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Optimal Energy Management in PV-Powered Switched Reluctance Motor Based Electric Vehicles

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ABSTRACT
This paper incorporates a PV module, a boost converter, a bidirectional converter, an Incremental Conductance (INC) Maximum Power Point Tracking (MPPT) algorithm and a Proportional-Integral (PI) controller for optimal energy management in Electric vehicle operation. The analysis evaluates efficiency, dynamic response and power management under varying irradiance conditions. The simulation results reveal that the PV module attains peak efficiency (99.35% –99.9%), ensuring effective energy conversion while the SRM drive, supported by the PI controller, maintains stable and precise operation. The bidirectional converter facilitates seamless battery charging and discharging, enhancing energy utilization and supporting regenerative braking. Battery performance shows stable voltage with adaptive current and power adjustments though the State of Charge declines under reduced PV output and reflecting load compensation. This research underscores the system's consistency, optimum cost and aptness for sustainable EV utilizations, representing robust motor control and power attainment. This study highlights the potential of SRM motor-based PV-powered EVs for effectual and ecological transportation solutions.
Keywords: *Switched Reluctance Motor, MPPT, PI Control, Bidirectional Converter and Incremental Conductance.*

INTRODUCTION

The increasing need for sustainable and energy-efficient transport has led to developments in EV technology. Due to that solar energy is readily accessible and ecologically helpful, it is a viable option for EV power. Effective energy management is essential when incorporating solar PV modules through electric vehicles (EVs). This research examines the performance of a Switched Reluctance Motor (SRM) drive control for solar-powered EVs with MATLAB Simulation. The planned system includes a solar PV module, bidirectional converter, boost regulator, INC MPPT and PI controller to enhance power flow, confirming consistent energy conversion and effectiveness of motor operation for enhanced efficiency and achievement.This research intends to analyse the efficiency, dynamic achievement and power management capability of the proposed system with variable operational conditions. These analysis shows an advantage of SRM in terms of productivity, reliability and offer understanding statistics about the feasibility of execution with solar-powered EVs.In [1], a solar photovoltaic-powered water pumping system is discovered, applying a 3-level quadratic boost DC-DC regulator paired with an SRM drive. With the help of the MPPT approach, it is taken and proved by a laboratory model under different constraints. This arrangement attains maximum energy extraction from photovoltaic (PV) panels by an importance on maximum voltage gain and reduced stress on power apparatuses. Similarly [2] examines a renewable system combining supercapacitors, battery and to drive an SRM, concentrating on the control of speed and load flow management. It is capability to tolerate stable running in the aspect of variable solar input is established via simulations which makes it suitable for utilization in industrial and automotive applications.In [3] presents a PV-connected water pumping system with battery storage system, employing a bidirectional DC-DC regulator with charge and discharge control as well as MPPT. The arrangement promises a stable source of water, and both simulation and practical results provide its efficacy. In difference [4] changes with the light EVs incorporating a solar PV with battery connected SRM drive assessed against the Indian driving Cycle. Its incorporation of sensorless speed valuation and power regeneration established by laboratory tests, validates its potential for reasonable EV utilizations. In [5] a hybrid boost regulator to improve the range of voltage with solar PV module driving an SRM for EVs with closed-loop speed control analysed via simulation were presented. This approach underscores the shift toward renewable-driven transportation to reduce pollution. In [6] a solar PV-powered SRM water pump with battery backup, utilizing a bidirectional converter for seamless operation across climatic variations with simulation results confirming its reliability was explored.

In [7], a bidirectional regulator with a multiport system for a PV-connected hybrid EV using an SRM Motor incorporating a high-gain KY converter and PI controllers for speed and power regulation was introduced. Its performance is substantiated through MATLAB simulations. A study in [8] adopts a similar multiport approach for hybrid EVs, emphasizing energy storage and transfer between PV, battery and SRM with simulation outcomes validating its efficacy. In [9], an autonomous PV-connected water pumping system is explained with highlighting a 1-input 2-output DC-DC regulator and a 4-phase SRM motor. Enhanced MPPT & control logic ensure balanced outputs, with simulation and test results affirming its practical viability. [10] focussed on EVs, integrating solar PV with an SRM drive and employing a hysteresis current controller to minimize torque ripple, alongside a tri-port inverter for energy management, validated through simulations. The study in [11] advances an EV SRM drive with grid, microgrid, and vehicle-to-vehicle connectivity, using an interleaved boost/buck converter and regenerative braking. It demonstrates versatile energy transfer capabilities, supported by experimental findings. In [12], SRM control in EVs and microgrids using fuzzy logic techniques, addressing torque consistency and power generation efficiency, though it highlights challenges such as noise and the need for precise rotor monitoring were explored.Collectively, the above works illustrate a robust foundation of research into SRM drives for solar PV-powered applications, spanning water pumping and EV systems. They prioritize cutting-edge control techniques, energy storage integration and creative converter designs, all of which are regularly validated by simulations and experiments, opening the door for effective and sustainable use of renewable energy.

SYSTEM MODELING

The block diagram shown in Fig.1 signifies a solar PV-powered scheme considered to drive an SRM motor for the usage of electric vehicle systems. The INC MPPT technique was used to increase the power production from the PV model, which varies depending on the environmental circumstances. To regulate the voltage, a boost regulator delivers a stable direct current bus. The battery charging and discharging process is done by using a bidirectional regulator, which assures continuous power supply. Performance is improved by using a position sensor system and converter to regulate the SRM motor. This arrangement increases energy proficiency, confirming consistent operation under variable circumstances for acceptable and renewable system utilizations.

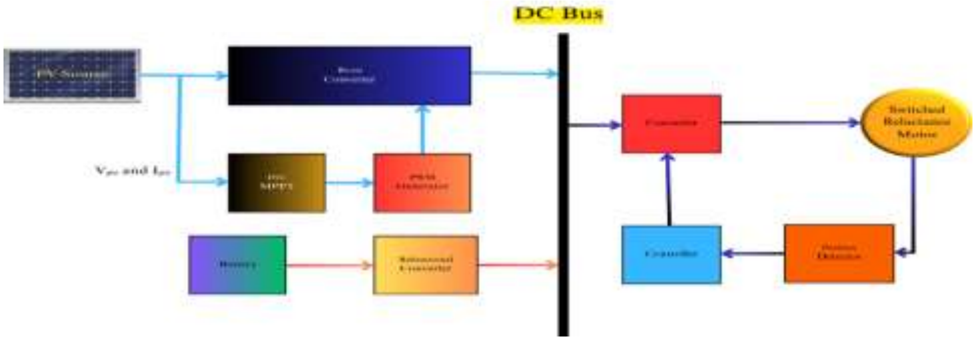


Figure-1 Block diagram of the proposed system

Solar PV Module

The simplified model of a PV cell, shown in Fig.2, its electrical behavior using a shunt resistance (R_{sh}), series resistance (R_s), diode, current source. The diode mimics the p-n junction, while the current source symbolizes power generation powered by sunshine. Internal losses are represented by Rs, and leakage currents are represented by R_{sh}. Diode and shunt currents are subtracted from the generated current to determine the output current. This model helps analyze PV performance and optimize energy harvesting in MATLABsimulations.

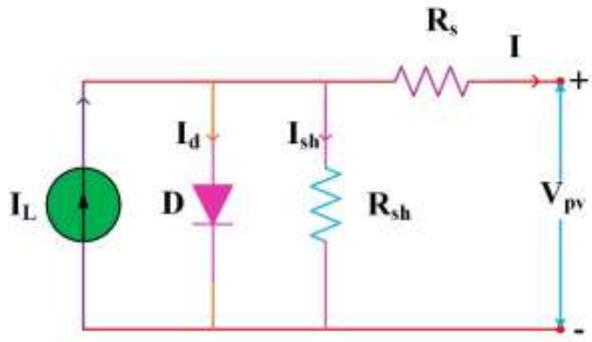


Figure-2 Simplified Model of a PV Circuit

Mathematical Expression of the Solar PV Cell

The current source output of the solar PV cell is:

$$I = I_L - I_d - I_{sh} \quad (1)$$

I_L = Current from light-generation
I_d = Current of the diode
I_{sh} = Current in shunt

The current of the diode follows the Shockley equation:

$$I_d = I_s\left(e^{\frac{V+IR_s}{nV_t}} - 1\right) \quad (2)$$

I_s = Saturation current in reverse
V= Voltage at terminal
R_s = Resistance in series
n = Ideality factor
V_t = Thermal voltage

The leakage current viaR_{sh} is mentioned that:

$$I_{sh} = \frac{V+IR_s}{R_{sh}} \quad (3)$$

Thus, final current equation of the PV cell is:

$$I = I_L - I_s\left(e^{\frac{V+IR_s}{nV_t}} - 1\right) - \frac{V+IR_s}{R_{sh}} \quad (4)$$

Effects of parameters on PV performance:

- Increase in R_s - Reduces output current and efficiency.
- Decrease in R_{sh} - Increases leakage current, reducing efficiency.
- Surge in Solar Irradiance - Increases I_L, leading to higher power output.

Boost converters

The boost converter, as shown in Fig. 3, increases the solar PV array outputat a higher level for direct current bus using a PWM-controlled switch. Its duty cycle controls the voltage gain, with a higher duty cycle leading to greater voltage output. The inductor stores energy during the "on" phase and releases it in the "off" phase, boosting the voltage. Capacitors reduce ripples and stabilize the output, ensuring a steady power supply. This setup enables efficient power conversion for solar-based applications.

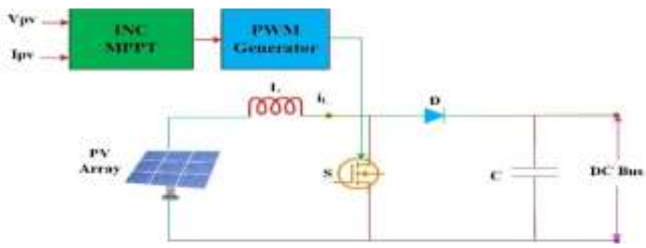


Figure-3 Boost Converter Circuit

Battery with Bidirectional Converters

The bidirectional converter, shown in Fig. 4, enables power flow among the EV battery and the DC link, supporting both charging and discharging modes. In boost mode, switch S1 controls energy transfer with the direct current link, whereas in mode of buck, S2switch allows battery charging. The inductor facilitates energy storage and transfer, while the capacitor stabilizes voltage. This converter improves energy efficiency, supports regenerative braking, and optimizes battery charging, making it essential for enhancing EV performance and energy management.

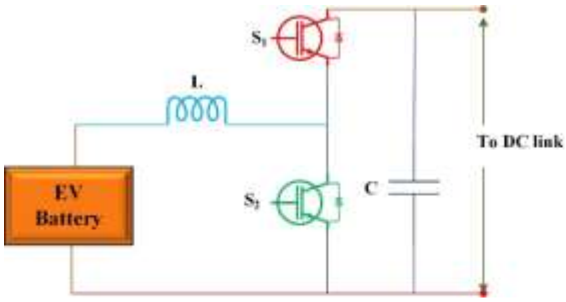


Figure-4 Battery with Bidirectional Converter Circuit

Step-up operation: Boost Mode

In this method, the battery voltage (V_{bat}) is boosted up to the V_{dc}.

Voltage Gain Equation:

$$V_{dc} = \frac{V_{bat}}{1-D} \quad (5)$$

D is the duty ratio of switch S_1.

Inductor Current Equation:

$$L\frac{dI_L}{dt} = V_{bat}, \quad \text{when } S_1 \text{ is ON} \quad (6)$$

$$L\frac{dI_L}{dt} = V_{bat} - V_{dc} \quad \text{when } S_1 \text{ is OFF} \quad (7)$$

Ripple Current of Inductor:

$$\triangle I_L = \frac{V_{bat}D}{Lf_s} \quad (8)$$

Output Voltage Ripple:

$$\triangle V_{dc} = \frac{I_{dc}(1-D)}{Cf_s} \quad (9)$$

Step-down operation: Buck Mode

Here, DC link voltage (V_{dc}) is stepped down to charge the battery.

Voltage Gain Equation:

$$V_{bat} = DV_{dc} \quad (10)$$

Inductor Current Equation:

$$L\frac{dI_L}{dt} = V_{dc} - V_{bat}, \quad \text{when } S_2 \text{ is ON} \quad (11)$$

$$L\frac{dI_L}{dt} = -V_{bat} \quad \text{when } S_2 \text{ is OFF} \quad (12)$$

Inductor Ripple Current:

$$\triangle I_L = \frac{V_{dc}D}{Lf_s} \quad (13)$$

Battery Charging Current:

$$I_{bat} = \frac{V_{bat}(1-D)}{R} \quad (14)$$

Power Transfer Equations

Power in Boost Mode:

$$P_{out} = P_{in} \times \eta = V_{dc}I_{dc} = \eta V_{bat}I_{bat} \quad (15)$$

Power in Buck Mode:

$$P_{bat} = \eta P_{dc} = \eta V_{dc}I_{dc} \quad (16)$$

PV CONTROL WITH INC MPPT

The INC MPPTtechnique is an effective method for improving power production from the PV model. It regulates the Maximum Power Point (MPP) by associating the INC (dI/dV) by the instant conductance (I/V).

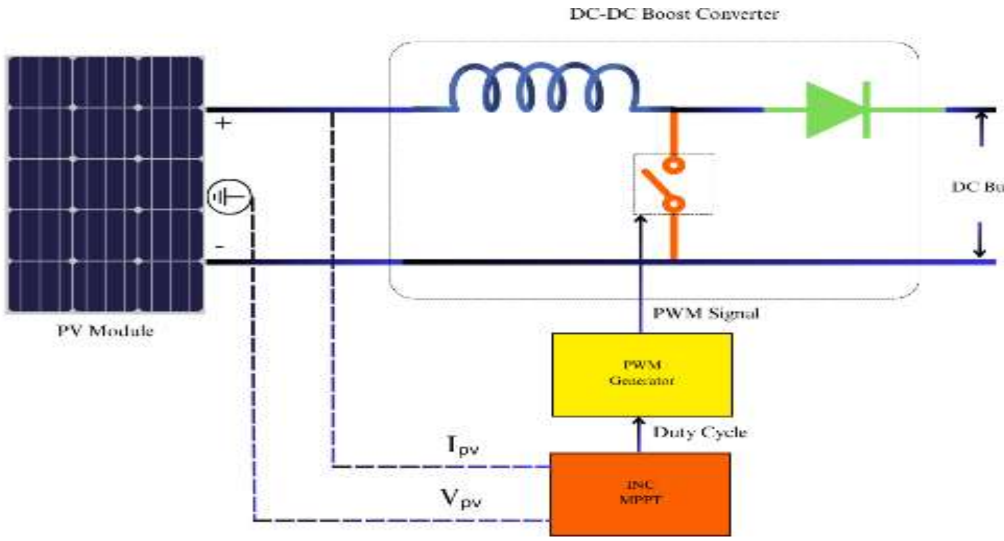
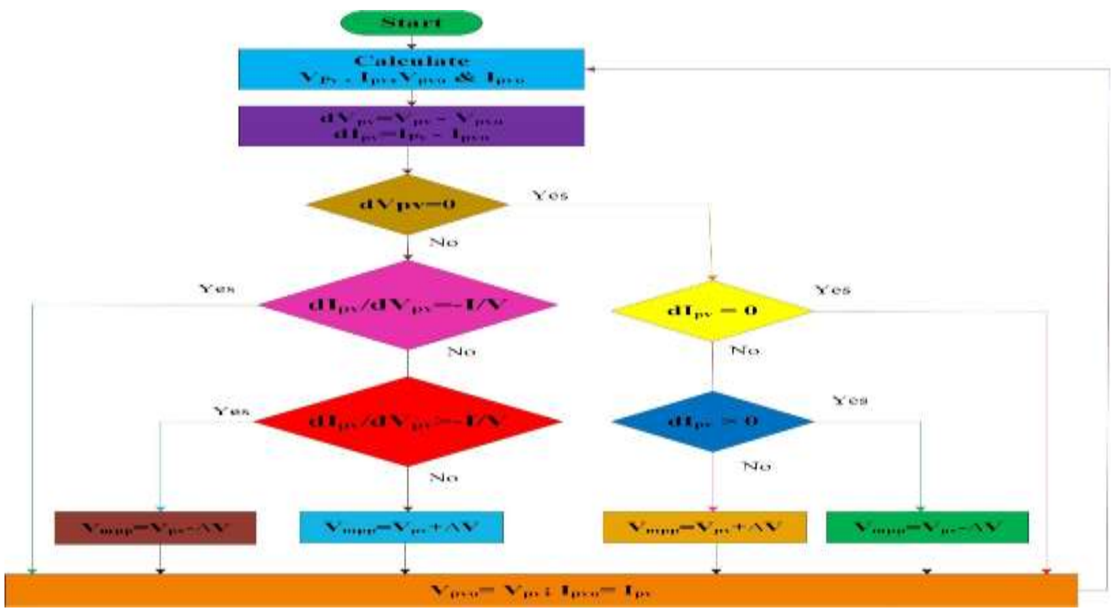


Figure-5 Implementation of INC MPPT

The MPP is recognized when dI/dV equals -I/V. If dI/dV is superior, the system rises the voltage, which its lower, the voltage will be reduced. This procedure is incorporatedin a DC-DC regulator, fine-tuning



the duty ratio based on practical power measurements.

Figure-6 Flowchart of INC MPPT

Under a diversity of ecological surroundings, INC MPPT improves power production by offering accurate monitoring and stable performance. The INC MPPT technique is executed with a boost regulator in Fig. 5, and the flowchart of the INC MPPT is shown in Fig. 6.

SWITCHED RELUCTANCE MOTOR WITH CONTROL CIRCUIT

The SRM drive system includes essential components for efficient operation represented in Fig.7. A power source supplies energy, which is conditioned by a converter to meet motor requirements. The SRM operates on reluctance variation, where the rotor aligns with stator poles to generate motion. A sensing device gives the controller feedback on variables like the speed and position of the rotor. To confirm smooth and precise control, the regulator adjusts the converter. By monitoring motor performance, this feedbackcontrol rises steadilywhile assuring optimum functionality and reliability across a range of utilizations.

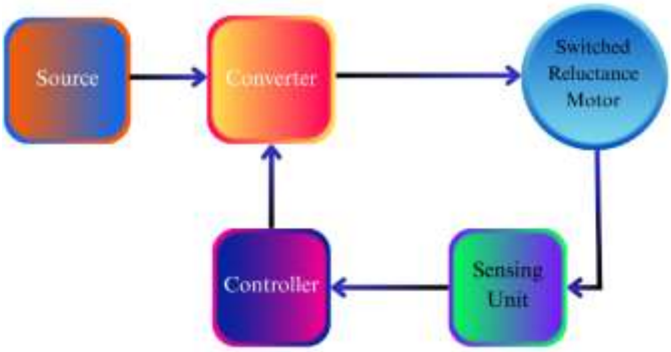


Figure-7 SRM Drive System

The PI controller is commonly used as a controller of the SRM motor. It computes the error among the voltagereference (Vref) and voltageactual (Vdc). Whereas integral gain (Ki) modifies increasing deviations over the period, the gain of proportional (Kp) responds to faults rapidly. To regulate motor operations, these portions yield a control indication. Constancy is agreed by the closedfeedback system, which corrects for instabilities and variations in load side. The SRM motor improves accuracy, efficacy, and reliability with a PI controller, which be it eligible for practical applications that demand stable and continuous operation. Fig.8 shows the PI controller operation of PI controller.

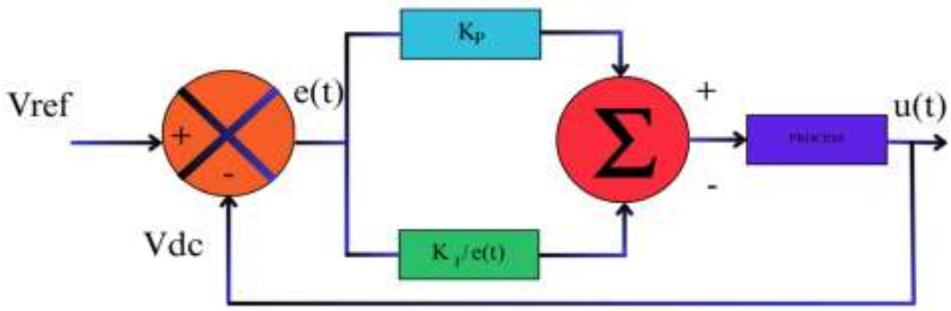
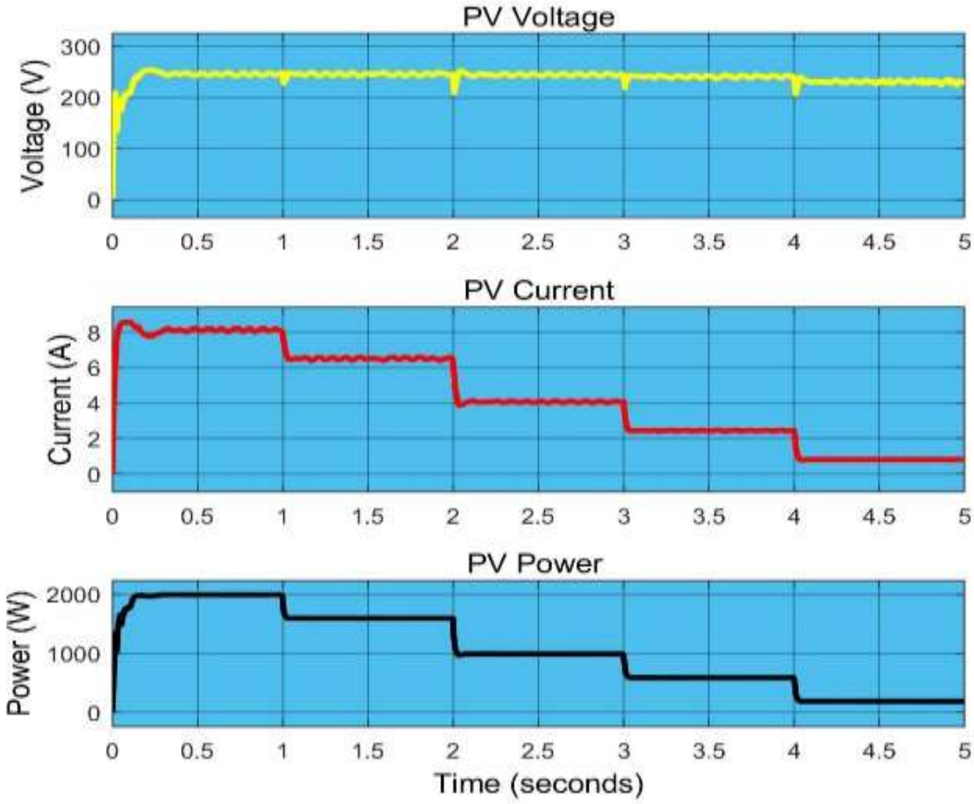


Figure-8 Representation of PI Controller

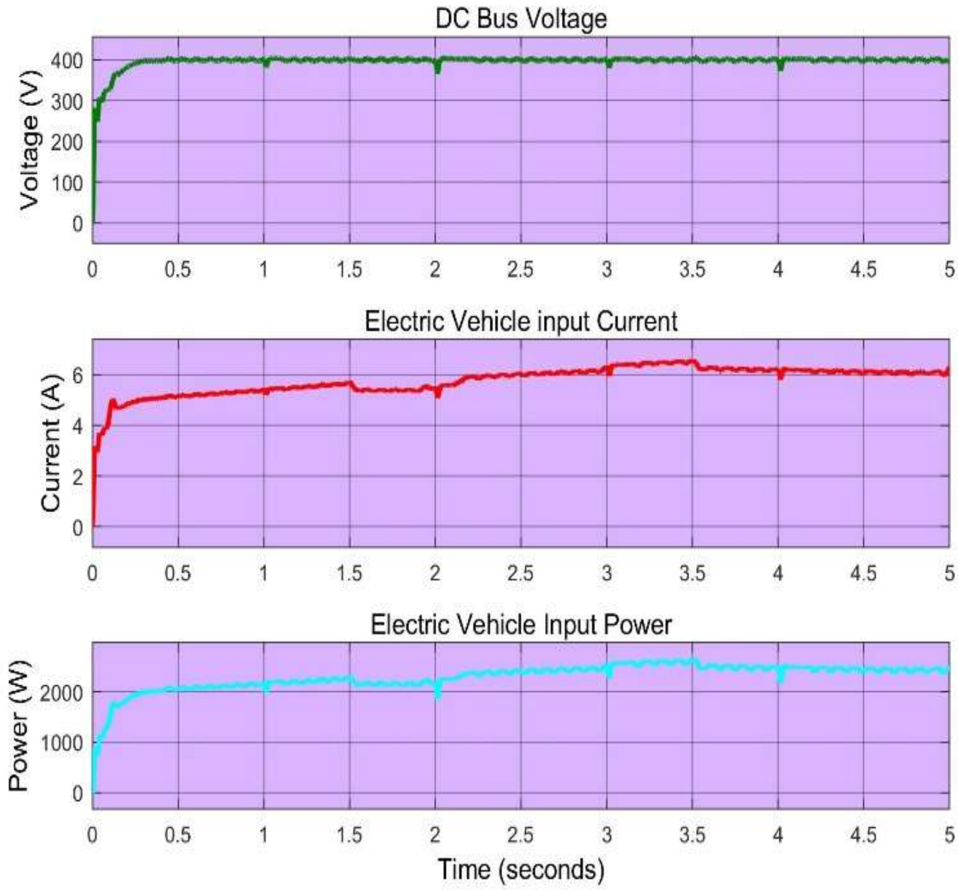
RESULTS AND DISCUSSION

The power, current and voltage characteristics of the PV and EVare represented in Fig 9(a) & 9(b), respectively. Simulation results consider aPV module working under varying irradiation conditions. The irradiance levels applied to the PV system change over time as follows: from 0 to 1 second, it is 1000

W/m²; from 1 to 2 seconds, it is 800 W/m²; from 2 to 3 seconds, it is 500 W/m²; from 3 to 4 seconds, it is 300 W/m²; and from 4 to 5 seconds, it is 100 W/m².



(a)



(b)

Figure-9 PV and EV Characteristics of Voltage, Current and Power

Table 1: PV Performance with Varying Irradiance

Irradiance (W/m^2)	Obtained Power (W)	Efficiency (η)
1000	1995	99.6%
800	1598	99.9%
500	992.9	99.8%
300	586.7	99.7%
100	185.8	99.35%

Table.1 demonstrates that the solar PV module operates at consistently higher efficiency with diverse irradiance conditions, ranging from 99.35% to 99.9%. The small variations in efficiency suggest that the arrangement efficiently changes obtainable PVpower into electrical energy, making it highly reliable for applications such as electric vehicle (EV) charging.

Fig.10 illustrates the battery parameters. The battery voltage remains stable, ensuring a consistent power supply. The current gradually increases over time with step variations, indicating dynamic charging behavior. Thepower follows a similar trend, rising as the current increases. The fluctuations suggest controlled charging adjustments to maintain efficient operation when the irradiance of the PV reduced gradually.

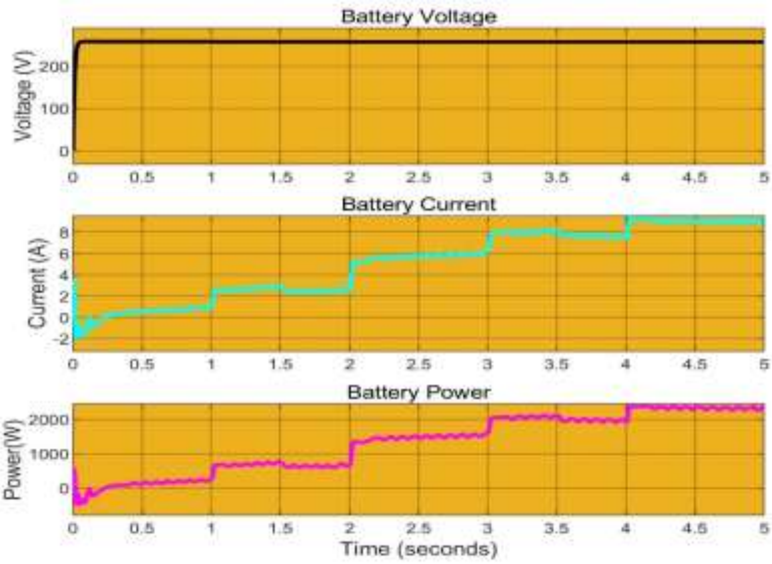


Figure-20 Battery Characteristics of Voltage, Current and Power

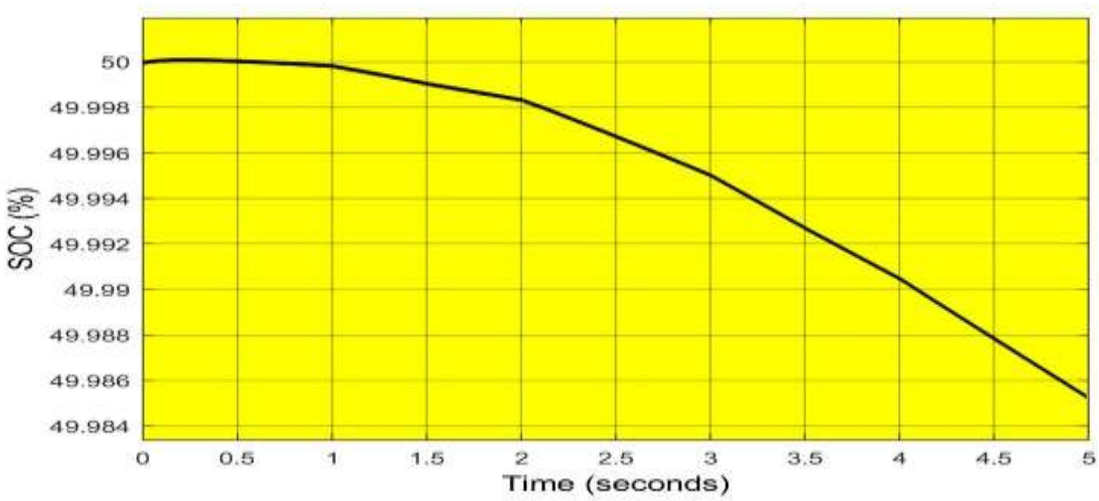


Figure-31 SOC of Storage Battery

Fig. 11 represents the SOC of the battery over the period. The SOC starts at 50% and gradually declines, indicatinga discharging state. The decrease becomes more prominent after 2 seconds, suggesting an increase in load or discharge rate. The trend reflects the battery's discharge behavior during operation.When PV power decreases and battery power increases, the battery undergoes discharge, leading to a reduction in its SOC. This indicates that the battery is supplying energy to compensate for the reduced PV output and meet the load demand.

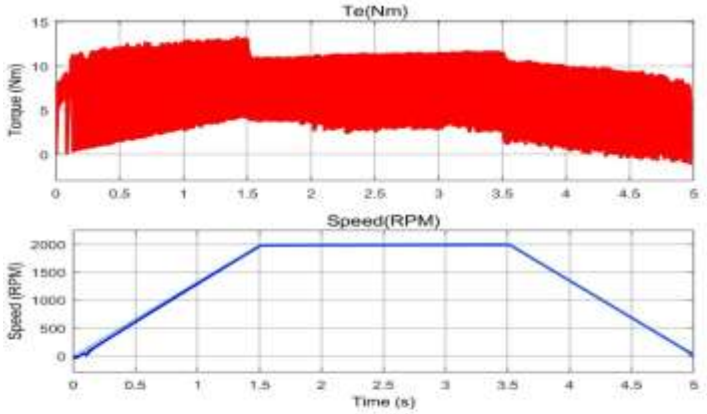


Figure-42 Speed -Torque Analysis of SRM Motor

Fig. 12 demonstrates the speed and torque analysis of SRM motor, in which Te (Nm) graph shows torque differences over the period, and Speed (RPM) graph represents the speed of the motor. The outcomes specify the steady torque response with variations and a controlled speed change, ensuring effective motor performance.

CONCLUSION

The study demonstrates the effective integration of a PV with an Incremental Conductance (INC) MPPT algorithm, a battery and a Switched Reluctance Motor (SRM) drive system for enhanced energy management. The INC MPPT efficiently tracks the MPP, optimizing power production under the variable period of irradiance. The results of the simulation indicate that the PV model operates at higher efficacy, maintaining values between 99.35% and 99.9%, ensuring reliable energy conversion for EV applications. The SRM drive system, equipped with a PI controller, ensures stable and precise operation of the motor by strongly fine-tuning the converter based on a practical approach. Accuracy, effectiveness, and overall system reliability are all enhanced by this closed-loop control. According to the battery performance study, the voltage remains constant while the power and current dynamically adapt to ensure effective charging. The SOC decreases as the battery discharges to compensate for reduced PV power, highlighting the arrangement’s capability to manage power supply and demand effectively. All things considered, the suggested system improves performance, stability and energy use, which qualifies it for EV applications based on renewable energy. Reliable and sustainable energy management systems are facilitated by the combination of controlled motor operation and effective power tracking, which guarantees optimal performance.

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