Dynamic model and control strategies of battery-supercapacitor hybrid power sources for electric vehicles: a review

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ABSTRACT

The addition of a supercapacitor to electric vehicles is considered beneficial for extending battery lifetime. Due to its higher power density compared to the battery, a supercapacitor can efficiently handle sudden high-current demands. However, to achieve energy efficiency, a specific control strategy is required for this battery-supercapacitor (Batt-SC) hybrid power source (HPS). This paper reviews the dynamic model of the Batt-SC as HPS for electric vehicles and explores its various control strategies in order to achieve energy efficiency. A high-fidelity model, a control-oriented model, and an integrated dynamic model are presented. Various control strategies are then discussed, including high-level control, low-level control, and DC bus voltage regulation. This paper also identifies several key research opportunities, such as developing an integrated dynamic model of a hybrid Batt-SC electric vehicle, combining high-level and low-level control into a unified control strategy, and designing an optimal-adaptive controller that can minimize a certain performance index by considering nonlinearity factors.

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1. INTRODUCTION

Electric vehicles play a pivotal role in replacing the conventional transportation system due to their eco-friendly characteristic. However, a key challenge that continues to be explored is the limitation of the battery used as the primary power source. Batteries have limitations such as low power density, long charging times, and limited life cycles [1], [2]. Recently, Lithium batteries have emerged as the most suitable energy source for electric vehicles, offering efficiencies ranging from 80% to 95%, although this highly depends on several conditions, such as driving technique and traveling profile [3]. To further enhance the performance of electric vehicles, as well as increase energy efficiency, one promising approach is the integration of a supercapacitor as an additional power source [4]. Unlike batteries, supercapacitors exhibit higher power density, enabling them to meet high current demands. Furthermore, they offer faster charging and discharging times compared to batteries, making them well-suited for applications such as sudden high-current demands and regenerative braking [5]-[8]. By leveraging the complementary characteristics of both power sources, the use of battery-supercapacitor (Batt-SC) as a hybrid power source (HPS) in electric vehicles has been shown to extend battery lifetime and improve system efficiency [9].

Although the Batt-SC HPS holds significant promise for electric vehicles, it has not yet been fully commercialized for widespread public use. Currently, the use of Batt-SC in electric vehicles remains in the research and development stage. Key factors that must be addressed before the technology can be applied include the low energy density of supercapacitors, high production costs, and the readiness of the supporting infrastructure [10]. Despite these challenges, the Batt-SC technology presents considerable potential for future development and adoption due to the complementary power and energy characteristics it offers. A case study has demonstrated that the use of a Batt-SC HPS in electric vehicles can result in cost savings of approximately 12% compared to electric vehicles powered solely by battery [4]. Additionally, this technology shows great promise for integration into other emerging renewable energy systems.

For the requirements of control design, the Batt-SC HPS must be comprehensively modeled to capture its dynamic behavior [11]-[13]. This modeling involves the physical characteristics of both the battery and the supercapacitor, as well as their interactions within the system. A detailed model ensures that the control algorithms can respond effectively to varying load demands, environmental factors, and system constraints. Three primary approaches can be used to model this system: the high-fidelity model, the control-oriented model, and the integrated dynamic model. The high-fidelity model provides a detailed and precise representation of the system, capturing the complex physical, chemical, and electrical processes within the battery and supercapacitor [14]. In contrast, the control-oriented models are simplified representations designed to retain the essential dynamics of the system while ensuring computational efficiency [15]-[19]. Integrated dynamic model, on the other hand, combines the dynamic behaviors of the battery, supercapacitor, and other system components, such as power electronics and the vehicle's drivetrain [16], [20]. Each of these modeling approaches serves a specific purpose, from precise analysis and optimization to efficient control system design.

The Batt-SC as an HPS system must also be effectively controlled for various vehicle travel conditions. The goal is that their currents can be adjusted according to needs. In principle, the supercapacitor is utilized when large load currents are required, such as during uphill driving, stop-and-go, and regenerative braking. HPS control generally operates at two levels: high-level control (known as energy management system (EMS)) and low-level control [21]. The high-level control is responsible for generating reference currents for each power source, based on the vehicle’s loading conditions. This controller ensures optimal energy distribution among the power sources, adapting dynamically to changes in load and driving conditions. The reference currents are then tracked by the low-level control, which also regulates the DC bus voltage. Additionally, the low-level control maintains system stability by ensuring the DC bus voltage stays within safe and efficient operating limits.

This paper provides a focused review of the dynamic modeling and control strategies of the Batt-SC HPS for electric vehicles. The primary contribution of this paper is to offer an overview of various dynamic modeling approaches and their corresponding control strategies, with particular emphasis on low-level control to enhance energy efficiency. Although several review articles on Batt-SC as an HPS for electric vehicles have been published previously, this review distinguishes itself by focusing on the dynamic modeling, low-level control applications, and challenges related to DC bus voltage regulation. In contrast, existing reviews have primarily addressed topics such as EMS [3], [22], [23], DC-DC converter topologies [24], and optimal sizing techniques [25], [26].

The remainder of this paper is organized as follows: i) Section 2 provides an overview of the dynamic modeling of the Batt-SC HPS system, followed by a discussion of its control strategies in section 3; ii) Section 4 addresses challenges related to DC bus regulation; iii) Potential research directions are presented in section 5; while iv) Section 6 concludes the study with a summary of key findings.

2. DYNAMIC MODEL OF BATT-SC HPS FOR ELECTRIC VEHICLES

The Batt-SC HPS for electric vehicles can be modelled using three main approaches: the high-fidelity model, the control-oriented model, and the integrated dynamic model. Figure 1 illustrates the configuration of the Batt-SC system as an HPS, which serves as the foundational circuit for reviewing the dynamic modeling approaches. This configuration includes two control inputs in the form of the duty cycle, the dynamic model of the Batt-SC HPS, two bidirectional DC-DC converters with a fully active topology, and a motor-vehicle model as the load.

2.1. High-fidelity model

The high-fidelity model is a dynamic approach characterized by high accuracy, as it incorporates the internal characteristics of each component. This model is commonly employed to test controller performance in simulation environments and to validate black-box models. Numerous studies on HPS controller design utilize high-fidelity models. For instance, research [14] developed a real-time nonlinear controller for Batt-SC systems in electric vehicles based on a high-fidelity model. This model integrates detailed internal characteristics of the Batt-SC, including series-parallel resistance, capacitance, and the number of cells used. Similarly, the DC-DC converter model accounts for elements such as inductor resistance R_L and switch-on resistance R_{ON}. The state variables and control signals in the high-fidelity model are defined as shown in (1) and (2):

$$x = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5\,]^* = [V_b \quad V_{sc} \quad i_b \quad i_{sc} \quad V_{bus}\,]^* \tag{1}$$

$$u = [u_1 \quad u_2]^* = [d_1 \quad d_3]^* \tag{2}$$

with V_b and V_{sc} are battery and supercapacitor voltages, i_b and i_{sc} are battery and supercapacitor currents, V_{bus} as the DC bus voltage, d_1 and d_3 are duty cycles for the DC-DC converter that is actively connected to the Batt-SC HPS. Based on these state variables, the nonlinear dynamic model can be obtained as (3)-(7):

$$\frac{dV_b}{dt} = -\frac{1}{R_bC_b}V_b - \frac{1}{C_b}i_b + \frac{V_{oc,b}}{R_bC_b} \tag{3}$$

$$\frac{dV_{sc}}{dt} = -\frac{1}{R_{sc}C_{sc}}V_b - \frac{1}{C_{sc}}i_{sc} + \frac{V_{oc,sc}}{R_{sc}C_{sc}} \tag{4}$$

$$\frac{di_b}{dt} = \frac{1}{L_1}V_b - \frac{R_{L1}+R_{ON2}}{L_1}i_b - \frac{1}{L_1}V_{bus} + \frac{R_{ON2}-R_{ON1}}{L_1}i_bd_1 + \frac{1}{L_1}V_{bus}d_1 \tag{5}$$

$$\frac{di_{sc}}{dt} = \frac{1}{L_2}V_{sc} - \frac{R_{L2}+R_{ON4}}{L_2}i_{sc} - \frac{1}{L_2}V_{bus} + \frac{R_{ON4}-R_{ON3}}{L_2}i_{sc}d_3 + \frac{1}{L_2}V_{bus}d_3 \tag{6}$$

$$\frac{dV_{bus}}{dt} = \frac{1}{C_{bus}}i_b + \frac{1}{C_{bus}}i_{sc} - \frac{1}{C_{bus}}i_bd_1 - \frac{1}{C_{bus}}i_{sc}d_3 - \frac{1}{C_{bus}}i_m \tag{7}$$

with R_b, C_b, and $V_{oc,b}$ respectively, are battery resistance, battery capacitance, and battery open-circuit voltage, R_{sc}, C_{sc}, and $V_{oc,sc}$ respectively, are supercapacitor resistance, supercapacitor capacitance, and supercapacitor open-circuit voltage, R_L and R_{ON} are resistance on the inductor and switching during the ON period, and i_m as motor current. By adopting this approach, an accurate dynamic model of Batt-SC as an HPS can be achieved.

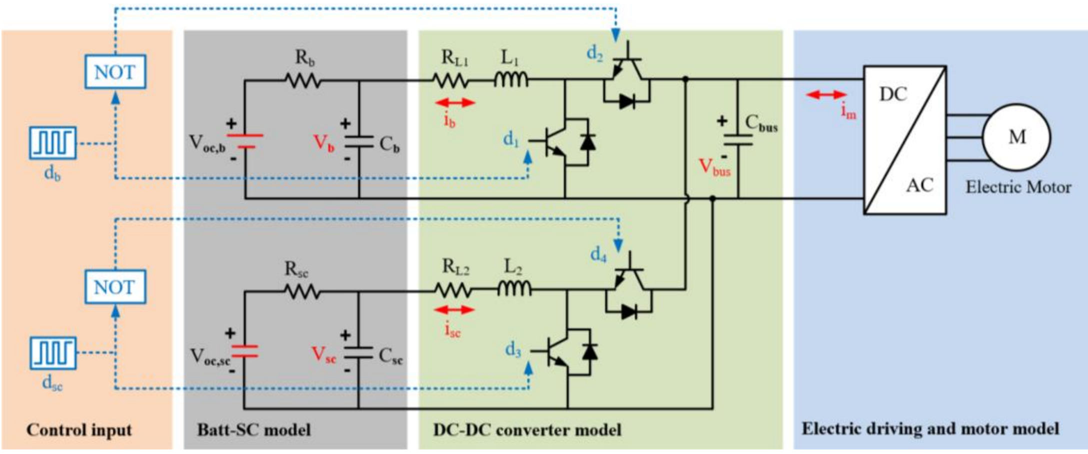

Figure 1. Typical dynamic model of Batt-SC as HPS for an electric vehicle

2.2. Control-oriented model

The control-oriented model is a dynamic model designed specifically for controller development and practical implementation. Unlike the high-fidelity model, it is derived by simplifying the system and neglecting the internal characteristics of each component, while still retaining essential parameters. This modeling approach is widely used in Batt-SC controller design [15]-[19]. In contrast to the high-fidelity model, the control-oriented model treats the Batt-SC system as a constant voltage source in the HPS configuration. Additionally, the DC-DC converter model in this approach excludes R_L and R_{ON}. Consequently, the nonlinear dynamic equations for the control-oriented model, governing i_b and i_{sc}, are defined as shown in (8) and (9):

$$\frac{di_b}{dt} = \frac{V_b}{L_1} - \frac{1}{L_1}V_{bus} + \frac{1}{L_1}V_{bus}d_1 \tag{8}$$

$$\frac{di_{sc}}{dt} = \frac{V_{sc}}{L_2} - \frac{1}{L_2}V_{bus} + \frac{1}{L_2}V_{bus}d_3 \tag{9}$$

where V_b and V_{sc} represents the Batt-SC voltages, which are assumed to remain constant. To incorporate the direction of the regenerative current, the averaged dynamic equation is derived and presented as shown in (10)-(12):

$$\frac{di_b}{dt} = \frac{V_b}{L_1} - \frac{1}{L_1} V_{bus} d_b \quad (10)$$

$$\frac{di_{sc}}{dt} = \frac{V_{sc}}{L_2} - \frac{1}{L_2} V_{bus} d_{sc} \quad (11)$$

$$\frac{dV_{bus}}{dt} = \frac{1}{C} i_b d_b + \frac{1}{C} i_{sc} d_{sc} - \frac{1}{C} i_m \quad (12)$$

where d_b and d_{sc} are averaging duty cycles for Batt-SC, which satisfy the following (13) and (14).

$$d_b = \begin{cases} 1 - d_1, & i_{b\_ref} > 0 \\ d_2, & i_{b\_ref} < 0 \end{cases} \quad (13)$$

$$d_{sc} = \begin{cases} 1 - d_3, & i_{sc\_ref} > 0 \\ d_4, & i_{sc\_ref} < 0 \end{cases} \quad (14)$$

This duty cycle configuration also applies to high-fidelity models with bidirectional DC-DC converters.

2.3. Integrated dynamic model

The integrated dynamic model combines the dynamics of the Batt-SC system as an HPS with a drive system comprising a DC-DC converter, an electric motor, and a vehicle dynamics model. Several studies have explored this approach, integrating the Batt-SC system with an induction motor [16], switched reluctance motor (SRM) model [17], and the permanent magnet synchronous motor (PMSM) model [27]. Regarding integration with the vehicle's longitudinal dynamics, an integrated battery-electric vehicle (IBEV) model has been developed [20], although it did not incorporate a supercapacitor as an additional power source. Consequently, developing a comprehensive integrated model that includes Batt-SC, DC-DC converters, electric motors, and vehicle longitudinal dynamics remains a promising area for future research. The vehicle longitudinal dynamics model based on Figure 2 can be written as in (15):

$$F_t = F_a + F_r + F_d + F_g \quad (15)$$

where F_t is the traction force required by the vehicle, F_a is the acceleration of the vehicle, F_r is the friction force of the wheels, F_d is the aerodynamic force of the vehicle, and F_g is the force of gravity.

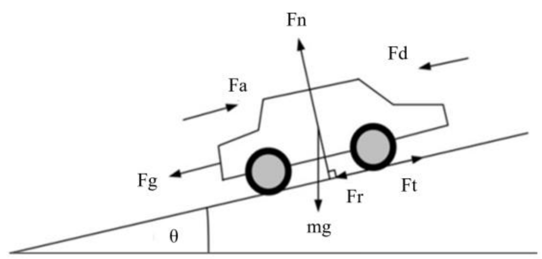

Figure 2. Longitudinal dynamics on vehicle

From (15), the vehicle longitudinal speed (v), motor speed (ω), and motor current (i_m) can be defined as additional state variables as shown in (16)-(18):

$$\frac{dv}{dt} = \frac{k_t}{m.r} i_m - \frac{1}{2m} \rho C_d A v^2 - g(C_r \cos\theta + \sin\theta) \quad (16)$$

$$\frac{d\omega}{dt} = \frac{k_t}{J} i_m - \frac{b}{J} \omega \quad (17)$$

$$\frac{di_m}{dt} = \frac{1}{L_m} V_{bus} - \frac{R_m}{L_m} i_m - \frac{k_e}{L_m} \omega \quad (18)$$

where k_t is motor torque constant, r is wheel radius, m is mass of vehicle, C_r is road resistive coefficient, C_d is aerodynamic drag coefficient, A is front cross-sectional area, ρ is air density constant, $g$is gravity constant, θ is slope of the road, J is the moment of inertia, b is friction coefficient, R_m is motor resistance, L_m is motor inductance, and k_e is motor back-emf constant. These additional state variables can be incorporated into the high-fidelity models discussed earlier, allowing the complete state variables to be expressed as shown in (19).

$$x = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6 \quad x_7 \quad x_8]^* = [V_b \quad V_{sc} \quad i_b \quad i_{sc} \quad V_{bus} \quad i_m \quad \omega \quad v]^* \qquad (19)$$

3. CONTROL STRATEGIES OF BATT-SC HPS FOR ELECTRIC VEHICLES

Figure 3 presents the general control strategy of the Batt-SC HPS, outlining the control structure and classification of the controller types. Figure 3(a) illustrates the block diagram of the Batt-SC control structure as an HPS. This configuration generally involves two levels of control. The high-level control utilizes information such as load (represented by current demand), road slope angles, or external environmental conditions to determine the HPS reference current. Subsequently, the low-level control ensures that the reference current is achieved. The specific objectives and roles of these two control levels differ and will be elaborated in the following section.

Furthermore, the controller methods applicable to these control levels are categorized in Figure 3(b). High-level control is divided into four types: rule-based, filter-based, optimization-based, and learning-based. Low-level control is classified into three types: classical control, optimal control, and robust control. A detailed explanation of both control levels and their respective methods will be provided in this section.

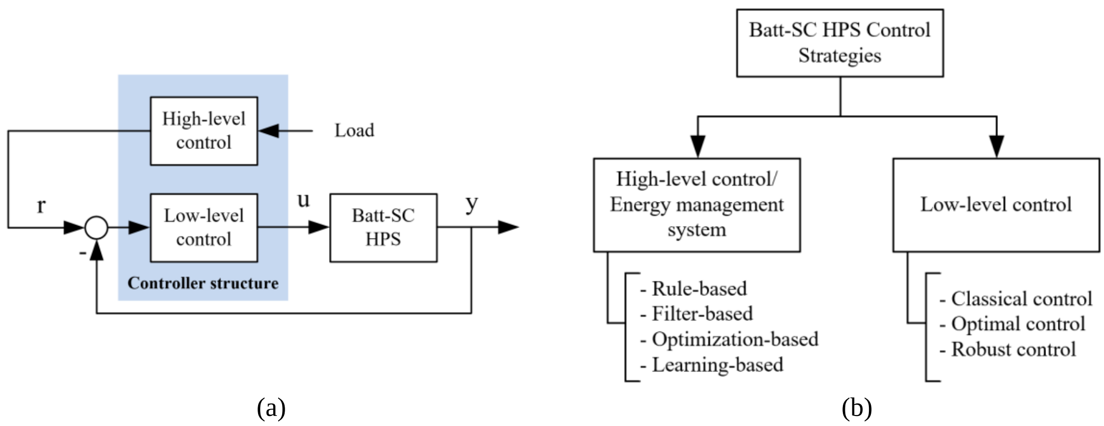

Figure 3. Batt-SC control strategies: (a) controller structure and (b) classification of Batt-SC control strategies

3.1. High-level control

High-level control, often referred to as EMS, is designed to generate the reference current for the HPS. This level of control employs a power distribution algorithm based on input variables such as resource conditions and load current requirements. The EMS optimizes energy allocation between power sources to ensure efficient operation, minimize losses, and extend the lifespan of the system components. By continuously monitoring the state of each power source and the overall system demand, the EMS dynamically adjusts the reference currents to adapt the varying driving conditions and load profiles.

3.1.1. Rule-based EMS

The rule-based EMS is the simplest approach, as it does not require a dynamic model for its design, making it computationally efficient and easier to implement. These control schemes rely on predefined rules and thresholds to manage energy distribution among the power sources, providing straightforward and reliable performance. Rule-based control schemes can be developed using fuzzy logic [28]-[30] and a state machine algorithm [23]. Fuzzy logic offers a flexible framework for handling uncertainties and non-linearities in system behavior, while state machine algorithms provide a structured approach for transitioning between discrete operating states based on specific conditions. This simplicity makes rule-based EMS highly suitable for real-time applications and systems with limited computational resources.

3.1.2. Filter-based EMS

The filter-based EMS employs a low-pass filter (LPF) to allocate power between the battery and the supercapacitor based on the frequency characteristics of the load demand. This method effectively separates the power demands into high-frequency and low-frequency components, enabling efficient energy management. The supercapacitor, with its high-power density and rapid charge-discharge capabilities, addresses high-frequency power demands, such as those caused by sudden accelerations or transient loads. In contrast, the battery, known for its high energy density, manages low-frequency power changes, such as steady-state driving or gradual speed variations [27], [31]-[33].

3.1.3. Optimization-based EMS

The optimization-based EMS is further divided into offline and online methods, each offering distinct advantages depending on the application requirements. Offline optimization techniques, such as genetic algorithms [34] and dynamic programming [35], provide pre-computed solutions by analyzing all possible scenarios beforehand. These methods are particularly effective for systems with well-defined operating conditions, as they minimize computational demands during operation. On the other hand, online optimization methods, like model predictive control (MPC), dynamically generate reference currents for the Batt-SC system in real-time. By continuously optimizing input variables such as load current, Batt-SC voltage, and DC bus voltage, MPC ensures that the system adapts to varying conditions and maintains optimal performance [36], [37]. This real-time adaptability makes online optimization particularly suitable for applications with highly dynamic and unpredictable operating environments.

3.1.4. Learning-based EMS

The learning-based EMS leverages advances in machine learning to achieve superior control performance and adaptability. This category includes reinforcement learning (RL) algorithms [38], deep learning [39], and artificial neural network (ANN) [40]. These methods enable the EMS to learn and optimize control strategies independently, allowing for precise regulation of Batt-SC currents based on real-time travel scenarios and system demands. Learning-based EMS approaches excel in handling complex, non-linear systems and unpredictable operating conditions, offering potential for improved efficiency and system longevity. However, their implementation poses significant challenges, including the need for robust computational resources and reliable, also high-quality datasets for training. The lack of readily available data and the increased complexity in algorithm design and validation can limit their practical deployment. Despite these challenges, the promise of superior adaptability and control performance makes learning-based EMS a compelling area of research and development.

3.2. Low-level control

Low-level control in the Batt-SC HPS system generally aims to track the reference current generated by the EMS. Referring to [21], the main objectives of the low-level controller are summarized as follows:

- Accurately tracking the time-varying reference current signal for the Batt-SC power sources.
- Precisely maintaining a constant DC bus voltage under load fluctuations.
- Ensuring the system remains asymptotically stable despite external disturbances and parameter variations.

In general, three types of control systems can be applied to the Batt-SC HPS system, namely classical single-input single-output (SISO) control, optimal control, and robust control. This section will elaborate and discuss these three types of low-level controllers. The classical SISO controller consists of a proportional-integral (PI) [27], [41] and hysteresis controller [36], optimal control consists of linear quadratic control [18], [19], [42], MPC [31], [43], and linear matrix inequality (LMI)-based optimization controller [14], while robust control consists of H_∞ controller [44], L_2-gain passive-based control [45], back-stepping control [46], and sliding mode control (SMC) [15], [16], [47]-[51].

3.2.1. Classical SISO controller

The classical SISO controller represents the simplest approach to control system design and implementation. Its simplicity lies in the independent design for each I/O in multi-input multi-output (MIMO) system, disregarding the interactions between different I/Os. This decoupled configuration, as depicted in Figure 4, is straightforward yet effective for basic control tasks. Among the SISO controllers applicable to the Batt-SC HPS, the PI controller and hysteresis control are widely utilized due to their ease of implementation and reliable performance.

The PI controller is a linear control method widely used to accurately track the reference currents of Batt-SC HPS system. Its implementation is often combined with nonlinear controllers to regulate DC bus voltage and generate reference load currents [27]. This hybrid approach enhances DC bus voltage regulation, reduces dependency on system parameters, and simplifies controller tuning. For example, in the study [41], a PI controller was employed to track Batt-SC current references generated via fuzzy supervisory control. While the PI controller demonstrated the ability to track reference currents in both simulations and experiments, the results were not entirely satisfactory. The limitations of the PI control method include its reliance on precise tuning of the Kp and Ki constants and its inability to account for the dynamic interactions between energy sources in a MIMO system. Furthermore, it does not guarantee stability or robustness under disturbances. In systems with inherently coupled dynamics, PI control treats the fully active topology as two independent SISO systems, potentially degrading the closed-loop dynamic performance. Despite its simplicity and ease of design, these drawbacks limit its effectiveness for complex hybrid power systems.

In hysteresis control, the current oscillates within a defined hysteresis band around the reference current (Iref). Specifically, the current fluctuates between an upper limit (Iref + upper bound and a lower limit (Iref − lower bound), maintaining close proximity to the desired reference. This control method has been applied in research [36] to regulate the HPS reference current derived from an MPC strategy. Although simulations and experiments have demonstrated the capability of hysteresis control to effectively track changes in load current, the resulting tracking response tends to lack smoothness, which may affect system performance in applications requiring high precision.

3.2.2. Optimal control

Optimal control is a modern control strategy well-suited for MIMO systems, offering a sophisticated approach to managing the dynamic interactions between multiple subsystems. In the context of Batt-SC HPS systems, two prominent optimal controllers are widely applied: linear quadratic control and MPC. Additionally, state-feedback control designed using a LMI-based optimization approach has also been explored. As illustrated in Figure 5, the optimal controllers involve deriving state-feedback gain through an optimization process. This process minimizes a predefined performance index function J, typically expressed as shown in (20):

$$J(x,u) = \int_0^\infty (x^*Qx + u^*Ru + 2x^*Nu)\,dt \tag{20}$$

where x is a state variable, u is the control signal, Q, R, and N are constant positive definite matrices.

Linear quadratic controller, or known as LQR/LQI, is an optimal control technique designed for linear systems. The primary objective of LQR/LQI is to minimize a cost function that balances two competing goals: reducing system error and minimizing control effort. This dual focus makes it a popular choice for managing trade-offs between performance and efficiency while ensuring system stability for linear applications. LQR/LQI has been widely applied in the context of Batt-SC HPS systems. For instance, research [18] utilized LQI as a low-level controller for a Batt-SC system under resistive loading conditions. The linearized model of the DC-DC converter served as the basis for deriving state feedback gains. To enhance set-point tracking, an integrator was incorporated into the error section. The study demonstrated that LQI could achieve good performance with minimal control effort by appropriately weighting the R matrix in the cost function. In another application, a rule-based LQR was proposed to manage power flow within the HPS [19], [42]. This approach aimed to reduce battery stress during high-demand events by limiting battery current to a predefined maximum value across different driving cycles. The implementation of LQR not only improved battery life and stability of energy storage devices but also enabled battery downsizing, contributing to overall system efficiency. However, the LQR method has limitations, particularly in its assumption of linear system behavior. By neglecting the nonlinear characteristics inherent in Batt-SC HPS systems, the approach cannot guarantee stability under all operating conditions. This limitation underscores the need for advanced control strategies capable of addressing system nonlinearity while maintaining robust performance.

Model predictive control (MPC) is among the most widely used optimal control strategies for HPS, particularly in applications involving Batt-SC systems. MPC operates by predicting future power requirements based on current system conditions and designing control strategies to optimize energy use. This includes minimizing energy costs or losses, extending battery lifetime, and ensuring system stability, while accounting for the physical limitations of the Batt-SC system. MPC is primarily utilized as a high-level control mechanism to generate reference currents for the HPS. For instance, studies [36], [52]-[55] demonstrate its effectiveness in this role. These studies highlight MPC's ability to handle dynamic operating conditions and optimize the power distribution between battery and supercapacitor, improving overall system performance. An alternative application of MPC is its use as a low-level controller. Research [31] implemented MPC to control Batt-SC currents generated from a filtering-based EMS. In this case, enumeration-based MPC was employed to determine the optimal switching sequences across a predictive horizon, enabling precise current tracking. Similarly, study [43] utilized MPC at the energy management level to optimize power flow within the hybrid energy storage system rather than focusing on power electronics control. This approach demonstrates MPC's versatility in addressing both high-level energy management and low-level power control challenges. However, a notable limitation of MPC is its high computational demand. Real-time optimization requires significant processing power, making implementation challenging in systems with limited computational resources.

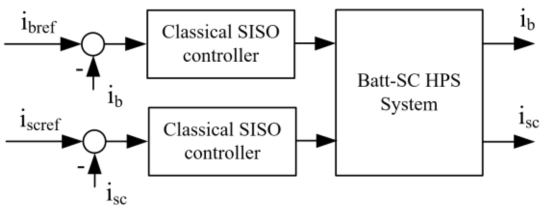

Figure 4. Classical SISO controller for Batt-SC HPS system

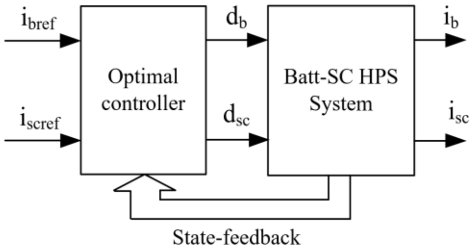

Figure 5. Optimal controller for Batt-SC HPS system

An LMI-based optimization state-feedback controller represents a sophisticated approach to control system design, particularly for complex systems like Batt-SC HPS. This method leverages a set of LMIs to formulate control problems as constrained optimization tasks, enabling the systematic design of controllers that meet specified performance and stability criteria. LMIs provide a powerful mathematical framework to address multiple objectives simultaneously, including stability, performance, and robustness against disturbances and uncertainties. The core principle of this approach lies in expressing constraints and performance measures as LMIs, which are then solved using efficient convex optimization algorithms. This results in a controller capable of handling both linear and certain nonlinear system dynamics. Moreover, it allows for the inclusion of practical considerations such as control signal saturation and state constraints. A notable application of the LMI-based state-feedback controller is demonstrated in the research [14]. In their study, the controller is designed to achieve robust tracking and ensure smooth transitions in the Batt-SC HPS. The methodology is rooted in the Lyapunov function and set invariance theories, providing a rigorous foundation for addressing system stability and input constraints. The study introduces a new state-space model for the fully active topology of Batt-SC systems, as shown in (21). This model serves as the basis for designing the state-feedback controller, where the LMI approach is employed to optimize performance while considering control signal saturation:

$$\dot{x}(t) = (A_0 + A_1 d_1 + A_2 d_2)x(t) + BV_e \tag{21}$$

where A_0, A_1, A_2, and B are constant matrices from system parameters, d_1 and d_2 are Batt-SC duty cycles for a bidirectional DC-DC converter, and V_e is the Batt-SC voltage vector. This model serves as the basis for designing the state-feedback controller, where the LMI approach is employed to optimize performance while considering control signal saturation. However, this method has only been tested at constant load currents, so its performance needs to be validated for time-varying currents.

4.2.3. Robust control

Robust control is a control methodology designed to maintain system performance and stability in the presence of disturbances, parameter uncertainties, and modeling errors. This approach ensures reliability even when operating conditions deviate from nominal values. Robust control can be implemented by explicitly incorporating the system sensitivity function into the controller design. For example, the H_∞ controller minimizes the worst-case gain from disturbance inputs to system outputs, thereby improving disturbance rejection. Similarly, the L_2-gain passivity-based control leverages passivity properties to ensure system stability and robustness against external disturbances. In addition to these sensitivity-based approaches, certain nonlinear controllers exhibit inherent robustness despite not explicitly utilizing the sensitivity function. For instance, back-stepping control systematically designs a Lyapunov function to achieve stability and robustness for nonlinear systems. The design methodology involves decomposing the overall system into simpler subsystems. Each subsystem is sequentially controlled, with the stability of each stage contributing to the overall system stability. This step-by-step approach makes back-stepping control highly effective for managing nonlinearity and addressing model uncertainties. Sliding mode control (SMC), another robust nonlinear technique, enforces system dynamics along a sliding surface, making it highly effective against matched uncertainties and disturbances. These robust control strategies are particularly advantageous for applications such as Batt-SC HPS, where disturbances and uncertainties are common due to fluctuating load demands and varying environmental conditions.

In the context of Batt-SC hybrid power systems, research conducted by [44] developed an H_∞ controller to regulate Batt-SC currents using a simplified second-order model. The study involved designing two H_∞ controllers: one for motoring and another for regenerating supercapacitor currents, based on the reference currents generated by a basic EMS. Experimental results demonstrated that the H_∞ controller achieved more robust tracking performance compared to traditional PID controllers, highlighting its capability to manage uncertainties and disturbances in the system. However, the limitation of this approach lies in its application to SISO models, restricting its ability to address the interactions and complexities of MIMO systems typically found in fully active Batt-SC configurations.

Research [45] applied a passivity-based controller to a fully active Batt-SC HPS designed for electric vehicles. The study demonstrated that this controller effectively ensures the asymptotic convergence of system states and robust tracking of reference currents within the HPS framework. The controller's ability to handle disturbances and maintain stability under varying conditions was a key highlight of the research findings. However, despite its advantages, the passivity-based L_2-gain controller faces challenges in application to highly complex or nonlinear systems. Identifying passive elements in such systems can be difficult, and the computational complexity of the design process may increase with system intricacy. These limitations highlight the need for further research to simplify implementation and expand its applicability to broader system configurations.

Research [46] demonstrates the practical utility of back-stepping control in the context of Batt-SC HPS. In this study, a cascade PI controller is combined with back-stepping control to enhance system performance. The PI controller regulates the DC bus voltage, while back-stepping control tracks the reference current generated by the PI controller. Simulation and experimental results validate the proposed controller's robustness against transients and its effectiveness in maintaining the DC bus voltage within desired parameters. Despite its advantages, back-stepping control's design complexity and reliance on precise system models remain significant challenges. These limitations underscore the need for further research to streamline the design process and enhance its adaptability to dynamic and uncertain environments.

Lastly, SMC is widely recognized as one of the most robust nonlinear control strategies, particularly suited for systems experiencing uncertainties and disturbances. Its robustness, stability, and disturbance rejection capabilities make SMC an excellent choice for managing Batt-SC HPS. The primary mechanism of SMC involves driving the system states toward a predefined sliding surface and ensuring that the system remains on this surface regardless of external disturbances or system parameter variations. SMC achieves robust tracking by leveraging various types of sliding surfaces, which dictate the system's dynamic behavior once it reaches the sliding surface. These types of sliding surfaces (i.e. integral and terminal sliding surfaces) fulfill the following (22) and (23), respectively.

$$s(e) = e + \lambda \int_0^t e(t)\, dt \tag{22}$$

$$s(e) = e + \lambda \left(\int_0^t e(t)\, dt \right)^{p/q} \tag{23}$$

Where $e(t)$is the tracking error, λ, p, and q are controller constants. Each type of sliding surface can be used according to the characteristics of the dynamic model and the control objectives.

The adaptive terminal SMC is designed to achieve robust tracking performance of HPS currents while maintaining a stable DC bus voltage, even in the presence of uncertainties and disturbances. Research [15] proposed an adaptive terminal SMC that incorporates a projection operator adaptive law to dynamically estimate and bound unknown parameters in the HPS model. This adaptive mechanism ensures reliable performance under parameter uncertainties and enhances the system's robustness. Building upon this approach, study [16] applied adaptive terminal SMC to a unified mathematical model of a hybrid electric vehicle (HEV). The controller not only managed HPS current and DC bus voltage but also demonstrated the capability to accurately track vehicle speed in accordance with the European extra-urban driving cycle (EUDC) profile. These studies highlight the versatility and effectiveness of adaptive terminal SMC in addressing both energy management and vehicular dynamics, ensuring reliable and robust control in complex systems.

To achieve setpoint tracking and DC bus voltage regulation in Batt-SC HPS, research [50] proposed a SMC combined with a Lyapunov function-based approach. This configuration ensures robust tracking of various variables across a wide range of HPS parameters. Building on advanced SMC techniques, study [47] introduced an adaptive SMC with a disturbance observer specifically for electric vehicle applications. This method effectively estimates mismatched and matched uncertainties, avoids differential explosion issues, and ensures semi-globally uniform boundedness of closed-loop signals. Experimental validations confirmed its fast response, reduced error, and robust stability under hybrid driving conditions.

In addition, an integral back-stepping SMC (IBSMC) was designed to accurately track the EUDC speed profile, Batt-SC currents, and maintain DC bus voltage for a unified hybrid electric vehicle model [48].

Meanwhile, a super-twisting SMC (STSMC) for Batt-SC HPS was developed, which ensures global stability using Lyapunov criteria [51]. This controller demonstrated superiority over conventional SMC and integral SMC in various performance aspects. Lastly, advanced SMC techniques including IBSMC, super-twisting adaptive SMC (STASMC), and real-twisting adaptive SMC (RTASMC) were compared by [49], highlighting their relative effectiveness and performance in hybrid electric vehicle systems. These advancements emphasize the potential of SMC methodologies to enhance robustness, stability, and tracking accuracy in HPS systems under dynamic and uncertain conditions.

3.2.4. Low-level control performance comparison

Robust tracking control is one of the most widely adopted objectives in low-level control, particularly for Batt-SC HPS in electric vehicles. Other low-level control objectives, such as DC bus voltage regulation, handling parameter uncertainties, and ensuring system stability, are also common focal points in this research. Table 1 presents a comparison of the advantages and limitations of various controllers used for low-level control. Based on this comparison, SMC emerges as the most robust and powerful control method due to its inherent robustness, compatibility with nonlinear systems, and ability to guarantee system stability. However, SMC does have some limitations, such as the chattering phenomenon and the requirement for precise determination of control parameters. Despite these challenges, numerous advanced SMC designs have been proposed to address these limitations, further enhancing their applicability and effectiveness in HPS systems.

Table 1. Performance comparison of Batt-SC low-level control strategy for electric vehicles

Low-level control types	Control strategies	Advantages	Limitations	References
Classical SISO control	PI controller	Easy design and implementation, accurate tracking	Only for the SISO model, ignore the interaction between Batt-SC and converter	[27], [41]
	Hysteresis control	Simple design, control signal generated as PWM	Tracking is not smooth, very noisy due to switching behavior	[36]
Optimal control	Linear quadratic control	Resulting in optimal control, can minimize the control signal	Not suitable for nonlinear model	[18], [19], [21], [42]
	Model predictive control	Good performance, involving system constraint	High computational cost, need an accurate model	[31], [43]
	State-feedback (LMI)-based optimization	Ensure system stability, good controller performance	High complexity computation, need to determine many parameters	[14]
Robust control	H_∞ controller	Include sensitivity function, guarantee system robustness	Relatively difficult implementation	[44]
	L_2-gain passivity-based control	Robust tracking, can handle parameter uncertainty	Very complex design process	[45]
	Back-stepping controller	Robust tracking, ensures global asymptotic stability	Require very accurate nonlinear model	[46]
	Sliding mode control	Strong robustness, ensures stability, performing very good tracking, relatively simple design	Produce chattering behavior, need to decide controller parameters	[15], [16], [47]- [51]

4. DC BUS VOLTAGE REGULATION PROBLEM

The Batt-SC HPS system can be classified as an under-actuated system because it has only two control signals (the duty cycles for each converter connected to the battery and supercapacitor) responsible for controlling three outputs: battery current, supercapacitor current, and DC bus voltage [56]. Among the control objectives, regulating the DC bus voltage is critical for ensuring the stable operation of the Batt-SC HPS. Based on the review, there are two main strategies for achieving DC bus voltage regulation in Batt-SC HPS for electric vehicles, as illustrated in Figure 6. The first strategy involves the cascade SISO control approach [36], [46], [50] as depicted in Figure 6(a). The second strategy employs a MIMO control approach [57], [58] as shown in Figure 6(b).

4.1. Cascade SISO control approach

This approach separates the DC bus voltage control loop from the Batt-SC current control loop, allowing the DC bus voltage to be independently controlled based on its reference. A classic SISO controller, such as a PI controller, can be used for this purpose [36], [46]. While the PI controller is simple to implement, it has notable limitations as mentioned previously. To address stability concerns, the DC bus voltage can also be regulated using a Lyapunov stability-based control method [50]. This method derives a control equation from the Lyapunov function to generate a reference current based on the DC bus voltage error, ensuring the stability of the DC bus voltage. However, the cascade control configuration has its own limitations, such as the need for designing multiple controllers because the control process is executed in separate loops.

4.2. MIMO control approach

The characteristics of an under-actuated system necessitate a type of controller capable of addressing the limitations imposed by the number of control signals. A widely adopted MIMO controller for such systems is SMC [57], [58]. The SMC design process facilitates managing the disparity between the number of control signals and outputs by defining a suitable sliding surface. This approach allows for the simultaneous regulation of multiple outputs, such as battery current, supercapacitor current, and DC bus voltage, using a single control framework.

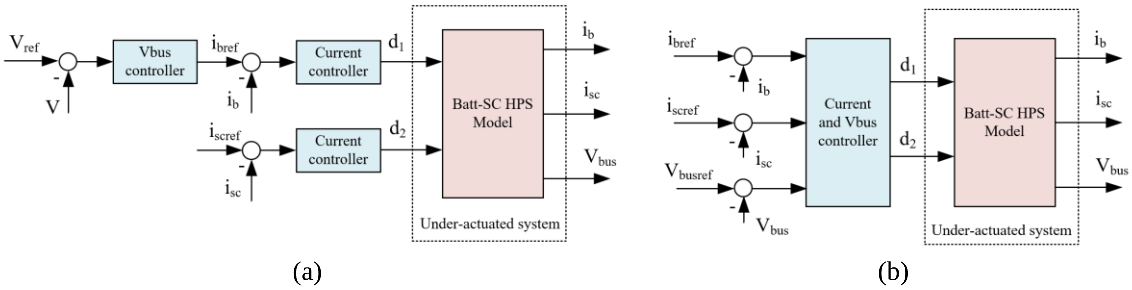

Figure 6. Controller approaches for regulating DC bus voltage: (a) cascade control and (b) MIMO control

5. POTENTIAL RESEARCH

Based on the literature review presented in this study, three significant research opportunities have been identified for future exploration: an integrated dynamic modeling, a unified high-low level control, and a nonlinear optimal-adaptive control strategy. This section provides a detailed discussion of these research directions alongside the insights gained from the previous review above.

5.1. Integrated hybrid Batt-SC electric vehicle dynamic model

Firstly, an integrated dynamic model encompassing the Batt-SC system, DC-DC converter, electric motor, and vehicle longitudinal dynamics can be developed. Additionally, incorporating vehicle lateral dynamics may be considered, as lateral speed and handling maneuvers influence energy consumption, especially during cornering or when driving on uneven terrain. However, longitudinal dynamics remain the dominant factor driving power consumption in electric vehicles, as they govern acceleration, braking, and resistance forces such as aerodynamic drag and rolling resistance [59].

5.2. Integrated high-low level control

Secondly, integrating high-level control and low-level control into a unified control system presents a promising challenge for future research. Most studies on HPS control focus on a single control level, either EMS or low-level control. These two levels of control seem to work independently. While the high-level control generates a reference based on load conditions, the low-level control operates independently, focusing solely on tracking the provided reference without accounting for the broader load dynamics. To enhance performance and efficiency, an integrated control framework may be proposed. This involves incorporating an adaptation law into the low-level control, enabling it to account for the load dynamics considered by the high-level control, as well as topographical information and variations in load current [60]. This integration ensures improved coordination between the two levels, fostering a more cohesive and effective control system.

5.3. Nonlinear optimal-adaptive control strategy

Thirdly, designing appropriate controllers to balance performance response and energy efficiency remains an open research area. For instance, developing SMC through an optimal control approach offers potential benefits [56], [61], [62]. SMC, a nonlinear control method, is known for its robust tracking capabilities and is well-suited for under-actuated systems like the Batt-SC HPS system. However, while existing studies on SMC emphasize robust tracking of time-varying currents, they often overlook how control signals are generated to ensure robust performance. Although some SMC designs incorporate control signal constraints, such as saturation functions [50], most focus primarily on tracking accuracy. In practice, minimizing control signals is crucial to reducing power losses in the DC-DC converter. Future work could explore control strategies that achieve robust performance while optimizing control signal efficiency, ensuring both energy efficiency and system reliability.

6. CONCLUSION

This paper has provided a comprehensive review of the dynamic modeling and control strategies for the Batt-SC HPS system in electric vehicles. The Batt-SC HPS system represents a critical technology for improving the performance, efficiency, and lifespan of energy storage in electric vehicles by combining the high energy density of a battery with the high-power density of a supercapacitor. Dynamic modeling plays a key role in understanding the interaction between these components, the DC-DC converters, the electric motor, and the vehicle as a whole. By capturing the complex relationships and transient behaviors within this system, the models serve as a foundation for developing effective control strategies tailored to optimize energy utilization and ensure stable operation. Regarding control strategies, an integrated configuration that combines EMS with low-level control is recommended to enhance system performance and coordination. The EMS operates as a high-level supervisory controller, strategically allocating power between the battery and supercapacitor based on real-time operating conditions and system demands. Meanwhile, the low-level control ensures precise execution by regulating the operation of components such as the DC-DC converters and the electric motor. By integrating these two levels of control, the system achieves a balance between strategic energy distribution and real-time operational accuracy, resulting in improved efficiency and responsiveness. Adopting an optimal control approach to develop SMC presents significant advantages. By integrating optimal control principles into the design of SMC, it becomes possible to achieve a balance between robustness and efficiency. The optimal control approach allows for the systematic determination of control parameters that minimize a predefined cost function, which could include metrics such as energy consumption, tracking error, or actuator usage. This synergy not only enhances the control performance but also mitigates issues like excessive chattering, ensuring smoother and more reliable system operation.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
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Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] A. Maiorino, C. Cilenti, F. Petruzziello, and C. Aprea, "A review on thermal management of battery packs for electric vehicles," *Applied Thermal Engineering*, vol. 238, p. 122035, Feb. 2024, doi: 10.1016/j.applthermaleng.2023.122035.

[2] Y. Miao, P. Hynan, A. von Jouanne, and A. Yokochi, "Current Li-ion battery technologies in electric vehicles and opportunities for advancements," *Energies*, vol. 12, no. 6, p. 1074, Mar. 2019, doi: 10.3390/en12061074.

[3] D. Lemian and F. Bode, "Battery-supercapacitor energy storage systems for electrical vehicles: A review," *Energies*, vol. 15, no. 15, 2022, doi: 10.3390/en15155683.

[4] Z. Song, J. Li, J. Hou, H. Hofmann, M. Ouyang, and J. Du, "The battery-supercapacitor hybrid energy storage system in electric vehicle applications: A case study," *Energy*, vol. 154, pp. 433–441, Jul. 2018, doi: 10.1016/j.energy.2018.04.148.

[5] K. Itani, A. De Bernardinis, Z. Khatir, A. Jammal, and M. Oueidat, "Regenerative braking modeling, control, and simulation of a hybrid energy storage system for an electric vehicle in extreme conditions," *IEEE Transactions on Transportation Electrification*, vol. 2, no. 4, pp. 465–479, Dec. 2016, doi: 10.1109/TTE.2016.2608763.

[6] F. Naseri, E. Farjah, and T. Ghanbari, "An efficient regenerative braking system based on battery/supercapacitor for electric, hybrid, and plug-in hybrid electric vehicles with BLDC motor," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 5, pp. 3724–3738, 2017, doi: 10.1109/TVT.2016.2611655.

[7] S. S. Pasupuleti, N. R. Tummuru, and H. Misra, "Power management of hybrid energy storage system based wireless charging system with regenerative braking capability," *IEEE Transactions on Industry Applications*, vol. 59, no. 3, pp. 3785–3794, May 2023, doi: 10.1109/TIA.2023.3234231.

[8] B. Z. Serykhanovna, R. Utebayev, M. Baktybayev, A. Temirzhanov, and M. M. Kunelbayev, "Development of a method for regenerative braking of an electric scooter," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 14, no. 3, p. 1331, Sep. 2023, doi: 10.11591/ijpeds.v14.i3.pp1331-1344.

[9] N. Vukajlović, D. Milićević, B. Dumnić, and B. Popadić, "Comparative analysis of the supercapacitor influence on lithium battery cycle life in electric vehicle energy storage," *Journal of Energy Storage*, vol. 31, p. 101603, Oct. 2020, doi: 10.1016/j.est.2020.101603.

[10] S. Huang, X. Zhu, S. Sarkar, and Y. Zhao, "Challenges and opportunities for supercapacitors," *APL Materials*, vol. 7, no. 10, Oct. 2019, doi: 10.1063/1.5116146.

[11] K. M. Moloelang, P. F. Le Roux, B. T. Abe, A. F. Nnachi, and T. P. Ratau, "Modeling and analysis of a battery-supercapacitor hybrid energy storage system (HESS) for Renewable energy applications," in *2023 6th International Conference on Renewable Energy and Power Engineering (REPE)*, Sep. 2023, pp. 293–299, doi: 10.1109/REPE59476.2023.10511902.

[12] G. Yasser, P. Theophile, M. Tedjani, and D. Sylvain, "Modeling, identification and simulation of hybrid battery/supercapacitor storage system used in vehicular applications," in *2019 6th International Conference on Electric Vehicular Technology (ICEVT)*, Nov. 2019, pp. 156–162, doi: 10.1109/ICEVT48285.2019.8994014.

[13] R. Sakthivelsamy and K. Subramaniyan, "Modelling and performance analysis of free body dynamics of electric vehicles," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 15, no. 1, p. 1, Mar. 2024, doi: 10.11591/ijpeds.v15.i1.pp1-7.

[14] H. Jung, H. Wang, and T. Hu, "Control design for robust tracking and smooth transition in power systems with battery/supercapacitor hybrid energy storage devices," *Journal of Power Sources*, vol. 267, pp. 566–575, Dec. 2014, doi: 10.1016/j.jpowsour.2014.05.061.

[15] D. Xu, Q. Liu, W. Yan, and W. Yang, "Adaptive terminal sliding mode control for hybrid energy storage systems of fuel cell, battery and supercapacitor," *IEEE Access*, vol. 7, pp. 29295–29303, 2019, doi: 10.1109/ACCESS.2019.2897015.

[16] M. M. Islam, S. A. Siffat, I. Ahmad, M. Liaquat, and S. A. Khan, "Adaptive nonlinear control of unified model of fuel cell, battery, ultracapacitor and induction motor based hybrid electric vehicles," *IEEE Access*, vol. 9, pp. 57486–57509, 2021, doi: 10.1109/ACCESS.2021.3072478.

[17] G. H. Eddine, B. Said, A. Houari, A. Dieroui, and T. Mesbahi, "Integral sliding mode control of synchronous reluctance machine based electric vehicle powered by battery/supercapacitor hybrid source," in *2022 19th International Multi-Conference on Systems, Signals & Devices (SSD)*, May 2022, pp. 2133–2138, doi: 10.1109/SSD54932.2022.9955985.

[18] S. F. Aini, A. R. Al Tahtawi, S. Yahya, and S. M. Ilman, "Linear quadratic integrator control design for battery-supercapacitor hybrid energy storage system," in *2023 10th International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE)*, Aug. 2023, pp. 236–241, doi: 10.1109/ICITACEE58587.2023.10276761.

[19] T. Sadeq, C. K. Wai, and E. Morris, "Current control of battery-supercapacitors system for electric vehicles based on rule-base linear quadratic regulator," *Advances in Science, Technology and Engineering Systems Journal*, vol. 6, no. 1, pp. 57–65, Jan. 2021, doi: 10.25046/aj060107.

[20] R. Ristiana, A. S. Rohman, C. Machbub, A. Purwadi, and E. Rijanto, "A new approach of EV modeling and its control applications to reduce energy consumption," *IEEE Access*, vol. 7, pp. 141209–141225, 2019, doi: 10.1109/ACCESS.2019.2941001.

[21] Y. Zhao, F. Qin, and Z. Zhang, "Robust tracking control design of hybrid battery-supercapacitor energy storage system in electric vehicles," *IEEE Transactions on Transportation Electrification*, vol. 11, no. 1, pp. 3262–3276, Feb. 2025, doi: 10.1109/TTE.2024.3436650.

[22] A. Wangsupphaphol, S. Phichaisawat, N. R. Nik Idris, A. Jusoh, N. D. Muhamad, and R. Lengkayan, "A systematic review of energy management systems for battery/supercapacitor electric vehicle applications," *Sustainability*, vol. 15, no. 14, p. 11200, Jul. 2023, doi: 10.3390/su151411200.

[23] Y. Wang, Z. Sun, and Z. Chen, "Energy management strategy for battery/supercapacitor/fuel cell hybrid source vehicles based on finite state machine," *Applied Energy*, vol. 254, p. 113707, Nov. 2019, doi: 10.1016/j.apenergy.2019.113707.

[24] F. Ju, Q. Zhang, W. Deng, and J. Li, "Review of structures and control of battery-supercapacitor hybrid energy storage system for electric vehicles," *Advances in Battery Manufacturing, Services, and Management Systems*, pp. 303–318, 2016, doi: 10.1002/9781119060741.ch13.

[25] A. S. Mohammed, S. M. Atnaw, A. O. Salau, and J. N. Eneh, "Review of optimal sizing and power management strategies for fuel cell/battery/super capacitor hybrid electric vehicles," *Energy Reports*, vol. 9, pp. 2213–2228, Dec. 2023, doi: 10.1016/j.egyr.2023.01.042.

[26] Z. Dong *et al.*, "A survey of battery–supercapacitor hybrid energy storage systems: concept, topology, control and application," *Symmetry*, vol. 14, no. 6, p. 1085, May 2022, doi: 10.3390/sym14061085.

[27] M. Suthar, U. B. Manthati, C. R. Arunkumar, P. Srinivas, F. Alsaif, and I. Zaitsev, "Enhancing electric vehicle performance with a hybrid PI-sliding mode controller for battery supercapacitor integration," *International Journal of Energy Research*, vol. 2024, no. 1, Jan. 2024, doi: 10.1155/2024/1105301.

[28] M. A. Khan *et al.*, "A novel supercapacitor/lithium-ion hybrid energy system with a fuzzy logic-controlled fast charging and intelligent energy management system," *Electronics (Switzerland)*, vol. 7, no. 5, 2018, doi: 10.3390/electronics7050063.

[29] M. Zand, M. A. Nasab, A. Hatami, M. Kargar, and H. R. Chamorro, "Using adaptive fuzzy logic for intelligent energy management in hybrid vehicles," in *2020 28th Iranian Conference on Electrical Engineering (ICEE)*, Aug. 2020, pp. 1–7, doi: 10.1109/ICEE50131.2020.9260941.

[30] Z. Shengzhe, W. Kai, and X. Wen, "Fuzzy logic-based control strategy for a battery/supercapacitor hybrid energy storage system in electric vehicles," in *2017 Chinese Automation Congress (CAC)*, Oct. 2017, pp. 5598–5601. doi: 10.1109/CAC.2017.8243780.

[31] D. F. Syahbana and B. R. Trilaksono, “MPC and filtering-based energy management in fuel cell/ battery/ supercapacitor hybrid source,” in *2019 International Conference on Electrical Engineering and Informatics (ICEEI)*, Jul. 2019, pp. 122–127, doi: 10.1109/ICEEI47359.2019.8988849.

[32] G. A. Ramos and R. Costa-Castelló, “Energy management strategies for hybrid energy storage systems based on filter control: analysis and comparison,” *Electronics (Switzerland)*, vol. 11, no. 10, 2022, doi: 10.3390/electronics11101631.

[33] J. Huang *et al.*, “Optimal filter-based energy management for hybrid energy storage systems with energy consumption minimization,” in *2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, Oct. 2020, pp. 1822–1827, doi: 10.1109/SMC42975.2020.9283163.

[34] A. Abdelkader, A. Rabeh, D. Mohamed Ali, and J. Mohamed, “Multi-objective genetic algorithm based sizing optimization of a stand-alone wind/PV power supply system with enhanced battery/supercapacitor hybrid energy storage,” *Energy*, vol. 163, pp. 351–363, Nov. 2018, doi: 10.1016/j.energy.2018.08.135.

[35] H. V. Dao *et al.*, “Optimization-Based Fuzzy Energy Management Strategy for PEM fuel cell/battery/supercapacitor hybrid construction excavator,” *International Journal of Precision Engineering and Manufacturing-Green Technology*, vol. 8, no. 4, pp. 1267–1285, Jul. 2021, doi: 10.1007/s40684-020-00262-y.

[36] Amin, R. T. Bambang, A. S. Rohman, C. J. Dronkers, R. Ortega, and A. Sasongko, “Energy management of fuel cell/battery/supercapacitor hybrid power sources using model predictive control,” *IEEE Transactions on Industrial Informatics*, vol. 10, no. 4, pp. 1992–2002, Nov. 2014, doi: 10.1109/TII.2014.2333873.

[37] J. Li, X. Wu, M. Xu, and Y. Liu, “A real-time optimization energy management of range extended electric vehicles for battery lifetime and energy consumption,” *Journal of Power Sources*, vol. 498, p. 229939, Jun. 2021, doi: 10.1016/j.jpowsour.2021.229939.

[38] R. Abdelhedi, A. Lahyani, A. C. Ammari, A. Sari, and P. Venet, “Reinforcement learning-based power sharing between batteries and supercapacitors in electric vehicles,” in *2018 IEEE International Conference on Industrial Technology (ICIT)*, Feb. 2018, pp. 2072–2077, doi: 10.1109/ICIT.2018.8352508.

[39] C. U. Udeogu and W. Lim, “Improved deep learning-based energy management strategy for battery-supercapacitor hybrid electric vehicle with adaptive velocity prediction,” *IEEE Access*, vol. 10, pp. 133789–133802, 2022, doi: 10.1109/ACCESS.2022.3232062.

[40] H. Bourenane, A. Berkani, K. Negadi, F. Marignetti, and K. Hebri, “Artificial neural networks based power management for a battery/supercapacitor and integrated photovoltaic hybrid storage system for electric vehicles,” *Journal Européen des Systèmes Automatisés*, vol. 56, no. 1, pp. 139–151, Feb. 2023, doi: 10.18280/jesa.560118.

[41] A. R. Al Tahtawi, M. R. Iskandar, S. Yahya, T. Tohir, and D. Aming, “Battery-supercapacitor current control using fuzzy supervisory with PI controller for electric vehicle application,” *Current Journal: International Journal Applied Technology Research*, vol. 3, no. 2, pp. 106–119, Oct. 2022, doi: 10.35313/ijatr.v3i2.82.

[42] T. Sadeq and C. K. Wai, “Linear quadratic regulator control scheme on hybrid energy storage system,” in *2020 IEEE International Conference on Automatic Control and Intelligent Systems (I2CACIS)*, Jun. 2020, pp. 219–223. doi: 10.1109/I2CACIS49202.2020.9140093.

[43] L. Zhang, X. Xia, and F. Barzegar, “Control of a battery/supercapacitor hybrid energy storage system for electric vehicles,” in *2017 36th Chinese Control Conference (CCC)*, Jul. 2017, pp. 9560–9565. doi: 10.23919/ChiCC.2017.8028883.

[44] Z. Bai, Z. Yan, X. Wu, J. Xu, and B. Cao, “H∞ control for battery/supercapacitor hybrid energy storage system used in electric vehicles,” *International Journal of Automotive Technology*, vol. 20, no. 6, pp. 1287–1296, Dec. 2019, doi: 10.1007/s12239-019-0120-x.

[45] X. Zhang, Z. Lu, X. Yuan, Y. Wang, and X. Shen, “L2-gain adaptive robust control for hybrid energy storage system in electric vehicles,” *IEEE Transactions on Power Electronics*, vol. 36, no. 6, pp. 7319–7332, Jun. 2021, doi: 10.1109/TPEL.2020.3041653.

[46] M. Mossadak, A. Chebak, N. Ouahabi, A. Rabhi, and A. A. Elmahjoub, “A novel hybrid PI–backstepping cascade controller for battery–supercapacitor electric vehicles considering various driving cycles scenarios,” *IET Power Electronics*, vol. 17, no. 9, pp. 1089–1105, Jul. 2024, doi: 10.1049/pel2.12697.

[47] X. Zhang, Y. Wang, X. Yuan, Y. Shen, and Z. Lu, “Adaptive dynamic surface control with disturbance observers for battery/supercapacitor-based hybrid energy sources in electric vehicles,” *IEEE Transactions on Transportation Electrification*, vol. 9, no. 4, pp. 5165–5181, Dec. 2023, doi: 10.1109/TTE.2022.3194034.

[48] S. A. Siffat, I. Ahmad, A. Ur Rahman, and Y. Islam, “Robust integral backstepping control for unified model of hybrid electric vehicles,” *IEEE Access*, vol. 8, pp. 49038–49052, 2020, doi: 10.1109/ACCESS.2020.2978258.

[49] W. Ahmad, L. Khan, Q. Khan, and I. Ullah, “Advanced sliding mode control techniques employed on electric hybrid vehicle,” in *2024 IEEE Texas Power and Energy Conference (TPEC)*, Feb. 2024, pp. 1–6, doi: 10.1109/TPEC60005.2024.10472230.

[50] Z. Song, J. Hou, H. Hofmann, J. Li, and M. Ouyang, “Sliding-mode and Lyapunov function-based control for battery/supercapacitor hybrid energy storage system used in electric vehicles,” *Energy*, vol. 122, pp. 601–612, Mar. 2017, doi: 10.1016/j.energy.2017.01.098.

[51] S. Ullah, R. Hayat, K. Zeb, A. Rasheed, and S. M. Muyeen, “Super-twisting sliding mode controller for energy storage system of a novel multisource hybrid electric vehicle: Simulation and hardware validation,” *International Journal of Hydrogen Energy*, vol. 71, pp. 952–963, Jun. 2024, doi: 10.1016/j.ijhydene.2024.05.326.

[52] H. Chen, R. Xiong, C. Lin, and W. Shen, “Model predictive control based real-time energy management for hybrid energy storage system,” *CSEE Journal of Power and Energy Systems*, vol. 7, no. 4, pp. 862–874, 2021, doi: 10.17775/CSEEJPES.2020.02180.

[53] C. Jia, J. Cui, W. Qiao, and L. Qu, “Real-time model predictive control for battery-supercapacitor hybrid energy storage systems using linear parameter-varying models,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 1, pp. 251–263, Feb. 2023, doi: 10.1109/JESTPE.2021.3130795.

[54] M. R. Larijani, S. H. Kia, M. Zolghadri, A. El Hajjaji, and A. Taghavipour, “Linear parameter-varying model predictive control for intelligent energy management in battery/supercapacitor electric vehicles,” *IEEE Access*, vol. 12, pp. 51026–51040, 2024, doi: 10.1109/ACCESS.2024.3385861.

[55] S. Liu, J. Peng, L. Li, X. Gong, and H. Lu, “A MPC based energy management strategy for battery-supercapacitor combined energy storage system of HEV,” in *2016 35th Chinese Control Conference (CCC)*, Jul. 2016, pp. 8727–8731, doi: 10.1109/ChiCC.2016.7554751.

[56] M. Nikkhah, H. Ashrafiuon, and K. R. Muske, “Optimal sliding mode control for underactuated systems,” in *2006 American Control Conference*, 2006, p. 6, doi: 10.1109/ACC.2006.1657461.

[57] A. R. Firdaus, “Design of sliding mode-based nonlinear control systems with nonlinear full-order state observers for underactuated coupled systems,” no. July, The University of Sheffield, UK, 2018, pp. 1–251.

[58] S. U. Din, Q. Khan, F.-U. Rehman, and R. Akmeliawanti, “A Comparative experimental study of robust sliding mode control strategies for underactuated systems,” *IEEE Access*, vol. 5, pp. 10068–10080, 2017, doi: 10.1109/ACCESS.2017.2712261.

[59] J. Jerrelind, P. Allen, P. Gruber, M. Berg, and L. Drugge, “Contributions of vehicle dynamics to the energy efficient operation of road and rail vehicles,” *Vehicle System Dynamics*, vol. 59, no. 7, pp. 1114–1147, Jul. 2021, doi: 10.1080/00423114.2021.1913194.

[60] T. Sadeq, C. K. Wai, E. Morris, Q. A. Tarboosh, and O. Aydogdu, "Optimal control strategy to maximize the performance of hybrid energy storage system for electric vehicle considering topography information," *IEEE Access*, vol. 8, pp. 216994–217007, 2020, doi: 10.1109/ACCESS.2020.3040869.
[61] M. Singla, L.-S. Shieh, G. Song, L. Xie, and Y. Zhang, "A new optimal sliding mode controller design using scalar sign function," *ISA Transactions*, vol. 53, no. 2, pp. 267–279, Mar. 2014, doi: 10.1016/j.isatra.2013.09.007.
[62] O. Gonzales and A. Rosales, "Sliding mode controller based on a linear quadratic integral regulator surface for power control on a dual active bridge converter," in *2018 IEEE Third Ecuador Technical Chapters Meeting (ETCM)*, Oct. 2018, pp. 1–6. doi: 10.1109/ETCM.2018.8580294.

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