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Development of a BLDC Motor Drive System Powered by Battery-Supercapacitor Hybrid Storage and Solar PV for Electric Vehicle Applications

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Abstract -This project presents the design and development of a Battery and Super-capacitor Fed Brushless DC (BLDC) Motor Drive System tailored for Electric Vehicle (EV) applications. The objective is to enhance the efficiency, dynamic performance, and reliability of EV powertrains by integrating a hybrid energy storage system comprising a battery and a super-capacitor. In this setup, the battery serves as the primary energy source, providing steady power during normal driving conditions, while the super-capacitor assists in handling transient load demands, such as rapid acceleration or hill climbing, and also absorbs energy during regenerative braking. This hybrid approach reduces stress on the battery, extends its lifespan, and improves overall system responsiveness. To further enhance energy utilization, the system can be integrated with a solar photovoltaic (PV) source, regulated using a Maximum Power Point Tracking (MPPT) algorithm. The MPPT controller ensures that the PV panel operates at its optimal power point under varying solar irradiance conditions, contributing to battery charging and reducing dependency on grid power.

Keywords—Brush Less DC Motor, Super-capacitor, Motor Drive System, Hybrid Energy Storage System, Battery, Maximum Power Point Tracking, Photo Voltaic Cell.

1.INTRODUCTION

The increasing demand for eco-friendly transportation has accelerated the shift toward electric vehicles (EVs) as a sustainable alternative to internal combustion engine vehicles Brushless DC (BLDC) motors are widely used in EV applications due to their high efficiency, compact size, and low maintenance requirements. Despite these advantages, the performance of BLDC motor drive systems depends significantly on the efficiency of the energy storage system . Lithium-ion batteries, although capable of storing large amounts of energy, are limited in power delivery during peak load conditions such as acceleration or regenerative braking . To overcome this limitation, hybrid energy storage systems (HESS) combining batteries and supercapacitors have been proposed, offering a balance of high energy and high power density]. Supercapacitors are particularly effective in absorbing regenerative energy and supplying quick bursts of power, thereby reducing stress on the battery and extending its lifespan. The integration of solar photovoltaic (PV) systems into EVs adds an additional renewable energy source, contributing to reduced dependency on grid charging . However, the inclusion of solar energy introduces complexities in power conditioning and energy flow control, which require advanced management strategies. Modern energy management systems (EMS) use intelligent algorithms to coordinate the power distribution between the battery, supercapacitor, and solar PV system in real-time. These EMS solutions enhance overall system efficiency, prolong battery life, and adapt to various driving conditions dynamically. Control strategies such as fuzzy logic, adaptive control, and model predictive control are being investigated to optimize the powertrain operation of such hybrid systems. This study focuses on the development of a BLDC motor drive system powered by battery-supercapacitor hybrid storage and supported by solar PV, designed specifically for electric vehicle applications [1-6].

2. SYSTEM CONFIGURATION

2.1 Hybrid Energy Storage System

Electric Vehicles (EVs) are at the forefront of the global shift toward clean transportation. Their efficiency and reliability heavily depend on the performance of the propulsion motor and the energy storage system. Traditional battery-powered EVs suffer from voltage sags, reduced efficiency under peak load, and reduced lifespan due to deep discharges. In recent years, hybrid energy storage systems (HESS) have emerged as a promising solution to bridge the gap between energy density and power density, by combining batteries and supercapacitors. The battery, characterized by high energy storage capacity, supplies sustained power during standard operation. On the other hand, the supercapacitor, known for rapid charge and discharge capabilities, addresses transient load conditions effectively. This synergy not only enhances system responsiveness but also reduces the thermal and electrical strain on the battery, ultimately prolonging its service life.

2.2Solar PV with MPPT Control

The integration of a solar photovoltaic (PV) system into the electric vehicle (EV) energy architecture offers a significant step toward achieving greener and more self-sufficient transportation. In the proposed system, the solar PV array functions as a supplementary energy source, contributing to the charging of the battery and supercapacitor units. This renewable energy input not only reduces the dependency on grid power but also enhances the sustainability of the EV by harnessing clean energy directly from the environment.

However, the electrical output of a solar panel varies significantly with changing weather conditions such as solar irradiance and ambient temperature. To ensure that the PV system consistently operates at its optimal power point under varying environmental conditions, a Maximum Power Point

Tracking (MPPT) algorithm is employed. MPPT dynamically adjusts the operating point of the PV array to extract the maximum possible power, thus enhancing the efficiency of solar energy conversion.

Several MPPT techniques can be used, such as Perturb and Observe (P&O), Incremental Conductance, or fuzzy logic-based approaches, depending on system requirements and computational resources. In the proposed design, the MPPT controller continuously senses the voltage and current output from the PV panel and modifies the duty cycle of the DC-DC converter accordingly. This process ensures that the solar panel operates at its most efficient point, even under rapidly changing sunlight conditions.

By implementing solar PV with MPPT, the system not only supplements battery charging during daytime operation but also contributes to reducing the frequency and depth of battery discharges. This reduces overall energy consumption from conventional sources and aligns the vehicle operation with global environmental and energy-saving goals. The integration of solar PV thus plays a crucial role in extending vehicle range, improving energy autonomy, and supporting a renewable energy-driven EV ecosystem.

2.3 Power Management Strategy

n the proposed system, effective power distribution is achieved through a centralized Power Management Unit (PMU), which plays a pivotal role in coordinating the energy exchange between the battery, supercapacitor, and the load, specifically the Brushless DC (BLDC) motor. The PMU continuously monitors real-time parameters such as current demand, state-of-charge (SoC) of storage units, and motor torque requirements to dynamically allocate power from the most appropriate source.

Under normal operating conditions, the battery acts as the primary energy source, delivering steady power to the motor. However, during transient load variations—such as sudden acceleration or regenerative braking—the supercapacitor is activated to either supplement the battery or absorb regenerative energy. This dual-source approach mitigates stress on the battery by minimizing high current discharges, thereby improving its lifespan and thermal stability.

When integrated with a solar photovoltaic (PV) source, the system incorporates a Maximum Power Point Tracking (MPPT) controller that optimizes solar energy harvesting based on real-time irradiance and temperature conditions. The energy captured from the PV panel is intelligently routed by the PMU to charge either the battery or the supercapacitor, depending on their respective SoC levels and the current demand profile.

The coordination of energy sources ensures that the BLDC motor operates efficiently across all driving modes. This intelligent power management not only enhances the system's responsiveness but also maximizes energy recovery, supports sustainability goals, and reduces the dependency on grid power in electric vehicle applications.

2.4BLDC Motor Propulsion System

The propulsion subsystem in the proposed electric vehicle architecture employs a Brushless DC (BLDC) motor, known for its compact design, high torque-to-weight ratio, and superior efficiency across a broad speed range. Unlike conventional brushed motors, the BLDC motor operates through electronic commutation, eliminating mechanical wear and enhancing reliability and lifespan—crucial for electric vehicle (EV) applications.
The BLDC motor is driven by an inverter circuit, which generates a three-phase AC output from the DC supply provided by the battery-supercapacitor hybrid system. Rotor position is detected in real-time using Hall-effect sensors, which enable precise timing of the inverter switching signals. This ensures that the stator magnetic field is always optimally aligned with the rotor, thereby maximizing torque production and minimizing power losses.

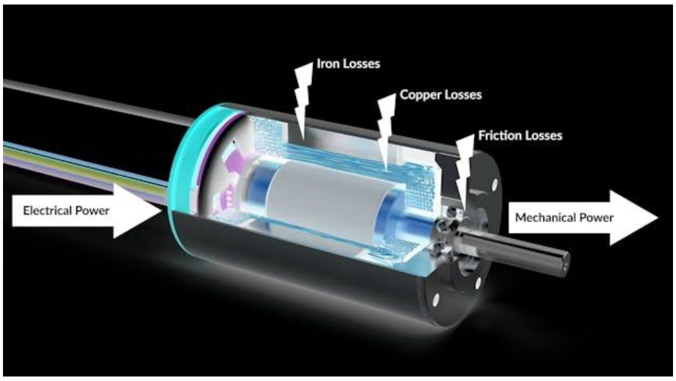

Fig 1 BLDC motor Construction

The motor's control algorithm adjusts voltage and current flow based on feedback signals such as rotor position, speed, and load torque. During regular driving, the motor receives smooth and continuous energy from the battery. During periods of high load demand, such as rapid acceleration or hill climbing, additional current is provided by the supercapacitor, reducing the burden on the battery and improving system responsiveness.

In braking or deceleration scenarios, the motor functions as a generator, converting kinetic energy back into electrical energy. This regenerative energy is captured and redirected by the Power Management Unit (PMU) to recharge the supercapacitor or battery, depending on their respective states of charge. This enhances overall energy efficiency and reduces the frequency of external recharging.

The integration of the BLDC motor with the intelligent energy storage and control systems ensures seamless propulsion, rapid response to dynamic driving conditions, and improved energy utilization—making it an ideal choice for modern electric mobility solutions.

3. OVERALL SIMULATION SYSTEM

3.1 Simulation Diagram

To support clean and renewable energy input, the system includes a solar PV array modeled with real-time irradiance and temperature variables. An MPPT algorithm dynamically

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adjusts the duty cycle of a DC-DC converter to ensure the PV panel operates at its optimal power point.

At the core of the system lies the hybrid energy storage unit, which integrates a battery and a supercapacitor in parallel. The battery supplies a stable energy flow during regular driving, while the supercapacitor provides rapid energy bursts during dynamic scenarios like acceleration and regenerative braking. This dual setup enhances power handling, improves responsiveness, and significantly reduces the operational stress on the battery, thereby extending its lifecycle.

An MPPT algorithm dynamically adjusts the duty cycle of a DC-DC converter To support clean and renewable energy input, the system includes a solar PV array modeled with real-time irradiance and temperature variables to ensure the PV panel operates at its optimal power point. The extracted solar energy is utilized for charging the storage units or directly powering the motor, depending on system demand and availability.

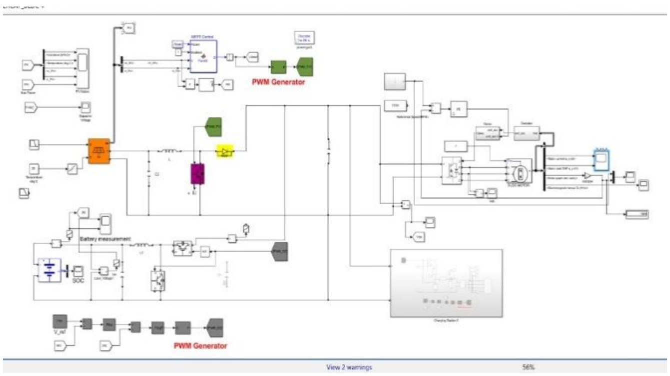

Fig-2 Simulation Diagram

The energy flow across the system is intelligently managed by the Power Management Unit. It evaluates parameters such as current load conditions, state-of-charge levels of the storage devices, and solar power input to determine the most efficient energy distribution path. Bidirectional converters play a crucial role in stabilizing voltage levels and controlling current direction, thereby maintaining system safety and performance.
The BLDC motor drive subsystem consists of a three-phase inverter, which is governed by electronic commutation using rotor position feedback from Hall-effect sensors. The inverter delivers appropriately timed switching pulses to the motor phases to ensure smooth and efficient operation. The motor is modeled with detailed electrical and mechanical characteristics to simulate both steady operation and dynamic transitions like rapid load changes.
This simulation setup provides a comprehensive view of the system's energy dynamics, enabling in-depth analysis of power flow, efficiency, and performance under a range of EV scenarios. It effectively demonstrates the viability and adaptability of the proposed hybrid system for sustainable transportation.

3.2 Super Capacitor

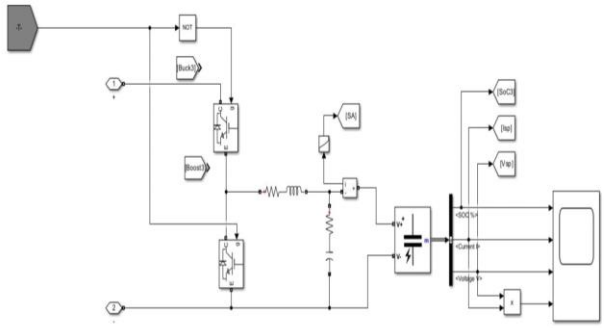

Fig 3 Super Capacitor In Simulink Model

In the simulation environment, the supercapacitor is modeled as a high-power, fast-responding energy storage element capable of handling sudden load variations. The Simulink model represents the supercapacitor using an equivalent electrical circuit composed of a series-connected capacitor and resistor, which accurately captures both its storage characteristics and internal losses.
The capacitance value in the model defines the energy storage capacity, while the equivalent series resistance (ESR) represents internal resistive losses that influence efficiency and voltage drop during high current flow. The voltage across the supercapacitor is continuously monitored and dynamically adjusted based on its charge and discharge states. During regenerative braking or deceleration events, the supercapacitor absorbs the recovered energy almost instantaneously. Conversely, during acceleration or other transient high-power demands, it supplies rapid bursts of current to assist the motor, thereby alleviating the load on the battery.
The model is integrated with a bidirectional DC-DC converter controlled via a Pulse Width Modulation (PWM) signal. This converter facilitates the bidirectional flow of energy between the supercapacitor and the DC link, enabling both charging (energy absorption) and discharging (energy delivery) operations. Control logic is applied to determine the supercapacitor's activation based on vehicle dynamics, power demand, and battery state-of-charge, ensuring optimal contribution without overcharging or over-discharging.
The supercapacitor's quick response time and high power density are clearly demonstrated in simulation waveforms, which show rapid voltage and current transitions in response to load changes. These results confirm the supercapacitor's essential role in stabilizing voltage, improving dynamic performance, and protecting the battery from high peak currents.

3.3 Stator Current and Back-EMF of BLDC Motor

Figure 4shows the stator current waveform and corresponding back-electromotive force (EMF) of one phase of the BLDC motor. The stator current waveform indicates a trapezoidal shape consistent with ideal BLDC commutation. The back-EMF also shows a typical trapezoidal waveform, aligned with rotor position, confirming correct motor operation.

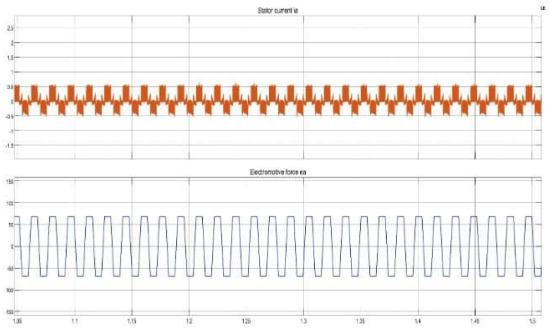

Fig 4 BLDC motor stator current and back EMF

3.4 Line-to-Line Voltage of Inverter Output

Figure 5 the output voltage waveform (Vab) from the three-phase inverter illustrates high-frequency PWM switching patterns. The voltage waveform has the expected step-like transitions, validating proper inverter switching and motor voltage application.

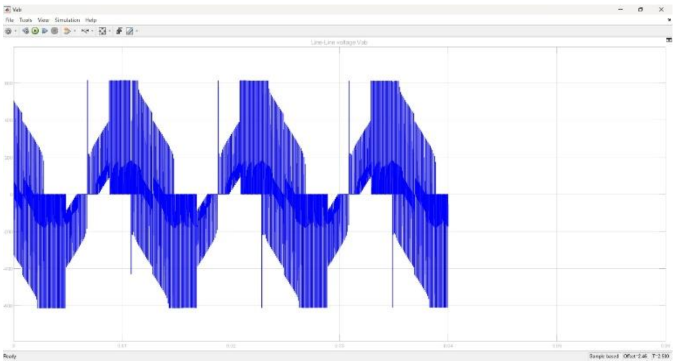

Fig 5 Line-to-Line Voltage of Inverter Output

3.5 Supercapacitor Voltage Response

The supercapacitor voltage behavior during dynamic conditions is illustrated in figure 4 Initially, the voltage rises sharply due to rapid charging and then gradually tapers as load sharing between the battery and supercapacitor stabilizes. This demonstrates the supercapacitor's ability to handle transient power demands efficiently**.**

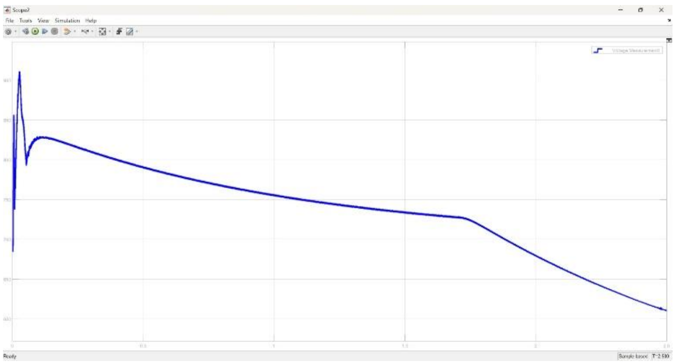

Fig 6 Supercapacitor Voltage Response

3.6 Solar PV Power and State of Charge (SOC) of Battery

Figure 7 displays the performance of the solar PV module along with battery SOC response. The irradiance decreases after 1.5 seconds, causing a corresponding drop in PV power, voltage, and current. Despite the changing solar input, the MPPT controller maintains a consistent power output until irradiance declines. The SOC plot indicates a steady rise, confirming successful charging of the battery from PV input.

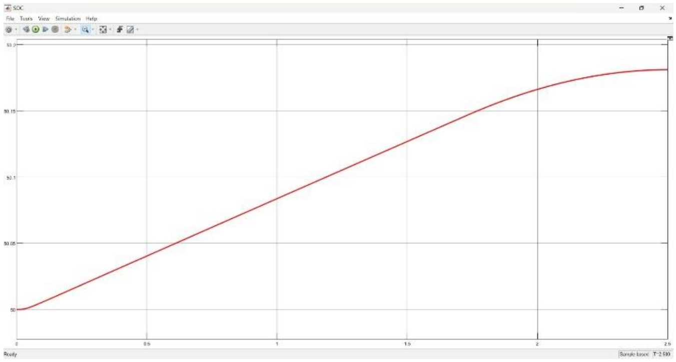

Fig 7 Super capacitor voltage profile

4. CONCLUSION

This paper presented the modeling, design, and simulation of a hybrid energy-based BLDC motor drive system for electric vehicle applications. The system integrates a battery and supercapacitor as the primary and auxiliary energy storage units, respectively, enhanced further by a solar photovoltaic (PV) input regulated through a Maximum Power Point Tracking (MPPT) algorithm. The use of a Power Management Unit (PMU) ensures intelligent and real-time allocation of energy resources, optimizing performance across diverse operating conditions.

The BLDC motor, known for its high efficiency and dynamic response, forms the core propulsion unit, benefiting from the hybrid storage system that enhances acceleration capability, supports regenerative braking, and reduces stress on the battery. Simulation results validate the system's capability to maintain voltage stability, deliver responsive torque during transients, and maximize energy recovery—contributing to both performance improvement and sustainable energy usage.

Overall, the proposed hybrid drive configuration offers a robust, efficient, and environmentally friendly solution for future electric mobility platforms. Its ability to combine renewable energy harvesting, intelligent energy distribution, and responsive motor control makes it a strong candidate for next-generation electric vehicle technologies.

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