Design and Analysis of a Solar-Powered Bldc Motor–Based Hybrid Electricvehicle

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***Abstract*—The increasing demands for sustainable and energy-efficient transportation has driven research toward hybrid electric vehicles (HEVs) powered by renewable energy sources. This study investigates the design and performance analysis of a solar-powered hybrid electric vehicle (HEV) driven by a brushless direct current (BLDC) motor. Solar energy, harvested through photovoltaic (PV) panels, is optimized using an incremental conductance-based maximum power point tracking (MPPT) algorithm, ensuring efficient energy conversion under dynamic environmental conditions. A DC-DC step-up converter regulates and boosts the variable voltage from the PV panels to a usable level for the hybrid energy storage system, comprising solar power and batteries. The BLDC motor, known for its high efficiency, low maintenance, and robust performance, is analyzed for speed and torque control using advanced modulation techniques. Simulation results validate the system's efficiency and reliability, highlighting its potential to deliver eco-friendly and cost-effective transportation solutions.**

***Index Terms*—Hybrid Electric Vehicle, MPPT, BLDC, DC-DC Converter, MATLAB**

I. INTRODUCTION

The transition to sustainable transportation has become imperative in addressing the growing concerns of environmental pollution and energy depletion. Solar-powered hybrid electric vehicles (HEVs) represent a promising solution by integrating renewable energy with advanced motor technologies. This study explores the design and analysis of a hybrid vehicle powered by solar energy and driven by a brushless direct current (BLDC) motor. Solar energy, captured through photovoltaic (PV) panels, is managed using an incremental conductance-based maximum power point tracking (MPPT) algorithm to ensure optimal energy utilization. The BLDC motor, with its high efficiency, durability, and compact design, serves as the primary propulsion system. By combining solar energy with battery storage, the hybrid energy system offers reliable performance, extended range, and reduced reliance on fossil fuels. This paper highlights the potential of solar-powered HEVs to revolutionize green mobility by offering apractical, eco-friendly, and cost-effective transportation solution.

The objective of this research is to develop a simulation model for the BLDC motor and its associated hybrid power train, incorporating solar energy and Incremental Conductance MPPT control. By evaluating the system’s performance under diverse load and environmental conditions, this study aims to demonstrate the feasibility and efficiency of using a solar-powered BLDC motor in hybrid vehicles. The findings offer insights into potential improvements in energy efficiency, cost reduction, and the practical implementation of renewable energy in transportation, contributing to the field of sustainable automotive technologies.

II. EQUIVALENT PHOTOVOLTAIC CELL

The equivalent circuit of a photovoltaic (PV) cell models its electrical behavior using a current source in parallel with a diode, representing the photocurrent and the cell's non-linear characteristics. A series resistance accounts for losses in the cell's material and connections, while a shunt resistance models leakage currents within the cell. This representation helps analyze key parameters such as the maximum power point, efficiency, and response to environmental changes like irradiance and temperature. Understanding this model is essential for optimizing PV performance in applications like hybrid electric vehicles, where consistent and efficient energy conversion is crucial.

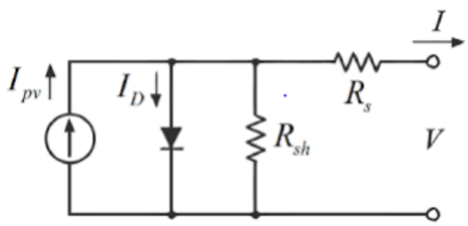

Fig1: Equivalent circuit of PV cell

The equation of Photo Voltaic cell is:

$I = I_{ph} - I_o\,[\exp(q\,(V+RsI)/AK_BT)-1] – V+R_sI/R_{sh}$ (1)

Where, I_{ph} = photo current,

I_D = diode current,

I_O = saturation current,

A= Ideal factor,

Q= electronic charge 1.6*10-9,

K_B = Boltzmann's constant 1.38*10-23

T = Cell temperature,

Rs = series resistance,

Rsh = shunt resistance,

I = cell current,

V= cell voltage

The power output of a solar cell is given by

$P_{pv} = V_{pv}*I_{pv}$ (2)

Where, I_{pv} = output current of Solar cell (A),

V_{pv} = solar cell Operating Voltage (V),

P_{pv}= output power of solar cell (W).

The power-voltage (P-V) characteristic of a photovoltaic module operating at a standard irradiance of 1000 W/m2 and temperature of 250 c shown below.

A. SIMULINK model of PV cell

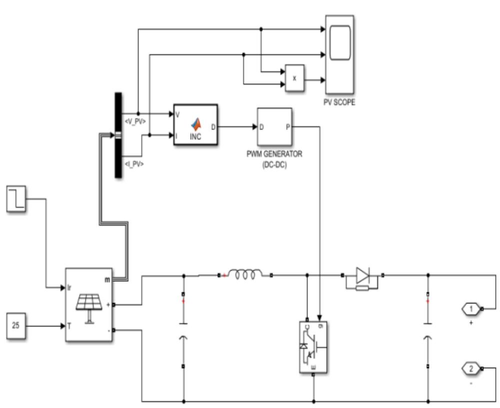

Fig 2: Simulink Model of PVCell

The P-V and I-V curves are generated as shown below:

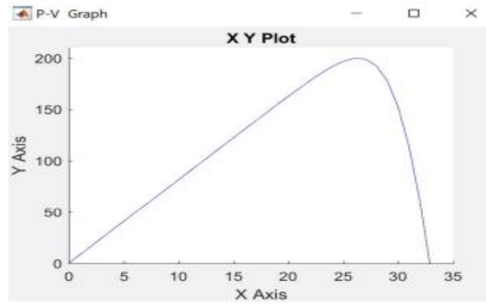

Fig3: Output of photovoltaic Cell I-V Curve

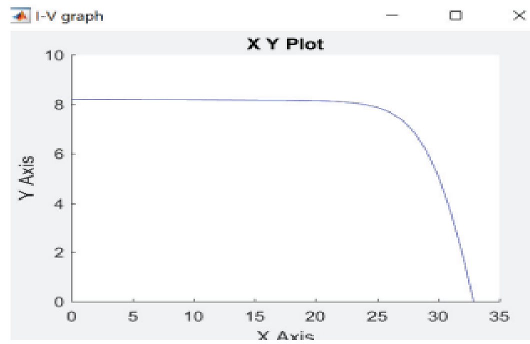

Fig4: Output of PV Cell P-V Curve

1.MPPT

Maximum Power Point Tracking (MPPT) is a critical technique used in photovoltaic (PV) systems to maximize power extraction under varying environmental conditions. Solar panels exhibit non-linear voltage-current (V-I) characteristics, with a unique operating point where power output is at its peak. MPPT algorithms, such as Incremental Conductance and Perturb and Observe, dynamically adjust the operating voltage of the PV array to ensure it remains at this maximum power point despite changes in sunlight intensity and temperature. In solar-powered hybrid electric vehicles (HEVs), MPPT ensures efficient energy transfer from PV panels to the battery or motor, optimizing performance and extending the vehicle's range. By enhancing energy conversion efficiency, MPPT significantly contributes to the reliability and sustainability of solar-powered transportation systems.

2. Incremental Conductance

Incremental Conductance is a maximum power point tracking (MPPT) algorithm used in photovoltaic (PV) systems to achieve optimal energy extraction. It works by comparing the incremental conductance (change in current to voltage ratio) with the instantaneous conductance to identify the maximum power point accurately under varying sunlight and temperature conditions. This method provides faster and more precise tracking, making it ideal for solar-powered hybrid electric vehicles, ensuring efficient energy utilization.

III. CONVERTER

A. DC-DC Step-up Converter:

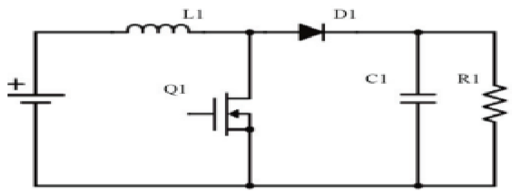

Fig5: Circuit diagram of Boost Converter.

A DC-DC step-up converter, or boost converter, elevates the low and variable voltage from photovoltaic (PV) panels to a higher, stable level suitable for powering the battery and motor in a hybrid electric vehicle. It uses inductors, capacitors, switches, and diodes to efficiently regulate and increase voltage while minimizing energy loss. This ensures consistent performance and optimal utilization of solar energy in the system.

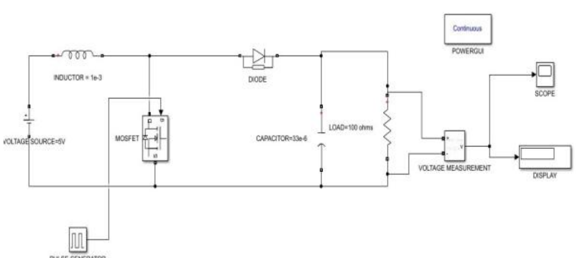

Fig6: Simulink model of Boost Converter

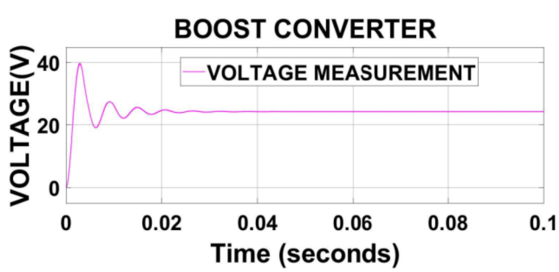

Fig7: Output of Boost Converter

B. Bidirectional Converter

A Bidirectional converter is a key component in hybrid electric vehicles (HEVs) that facilitates the transfer of energy between the battery and other power systems, such as the motor or regenerative braking unit. It operates in two modes: boost mode, where it steps up the battery voltage to power the BLDC motor, and buck mode, where it steps down the voltage during regenerative braking to store energy back into the battery. This dual functionality enhances energy efficiency and supports extended vehicle range. In solar-powered HEVs, the bidirectional converter also ensures seamless energy management between the solar panels, battery storage,and motor, optimizing overall performance and system reliability.

IV. BATTERY

Modeling of the battery is essential for effective energy management and system efficiency. Battery modeling involves understanding and simulating various characteristics, such as charge and discharge behavior, voltage response, state of charge (SOC), temperature effects, and aging, to optimize its integration with other vehicle components, including the motor, solar array, and power converters. A precise model enables the prediction of battery performance under diverse operating conditions, ensuring reliable energy storage and efficient power delivery. Typically, lithium-ion batteries are used due to theirhigh energy density, efficiency, and longevity, making them well-suited for hybrid applications. Battery models can vary from simple equivalent circuit models, which approximate the battery's behavior with resistors and capacitors, to morecomplex electrochemical models thatsimulate internal reactions for greateraccuracy. Integration with a Battery Management System (BMS) is critical, as it monitors the battery's state of charge, temperature, and health, protecting against overcharging and deep discharge. Accurate battery modeling not only supports optimal power flow and enhances energy recovery (e.g., through regenerative braking) but also prolongs battery life and improves vehicle range. In a hybrid configuration, this enables effective coordination with the DC-DC converter, motor, and solar panel system, maximizing renewable energy use and minimizing fuel consumption.

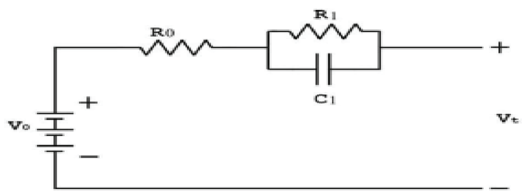

Fig8: Circuit Diagram of Battery

V. BLDC DRIVE

The Brushless DC (BLDC) drive is a pivotal component, responsible for efficient, smooth, and precise control of the BLDC motor, which directly affects vehicle performance and energy efficiency. The BLDC motor is favored in HEVs due to its high efficiency, high torque-to-weight ratio, and durability, making it ideal for applications that demand variable speeds and frequent start-stop operations. Unlike traditional motors, the BLDC motor operates without brushes, using an electronic controller to switch currents in the motor windings, which reduces maintenance and increases longevity. The BLDC drive uses advanced Control algorithms, such as Field-Oriented Control (FOC) or Direct Torque Control (DTC), to regulate the motor's torque and speed, adapting to load variations and ensuring optimal performance. Integrated with the solar and battery systems, the drive responds to changing power inputs, whether from stored battery energy or Directsolar power, to deliver smooth propulsion. Additionally, the BLDC drive facilitates regenerative braking, converting kinetic energy back into electrical energy to recharge the battery, and further enhancing system efficiency. By precisely managing the BLDCmotor, the drive contributes to improved vehicle responsiveness, reduced energy loss, and extended driving range, all essential for sustainable transportation in a hybrid electric vehicle

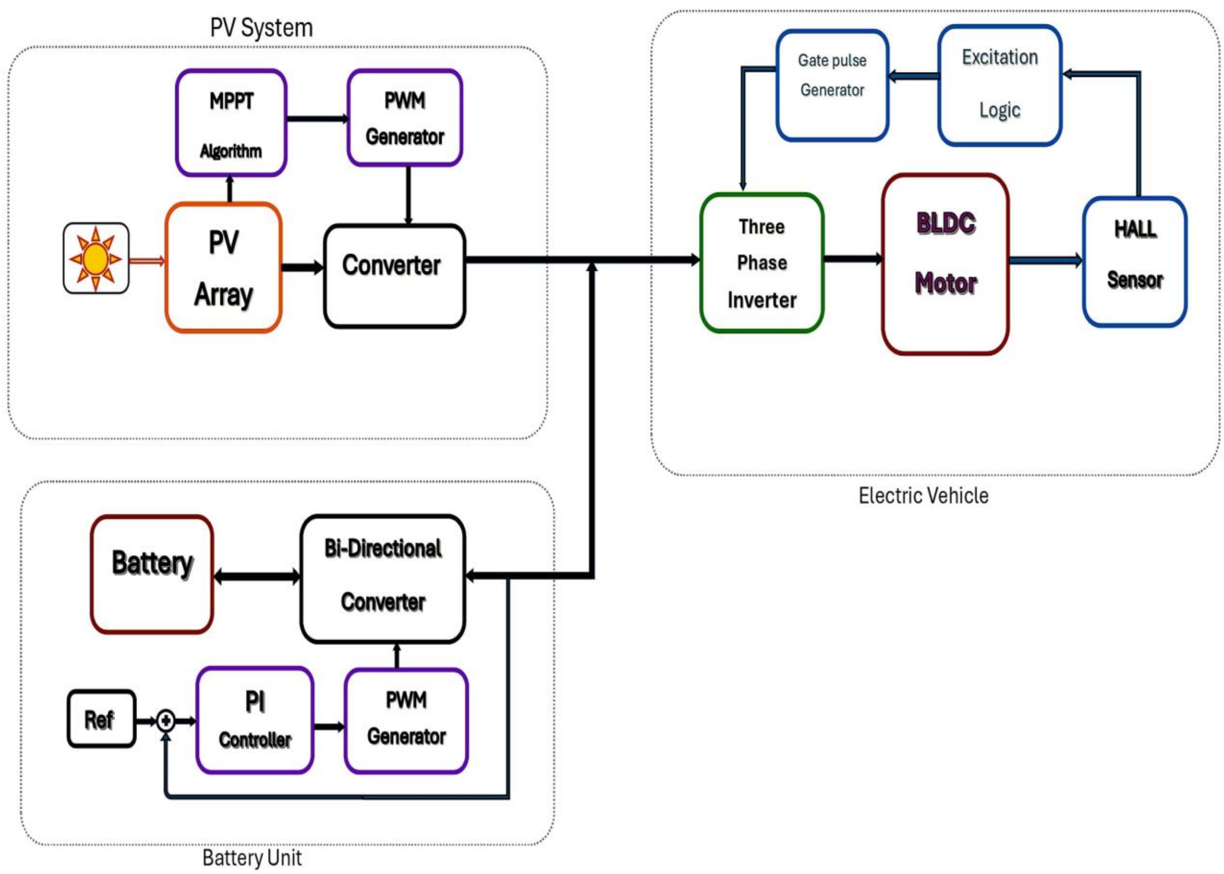

Fig9: Schematic diagram of BLDC Motor

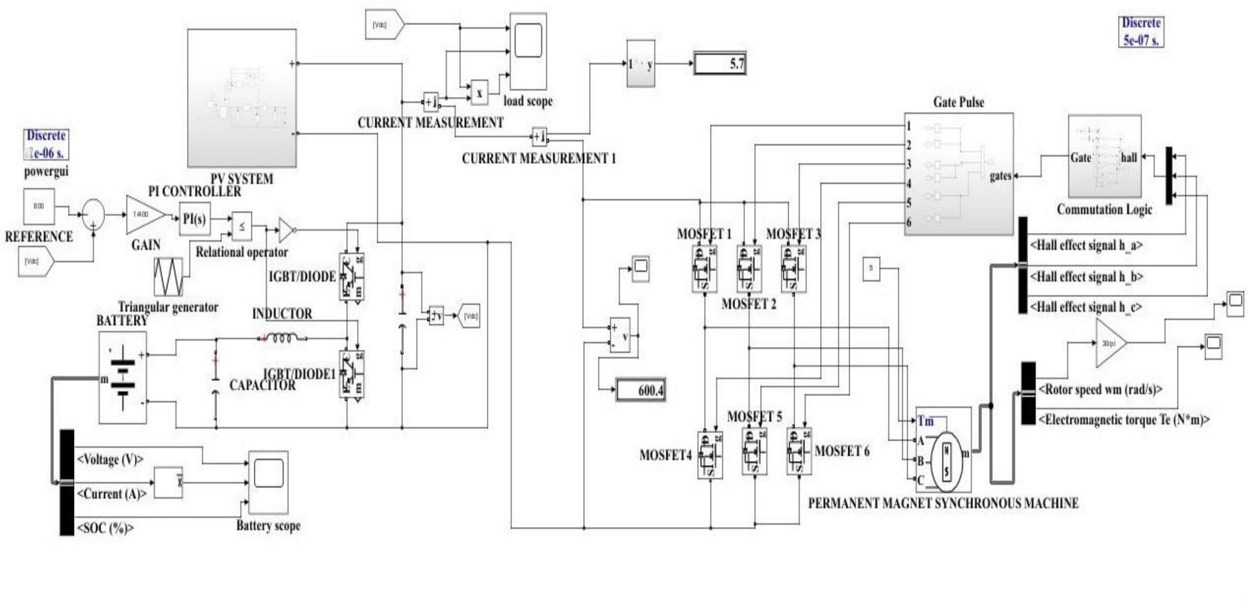

Fig10: Simulink Model of BLDC motor based HEV

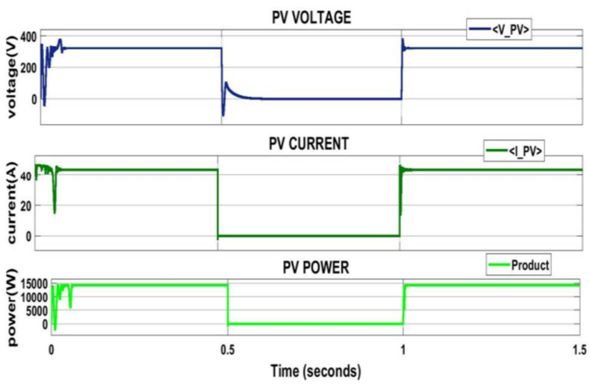

Fig11: PV Voltage, PVCurrent, PVPower with aVariation of irradiance

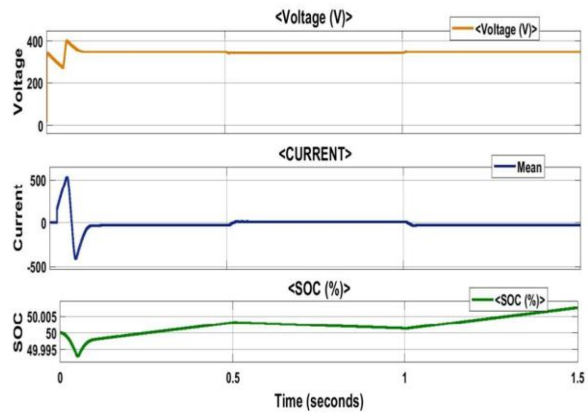

Fig15: Battery Voltage, Battery Current, SOC of the Battery

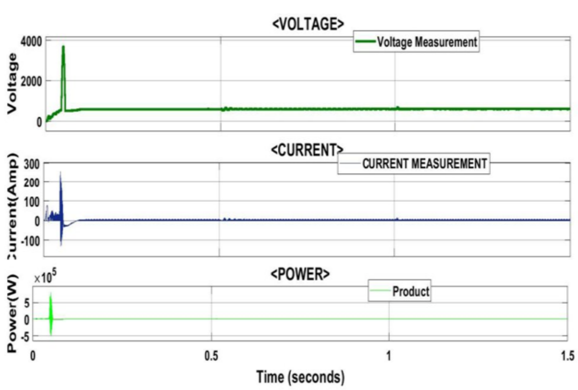

Fig12: Load voltage, load current, load power

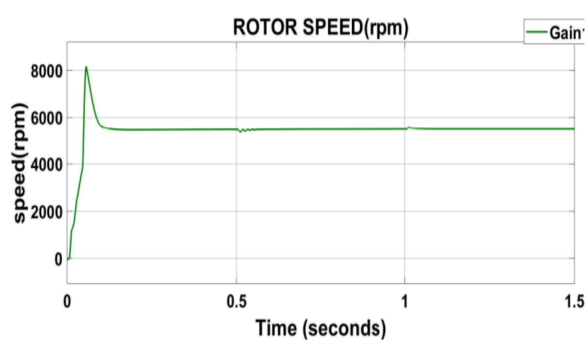

Fig13: Rotor Speed graph of BLDC Motor

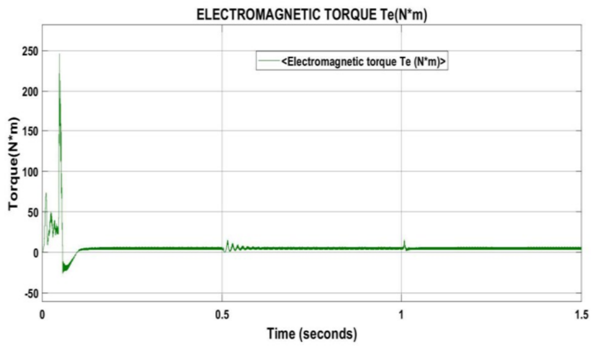

Fig14: Electromagnetic torque graph of BLDC Motor

VI. CONCLUSION

This study highlights the potential of a solar-powered BLDC motor–based hybrid electric vehicle (HEV) as a sustainable and efficient transportation solution. By integrating photovoltaic (PV) panels, an MPPT algorithm, and advanced power converters, the proposed system achieves optimal energy utilization and reduced environmental impact. The BLDC motor ensures high performance, reliability, and low maintenance, making it ideal for hybrid vehicle applications. Future research can focus on improving PV panel efficiency, developing advanced energy storage systems such as solid-state batteries, and incorporating machine learning algorithms for adaptive energy management. Additionally, exploring lightweight vehicle materials and integrating wireless charging technologies can further enhance the practicality and scalability of solar-powered HEVs.

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