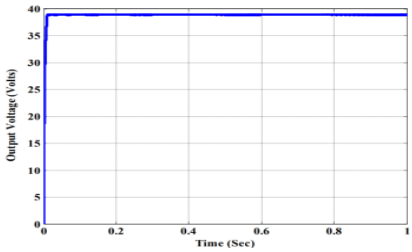

Figure 7. Output voltage of proposed converter with ANN controller

Table 1. Performance evaluation of DC–DC converter using MATLAB with different controller

Controller	Voltage		Time	
	Maximum	Minimum	Maximum	Minimum
PI	19 V	-19 V	0.09 Sec	0.08 Sec
PID	18 V	-17 V	0.06 Sec	0.05 Sec
ANN	20 V	-20 V	1.001 Sec	0.9 Sec

4. RESULTS AND DISCUSSION

The system is the resembles V2H system that allows the use of electricity already stored in the EV to power the household, while the V2G system supports selling the electricity already stored in the EVs to the grid. The manner of operation is determined by ANN. The PV battery will investigate if the battery SoC is 50% or above then it investigates EV battery. If less than 50% is present in EV battery, PV battery exclusively feeds EV battery; otherwise, EV battery will deliver energy to the grid. The primary source charges the EV battery and provides electricity to the consumer if the PV battery SoC is less than 50%.

The Figure 8, below illustrates that the BMS hybrid mode control with ANN. The work shown has major benefits in terms of improving overall performance and optimizing energy economy. The hybrid strategy efficiently balances energy consumption, increases battery life, and boosts the dependability of energy storage systems by smoothly merging machine learning algorithms with conventional BMS. The proposed hardware system shown in Figure 9, connected to the solar system and the entire system is trained with the ANN by the different data set values. The ANN collects data from the battery and process the values collected and train them accordingly to perform the conditions.

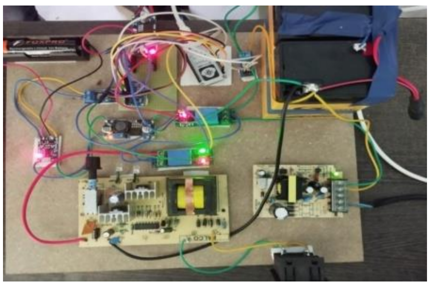

Figure 8. Hardware diagram

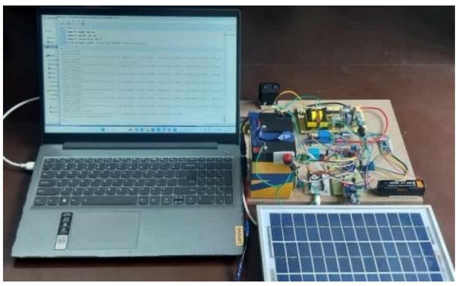

Figure 9. Proposed system ANN data training connected with PV system

- Condition 1 and 2

The SoC of the lead acid battery which is charged by solar energy and the lithium-ion battery in the electrical vehicle is 50% above is shown in Figure 10. The energy from the both battery delivers the DC current to the inverter. The DC current is converted into AC supply and it is given to the grid to supply the home. The SoC of the lead acid battery if it is 50% below, so the ANN shifts to main supply and if the SoC of the EV battery is 50% shown in Figure 11, below then the EV battery gets charged at the same time from the main supply. If it exceeds then the energy from the EV battery is given to the inverter and supplied to the mains.

Figure 10. Experimental results of condition 1 in prototype

Figure 11. Experimental results of condition 2 in prototype

This work investigated the implementation of a hybrid power system integrating PV, battery storage, and EV charging with an ANN-based energy management algorithm. While previous research has explored hybrid power systems and their control strategies, there is a gap in understanding how intelligent energy management can optimize power distribution between PV, batteries, and the grid in real-world dynamic conditions. The experimental results showed that the ANN-based control algorithm effectively optimized energy distribution within the hybrid system. During periods of high solar irradiance, the system stored excess energy in the batteries, allowing for efficient energy usage during low irradiance periods. The ANN successfully managed power flow by prioritizing renewable energy sources, reducing reliance on grid power by approximately 30% compared to traditional control methods. The system maintained a stable SoC for the batteries, ensuring a consistent supply for EV charging and household demands. The work indicates that the integration of an ANN-based energy management system can significantly improve the efficiency and reliability of hybrid power systems. Compared to conventional control methods, the ANN demonstrated superior adaptability to fluctuating solar conditions and load demands, reducing energy losses and optimizing battery usage. This aligns with findings from other studies that highlight the potential of intelligent control in renewable energy integration, particularly in enhancing the sustainability of energy systems.

5. CONCLUSION

The work proposes a power management system that monitors the SoC is continuously by ANN algorithm. The DC-DC converter circuit's dynamic switched depending on the two conditions of the two batteries connected to the PV and EV. The ANN algorithm used in the battery's SoC control mechanism priorities the EV charging circuit or the inverter circuit to supply the grid. These conditions used in the proposed work not only encourages the use of renewable energy sources efficiently but also takes care of the battery health. The work is evaluated with the MATLAB simulation for different conditions and results are compared with different controllers such as PI, PID, and ANN. The prototype operates in the two conditions and the ANN shifts the conditions and effectively utilize the battery and the excess energy is delivered to the grid through the inverter. The findings provide strong evidence that intelligent energy management can significantly enhance renewable energy utilization, maintain battery health, and reduce grid dependence. This research contributes to the development of more sustainable and resilient energy infrastructures, promoting a cleaner and more efficient energy future. In the future the research has possibility to explore the incorporation of additional renewable sources, such as wind energy, to create a more resilient and flexible hybrid system. Additionally, advanced control algorithms like reinforcement learning could be investigated to further optimize energy management. Exploring scalable solutions for microgrids or community-based energy systems could also broaden the impact of this research.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Vinoth Kumar Ponnusamy	✓		✓	✓	✓			✓	✓	✓			✓	
Gunapriya Devarajan		✓				✓		✓		✓	✓	✓		
Gomathi Easwaram	✓		✓	✓		✓			✓		✓		✓	
Geetha Murugesan		✓				✓				✓		✓		
Rathinam Marimuthu Sekar		✓			✓		✓			✓		✓		
R. Delshi Howsalya Devi	✓			✓				✓					✓	

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

Derived data supporting the findings of this study are available from the corresponding author Vinoth Kumar Ponnusamy on request.

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