

SLIDING MODE CONTROLLER DESIGN BASED ON AVERAGING MODEL FOR ELECTRIC VEHICLE SYSTEMS

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Received: December 22, 2025; Revised: February 10, 2026; Accepted: March 02, 2026

Abstract

Driven by increasing concerns over greenhouse gas emissions from conventional combustion vehicles, electric vehicles (EVs) have gained rapid popularity. Their efficient operation depends on a control system for the power electronic circuits integrated within the vehicle architecture. This article presents a sliding mode controller design for a bidirectional half-bridge DC-DC converter deployed in battery EV (BEV) systems. The design is based on a sliding surface equation formulated as a linear combination of state variables and a mathematical model derived from the generalized state-space averaging method for computing the control signal equation. The controller parameters are selected via a trial-and-error approach. Simulations using MATLAB/SIMULINK demonstrate that the proposed sliding mode controller regulates the DC bus voltage in compliance with ISO 21498-1,2 standards under varying load conditions and exhibits robustness against system parameter variations. This confirms that the electric powertrain system of the vehicle can operate effectively.

Keywords: Sliding Model Controller; Battery Electric Vehicles; Bidirectional DC-DC Converter; Mathematical Model; GSSA Method

BEV	Battery Electric Vehicle	d	Duty cycle of the converter
SMC	Sliding Mode Controller	T_s	Switching period
L	Inductance of converter	Δi_L	Ripple current
C_i	Capacitance of converter at DC voltage source side	Δv_{C_o}	Ripple voltage across C_o
C_o	Capacitance of converter at DC bus voltage side	Δv_{C_i}	Ripple voltage across C_i
V_{BATT}	DC voltage source	f_s	Switching frequency
R_{CPL}	Resistance of constant power load	A_r	Amplitude of the carrier signal for PWM
		V_o^{ref}	Voltage reference

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i_L	Inductor current
v_L	Voltage across L
i_{C_o}	Current through C_o
v_{C_o}	DC bus voltage
I_{CPL}	Current through constant power load
P_{CPL}	Constant Power Load
$u(t)$	The switching function of the converter
S	Sliding surface equation
a	Parameter a of the SMC
b	Parameter b of the SMC
m	Parameter m of the SMC
K	Parameter K of the SMC
e_1	The current error
e_2	The voltage error
e_3	The integral of the current and voltage errors
i_{ref}	The reference current
u_{eq}	The control signal

Introduction

Over the past decade, electric vehicles (EVs) have gained global attention, as most national policies are aimed at reducing greenhouse gas emissions in the transportation sector. Consequently, battery electric vehicles (BEVs), which rely on batteries as their primary energy source, have experienced steadily rising annual sales (Chakraborty *et al.*, 2019). This growth is driven by several factors, including increased affordability, improved efficiency, extended driving range per charge, and, most importantly, zero operational greenhouse gas emissions (Malik *et al.*, 2025).

In BEV architectures, the power converter represents a critical component responsible for bidirectional energy management: conversion and transfer of electrical power from the battery to system loads in driving mode and/or recuperation of electrical energy from the electric motor in the regenerative braking mode. The power converter also plays a crucial role in regulating the DC bus voltage thereby maintaining a desired constant level with current and emerging BEV architectures typically employing an 800 V DC bus (Reimers *et al.*, 2019; Ehsani *et al.*, 2021; Poorfakhraei *et al.*, 2021; Hren *et al.*, 2023; Islam *et al.*, 2023). Consequently, the controller of the power converter is essential for stable DC bus voltage regulation and efficient BEV powertrain operation. The proportional-integral (PI) controller is commonly used in these applications owing to its facile design and ability to eliminate steady-state errors. However, PI controllers may exhibit slow dynamic responses and limited robustness against external disturbances (Farooq *et al.*, 2019; Mohanty *et al.*, 2021). Conversely, advanced control techniques, such as hysteresis, fuzzy-logic, space vector

modulation, and neural network-based controls, offer superior performance under disturbances and system nonlinearities, although they typically demand more complex designs and computational processes (Xu *et al.*, 2021; Muthukumar *et al.*, 2024). Notably, sliding mode control (SMC) has recently emerged as an effective approach owing to its distinct advantages, including applicability across linear and nonlinear systems, fast dynamic responses, and high robustness against external disturbances (Kanthi and Abraham, 2020; Wu *et al.*, 2022; Noor *et al.*, 2024).

Therefore, this article presents the design of a sliding mode controller for a bidirectional half-bridge DC-DC converter deployed in BEV systems. The controller is formulated using a sliding surface equation defined as a linear combination of state variables, ensuring design and implementation simplicity. Additionally, the mathematical model of the system, which is derived via the generalized state-space averaging (GSSA) method, is employed to define the control signal equation. Further, a trial-and-error approach is adopted for parameter selection since there is no general approach for such a controller. The intensive time-domain simulations were performed in MATLAB/SIMULINK to evaluate the performance of the proposed controller. The results reveal that the designed SMC effectively regulates the DC bus voltage to the desired constant value, maintaining compliance with ISO 21498-1,2 across varying load conditions and exhibiting robustness against system parameter variations.

The remainder of this article is organized as follows; Section II presents the BEV system under consideration. Section III describes the proposed SMC design, where the GSSA-based model derivation is also presented in the appropriate subsection. Section IV presents the evaluation of the performance of the controller via simulations. Finally, Section V concludes the study, outlining directions for future research.

Considered BEV System

The BEV system under consideration is illustrated in Figure 1. It comprises three main components: the battery, which serves as the primary source of electrical power; a bidirectional half-bridge DC-DC converter, which regulates the DC bus voltage and manages power delivery via SMC; and the EV driving unit, which comprises the electric motor and a controlled power converter, behaving as a constant power load (CPL) (Emadi *et al.*, 2006; AL-Nussairi *et al.*, 2017; Tang *et al.*, 2020;

Martínez-Treviño *et al.*, 2021). Therefore, it is modeled as an ideal CPL in this study.

Generally, EVs operate in two modes: the driving and regenerative braking modes. However, only the driving mode is explored in this study, as it represents the primary operating condition of the system. Further, the passive components of the system include the inductor (L) and capacitor (C), as illustrated in part II of Figure 1. These elements can be designed based on the principles of the linked-flux balance in the inductors, the charge balance in the capacitors, and small-signal approximation, as expressed in (1), (2), and (3). Consequently, the resulting parameters of the considered BEV system are summarized in Table 1.

$$L \geq \frac{dT_s V_{BATT}}{z \Delta i_L} \quad (1)$$

$$C_i \geq \frac{\Delta i_L T_s}{8 \Delta v_{C_i}} \quad (2)$$

$$C_o \geq \frac{dT_s V_{BATT}}{2 \Delta v_{C_o} R_{CPL}(1-d)} \quad (3)$$

SMC Design

The SMC design begins with an overview of its operating principles, followed by the derivation of

a time-invariant mathematical model for the BEV system using the GSSA method. The resulting model is subsequently integrated with the sliding surface equation to compute the control signal equation. The details are presented as follows.

The SMC principles are illustrated in Figure 2. The system state variables, denoted here as x_1 and x_2 , with an initial condition at $x(t_0)$, are controlled to follow a trajectory that converges toward the sliding surface at $x(t_f)$. The phase in which the trajectory is driven toward the sliding surface is referred to as the reaching phase. Once the trajectory reaches the sliding surface, the state variables track along the surface toward the origin, where the sliding surface equation equals zero. This highlights the capability of the controller to regulate the system. Consequently, designing the SMC requires defining the sliding surface equation and the system state variables. In this study, the sliding surface equation is defined as a linear combination of the state variables, and the system state variables are the inductor current (i_L) and the DC bus voltage (v_{C_o}), which are obtained from the GSSA-based time-invariant mathematical model of the bidirectional half-bridge DC-DC converter.

The time-invariant model derivation begins with formatting the switched model by analyzing the circuit operation in each mode.

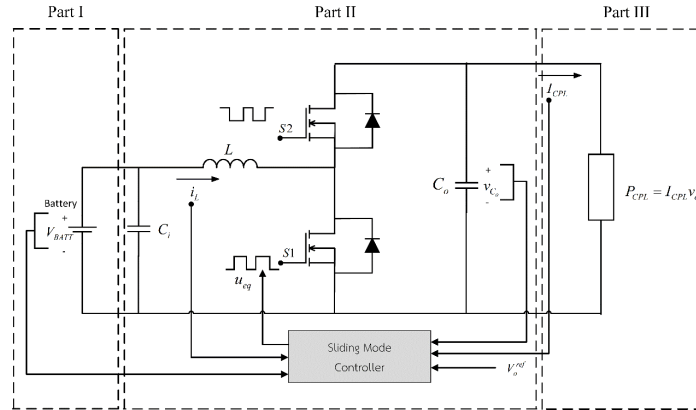


Figure 1. The considered BEV system

Table 1. The parameters of the considered BEV system

Parameters	Values	Descriptions
V_{BATT}	662 V	DC voltage source
L ($\Delta i_L \leq 8.61$ A)	0.663 mH	The inductances of the bidirectional half-bridge DC-DC converter
C_i ($\Delta v_{C_i} \leq 3$ V)	35.877 μ F	The input capacitance of the bidirectional half-bridge DC-DC converter
C_o ($\Delta v_{C_o} \leq 3$ V)	2 mF	The output capacitance of the bidirectional half-bridge DC/DC converter
f_s	10 kHz	Switching frequency
A_r	10	Amplitude of the carrier signal for PWM
V_o^{ref}	800 V	Voltage reference

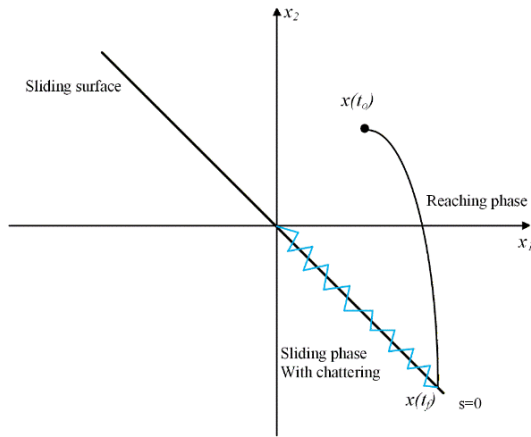


Figure 2. Concept of SMC

In Mode 1, Switches $S1$ and $S2$ are turned ON and OFF, respectively as shown in Figure 3, whereas in Mode 2, $S1$ and $S2$ are turned OFF and ON, respectively as shown in Figure 4. Applying Kirchhoff's voltage and current laws to the analysis of the circuit in each mode yields the differential equations governing the inductor current (i_L) and the DC bus voltage ($\dot{v}_{C_o}$) for Modes 1 and 2, as expressed in (4) and (5), respectively.

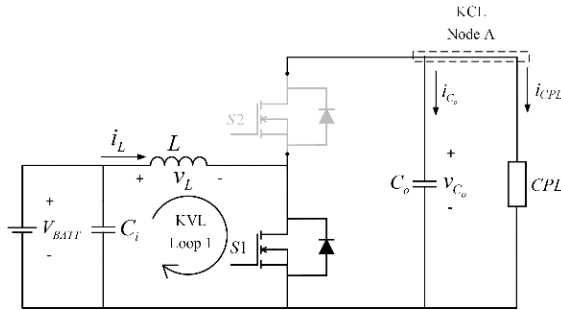


Figure 3. Bidirectional half-bridge DC-DC converter operates in Mode 1

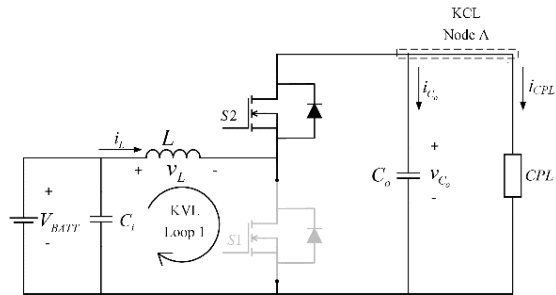


Figure 4. Bidirectional half-bridge DC-DC converter operates in Mode 2

$$\begin{cases} \dot{i}_L = \frac{1}{L} V_{BATT} \\ \dot{v}_{C_o} = -\frac{P_{CPL}}{v_{C_o} C_o} \end{cases} \quad (4)$$

$$\begin{cases} \dot{i}_L = \frac{1}{L} V_{BATT} - \frac{1}{L} v_{C_o} \\ \dot{v}_{C_o} = \frac{1}{C_o} i_L - \frac{P_{CPL}}{v_{C_o} C_o} \end{cases} \quad (5)$$

Thereafter, i_L and $\dot{v}_{C_o}$ for each mode are combined using a validation functions (h_i). As the circuit under consideration operates in two modes, two validation functions, h_1 and $h_2 = 1 - h_1$, are utilized, with the following specific conditions;

$$\begin{aligned} S1 \text{ ON and } S2 \text{ OFF: } h_1 &= 1 \text{ and } h_2 = 0 \\ S1 \text{ OFF and } S2 \text{ ON: } h_1 &= 0 \text{ and } h_2 = 1 \end{aligned}$$

Therefore, i_L and $\dot{v}_{C_o}$ are expressed in (6) in validation function forms.

$$\begin{cases} \dot{i}_L = \left(\frac{1}{L} V_{BATT} \right) h_1 + \left(\frac{1}{L} V_{BATT} - \frac{1}{L} v_{C_o} \right) h_2 \\ \dot{v}_{C_o} = \left(-\frac{P_{CPL}}{v_{C_o} C_o} \right) h_1 + \left(\frac{1}{C_o} i_L - \frac{P_{CPL}}{v_{C_o} C_o} \right) h_2 \end{cases} \quad (6)$$

$$\begin{cases} \dot{i}_L = \frac{1}{L} V_{BATT} + \frac{(u(t)-1)}{L} v_{C_o} \\ \dot{v}_{C_o} = \frac{(1-u(t))}{C_o} i_L - \frac{P_{CPL}}{C_o v_{C_o}} \end{cases} \quad (7)$$

$$\text{Where } u(t) = \begin{cases} 1, 0 < t < dT_s \\ 0, dT_s < t < T_s \end{cases}$$

Subsequently, equation (6) is converted into a bilinear form of the switched model by replacing the validation functions with the switching function ($u(t)$), where $u(t) = h_1$ and $h_2 = 1 - h_1 = 1 - u(t)$. This yields the differential equations expressed in terms of the switching function as shown in (7), still representing a time-varying model. Directly employing this model to design an SMC complicates the procedure. Therefore, the GSSA method is employed to eliminate the switching effects and realize a time-invariant model. An overview is given as follows;

Generally, any periodic signal $f(t)$ with a period T can be expressed in the form of a complex Fourier series (Gamelin, 2001), as shown in (8).

$$f(t) = \sum_{k=-\infty}^{\infty} \langle x \rangle_k(t) e^{jk\omega_s t} \quad (8)$$

where $\omega_s = \frac{2\pi}{T}$ and $\langle x \rangle_k(t)$ is the complex Fourier coefficients.

The GSSA method employs the $\langle x \rangle_k(t)$ of the signal to represent the system state variables. The $\langle x \rangle_k(t)$ is obtained as follows.

$$\langle x \rangle_k(t) = \frac{1}{T} \int_{t-T}^t f(t) e^{-j\omega_s t} dt \quad (9)$$

The essential properties of the complex Fourier coefficients for deriving the mathematical model of power converters (Sanders *et al.*, 1991) can be summarized in three points:

Property 1: The time-derivative property, which can be expressed as shown in (10).

$$\frac{d}{dt} \langle x \rangle_k = \left\langle \frac{dx}{dt} \right\rangle_k - jk\omega \langle x \rangle_k \quad (10)$$

Property 2: The property of the multiplication relationship, which can be expressed as shown in (11).

$$\langle xy \rangle_k = \sum_i \langle x \rangle_{k-i} \langle y \rangle_i \quad (11)$$

Property 3: Assuming $f(t)$ is a real value, the complex Fourier coefficients for negative k can be expressed using (12).

$$\langle x \rangle_{-k} = \overline{\langle x \rangle_k} = \langle x \rangle_k^* \quad (12)$$

Index k in (8) and (9) indicates model accuracy. The model error becomes zero assuming k approaches infinity. For signals not exhibiting notable oscillations, k can be set to zero, and this is called the zero-order approximation (Mahdavi *et al.*, 1997; Emadi *et al.*, 2004). If the signal exhibits oscillations, k can be set to -1, 0, 1, which is known as the first-order approximation (Mahdavi *et al.*, 1997; Emadi *et al.*, 2004). In this study, the zero-order approximation ($k = 0$) is applied based on the assumption that the passive components of the considered system are designed to produce negligible signal ripple, allowing for the neglect of the effects of such ripples. Therefore, under the zero-order approximation of (8), the state variables, i_L and $\dot{v}_{C_o}$, of the model can be expressed by distributing the terms of the complex Fourier series as shown in (13) and (14), respectively.

$$i_L = \langle i_L \rangle_0 \quad (13)$$

$$v_{C_o} = \langle v_{C_o} \rangle_0 \quad (14)$$

Following (7), applying Property 1 of the complex Fourier coefficients and considering $k = 0$ can transform the expression into (15).

$$\begin{cases} \langle \dot{i}_L \rangle_0 = \frac{1}{L} \langle V_{BATT} \rangle_0 - \frac{\langle 1-u \rangle_0}{L} \langle v_{C_o} \rangle_0 - j(0)\omega_s \langle i_L \rangle_0 \\ \langle \dot{v}_{C_o} \rangle_0 = \frac{\langle 1-u \rangle_0}{C_o} \langle i_L \rangle_0 - \frac{P_{CPL}}{C_o \langle v_{C_o} \rangle_0} - j(0)\omega_s \langle v_{C_o} \rangle_0 \end{cases} \quad (15)$$

Additionally, from (9), the complex Fourier coefficient of $u(t)$ for $k = 0$ is derived in (16).

$$\langle u \rangle_0 = \frac{1}{T_s} [t]_0^{t=dT_s} = d \quad (16)$$

Where d denotes the duty cycle

Consequently, based on (13) to (16), the GSSA-derived time-invariant mathematical model of the considered BEV can be obtained in (17).

$$\begin{cases} \dot{i}_L = \frac{1}{L} V_{BATT} - \frac{(1-d)}{L} v_{C_o} \\ \dot{v}_{C_o} = \frac{(1-d)}{C_o} i_L - \frac{P_{CPL}}{C_o v_{C_o}} \end{cases} \quad (17)$$

By analyzing the sliding surface equation, which is defined as a linear combination of state variables, the equation can be written as (18).

$$S = ae_1 + be_2 + me_3 \quad (18)$$

where a , b , and m are the parameters of the SMC.

Based on (18), e_1 and e_2 denote the current and voltage errors, respectively, and e_3 represents the integral of e_1 and e_2 , which are obtained from (19).

$$\begin{cases} e_1 = i_{ref} - i_L \\ e_2 = V_o^{ref} - v_{C_o} \\ e_3 = \int [e_1 + e_2] dt \end{cases} \quad (19)$$

where the reference current (i_{ref}) is determined using (20), with K denoting the gain of e_2 .

$$i_{ref} = K[V_o^{ref} - v_{C_o}] \quad (20)$$

In SMC, the ideal system behavior is to move along the sliding surface toward the point where the sliding surface equation is zero ($S = 0$). This state consequently yields a zero derivative of the sliding surface ($\dot{S} = 0$). This condition ensures the system enters the control regime. Consequently, deriving the sliding surface for the proposed controller using (18) in conjunction with (19) and (20) allows the derivative to be expressed as (21).

$$\begin{aligned} \dot{S} = & a\dot{i}_{ref} - a\dot{i}_L + b\dot{V}_o^{ref} - b\dot{v}_{C_o} \\ & + m[(K+1)[V_o^{ref} - v_{C_o}] - i_L] \end{aligned} \quad (21)$$

Notably, (21) reveals that the system state variables of the BEV under consideration, i_L and $\dot{v}_{C_o}$, appear in the equation. These variables can be substituted using the proposed model as given in (17). This substitution yields (22) under condition $\dot{S}=0$, and by setting the duty cycle to be equal to the control signal ($d = u_{eq}$). By rearranging (22), the control signal for regulating the DC bus voltage of the BEV system using the proposed SMC is obtained as expressed in (23).

$$0 = -aK \left[\frac{(1-u_{eq})}{C_o} i_L - \frac{P_{CPL}}{C_o v_{C_o}} \right] - a \left[\frac{1}{L} V_{BATT} + \frac{(u_{eq}-1)}{L} v_{C_o} \right] - b \left[\frac{(1-u_{eq})}{C_o} i_L - \frac{P_{CPL}}{C_o v_{C_o}} \right] + m[(K+1)[V_o^{ref} - v_{C_o}] - i_L] \quad (22)$$

$$u_{eq} = \frac{[aLK+bL]i_L v_{C_o} - [aLK+bL]P_{CPL} + aC_o V_{BATT} v_{C_o} - aC_o v_{C_o}^2 - mL C_o v_{C_o} [(K+1)[V_o^{ref} - v_{C_o}] - i_L]}{[aLK+bL]i_L v_{C_o} - aC_o v_{C_o}^2} \quad (23)$$

According to (23), the SMC parameters (a , b , m , and K) must be defined. As there is no general design method, these parameters are determined in this study via a trial-and-error approach. The performance of the controller is evaluated via intensive time-domain simulations using the SimPowerSystem® blockset in MATLAB/SIMULINK. The block diagram of the BEV system is illustrated in Figure 5. To assess the performance, the CPL step change from 10 kW to

10.5 kW is applied at $t = 0.5$ s., and the transient system response is examined. The resulting controller parameters configuration is detailed as follows:

Design of the parameter a

The performance of the controller obtained by setting parameter a to 0.00000001, 0.00000001, and 0.000000001 while maintaining $b = 0.000000001$, $m = 55$, and $K = 25$ is shown in Figure 6. The result reveals that at $a = 0.00000001$, the controller effectively maintains the DC bus voltage value of 800 V. Conversely, for $a = 0.00000001$ and 0.000000001, the controller fails to regulate the DC bus voltage at the 800 V point.

Design of the parameter b

The performance obtained by setting parameter b to 0.00000001, 0.000000001, and 0.000000005 while maintaining $a = 0.00000001$, $m = 55$, and $K = 25$ is illustrated in Figure 7. The results indicate that all three values of b effectively maintain the DC bus voltage at 800 V.

Design of the parameter m

The performance of the controller obtained by varying parameter m to 30, 55, and 70 while maintaining $a = 0.00000001$, $b = 0.000000001$, and $K = 25$ is shown in Figure 8. The results indicate that at $m = 55$, the controller effectively regulates the DC bus voltage at the 800 V setpoint. Conversely, at $m = 30$ and $m = 70$, the controller fails to maintain the DC bus voltage at 800 V.

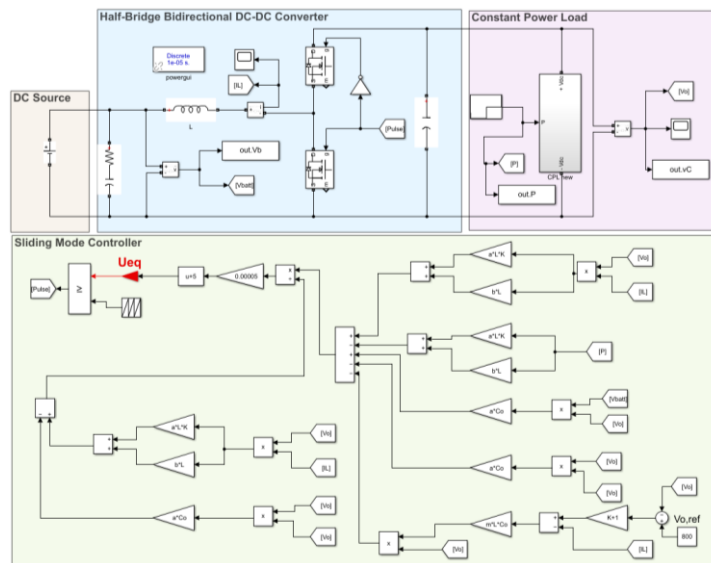
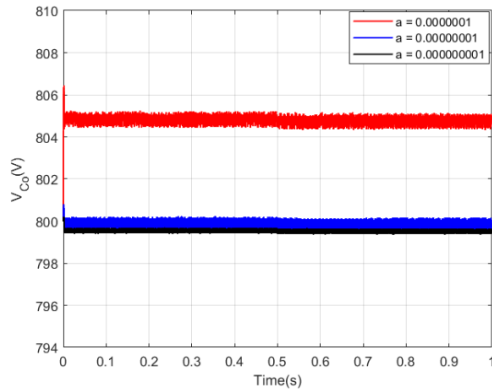
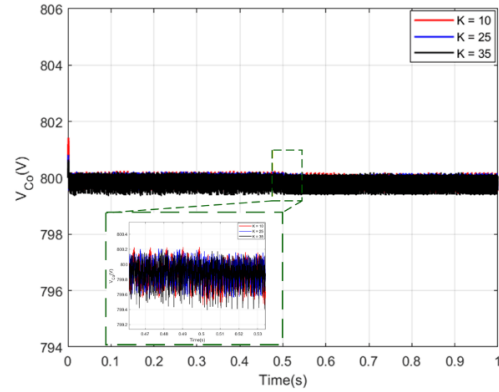
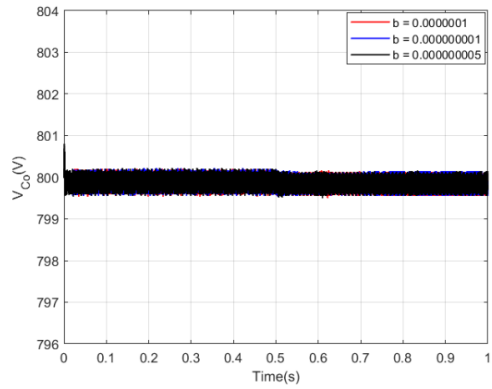
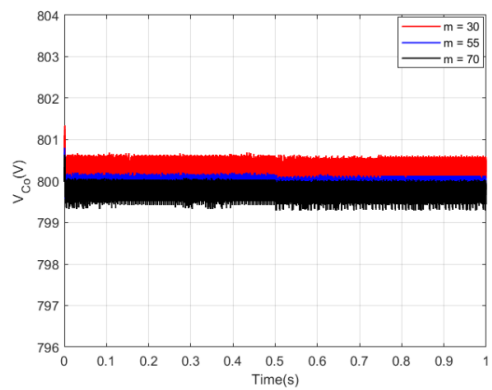


Figure 5. The SimPowerSystem® block of the considered BEV system

Figure 6. Design results of the parameter a Figure 9. Design results of the parameter K Figure 7. Design results of the parameter b Figure 8. Design results of the parameter m

Design of the parameter K

The performance of the controller obtained by varying parameter K to 10, 25, and 35 while maintaining $a = 0.00000001$, $b = 0.000000001$, and $m = 55$ is shown in Figure 9. The results reveal that all three K values effectively regulate the v_{Co} at the desired 800 V setpoint. However, the $K = 25$ case yields the smallest steady-state error.

The above design procedure reveals that parameter a exerts the strongest influence on the system response. The control signal equation given in (23) reveals that a appears almost across all terms and is multiplied by all system parameters. Consequently, the following SMC parameters are selected for the considered BEV system: $a = 0.00000001$, $b = 0.000000001$, $m = 55$, and $K = 25$. The control performance of the system under load variations, using the designed parameters, is evaluated and presented in the next section.

Simulation Results

This section evaluates the control performance under load variations via simulation. The evaluation is performed under three cases, as described in the following.

Case I - Step change in load power (worst-case scenario): The test conditions are defined by a CPL decrease from 9.5 kW to 9 kW at $t = 0.5$ s., followed by increases from 9 kW to 10 kW at $t = 1$ s. and 10 kW to 11 kW at $t = 1.5$ s. The evaluation results are shown in Figure 10. As observed from the DC bus voltage response (v_{Co}), the proposed SMC effectively regulates the voltage of the considered BEV system at the desired value of 800 V. The controller also delivers excellent dynamic performances, with a recovery time of only 0.6 ms. and almost 0% undershoot and overshoot. Additionally, the controller maintains the DC bus voltage within the ranges specified by ISO 21498-1, 2, the standards that designers and manufacturers of EV systems must follow, even under varying load conditions.

Case II - Gradual power variations: A realistic EV operating scenario is simulated, where acceleration increases the power demand of the electric motor, whereas deceleration reduces the

required power (Liu *et al.*, 2023). Accordingly, the simulation conditions are defined such that the vehicle accelerates from 1 s. to 2 s., resulting in a gradual increase in load power. Afterward, the vehicle operates at a constant speed until 4 s., followed by a deceleration phase until 6 s., reducing the load power. The simulation results in Figure 11 indicate that the proposed sliding mode controller effectively regulates the DC bus voltage at 800 V, maintaining compliance with the ISO 21498-1,2 standards despite the gradual load power variations.

Case III - Robustness: The controller performance is evaluated under constant load power variations similar to Case I, whereas the system parameters, L and C_o , are varied by $\pm 20\%$ from their

nominal values. The simulation results shown in Figure 12 indicate that the proposed sliding mode controller effectively regulates the DC bus voltage at 800 V despite parameter variations. These results maintain compliance with the ISO standards, confirming the robustness of the proposed sliding mode controller.

Consequently, it can be confirmed that the SMC design based on the GSSA-derived mathematical model and the trial-and-error parameter selection approach effectively regulates the DC bus voltage to meet the required standards, thereby ensuring the efficient operation of BEV powertrain systems.

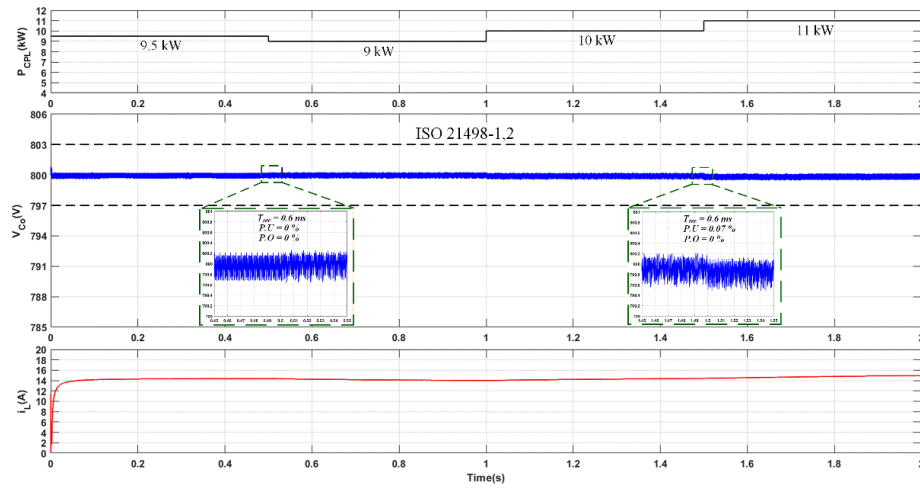


Figure 10. Simulation result for the proposed controller performance evaluation (Case I)

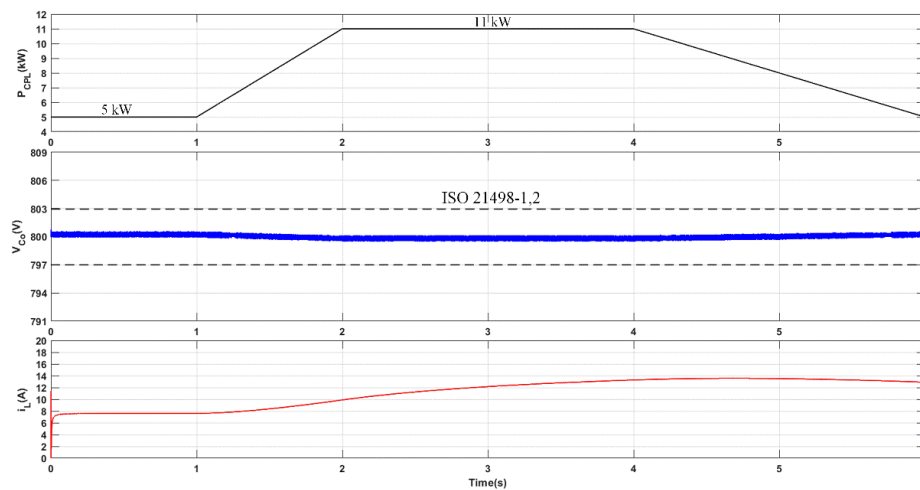


Figure 11. Simulation result for the proposed controller performance evaluation (Case II)

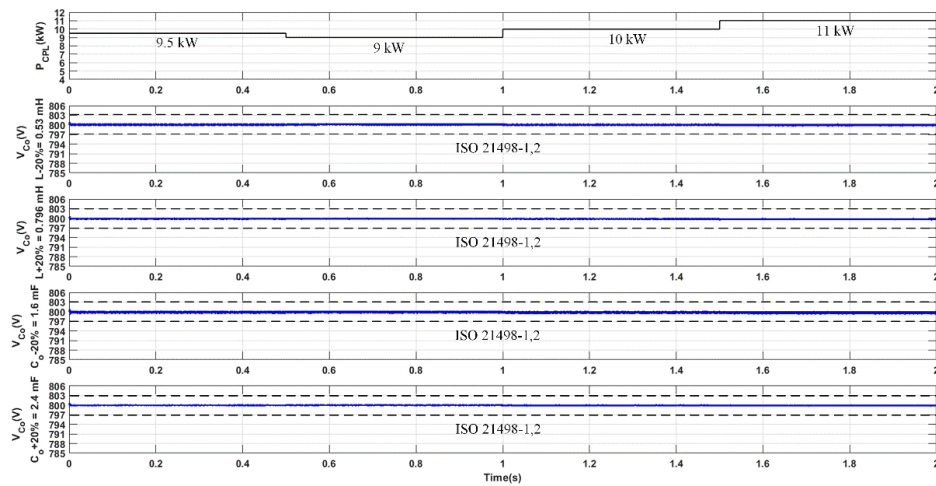


Figure 12. Simulation result for the proposed controller performance evaluation (Case III)

Conclusions

This article presents the design of a SMC for a bidirectional half-bridge DC–DC converter within a BEV system. The design is based on a sliding surface defined as a linear combination of state variables in conjunction with a GSSA-derived time-invariant mathematical model for formulating the control signal equation. Further, the controller parameters are selected via a trial-and-error approach. Simulations in MATLAB/SIMULINK demonstrate that the proposed SMC effectively regulates the DC bus voltage of the considered BEV system to a constant value of 800 V in compliance with ISO 21498-1,2. The proposed controller also exhibits excellent dynamic performances, characterized by rapid recovery and negligible percent overshoot/undershoot, even under considerable load and system parameter variations (robustness). Therefore, the proposed design effectively ensures DC bus voltage regulation in compliance with the required standards, supporting the efficient operation of the BEV powertrain. However, a major disadvantage of SMC remains the lack of a general procedure for selecting parameters. Thus, applying artificial intelligence (AI) techniques to SMC parameter design represents a notable direction for future research. Such approaches can provide systematic design guidelines and further enhance overall control performance.

Funding

The author (Aphirak Srichana) received financial support from the Graduate Degree Scholarship for Honor, Suranaree University of Technology.

Author Contributions

Conceptualization: Api.S.; Methodology: Api.S.; Software: Aph.S.; Validation: K.A.; Investigation: Api.S.; Data Curation: Aph.S.; Writing – Original Draft: Api.S.; Supervision: K.A.

Ethics Statement

Ethical approval was not required for this study because it did not involve human participants, animals, identifiable personal data, or materials requiring institutional ethical review.

Declaration of Generative AI Use

The authors declare that no Generative AI tools were used in the preparation of this manuscript.
Dear Author,

Conflict of Interest

The authors declare that they have no conflicts of interest related to this work.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the authors upon reasonable request.

Acknowledgement

This work was supported by Suranaree University of Technology (SUT)

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