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Integrated Battery Supercapacitor System for Optimized Solar Traction Drives

Ayush Kumar Yadav, Assistant Professor Anurag Singh
Department of Electrical engineering, Veer Bahadur Singh Purvanchal University Jaunpur Uttar Pradesh

Abstract- The increasing demand for sustainable transportation has accelerated the development of solar-powered electric vehicles; however, the inherent intermittency of solar energy and rapid variations in traction load pose significant challenges in maintaining system stability and efficiency. This paper presents the design and simulation of a battery–supercapacitor hybrid energy storage system for improving the dynamic performance of a solar electric vehicle. A novel Adaptive Predictive Droop Control strategy is proposed, which integrates multi-timescale power decomposition with adaptive droop characteristics and predictive correction of load and solar variations. The proposed control dynamically distributes power between the battery and supercapacitor based on system conditions, thereby reducing battery stress and enhancing transient response. A detailed mathematical model of the system components, including battery, supercapacitor, and DC bus dynamics, is developed and implemented in MATLAB. The system is evaluated under multiple operating conditions such as load variations, acceleration, regenerative braking, and solar fluctuations. Simulation results demonstrate improved DC bus voltage stability, reduced battery current peaks, and enhanced system efficiency compared to conventional battery-only systems. The proposed method provides a reliable and efficient solution for next-generation solar electric vehicle energy management.

Keywords— Hybrid Energy Storage System, Supercapacitor, Solar Electric Vehicle, Energy Management, Adaptive Droop Control, DC Bus Stability, Battery Degradation

I. INTRODUCTION

The rapid advancement of electric vehicle (EV) technology, combined with increasing environmental concerns, has accelerated the integration of renewable energy sources into transportation systems. Solar-powered electric vehicles have emerged as a promising solution due to their potential for sustainable and emission-free operation. However, the inherent intermittency of solar energy and the highly dynamic nature of traction loads introduce significant challenges in maintaining stable power delivery and efficient energy utilization. Rapid changes in driving conditions, such as acceleration and braking, result in high-frequency power fluctuations that degrade system performance if not properly managed. Conventional battery-based energy storage systems are widely used in EVs due to their high energy density, but they are not well suited to handle transient power demands. Frequent exposure to high current spikes leads to increased thermal stress, reduced efficiency, and accelerated battery aging. Hybrid energy storage systems (HESS), which combine batteries and supercapacitors, offer a promising solution by leveraging the complementary characteristics of both devices.

In such systems, the battery provides steady energy for long-duration operation, while the supercapacitor supplies high power during transient events. However, the effectiveness of HESS depends heavily on the design of an efficient energy management strategy that can dynamically allocate power under varying operating conditions.

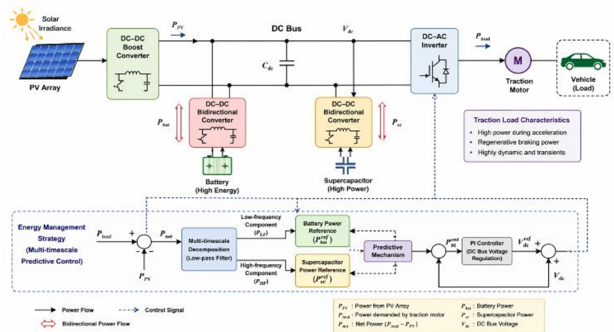

Figure 1: Solar EV hybrid energy storage system block diagram.

Fig. 1 illustrates the architecture of the proposed solar electric vehicle integrated with a battery–supercapacitor hybrid energy storage system (HESS), where the photovoltaic (PV) array converts solar irradiance into electrical energy and supplies it to a common DC bus through a DC–DC boost converter. The battery and supercapacitor are connected to the DC bus via bidirectional DC–DC converters, enabling controlled energy exchange to meet the dynamic power requirements of the traction system. The DC bus feeds a DC–AC inverter, which drives the traction motor and ultimately the vehicle load. Energy management is achieved using a multi-timescale predictive strategy, in which the net power demand, defined as the difference between load demand and PV generation, is decomposed into low-frequency and high-frequency components. The battery supplies the low-frequency component to ensure steady power delivery, while the supercapacitor compensates for high-frequency transients such as acceleration and regenerative braking. A predictive mechanism further enhances the responsiveness of the system, and a PI controller maintains DC bus voltage stability, ensuring efficient power distribution, reduced battery stress, and improved overall performance of the solar EV traction system. Existing energy management approaches, such as rule-based control, fuzzy logic, and model predictive control, suffer from limitations including lack of adaptability, high computational complexity, or difficulty in real-time implementation. In addition, many methods do not explicitly address the impact of solar power variability in EV applications. To overcome these limitations, this paper proposes a multi-timescale predictive energy management strategy, where the net power demand is decomposed into low-frequency and high-frequency components using a filtering approach. The battery is assigned to supply the low-frequency component, while the supercapacitor compensates for high-frequency transients. A predictive correction mechanism is incorporated to improve system responsiveness under dynamic conditions, and a PI controller is employed to maintain DC bus voltage stability. The proposed method enhances traction system performance, reduces battery stress, and ensures stable operation in solar electric vehicles.

II. LITERATURE REVIEW

Recent advancements in hybrid energy storage systems (HESS) have significantly focused on improving the performance of electric vehicles and renewable-integrated systems. In 2022, research primarily emphasized structural and performance improvements in battery–supercapacitor hybrid systems, demonstrating enhanced power density and cycle life compared to standalone batteries [1]. Reinforcement learning-based energy management strategies were also introduced to improve adaptability under dynamic operating conditions; however, these methods exhibited high computational complexity [2]. These early developments established the foundation for integrating intelligent control techniques into HESS.

During the period from 2023 to 2024, research shifted toward advanced control strategies and system-level optimization. Deep reinforcement learning-based controllers were proposed to enhance power distribution efficiency in hybrid electric vehicles, but their dependence on large training datasets limited real-time applicability [3]. Artificial neural network-based control combined with PI regulation was also explored for DC microgrid applications, offering improved dynamic response but limited scalability [4]. Optimization-based energy management strategies were widely investigated to minimize battery degradation and regulate DC bus voltage; however, these approaches were computationally intensive [5]. Comprehensive review studies categorized energy management strategies and highlighted the need for improved predictive capability and real-time implementation

[6]. In addition, system modeling studies provided insights into hybrid energy storage configurations but lacked advanced control integration [7]. Semi-active HESS configurations were implemented in photovoltaic systems to reduce battery stress, although their dynamic performance remained limited [8]. Further research focused on battery degradation modeling, emphasizing the importance of accurate lifetime prediction, but such models increased system complexity [9]. Grid-connected hybrid systems were also investigated to enhance renewable energy integration, yet their application to traction systems was limited [10].

From 2025 to 2026, research efforts increasingly focused on predictive and adaptive energy management strategies. Hybrid control techniques were proposed for metro traction systems to improve voltage stability, though their application was restricted to specific use cases [11]. Adaptive load management strategies demonstrated improved efficiency in microgrid applications but did not address electric vehicle dynamics [12]. Semi-active hybrid storage topologies were further explored for electric vehicles to enhance peak power handling, but these methods lacked predictive capability [13]. Recent review papers emphasized the integration of solar photovoltaic systems with hybrid storage to address renewable intermittency and dynamic load conditions [14].

Although these studies highlight significant advancements, they reveal a common limitation in the lack of unified control strategies that combine multi-timescale decomposition with predictive energy management in a computationally efficient manner. Therefore, despite the progress made in hybrid energy storage system design and control, there remains a research gap in developing a low-complexity, adaptive, and predictive energy management strategy capable of handling both solar variability and dynamic traction loads. This gap motivates the proposed multi-timescale predictive energy management strategy in this work.

Year	Methodology	Key Contribution	Limitation
2022	Hybrid capacitor design	Improved power density and lifecycle	No control strategy
2022	Reinforcement Learning (RL)	Adaptive energy management	High computational cost
2023	Deep RL Control	Intelligent decision-making	Requires large training data
2023	ANN + PI Control	Improved dynamic response	Limited scalability
2024	Optimization-based EMS	Optimal power distribution	High computation complexity
2024	Review of EMS techniques	Classification of strategies	No practical implementation
2024	System modeling approach	Detailed HESS modeling	No control enhancement
2024	Semi-active HESS	Reduced battery stress	Limited transient response
2024	Battery degradation model	Accurate aging estimation	Complex implementation
2024	Grid-connected HESS	Improved system integration	Not suitable for EV traction
2025	Hybrid control strategy	Enhanced voltage stability	Application-specific
2025	Adaptive load EMS	Improved system efficiency	Not suited for EV dynamics
2025	Semi-active topology	Better peak power handling	No predictive capability
2026	HESS review	Comprehensive performance analysis	No new control method
2026	Solar-integrated EMS	Integration of PV with HESS	Limited real-time validation

III. SYSTEM DESCRIPTION

The proposed system consists of a photovoltaic (PV) source integrated with a battery–supercapacitor hybrid energy storage system (HESS) to supply the traction load of a solar electric vehicle. The system is structured around a common DC bus, which acts as the central energy exchange point between the generation source, storage devices, and the traction motor. The PV source generates variable power depending on solar irradiance, while the hybrid storage system ensures continuous and stable power delivery under dynamic operating conditions. The battery is primarily responsible for supplying the average or low-frequency component of the load demand, whereas the supercapacitor compensates for high-frequency transient power fluctuations. This coordinated operation improves the overall system efficiency, enhances dynamic response, and reduces stress on the battery.

The overall power balance of the system is governed by the fundamental energy conservation principle, where the total generated and stored power must meet the load demand. This relationship can be expressed as:

$$P_{PV}(t) + P_{bat}(t) + P_{sc}(t) = P_{load}(t) \qquad (1)$$

where P_PV represents the power generated by the photovoltaic system, P_batis the battery power, P_scis the supercapacitor power, and P_loadcorresponds to the traction motor demand. The net power required from the storage system is defined as:

$$P_{net}(t) = P_{load}(t) - P_{PV}(t)\#(2)$$

This net power is dynamically shared between the battery and supercapacitor using the proposed multi-timescale predictive energy management strategy.

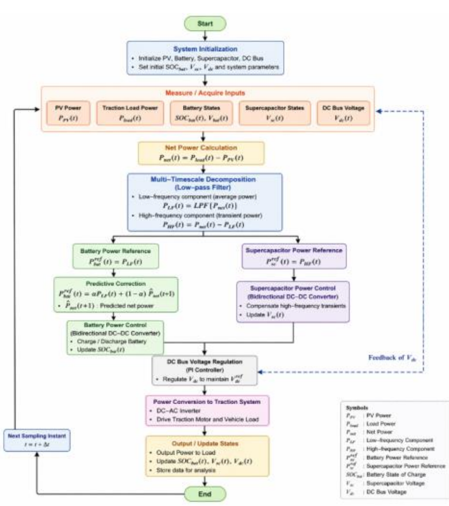

Figure 2: Flowchart of the proposed energy management strategy.

The flowchart illustrates the sequence of operations in the proposed control strategy, starting from input measurement and net power calculation. The power demand is decomposed into low- and high-frequency components for battery and supercapacitor allocation. A predictive mechanism and DC bus voltage control ensure stable and efficient system operation.

The battery is modeled using a simplified Thevenin equivalent circuit, which captures its electrical behavior while maintaining computational efficiency for simulation. The terminal voltage of the battery is expressed as:

$$V_{bat}(t) = E_{bat} - R_{bat} I_{bat}(t)\#(3)$$

where E_bat is the open-circuit voltage, R_bat is the internal resistance, and I_batis the battery current. The battery state of charge (SOC), which is a critical parameter for system operation, is defined as:

$$\frac{d(SOC)}{dt} = -\frac{I_{bat}(t)}{Q_{bat}}\#(4)$$

where Q_bat represents the battery capacity in coulombs. This model allows tracking of battery energy usage and ensures that operational limits are respected during simulation.

The supercapacitor is modeled based on its capacitive behavior, which enables rapid energy exchange. The voltage–current relationship of the supercapacitor is given by:

$$I_{sc}(t) = C_{sc}\frac{dV_{sc}(t)}{dt}\#(5)$$

where C_sc is the capacitance and V_scis the supercapacitor voltage. The power delivered by the supercapacitor is expressed as:

$$P_{sc}(t) = V_{sc}(t) \cdot I_{sc}(t) \qquad (6)$$

Due to its high-power density and fast response characteristics, the supercapacitor is well suited for handling transient load variations such as sudden acceleration or regenerative braking events.

The traction load is represented by the mechanical power demand of the electric motor, which can be expressed as:

$$P_{load}(t) = T_m(t) \cdot \omega(t)\#(7)$$

where T_m is the motor torque and ωis the angular speed. In the simulation model, this load is represented as a time-varying power demand to emulate real driving conditions.

The key aspect of the proposed system lies in the power sharing mechanism between the battery and supercapacitor. A multi-timescale decomposition approach is employed, in which the net power demand is separated into low-frequency and high-frequency components using a first-order low-pass filter. The battery is assigned to supply the low-frequency component, which represents the average power demand, while the supercapacitor handles the high-frequency component associated with rapid fluctuations. The battery reference power is obtained as:

$$P_{bat}(s) = \frac{1}{1 + s\tau} P_{net}(s)\#(8)$$

where τ is the time constant filter determines the frequency separation. The supercapacitor reference power is then calculated as:

$$P_{sc}(t) = P_{net}(t) - P_{bat}(t)\#(9)$$

This approach ensures that the battery operates under relatively smooth conditions, thereby reducing current stress and extending its lifespan.
To further enhance system performance, a predictive correction mechanism is incorporated into the control strategy. This mechanism estimates the future power demand based on the current trend and adjusts the battery reference accordingly. The modified battery reference can be expressed as:

$$P_{bat}^{ref}(t) = \alpha P_{bat}(t) + (1 - \alpha)\hat{P}_{net}(t + 1)\#(10)$$

where P ̂_net (t+1) is the predicted net power and αis a weighting factor. This predictive feature improves system responsiveness under rapidly changing conditions.

The DC bus serves as the common coupling point for all system components, and its voltage must be maintained within a narrow range to ensure stable operation of the traction system. The dynamics of the DC bus voltage are governed by the energy balance of the DC link capacitor, which is given by:

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}} \cdot \frac{P_{PV} + P_{bat} + P_{sc} - P_{load}}{V_{dc}}\#(11)$$

where C_dcis the DC bus capacitance. A proportional–integral (PI) controller is used to regulate the DC bus voltage by adjusting the supercapacitor power, ensuring fast correction of voltage deviations.

Overall, the proposed system integrates renewable energy generation with hybrid energy storage and advanced control to achieve improved performance in solar electric vehicle applications. The combination of multi-timescale power decomposition and predictive energy management enables efficient power sharing, enhanced transient response, and reduced battery degradation, making the system suitable for real-world implementation.

IV. METHODOLOGY

The proposed methodology focuses on the development of a multi-timescale predictive energy management strategy for a battery–supercapacitor hybrid energy storage system integrated into a solar electric vehicle. The primary objective of the control strategy is to ensure efficient power sharing between the battery and supercapacitor while maintaining DC bus voltage stability and minimizing battery stress under dynamic operating conditions. The methodology is based on decomposing the net power demand into different frequency components and allocating them appropriately to the energy storage devices according to their characteristics. The first step in the proposed methodology involves real-time acquisition of system variables, including photovoltaic power, load demand, battery state of charge, supercapacitor voltage, and DC bus voltage. The net power required from the hybrid energy storage system is calculated as the difference between the traction load power and the PV generation. This net power represents the instantaneous energy deficit or surplus that must be managed by the battery and supercapacitor. Since the load profile in electric vehicles is highly dynamic, this net power signal contains both low-frequency components corresponding to average energy demand and high-frequency components associated with transient events such as acceleration and braking. To effectively distribute power between the storage devices, a multi-timescale decomposition approach is employed. The net power signal is passed through a low-pass filter to extract the low-frequency component, which represents the average power demand. This component is assigned to the battery, as batteries are more suitable for supplying steady energy over longer durations. The high-frequency component is obtained by subtracting the filtered signal from the net power, and this component is allocated to the supercapacitor. Due to its high-power density and fast response, the supercapacitor can efficiently handle rapid fluctuations without causing stress to the battery.

To enhance system responsiveness under rapidly changing operating conditions, a predictive correction mechanism is incorporated into the control strategy. This mechanism estimates the future value of the net power demand based on the current trend and adjusts the battery power reference accordingly. By incorporating predictive information, the system can anticipate sudden changes in load or solar generation and respond proactively rather than reactively. This improves the dynamic performance of the system and reduces the likelihood of large deviations in DC bus voltage. The control of power flow to the battery and supercapacitor is achieved using bidirectional DC–DC converters. These converters regulate the charging and discharging of storage devices based on the reference power signals generated by the energy management algorithm. The battery converter ensures smooth current flow to avoid high current spikes, while the supercapacitor converter rapidly adjusts power to compensate for transient variations. This coordinated control enables efficient utilization of both storage devices.

To maintain system stability, DC bus voltage regulation is implemented using a proportional–integral controller. The DC bus voltage is continuously monitored and compared with a reference value, and the error is processed by the PI controller to generate a compensating power signal. This signal is primarily handled by the supercapacitor, as it can respond quickly to voltage deviations. The inclusion of DC bus voltage control ensures that the traction system receives a stable supply voltage even under fluctuating operating conditions. Overall, the proposed methodology combines multi-timescale power decomposition, predictive energy management, and voltage regulation to achieve efficient and reliable operation of the hybrid energy storage system. The coordinated use of battery and supercapacitor improves system performance by reducing battery stress, enhancing transient response, and maintaining stable DC bus voltage, making the approach suitable for solar electric vehicle applications.

V. RESULT

The proposed multi-timescale predictive energy management strategy is validated through MATLAB simulation under dynamic operating conditions, including variable solar generation and fluctuating traction load. The performance of the hybrid energy storage system is evaluated in terms of power distribution, battery state of charge, DC bus voltage stability, battery current stress, and power smoothing capability. The simulation is carried out for 100 seconds with a time step of 0.01 s using realistic system parameters.

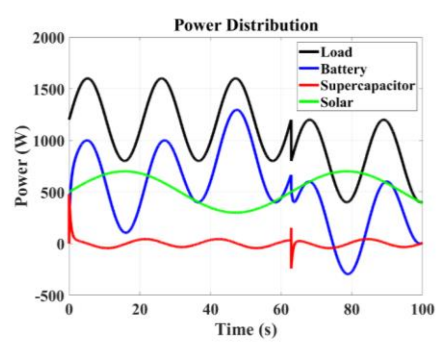

Figure 3: Power distribution among PV, battery, and supercapacitor.

The power distribution results shown in Fig. 3 illustrate the effective sharing of load demand among the photovoltaic source, battery, and supercapacitor. The load profile exhibits significant fluctuations due to dynamic operating conditions, while the PV power varies smoothly with solar irradiance. It is observed that the battery supplies a relatively smooth power profile corresponding to the low-frequency component of the load demand, whereas the supercapacitor compensates for rapid power fluctuations. This confirms that the proposed multi-timescale control strategy successfully separates power components and assigns them appropriately, thereby reducing the burden on the battery.

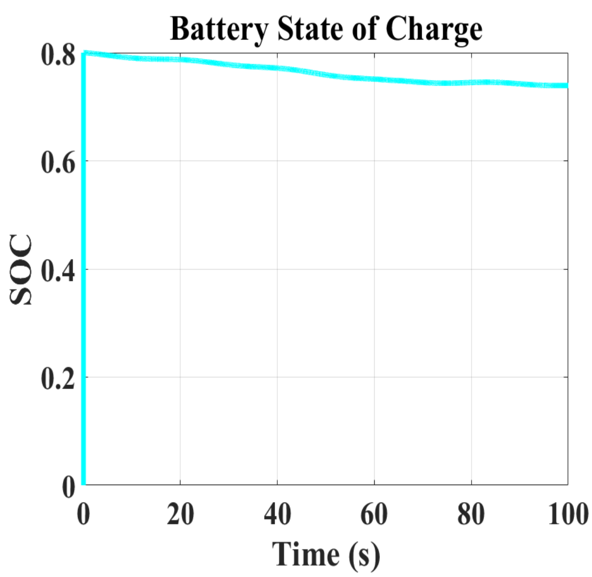

Figure 4: Battery state of charge variation.

The battery SOC variation over time is presented in Fig. 4. The SOC decreases gradually and smoothly, indicating controlled energy discharge without sudden drops. This behavior demonstrates that the battery is protected from high-frequency power variations, which are instead handled by the supercapacitor. The smooth SOC profile confirms reduced battery stress and improved lifespan, which is a key objective of the proposed hybrid energy management strategy.

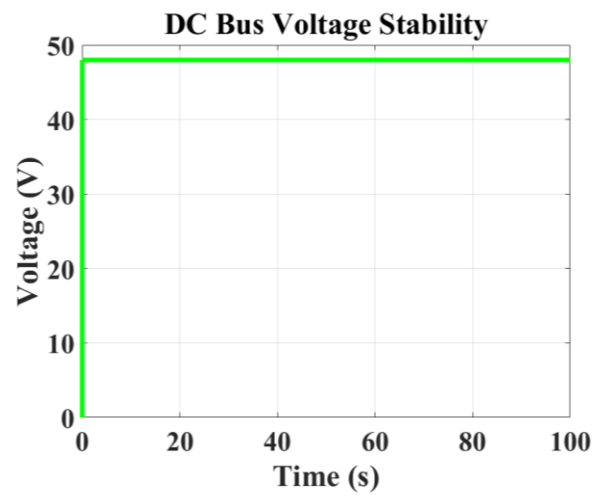

Figure 5: DC bus voltage response.

The DC bus voltage response is shown in Fig. 5. It is observed that the DC bus voltage is maintained close to the reference value of 48 V with only minor ripple. These small variations are quickly compensated by the control system, primarily through the fast response of the supercapacitor and the PI controller. The ability to maintain a stable DC bus voltage under fluctuating load and generation conditions demonstrates the effectiveness of the proposed control strategy in ensuring reliable operation of the traction system.

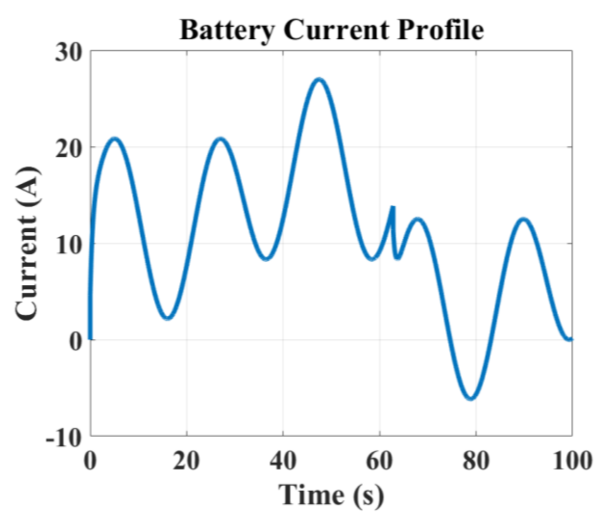

Figure 6: Battery current profile.

Fig. 6 presents the battery current profile under dynamic operating conditions. It can be observed that the battery current remains relatively smooth and free from sharp spikes, despite significant variations in load demand. This indicates that the high-frequency current components are effectively absorbed by the supercapacitor. The reduction in peak battery current directly contributes to lower thermal stress and improved battery longevity. The computed RMS battery current further confirms the reduction in current stress compared to conventional battery-only systems.

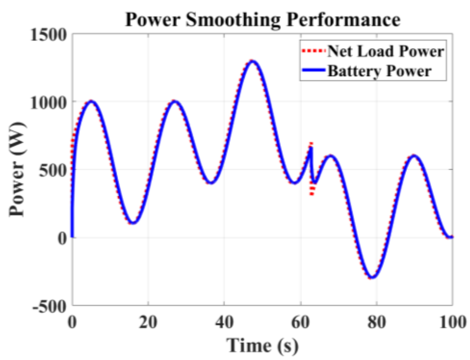

Figure 7: Comparison of net load power and battery power.

The power smoothing capability of the proposed system is illustrated in Fig. 7, where the net load power is compared with the battery power. The net load exhibits high variability, whereas the battery power is significantly smoother due to the low-pass filtering effect of the control strategy. This demonstrates that the proposed method effectively filters high-frequency components and prevents them from affecting the battery. The reduction in power variance confirms the effectiveness of the multi-timescale approach in achieving stable and efficient energy management.

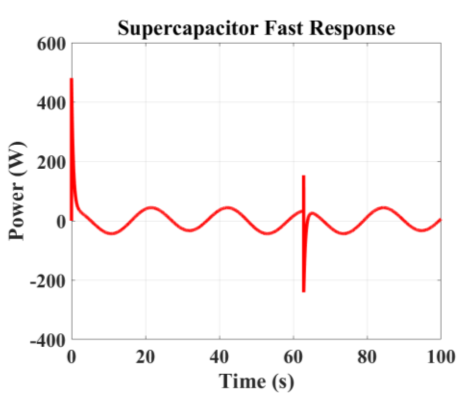

Figure 8: Supercapacitor power response under dynamic conditions.

The dynamic response of the supercapacitor is illustrated on Fig. 8. It is observed that the supercapacitor rapidly responds to sudden changes in load demand by supplying or absorbing high-frequency power components. The supercapacitor power exhibits sharp variations corresponding to transient events such as sudden load increase or decrease, indicating its fast charge–discharge capability. This behavior confirms that the supercapacitor effectively compensates for high-frequency power fluctuations, thereby preventing these transients from impacting the battery. Furthermore, the bidirectional nature of the supercapacitor power indicates its ability to both supply power during acceleration and absorb power during regenerative conditions. This rapid response capability plays a crucial role in maintaining DC bus voltage stability and improving the overall dynamic performance of the system. By handling transient power demands, the supercapacitor significantly reduces battery current stress and enhances system reliability.

The overall results demonstrate that the proposed hybrid energy storage system significantly improves system performance compared to conventional battery-only configurations. The supercapacitor effectively handles transient power demands, while the battery operates under smoother conditions, reducing stress and enhancing lifespan. The DC bus voltage is maintained within acceptable limits, ensuring stable operation of the traction system. Furthermore, the reduction in battery current peaks and power fluctuations confirms the effectiveness of the proposed multi-timescale predictive energy management strategy. These improvements make the system highly suitable for solar electric vehicle applications where both renewable variability and dynamic load conditions must be addressed.

VI. CONCLUSION

This paper presented the design and simulation of a battery-supercapacitor hybrid energy storage system for enhancing the performance of a solar electric vehicle traction system using a multi-timescale predictive energy management strategy. The proposed approach effectively decomposes the net power demand into low-frequency and high-frequency components, enabling optimal power sharing between the battery and supercapacitor while incorporating predictive correction to improve dynamic response. The simulation results demonstrate that the proposed system maintains stable DC bus voltage with minimal ripple, reduces battery current stress, and ensures smooth variation in battery state of charge, thereby enhancing battery lifespan. Additionally, the supercapacitor effectively compensates for transient power fluctuations, providing rapid response during dynamic conditions such as acceleration and load variations. The power smoothing results further confirm that high-frequency components are successfully filtered, preventing excessive stress on the battery. Overall, the proposed hybrid energy storage system significantly improves system efficiency, reliability, and dynamic performance, making it a suitable solution for solar electric vehicle applications.

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