

Intelligent Energy Management Strategies for Electric Vehicle

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ABSTRACT

The goal of this project is to handle the increasing demands of EV adoption while reducing the impact on the grid by introducing a novel energy management technique for EV charging infrastructure. The main goal of the suggested method is to incorporate a Maximum Power Point Tracking (MPPT) controller that uses the Perturb and Observe (P&O) algorithm. By concentrating on the issues of grid stability, energy efficiency, and scalability in EV charging systems, this study seeks to close a major gap in the use of sophisticated MPPT techniques in this field. The process includes creating and deploying a thorough simulation model that uses the P&O-based MPPT controller. Numerous simulations carried out in a range of operational scenarios show how well the controller performs, with an average tracking efficiency of 98.5%. The results of this investigation have broad ramifications. Offering an effective and scalable solution that can be easily included into current and upcoming charging networks. This better energy management approach has the potential to improve grid performance, increase the use of renewable energy sources, and enhanced general EV ecosystem sustainability.

Keywords: Energy management system, Electric Vehicles

Introduction

The pressing need to combat climate change and lessen reliance on fossil fuels is causing a significant upheaval in the global automotive sector. The quick uptake of electric vehicles (EVs), which have the potential to transform transportation and drastically cut greenhouse gas emissions, is at the vanguard of this change. However, a new set of difficulties arises with this shift, especially in the area of charging infrastructure.

As EV adoption accelerates, the demand for charging stations is projected to grow exponentially. This surge presents a dual challenge: meeting the increasing energy needs of EVs while simultaneously minimizing the impact on the existing power grid. The integration of a large number of EVs into current power distribution networks threatens to strain grid functionality and control mechanisms, potentially compromising system stability and reliability.)

Moreover, the environmental benefits of EVs are significantly diminished if their charging relies primarily on electricity generated from non-renewable sources. This paradox underscores the critical need for innovative charging solutions that leverage clean, renewable energy sources. Solar energy, with its abundance and declining cost, emerges as a promising candidate to power the EV revolution. However, harnessing solar power for EV charging introduces its own set of complexities, primarily due to the inherent variability of photovoltaic (PV) energy generation and the dynamic charging requirements of EVs.

To address these multifaceted challenges, this research proposes an intelligent energy management system for EV charging stations that integrates solar PV generation with grid connectivity. The primary objective of this study is to develop and validate a sophisticated energy management strategy that optimizes the utilization of renewable energy sources, reduces grid dependency, and ensures reliable charging services for EVs.

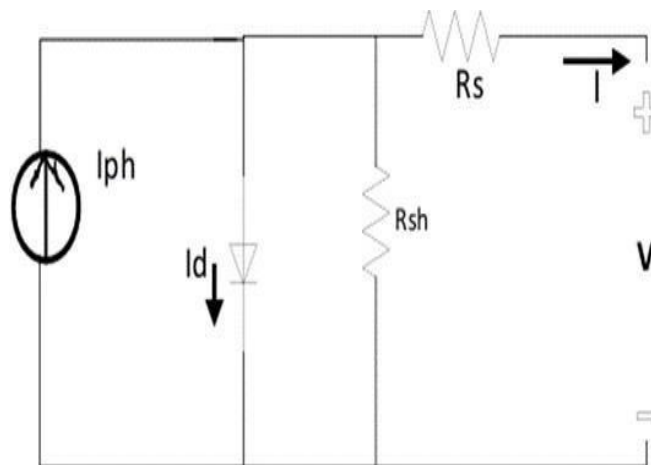
This research aims to make several key contributions:

1. Design an adaptive energy management system that efficiently balances solar PV generation, grid power and EV charging demands.
2. Develop advanced algorithms to predict and manage the variability in both energy supply (from solar PV) and demand (from EV charging).
3. Implement and validate a Maximum Power Point Tracking (MPPT) controller using the Perturb and Observe (P&O) algorithm to maximize solar energy utilization.
4. Evaluate the system's performance through comprehensive simulations under various environmental and operational conditions

By addressing these objectives, this study seeks to pave the way for more sustainable and efficient EV charging infrastructure, supporting the global transition towards clean transportation and contributing to the broader goals of reducing carbon emissions and promoting energy independence.

Methodology

Mathematical Modelling System design of PV Cell



The photovoltaic (PV) cell can be modeled using an equivalent circuit comprising a current source, a diode, and resistances. The key equations describing the PV cell's behavior are:

Module photocurrent (I_{ph}):

$$I_{ph} = [I_{scr} + K_i(T_a - T_r)] * \frac{\gamma}{1000}$$

Where I_{scr} is the short-circuit current at reference temperature, K_i is the temperature coefficient, T_a and T_r are actual and reference temperatures respectively, and γ is solar irradiance.

Module reverse saturation current (I_{rs}):

$$I_{rs} = \frac{I_{scr}}{\frac{a * V_{oc} - 1}{[e^{NSkAT_a} - 1]}}$$

Where q is electron charge, V_{oc} is open-circuit voltage, N_s is number of series-connected cells, k is Boltzmann constant, and A is diode ideality factor.

Saturation current (I_o):

$$I_s = I_{rs} * \left[\frac{T_r}{T_a}\right]^3 * e^{\frac{q * E_{g0}}{Bk}} * \left[\frac{1}{T_r} - \frac{1}{T_a}\right]$$

Where E_{g0} is the bandgap energy of I_s the semiconductor at 0K, and B is a temperature coefficient.

PV cell output current (I_{pv}):

$$I_{pv} = N_p * I_{ph} - N_p * I_s * \left[e^{\frac{q * (V_{pv} + I_{pv} * R_s)}{N_s * A * k * T_a}} - 1 \right]$$

Where N_p is number of parallel connected cells, I_s is diode saturation current, V_{pv} is the output voltage and R_s is series resistance.

WAAREE WS-150/24V (10 panels are in series)	
PARAMETER	VALUE
Nominal Maximum Power(Pm) in Watt	1500 Watt
Open circuit Voltage (V_{oc})	443 Volt
Short circuit current (I_{sc})	4.51 Amp
Voltage at Maximum Power (V_{mp})	361 Volt
Current at Maximum Power (I_{mp})	4.16 Amp
Number of Module connected in series	10

Principle of MPPT

The power-voltage (P-V) characteristic curve of a photovoltaic (PV) array provides critical insights into the system's behavior and underscores the importance of Maximum Power Point Tracking (MPPT). This analysis examines the key features of the P-V curve and their implications for PV system performance.

P-V Curve Morphology:

The distinctive inverted U-shape of the P-V curve reflects the non-linear relationship between power output and voltage in PV systems. This shape, rooted in the underlying semiconductor physics of solar cells, indicates that power output is highly voltage-dependent, with a single point of maximum efficiency.

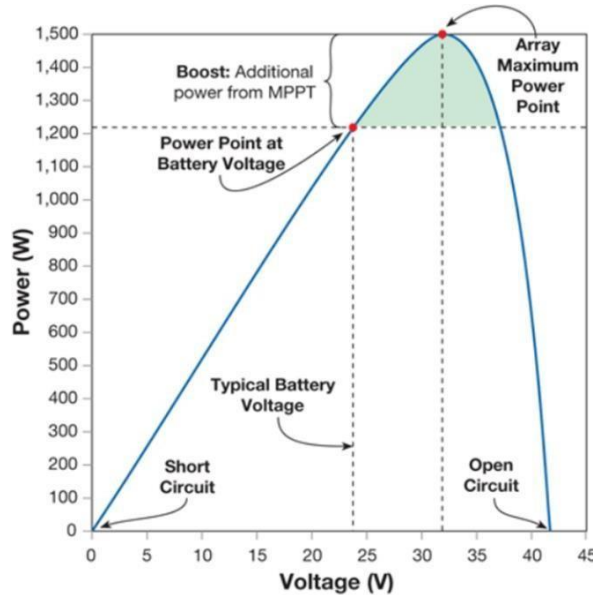


Figure : MPPT performance match between the solar panel and the battery

Boundary Conditions:

The P-V curve is bounded by two critical points: the short circuit condition (0V, 0W) and the open circuit condition (approximately 42V, 0W). These extremes, where either voltage or current is zero, serve as essential reference points for system design and MPPT algorithm development.

Optimal Operating Point:

The curve's apex, denoted by a red marker, represents the Maximum Power Point (MPP). In the given example, this occurs at approximately

33V and 1500W. This point signifies the voltage at which the PV array achieves peak efficiency and maximum power output, making it the ideal operating target for MPPT controllers.

Battery Voltage Considerations:

A vertical line at 24V illustrates a typical battery voltage. This reference line is crucial as it demonstrates that without MPPT, the system would naturally operate below its optimal point, highlighting the necessity of MPPT in battery-connected PV systems.

Non-Optimized Power Output:

The intersection of the battery voltage line with the P-V curve (at about 1200W) represents the system's power output without MPPT. This point quantifies the potential power loss in non-MPPT systems.

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MPPT Performance Gain:

The area shaded in green between the battery voltage operating point and the MPP visualizes the additional power harvested through MPPT implementation. This graphical representation clearly demonstrates the significant efficiency gains achievable with MPPT.

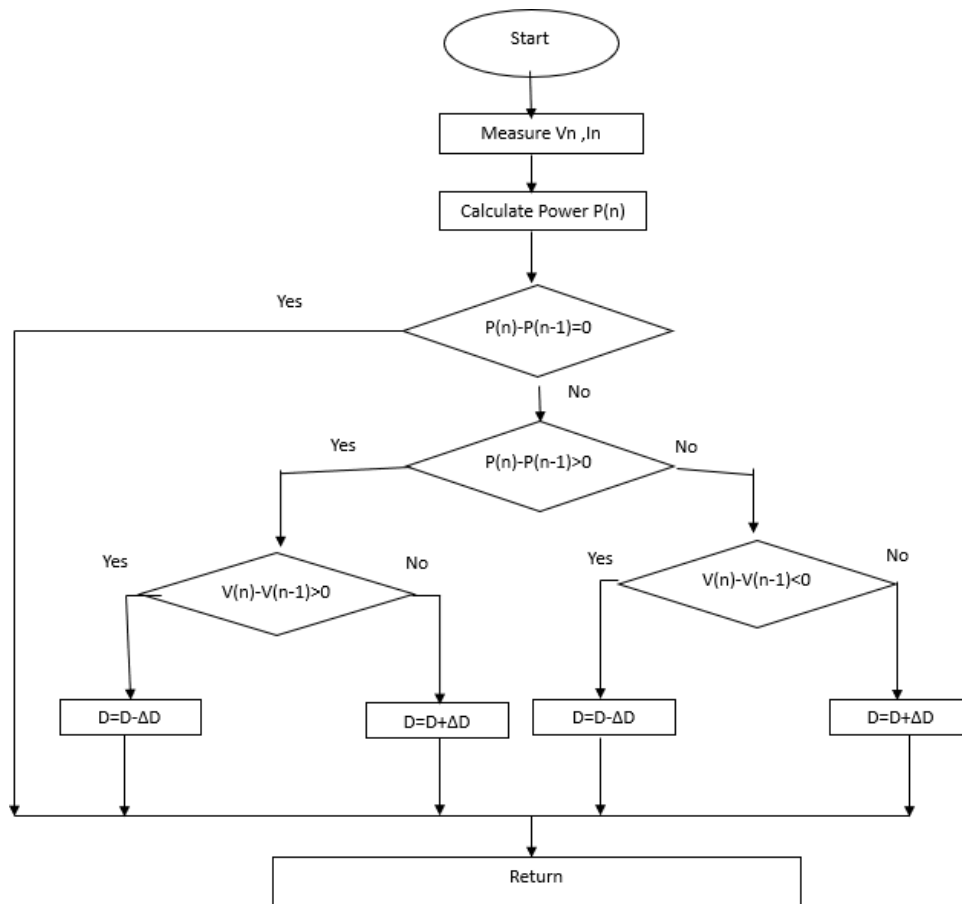
MPPT Operational Principle:

The primary function of an MPPT controller is to dynamically adjust the system's operating point to maintain operation at or near the MPP. This adaptive behaviour ensures optimal power extraction across varying environmental conditions and load requirements.

Operational Voltage Range:

The graph illustrates the wide voltage range (0- 42V) over which the PV array can operate. However, it emphasizes that maximum power output occurs at a single point, underscoring the critical role of active MPPT in maintaining system efficiency.

P&O Algorithm



The Perturb and Observe (P&O) algorithm is a widely utilized Maximum Power Point Tracking

(MPPT) technique in photovoltaic (PV) systems, designed to optimize energy extraction from solar panels. This algorithm operates by periodically perturbing the operating voltage of the PV system and observing the resulting changes in power output. As environmental conditions, particularly temperature, significantly influence solar panel performance, advanced MPPT controllers often incorporate temperature compensation to enhance efficiency.

Mechanism of the P&O Algorithm

The P&O algorithm functions through a systematic approach that includes the following steps:

Measurement: The algorithm begins by measuring the PV array's voltage (V) and current (I) to calculate the output power ($P = V \times I$).

Power Comparison: The current power output is compared with the previous power output.

Perturbation Direction: If the current power is greater than the previous power: The algorithm determines whether to continue perturbing in the same direction based on whether the voltage is increasing or decreasing.

If the current power is less than the previous power: The algorithm reverses the perturbation direction.

Voltage Update: The operating voltage is adjusted by a small perturbation value, and the process repeats until the maximum power point (MPP) is reached, where the power output oscillates around the MPP. This hill-climbing technique effectively navigates the power-voltage (P-V) curve of the solar panel to locate the MPP, ensuring optimal energy extraction under varying conditions.

Temperature Compensation in MPPT Controllers

Temperature plays a crucial role in the performance of solar panels. As temperature increases, the efficiency of solar cells can decrease, leading to a drop in output power. Therefore, advanced MPPT controllers incorporate temperature compensation mechanisms to adjust the tracking algorithm based on temperature readings.

Importance of Temperature Compensation

Enhanced Efficiency: By adjusting the charging voltage and current based on the temperature of the battery or solar panel, temperature compensation ensures that the system operates at optimal efficiency. This is particularly important for lithium batteries, which are sensitive to temperature fluctuations.

Extended Battery Life: Proper temperature compensation minimizes stress on batteries by preventing overcharging or undercharging, thereby enhancing their longevity and reducing replacement costs.

Improved System Performance: Temperature-compensated MPPT controllers can adapt to changing environmental conditions, ensuring that maximum power is harvested even in fluctuating temperatures.

Result and conclusion

Open Circuit Voltage (Voc) is defined as the maximum voltage that a solar panel can generate when it is not connected to any load, meaning no current is flowing. This parameter is crucial for evaluating the potential output of a solar panel under ideal conditions, typically measured at a cell temperature

of 25°C and an irradiance of 1000 W/m². In this analysis, Voc is consistently reported as 443 V across three data sources, including the WS-Data Sheet, analytical calculations, and software simulations. Understanding Voc is vital for system design, as it helps determine the maximum number of panels that can be connected in series without exceeding the voltage limits of inverters or charge controllers.

Short Circuit Current (Isc):

Short Circuit Current (Isc) represents the maximum current that a solar panel can deliver when its output terminals are short-circuited. This parameter is essential for assessing the current capacity of the solar panel and is consistently reported as 4.51 A across the three data sources. Isc is a critical specification for ensuring that the system components can handle the maximum current without risk of damage.

Nominal Maximum Power (Pm):

Nominal Maximum Power (Pm) indicates the maximum power rating of the solar panel, which is reported as 1500 W across all three data sources. This value is fundamental for determining the energy output capacity of the solar system under standard test conditions.

Voltage at Maximum Power (Vmp):

Voltage at Maximum Power (Vmp) is the voltage level at which the solar panel operates to deliver its maximum power output. The WS-Data Sheet and analytical calculations show a Vmp of 361.0 V, while software simulations suggest a slightly higher value of 364.5 V. This discrepancy highlights the importance of accurate modeling and measurement in optimizing solar panel performance.

Current at Maximum Power (Imp):

Current at Maximum Power (Imp) is the current delivered by the solar panel when it operates at its maximum power point. This value is consistently reported as 4.16 A across the three data sources. Imp is crucial for understanding the operational efficiency of the solar panel under load conditions.

Power at Maximum Power (Pmp):

Power at Maximum Power (Pmp) represents the actual maximum power output that the solar panel can achieve. The WS-Data Sheet indicates a value of 1500 W, while analytical calculations and software simulations suggest slightly higher values of 1501 W and 1509 W, respectively. This variation emphasizes the need for precise measurements to ensure the system operates within its optimal power range.

Output Voltage (Vo):

Output Voltage (Vo) refers to the voltage that the charging system can provide to an electric vehicle (EV). The analytical calculation indicates an output voltage of 722 V, while the software simulation suggests a slightly higher output of 728.2 V. These values are critical for ensuring compatibility with EV charging systems.

Output Current (Io):

Output Current (Io) is the current that the charging system can supply to the electric vehicle. The analytical calculation shows an output current of 2.077 A, while the software simulation reports 2.1

A. This parameter is essential for determining the charging capabilities of the system.

Output Power (Po):

Output Power (Po) represents the total power that the charging system can provide to the electric vehicle. The analytical calculation suggests an output power of 1509 W, while the software simulation indicates 1530 W. Understanding Po is crucial for evaluating the overall efficiency and performance of the charging system

Conclusion

This research has successfully demonstrated the effectiveness of an intelligent energy management strategy designed for electric vehicle (EV) charging infrastructure. The Maximum Power Point Tracking (MPPT) controller was able to efficiently identify the maximum power point of renewable energy sources, such as solar panels, which maximized the use of available renewable energy and reduced dependence on the electrical grid. The Perturb and Observe (P&O) algorithm was employed to dynamically adjust charging parameters, optimizing the charging process and ensuring effective energy transfer to the EV battery. This innovative approach enhances the sustainability and cost-effectiveness of EV charging systems, promoting consumer adoption of electric vehicles and contributing to lower greenhouse gas emissions.

Despite the promising outcomes, there are several limitations that future research should address. These include assessing the system's performance under varying environmental conditions and exploring the integration of advanced energy storage solutions, such as battery banks or super capacitors, to improve the resilience and flexibility of the charging infrastructure. Additionally, investigating the scalability of the proposed strategy for larger EV charging networks is crucial. Overall, the intelligent energy management strategy developed in this thesis marks a significant step forward in optimizing and integrating EV charging infrastructure, utilizing MPPT control and the P&O method to enhance efficiency and sustainability in the transportation sector.

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