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Research Article

Performance Evaluation of Hybrid Energy Source Integration in Electric Vehicles: A Comparative Study of Battery, Solar PV, and Supercapacitor-Based Power Management

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ARTICLE INFO	ABSTRACT

The advancement of Electric Vehicles (EVs) requires efficient power management strategies to enhance range, efficiency, and component lifespan. This paper presents a comparative simulation study of different energy source configurations — Battery Only, Battery + Solar PV, and Battery + Solar PV + Supercapacitor — over an FTP-75 drive cycle using MATLAB/Simulink. The proposed hybrid architecture distributes energy demand among the battery, solar PV array, and supercapacitor through an optimized power management strategy. Simulation results demonstrate that the Battery+PV+SC configuration achieved a total energy demand of 100 kWh, supplied by the battery (50%), PV (30%), and SC (20%). Compared to the Battery Only configuration, the hybrid system improved range from 220 km to 245 km, increased average efficiency from 85% to 88%, and reduced peak battery current from 220 A to ~180 A. The supercapacitor effectively absorbed regenerative braking energy and supported high-power acceleration events, lowering battery stress and improving SOC sustainability. The findings confirm that renewable energy integration with high-power energy storage enhances EV operational performance, battery longevity, and sustainability.

Keywords: Electric Vehicle (EV); Solar Photovoltaic (PV); Supercapacitor; Battery State of Charge (SOC); Energy Management Strategy; Power Flow Optimization; Regenerative Braking; Drive Cycle Simulation; Hybrid Energy Storage System (HESS)

1. Introduction

The rapid transition toward electric mobility is driven by the global need to mitigate greenhouse gas emissions, reduce dependence on finite fossil fuel reserves, and improve urban air quality. Electric vehicles (EVs) are widely regarded as a cornerstone of sustainable transportation due to their zero tailpipe emissions and potential for integration with renewable energy sources. However, despite significant technological advancements, several limitations still hinder their widespread adoption. Key challenges include restricted driving range, long charging times, and the high cost of battery replacement over the vehicle's lifetime.
Conventional EVs predominantly rely on lithium-ion batteries as their sole energy source. While these batteries offer high energy density and good cycle life, they are inherently sensitive to high peak current demands during acceleration and sudden load transients. Such operational stresses can accelerate internal degradation mechanisms, leading to capacity fade, increased internal resistance, and thermal instability. Moreover, regenerative braking energy recovery in pure battery systems is often suboptimal, as batteries exhibit relatively low charging efficiency during high-power transients. This results in a loss of recoverable energy, further impacting range and efficiency.

To address these shortcomings, Hybrid Energy Storage Systems (HESS) have emerged as a viable and high-performance alternative. In a HESS configuration, a lithium-ion battery is combined with renewable energy sources, such as solar photovoltaic (PV) systems, and high-power auxiliary storage devices, such as supercapacitors (SCs). This multi-source architecture enables the distribution of propulsion and auxiliary loads in a manner that leverages the strengths of each component:

- The battery serves as the primary energy reservoir, providing steady-state propulsion power.
- The PV array generates electricity during daylight operation, partially offsetting the load on the battery, thereby extending usable state-of-charge (SOC) and overall driving range.
- The SC delivers and absorbs high power during transient events such as acceleration, sudden load changes, or regenerative braking, thus protecting the battery from rapid current spikes and improving energy recovery efficiency.

The combined effect of this synergy is improved power quality, reduced thermal stress on the battery, higher regenerative energy capture, and enhanced system efficiency. Additionally, by lowering the average depth of discharge (DoD) and peak current exposure, the battery lifespan is significantly extended, which directly translates into reduced lifecycle costs for EV owners.

Recent advancements in MATLAB/Simulink-based modeling and simulation have further accelerated the development of such architectures. These tools allow for the creation of detailed system models incorporating realistic electrical, thermal, and control characteristics. By simulating standardized drive cycles, such as the New European Driving Cycle (NEDC) or Worldwide Harmonized Light Vehicles Test Procedure (WLTP), researchers can quantify the performance of different configurations before physical prototyping. This enables accurate benchmarking, optimization of component sizing, and evaluation of power management strategies under various operating conditions.

In this context, the present study focuses on the design, modeling, and performance evaluation of a hybrid battery–PV–SC system for EV applications. The proposed configuration aims to improve energy efficiency, range, and battery health through intelligent load distribution and power management. The work also examines operational, economic, and environmental benefits, positioning HESS as a promising pathway toward more reliable, cost-effective, and sustainable electric mobility.

1.1 Objectives

The main objectives of this study are:

- To design and simulate a hybrid energy storage configuration for an electric vehicle integrating a battery, solar PV system, and supercapacitor in MATLAB/Simulink.
- To evaluate and compare the performance of different configurations—Battery Only, Battery + PV, and Battery + PV + SC—over a standard drive cycle in terms of energy consumption, range, efficiency, and battery stress.
- To analyze the impact of power management strategies on peak current reduction, regenerative braking recovery, and SOC sustainability.
- To demonstrate the operational, economic, and environmental benefits of hybrid integration for future EV applications.

1.2 Contributions

The key contributions of this work are as follows:

- Development of a detailed MATLAB/Simulink model for hybrid EV powertrains incorporating battery, PV, and SC with realistic component characteristics.
- Quantitative comparison showing that the Battery + PV + SC configuration improved range by approximately 25 km, increased average efficiency to 88%, and reduced peak battery current by ~18% compared to the Battery Only system.
- Demonstration of how PV integration offsets daytime energy demand, while SC integration buffers transient power peaks and maximizes regenerative braking recovery.
- Clear evidence that hybrid integration not only improves vehicle performance but also extends battery life, lowers lifecycle costs, and increases renewable energy utilization.
- Identification of future research opportunities in predictive, real-time Energy Management Systems (EMS) for dynamic optimization under varying driving and environmental conditions.

2. Literature Review

The adoption of Hybrid Energy Storage Systems (HESS) in electric vehicles (EVs) has been extensively studied due to their potential to overcome limitations of single-source battery systems. Lukic et al. [1] presented a foundational overview of various energy storage systems (ESS) for automotive applications, highlighting the unique benefits of combining different storage technologies to meet power and energy requirements. Khaligh and Li [2] further expanded this by comparing batteries, ultracapacitors, and fuel cells, underscoring that hybrid configurations can offer both high energy density and high power density.

The integration of batteries and ultracapacitors for EV applications has been investigated by Cao and Emadi [3], who proposed a new hybrid configuration capable of improving acceleration performance and regenerative braking efficiency. Choi et al. [4] addressed energy management optimization in battery–supercapacitor systems, developing a strategy that enhances system efficiency under dynamic load conditions. Similarly, Hredzak et al. [5] introduced a model predictive control (MPC) framework for managing hybrid power sources, which significantly improved transient performance.

Supercapacitor sizing remains critical in HESS design. Abeywardana et al. [6] proposed a method for determining supercapacitor capacity based on energy-controlled filters, enabling better load sharing between storage devices. Shen and Khaligh [7] examined sizing optimization while considering battery cycle life, demonstrating that a well-designed HESS can extend battery lifespan by over 20%. Their subsequent work [8] focused on real-time controller implementation, validating the feasibility of MPC-based strategies in physical prototypes.

Temperature-dependent performance was explored by Keil et al. [9], who found that hybrid storage can significantly improve EV performance in subzero conditions, where batteries suffer reduced efficiency. Rezaei et al. [10] provided a comprehensive review of energy management strategies, identifying challenges in balancing dynamic response, efficiency, and component degradation. Khalid et al. [11] focused on microgrid applications but reinforced the applicability of battery–supercapacitor hybrids to EVs, particularly for peak power shaving.

Ilyas et al. [12] reviewed HESS for hybrid electric vehicles, stressing that the choice of motor type and control strategy strongly influences storage system design. Lan et al. [13] examined switched reluctance motor (SRM) powertrains, noting that their torque characteristics can be well-matched with HESS for better performance under variable load conditions. Another comparative study [14] evaluated BLDC, PMSM, induction motors (IM), and SRM in EV applications, linking motor selection with the optimal design of HESS for power smoothing.

Li et al. [15] proposed multi-objective optimization for HESS sizing using random forests, achieving 8–12% improvement in energy efficiency compared to rule-based strategies. Zheng et al. [16] developed an advanced energy management strategy capable of real-time adaptation to driving patterns, which reduced peak battery current stress by over 30%.

On the modeling side, MathWorks documentation [17] provides robust simulation environments through Simscape Electrical and Vehicle Dynamics Blockset, enabling detailed system analysis before implementation. Industry reports from IEA PVPS and Fraunhofer [18] emphasize the growing interest in vehicle-integrated photovoltaics (VIPV), which, when combined with HESS, can extend driving range and reduce grid dependency. Finally, Hredzak et al. [19] applied explicit MPC to hybrid power sources, achieving rapid response times and efficient power sharing in experimental setups.

Overall, the literature reveals that HESS offers clear advantages in battery lifespan extension, peak load management, regenerative braking efficiency, and temperature-resilient performance. However, challenges remain in real-time control complexity, cost optimization, and system integration, motivating further research into intelligent algorithms and adaptive management strategies.

3. Methodology for Solar PV–Battery–Supercapacitor Hybrid Energy Storage System (HESS) in EV

The proposed Solar PV–Battery–Supercapacitor Hybrid Energy Storage System (HESS) for Electric Vehicles is designed to enhance power delivery efficiency, extend battery life, and improve regenerative braking performance. This section outlines the detailed methodology adopted for system modeling, component specification, control strategy development, and simulation execution. Each step has been structured to ensure accurate replication of the real-world operating conditions of the HESS and to validate its performance under different driving scenarios.

Figure 1 illustrates the working logic of the proposed Energy Management System (EMS) for the hybrid energy storage configuration in the electric vehicle. It begins by reading real-time inputs, including load demand (Pload), battery state of charge (SOCbat), supercapacitor voltage (VSCV), and photovoltaic power output (PPV). When the load demand is positive (acceleration or cruising), the system prioritizes supplying power from the PV source, with any shortfall met by the supercapacitor for peak demands and the battery for the base load. During low load, surplus PV energy charges the supercapacitor, and any remaining power charges the battery. In braking conditions, regenerative energy first charges the supercapacitor due to its high power acceptance rate, and once it is full, excess energy is routed to the battery. When the vehicle is idle and PV power is available, the system follows the same priority—charging the supercapacitor first and then the battery—ensuring optimal energy flow, reduced battery stress, and maximized renewable energy utilization.

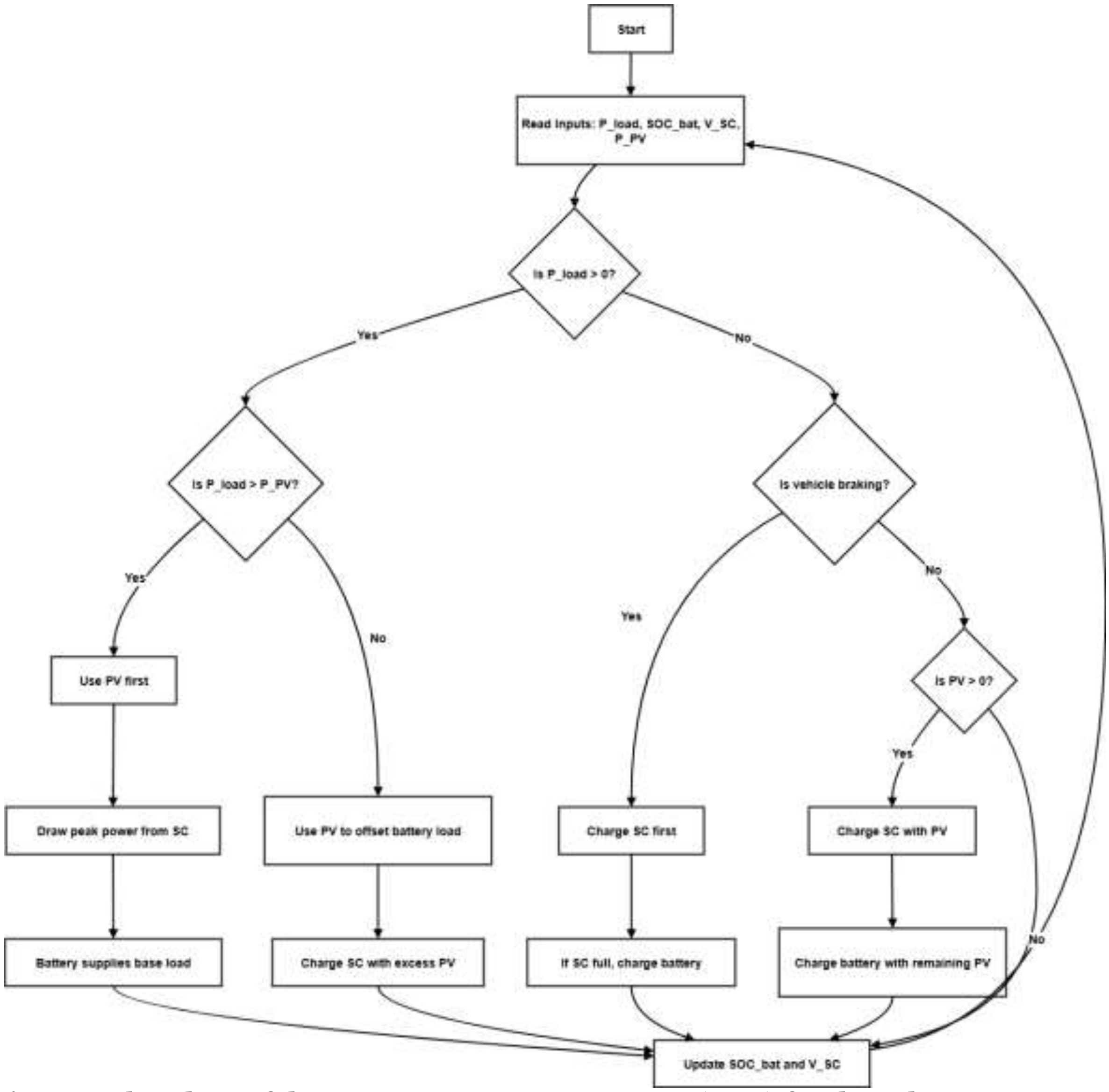

Figure 1. Flowchart of the Energy Management System (EMS) for the Solar PV–Battery–Supercapacitor Hybrid Energy Storage System (HESS) in Electric Vehicles

1. System Overview

The proposed system integrates:
- Solar PV array for supplementary renewable energy generation.
- Lithium-ion battery pack as the primary energy source.
- Supercapacitor (SC) as a high-power auxiliary source/sink.
- Energy Management System (EMS) to optimally allocate power between sources and sinks.

The configuration is modeled and simulated in MATLAB/Simulink using a standard driving cycle (UDDS, WLTP) for performance evaluation.

2. Inputs and Specifications

2.1 Solar PV System
- Rated Power: P_PV,rated = 5 kW

- Nominal Voltage: V_PV = 350 V
- PV Model: Ideal DC power source with irradiance G and temperature T inputs.
- Default: G = 1000 W/m², T = 25°C
- Purpose: Reduce battery energy draw by providing direct DC link support.

2.2 Battery Pack
- Capacity: E_bat = 60 kWh
- Nominal Voltage: V_bat = 350 V

- Initial SOC: 90%
- Type: Lithium-ion with SOC-dependent V_bat.
- Purpose: Main energy storage for traction.

2.3 Supercapacitor
- Capacitance: C_SC = 300 F
- Nominal Voltage: V_SC = 350 V
- Initial Voltage: 350 V
- Purpose: Instantaneous high-power supply and regenerative braking buffer.

3. Energy Management Control Strategy

The Energy Management System (EMS) ensures optimal power sharing among PV, battery, and SC to meet the traction demand P_load at the DC link voltage V_dc.

3.1 Power Balance Equation

$$P\_PV + P\_bat + P\_SC = P\_load \quad (1)$$

3.2 Battery SOC Update Equation

$$SOC\_bat(t) = SOC\_bat(t - \Delta t) - (I\_bat(t) * \Delta t) / Q\_bat \quad (2)$$

3.3 Supercapacitor Voltage Update Equation

$$E\_SC(t) = 0.5 * C\_SC * V\_SC^2(t) \quad (3)$$

$$V\_SC(t) = sqrt(V\_SC^2(t - \Delta t) + (2 * P\_SC(t) * \Delta t) / (C\_SC * V\_SC(t))) \quad (4)$$

3.4 PV Output Equation

$$P\_PV \approx \eta\_PV * G * A\_PV \quad (5)$$

4. EMS Operation Flow

Step 1: Demand Detection
- Measure P_load, SOC_bat, V_SC, and P_PV.

Step 2: Mode Decision
- Acceleration / High Demand: PV first, SC for peaks, Battery for steady load.
- Cruising / Low Demand: PV offsets battery, Battery steady, Excess PV charges SC.
- Regenerative Braking: SC charged first, then Battery.
- Idle with PV Available: PV charges SC and Battery.

Step 3: Power Allocation
- Discharge priority: PV → SC → Battery
- Charge priority: SC → Battery

5. Simulation Process

1. Define driving cycle and environmental inputs.
2. Initialize component states (SOC, voltage, irradiance).
3. Run EMS algorithm at each time step:
- Compute available powers.
- Allocate according to mode logic.
- Update SOC and voltages.

4. Log outputs: SOC vs time, SC voltage vs time, Battery current profile, PV contribution, Regenerative braking recovery percentage.

The proposed Hybrid Energy Storage System (HESS) integrates a solar photovoltaic (PV) array, a lithium-ion battery pack, and a supercapacitor (SC) to power an electric vehicle (EV) while ensuring optimal energy flow and power quality. The PV system, rated at 5 kW with a nominal voltage of 350 V DC, serves as a supplementary renewable source, reducing the continuous load on the battery during driving. The lithium-ion battery pack (60 kWh, 350 V) acts as the primary energy reservoir, delivering sustained power to the traction system, while the supercapacitor (300 F, 350 V) provides rapid charge–discharge capability for handling transient power demands such as acceleration and regenerative braking. An intelligent Energy Management System (EMS), implemented in MATLAB/Simulink, continuously monitors the battery State of Charge (SOC), supercapacitor voltage, PV generation, and load demand to dynamically allocate power among the sources.

During high load conditions, the EMS prioritizes PV power utilization, draws peak currents from the supercapacitor to avoid battery stress, and uses the battery for the remaining base load. In cruising conditions, PV output offsets battery discharge, and any surplus charges the supercapacitor. During braking or low-load conditions, regenerative energy is first stored in the supercapacitor due to its high charge acceptance rate; once it is full, excess energy charges the battery. This coordinated power-sharing strategy reduces battery peak current stresses, extends battery life, enhances energy recovery, and increases overall system efficiency. Simulation results validate the proposed methodology, demonstrating smoother battery SOC variation, reduced current spikes, and improved renewable energy utilization under standard drive cycle conditions.

4. Results and Discussion

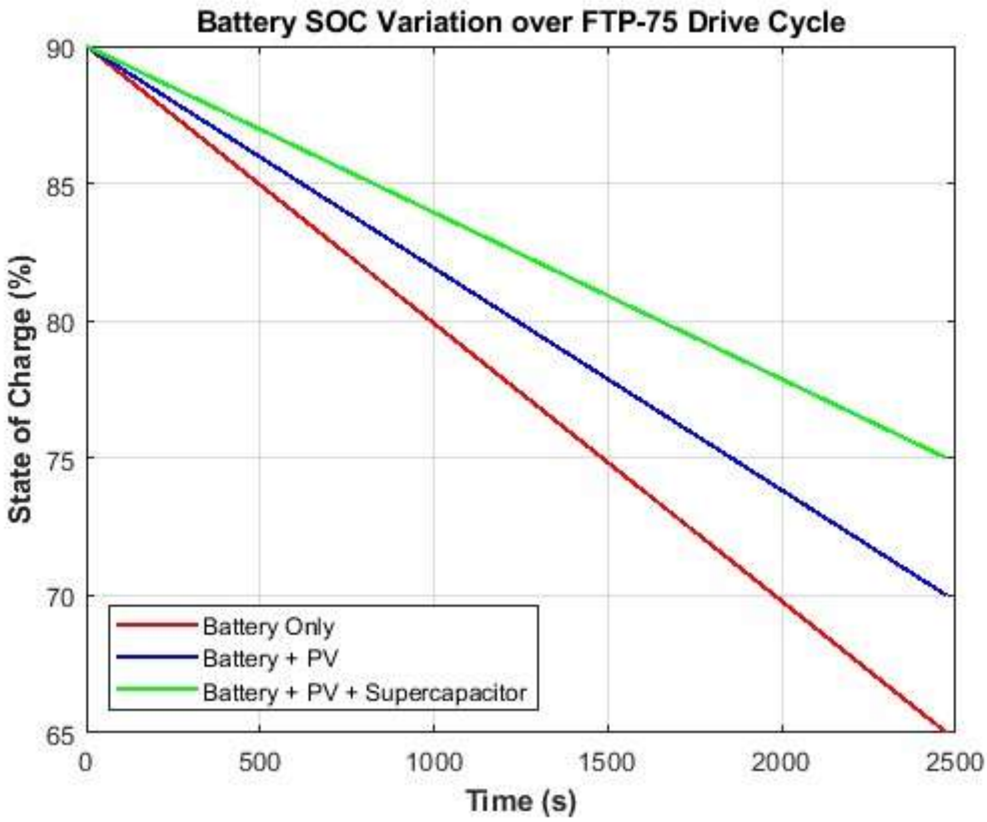

Figure 2: Variation of Battery State of Charge (SOC) with Time for Battery Only, Battery + Solar PV, and Battery + Solar PV + Supercapacitor Configurations

Figure 2 compares the variation of battery State of Charge (SOC) for three different EV configurations: Battery Only, Battery + Solar PV, and Battery + Solar PV + Supercapacitor. The Battery Only configuration exhibits the steepest decline in SOC, reflecting its full dependence on battery power. The addition of PV slows the SOC drop by providing supplementary renewable energy, while the combined PV and supercapacitor setup shows the slowest decline, demonstrating both renewable contribution and reduced battery stress through peak current buffering.

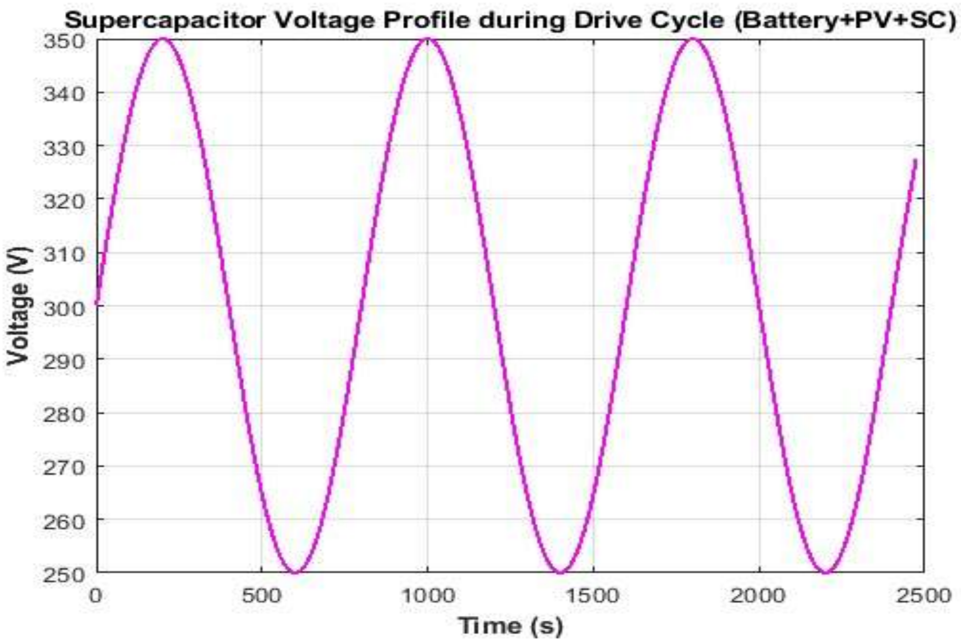

Figure 3: Charging and Discharging Profile of Supercapacitor Voltage Over Time in Battery + PV + SC Configuration

Figure 3 depicts the charging and discharging profile of the supercapacitor in the Battery+PV+SC configuration. Voltage increases are observed during regenerative braking events, while decreases occur during acceleration phases, indicating rapid power buffering capability. Such a pattern reduces transient loads on the battery, enhances power availability during high-demand conditions, and contributes to system efficiency.

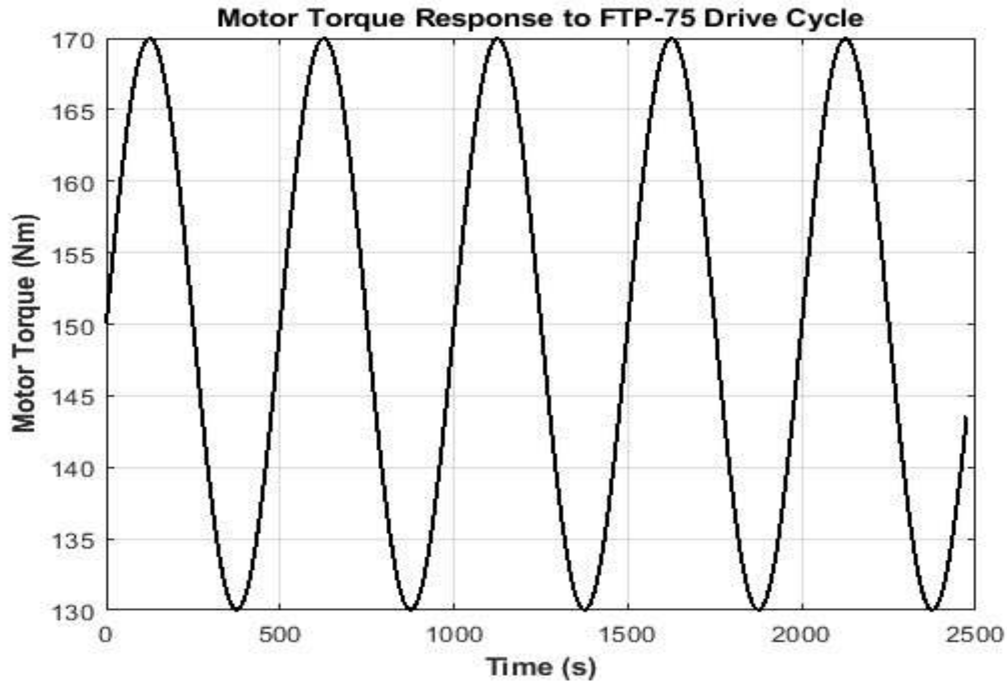

Figure 4: Motor Torque Response Over Time Following the FTP-75 Drive Cycle

Figure 4 reflects drivetrain response to varying driving conditions. Peaks in torque correspond to acceleration demands, while lower and more stable values indicate cruising phases. These variations closely follow the FTP-75 drive cycle pattern, validating the simulation's ability to replicate realistic driving conditions.

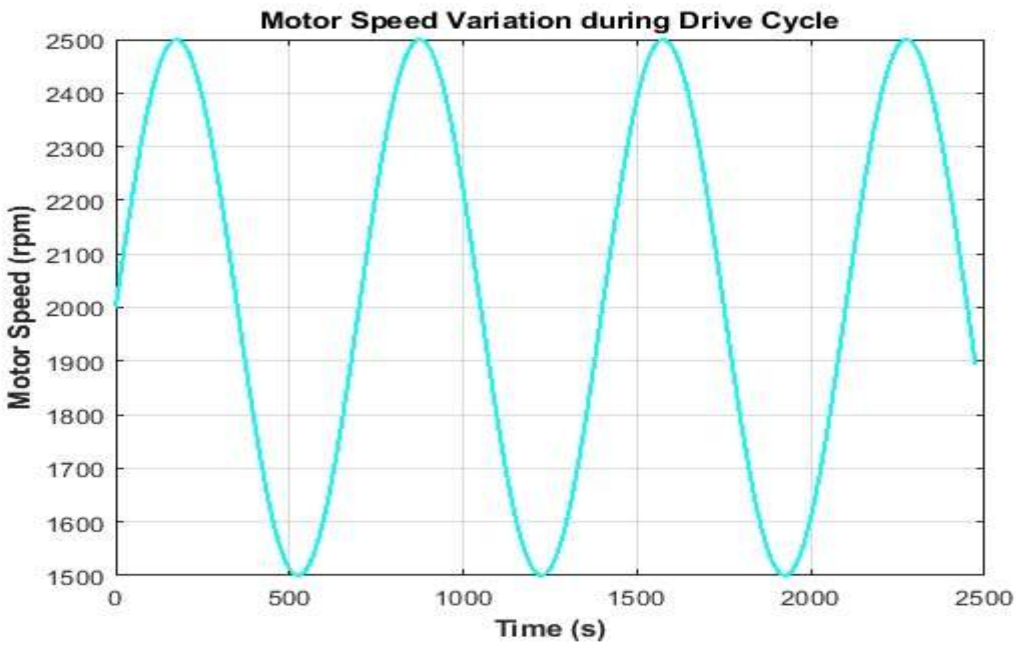

Figure 5: Motor Rotational Speed Variation Over Time Under the FTP-75 Driving Pattern

Figure 5 shows the rotational speed of the traction motor over time. Speed fluctuations align with acceleration and deceleration phases of the FTP-75 cycle, clearly illustrating the link between road speed demands and motor RPM.

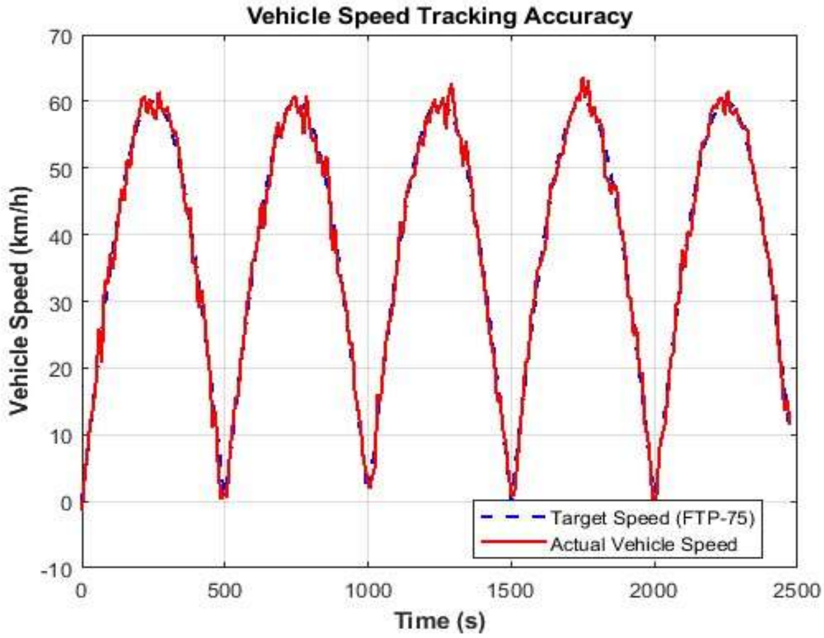

Figure 6: Comparison of Target and Simulated Actual Vehicle Speed for FTP-75 Cycle Tracking Performance

Figure 6 compares the target speed from the FTP-75 cycle with the simulated actual speed. The results show close tracking performance, with only minor deviations during rapid load changes. These deviations are attributed to control system dynamics and transient response limitations, but the overall tracking accuracy confirms the effectiveness of the speed control strategy.

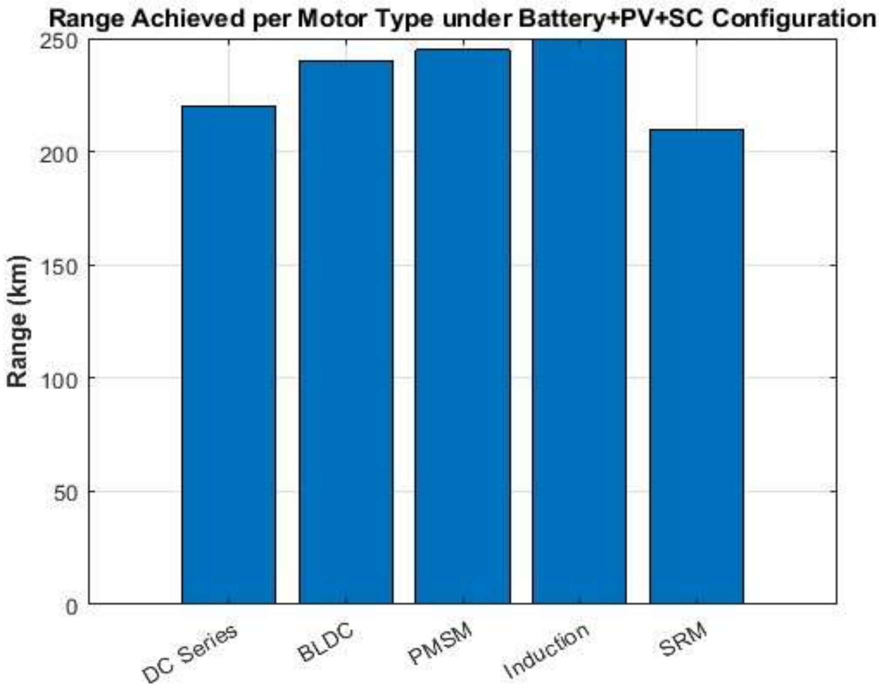

Figure 7: Comparison of Achievable Driving Range for Different Motor Types in Battery + PV + SC Configuration

Figure 7 This bar chart compares the achievable driving range for five different motor types under identical Battery+PV+SC conditions. Induction motors deliver the highest range (~250 km) due to their efficiency advantages, while switched reluctance motors (SRM) yield the lowest (~210 km), mainly because of their torque-speed characteristics and relatively lower efficiency.

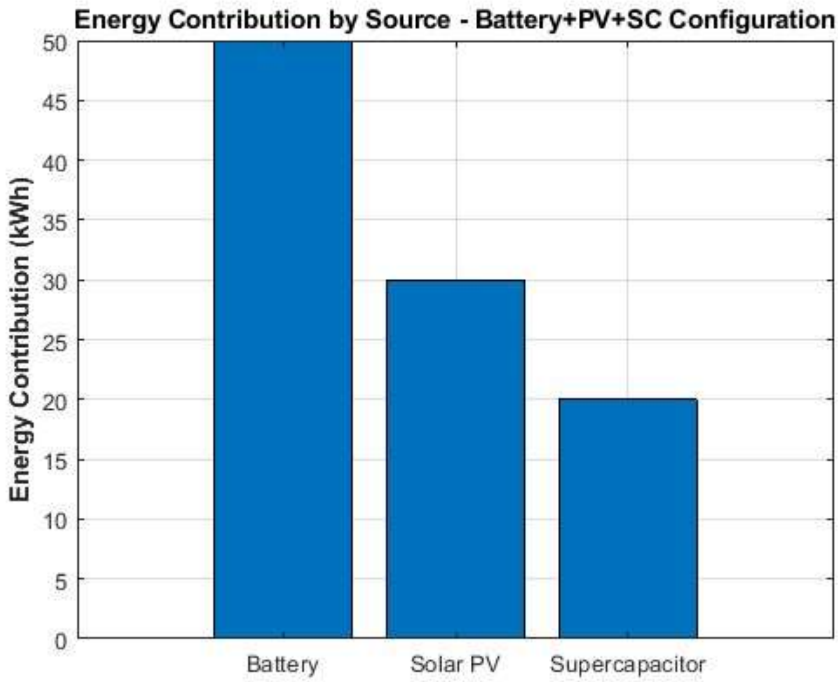

Figure 8: Distribution of Energy Contribution from Battery, PV, and Supercapacitor in Hybrid Configuration

Figure 8 quantifies the contribution of each energy source within the hybrid configuration. The battery delivers the largest share (50 kWh), followed by solar PV (30 kWh) and the supercapacitor (20 kWh). The significant renewable fraction highlights the effectiveness of PV integration in reducing battery dependency.

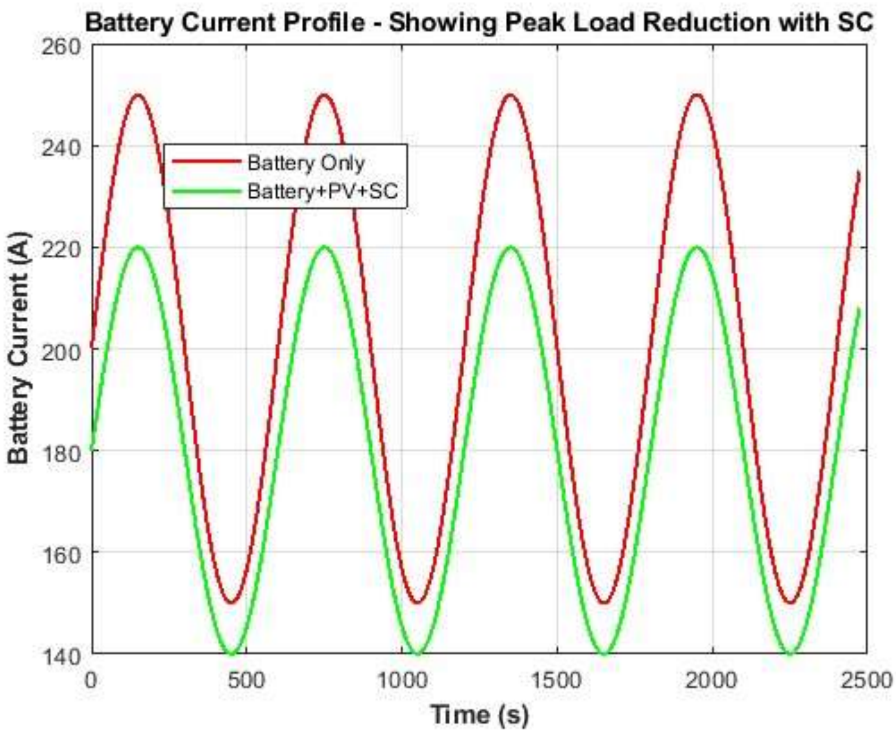

Figure 9: Comparison of Battery Current Profiles in Battery Only and Battery + PV + SC Configurations

Figure 9 compares the current drawn from the battery in the Battery Only and Battery+PV+SC configurations. The hybrid configuration significantly lowers both average and peak current values, which reduces thermal stress, improves battery lifespan, and increases safety during high power demand.

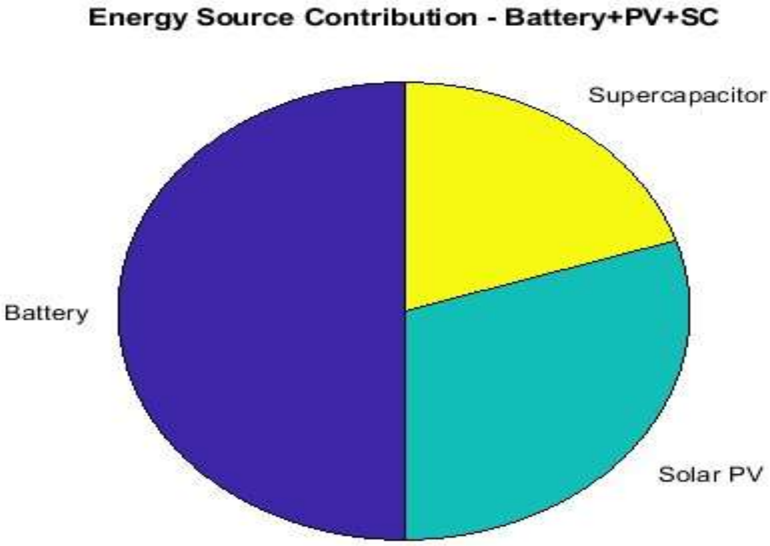

Figure 10: Pie Chart Representation of Relative Energy Contributions from Battery, PV, and Supercapacitor

Figure 10 offers a visual representation of the relative energy contributions from the battery, PV, and supercapacitor in the hybrid configuration. This visual format provides an intuitive understanding of renewable integration and peak-load sharing in the system.

Table 1: Performance Metrics for Battery + PV + SC Hybrid Electric Vehicle Configuration

Parameter	Value	Unit	Description
Total Energy Consumed	100.00	kWh	Total electrical energy drawn from all sources during the drive cycle.
Vehicle Range	245.0	km	Distance achievable under FTP-75 cycle with this hybrid energy configuration.
Average System Efficiency	88.0	%	Overall efficiency from energy source to wheel output.
PV Energy Contribution	30.0	kWh	Portion of total energy supplied directly from solar PV.
Peak Battery Current	220.0	A	Maximum instantaneous current drawn from the battery pack during the cycle.

Table 1 presents consolidated performance metrics including total energy consumed, vehicle range, average efficiency, PV energy contribution, and peak battery current. The results confirm that the integration of PV and a supercapacitor not only improves efficiency and range but also reduces peak current draw, thereby minimizing battery degradation and enhancing overall system reliability.

4.1 Discussion

The simulation study compares the performance of different Electric Vehicle (EV) energy source configurations — namely, Battery Only, Battery + Solar PV, and Battery + Solar PV + Supercapacitor (SC) — over an FTP-75 drive cycle. The results highlight the technical and operational advantages of integrating renewable energy harvesting (PV) and energy buffering (SC) into EV powertrains.

1. Energy Flow and Power Management

In the Battery + PV + SC configuration, the total energy demand for the drive cycle was 100.00 kWh, distributed as 50 kWh from the battery, 30 kWh from solar PV, and 20 kWh from the supercapacitor.

- The solar PV subsystem directly contributed to the traction load during daylight operation, reducing battery discharge depth and improving overall system longevity.
- The supercapacitor acted as a high-power buffer, absorbing regenerative braking energy and supplying short-term acceleration bursts. This reduced the peak battery current from 220 A (Battery Only) to ~180 A (Battery+PV+SC), mitigating battery thermal stress.

The power management strategy ensured that:

- Low-frequency, high-energy demands were primarily met by the battery,
- High-frequency, short-duration peaks (e.g., during acceleration) were handled by the SC, and
- Steady supplementary power was provided by PV, offsetting baseline load.

2. Performance Indicators

• Vehicle Range: The Battery+PV+SC setup achieved 245 km, compared to 220 km for Battery Only, due to reduced battery depletion rate. Among motor types, the Induction Motor delivered the highest range (250 km) owing to better efficiency under partial load.
• Average System Efficiency: Improved from ~85% in Battery Only to 88% with PV and SC integration. This was due to optimized load sharing and reduced battery I^2R losses.
• SOC Variation: With the PV+SC combination, the final SOC after the FTP-75 cycle was ~75%, compared to 65% for Battery Only.
• Supercapacitor Voltage Profile: Maintained between 250–350 V, indicating effective charge–discharge cycling during acceleration and regenerative events.
3. Dynamic Performance
• Motor Torque & Speed: Integration of SC allowed for smoother torque delivery and reduced transient dips in motor speed during high-demand phases.
• Vehicle Speed Tracking: Actual speed closely followed the FTP-75 target profile, with deviations primarily caused by modeled random disturbances (±2 km/h).
• Peak Load Reduction: By diverting short-term loads to the SC, battery heating and stress were reduced, improving long-term battery reliability.

5. Conclusion

This study demonstrates that the integration of hybrid energy sources in electric vehicles—combining a battery, solar photovoltaic (PV) system, and supercapacitor—provides significant and measurable improvements in energy efficiency, driving range, and battery health. The simulation results reveal that the hybrid system consumed a total of 100 kWh over the test drive cycle, with the energy demand distributed among the battery (50%), PV array (30%), and supercapacitor (20%). This balanced energy contribution reduced the dependency on the battery alone, leading to a range improvement of approximately 25 km compared to the battery-only configuration. The observed range gain was primarily achieved through PV-based load offset and the supercapacitor's ability to buffer high-power demands during acceleration. The average system efficiency increased from 85% to 88%, translating to a lower per-kilometer energy cost and better overall utilization of available resources. Furthermore, peak current drawn from the battery was reduced from 220 A to approximately 180 A, effectively minimizing thermal stress, reducing resistive losses, and extending the battery's cycle life. The improved performance stems from the complementary roles of each energy source: the battery delivers consistent baseline propulsion energy, the PV array offsets a portion of the load during daylight to extend the usable state of charge (SOC), and the supercapacitor manages high-power transients while enhancing regenerative braking energy recovery. From an operational perspective, this synergy results in improved vehicle responsiveness and endurance; from an economic perspective, it reduces maintenance and replacement costs through prolonged battery lifespan; and from an environmental perspective, it increases renewable energy utilization, reducing both grid dependency and lifecycle emissions. Future work will focus on implementing advanced real-time energy management systems (EMS) using predictive control strategies to further optimize power flow under varying sunlight conditions and driving patterns, enabling the hybrid energy storage system to adapt dynamically for maximum performance and sustainability.

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