DOI: 10.5370/JEET.2011.6.1.067

Application of a Robust Fuzzy Sliding Mode Controller Synthesis on a Buck-Boost DC-DC Converter Power Supply for an Electric Vehicle Propulsion System

Boumediène ALLAOUA† and Abdellah LAOUFI*

Abstract - The development of electric vehicle power electronics system control, composed of DC-AC inverters and DC-DC converters, attract much research interest in the modern industry. A DC-AC inverter supplies the high-power motor torques of the propulsion system and utility loads of electric vehicles, whereas a DC-DC converter supplies the conventional low-power and low-voltage loads. However, the need for high-power bidirectional DC-DC converters in future electric vehicles has led to the development of many new topologies of DC-DC converters. The nonlinear control of power converters is an active research area in the field of power electronics. This paper focuses on the use of the fuzzy sliding mode strategy as a control strategy for buck-boost DC-DC converter power supplies in electric vehicles. The proposed fuzzy controller specifies changes in control signals based on the surface and knowledge on surface changes to satisfy the sliding mode stability and attraction conditions. The performance of the proposed fuzzy sliding controller is compared to that of the classical sliding mode controller. The satisfactory simulation results show the efficiency of the proposed control law, which reduces the chattering phenomenon. Moreover, the obtained results prove the robustness of the proposed control law against variations in load resistance and input voltage in the studied converter.

Keywords: Buck-boost DC-DC converter, Power electronic supply, Electric vehicle, FSMS, Control robustness

1. Introduction

Electric vehicle power management is significant because it can determine the power status of electric vehicles in an efficient economy. Power management is the way in which energy is moved to and from the energy storage device and the electric motor. It also involves the quantity of energy and the duration of energy transfer [1], [2].

Numerous researchers use constant energy source alimentation for their electric vehicles. However, this does not match reality because all batteries are autonomous and dependent on their specific energy storage (state of charge and depth of discharge), and output voltage is not constant [3], [4]. For this reason, DC-DC converters with a control strategy are used to ensure that the energy requirements of electric vehicles and propulsion systems are met. The proposed control strategy for DC-DC converters ensures and maintains the DC output voltage constant against load variations, satisfying the demand inputs of electric vehicle inverters.

Energy storage or power supply devices vary their output voltage according to load or charge states. This creates major challenges for electric vehicle designers when integrating the energy storage or power supply devices with a traction drive [2], [4]. DC-DC converters can be used to interface elements in the electric power train by boosting or chopping voltage levels [5]. However, their use is limited due to the size, weight, efficiency, and cost of current buck-boost DC-DC converters [6], [7]. Recent power supply designs employ buck-boost DC-DC converters; the required output is inverted directly from the input voltage and the output voltage can be either higher or lower than the input voltage [6], [8]. Buck-boost power converters are widely used in automotive and marine applications.

A buck-boost DC-DC converter with a robust control strategy used in battery-operated electric vehicles must provide a regulated DC output voltage under varying loads or when the battery charge state varies as the input voltage varies [8], [9]. Generally, conventional linear control solutions applied to power electronic systems, especially for buck-boost DC-DC converters, fail to accomplish robustness under nonlinearity, parameter variation, load disturbance, and input voltage variation. Consequently, there is greater interest in developing more advanced and nonconventional nonlinear robust control structures to improve the performance of buck-boost DC-DC converters [9], [10].

The fuzzy sliding mode strategy (FSMS) has been proposed to improve the robustness and the dynamic response of switch mode power supplies. FSMS is a control approach, which complies with the nonlinear nature of switch

† Corresponding Author: Dept. of Technology, Faculty of the Sciences and the Technology, Bechar University, B.P 417 BECHAR (08000), Algeria. (elec_allaoua2bf@yahoo.fr)
* Dept. of Technology, Faculty of the Sciences and the Technology, Bechar University, B.P 417 BECHAR (08000), Algeria. (laoufi_ab@yahoo.fr)
Received: April 22, 2010; Accepted: December 2, 2010

mode power supplies. This control technique offers several advantages compared to traditional control methods: stability even for large line and load variations, robustness, and good dynamic response [11], [12]. The output voltage and its derivative are both continuous and accessible for measurement. Before going forward to the application of FSMS for switch mode power supplies, let us take a brief look at the theory of FSMS.

Fuzzy logic control and sliding mode control (SMC) have been combined in various ways in sliding surface designs [13], [14]. The approaches can be classified into two categories. The first approach, taken by many researchers, is to use fuzzy logic control for the determination of the sliding surface movement of the classical SMC [14], [15]. A Takagi–Sugeno type fuzzy tuning algorithm is used for the movement of the sliding surface [16]-[18]. The objective of the second approach is to determine directly the sliding surface based on fuzzy logic. This method is called FSMS.

This paper proposes a robust FSMS to control the buck-boost DC-DC converter power supply for electric vehicle applications. In this scheme, an SMC is investigated, in which the fuzzy logic system is used to replace the discontinuous control action of the classical SMC law to improve the DC output voltage performance of the buck-boost DC-DC converter. The obtained results are compared, in terms of start-up behavior and robustness to disturbances, with those achieved using the classical SMC.

2. Buck-Boost DC-DC Converter for Electric Vehicles

Buck-boost DC-DC converters find applications in places where battery charging, regenerative braking, and backup power are required. The power flow in a bidirectional converter is usually from a low voltage end, such as a battery or a super capacitor, to a high voltage side. This is referred to as boost operation [3], [19].

An electric vehicle buck-boost converter provides an output voltage, which can be higher or lower than the battery input voltage [3], [20], [21]. Output voltage polarity is opposite to that of the input voltage. Fig. 1 shows a simplified structure of the buck-boost converter associated with the electric vehicle drive. It consists of a battery DC input voltage source (V_{input}), DC output voltage (V_{output}) delivered to the electric vehicle drive, a controlled switch (C_{switch}), a diode (D), a filter inductor (L), a filter capacitor (C), and a load resistance (R).

During the normal operation of the buck-boost power stage, C_{switch} is switched ON and OFF repeatedly with the on and off times under the control of the duty ratio. Depending on whether the switch (C_{switch}) is ON or OFF, the converter operation can be divided into two modes of operation. At mode -I-, the switch (C_{switch}) is conducting and at mode -II-, the switch (C_{switch}) is open. When the switch is ON, the system is linear and the state space equations can be written as follows:

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L} V_{input} \\ \dfrac{dV_{output}}{dt} = -\dfrac{1}{RC} V_{output} \end{cases} \tag{1}$$

where inductance currents (i_L) and capacitance voltages (V_{output}) are the state variables.

When the switch is OFF, the system is also linear and the state space equations are given by

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{1}{L} V_{output} \\ \dfrac{dV_{output}}{dt} = -\dfrac{1}{C} i_L - \dfrac{1}{RC} V_{output} \end{cases} \tag{2}$$

The choice of the state vector $x = \begin{bmatrix} x_I \\ x_{II} \end{bmatrix} = \begin{bmatrix} i_L \\ V_{output} \end{bmatrix}$ allows state space representation for mode -I- by

$$\begin{cases} \dot{x}_I = A_I \cdot x + B_I \cdot u \\ V_{output} = C_I \cdot x \end{cases} \tag{3}$$

where $A_I = \begin{bmatrix} 0 & 0 \\ 0 & -\dfrac{1}{RC} \end{bmatrix}$, $B_I = \begin{bmatrix} \dfrac{1}{L} \\ 0 \end{bmatrix}$, $C_I = [0 \quad 1]$, and $u = V_{input}$.

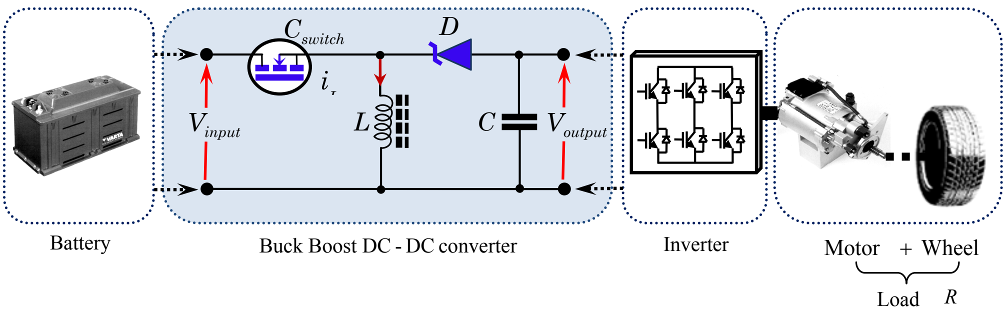

Fig. 1. Studied buck-boost converter structure for the electric vehicle drive.

Additionally, the state space representation for mode -II- is given by

$$\begin{cases} \dot{x}_{II} = A_{II} \cdot x + B_{II} \cdot u \\ V_{output} = C_{II} \cdot x \end{cases} \tag{4}$$

where

$A_{II} = \begin{bmatrix} 0 & \frac{1}{L} \\ -\frac{1}{C} & -\frac{1}{RC} \end{bmatrix}$, $B_{II} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$, $C_{II} = \begin{bmatrix} 0 & 1 \end{bmatrix}$, and $u = V_{input}$.

The state space averaging method replaces the state equations by a single state space description, which represents approximately the behavior of the circuit across the whole period. From the state space representation of mode -I- (ON mode) and mode -II- (OFF mode) described in (3) and (4), the average state space representation of the buck-boost converter system is obtained and represented by the following equations:

$$\begin{cases} \dot{x} = \left[d \cdot A_I + (1-d)A_{II}\right]x + \left[d \cdot B_I + (1-d)B_{II}\right]V_{input} \\ V_{output} = \left[d \cdot C_I + (1-d)C_{II}\right]x \end{cases} \tag{5}$$

where the switcher state $d = \begin{cases} 1 & in\ ON\ state \\ 0 & in\ OFF\ state \end{cases}$

$$\begin{cases} \dot{x} = \begin{bmatrix} 0 & \frac{1-d}{L} \\ -\frac{1-d}{C} & -\frac{1}{RC} \end{bmatrix} x + \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix} V_{input} \\ V_{output} = \begin{bmatrix} 0 & 1 \end{bmatrix} x \end{cases} \tag{6}$$

3. Sliding Mode Control Design

Sliding mode is a phenomenon that may appear in a dynamic system governed by ordinary differential equations with discontinuous right-hand sides. It may happen when the control, as a function of the system state, switches at high frequency. This motion is called a sliding mode [22]-[24].

SMC is a nonlinear control approach, which complies with the nonlinear characteristic of buck-boost converters. Such control technique is robust even against plant parametric variations and can compensate for modeling approximations. In addition, it is characterized by a good dynamic response. Moreover, SMC is simple to implement [25], [26].

The first step in designing a sliding mode control is determining the sliding surface with the desired dynamics of the corresponding sliding motion. As an example, let us consider the following sliding surface S:

$$S = K_1\left(i_L - i_L^*\right) + K_2\left(V_{output} - V_{output}^*\right) \tag{7}$$

where K_1 and K_2 are the sliding coefficients, V^*_{output} is the desired output voltage, and i^*_L is the desired output current.

From Equation (6), it can be deduced that at the stability point, the reference inductor current i^*_L can be written as follows:

$$i_L^* = -\frac{V_{output}^*}{R}\frac{\left(V_{output}^* - V_{input}\right)}{V_{input}} \tag{8}$$

The sliding mode control signal d consists of two components, a nonlinear component d_n and an equivalent component d_{eq}:

$$d = d_{eq} + d_n \tag{9}$$

The equivalent control can be obtained when $S = \dot{S} = 0$. It is expressed as follows:

$$d_{eq} = \frac{K_1RCV_{output} + K_2LRi_L + K_2LV_{output}}{K_2LRi_L + K_1RC\left(V_{input} - V_{output}\right)} \tag{10}$$

The next step is designing the control input so that the state trajectories are driven and attracted toward the sliding surface, and then remain sliding on it for all subsequent time. Let us consider the positive definite Lyapunov function P defined as follows:

$$P = \frac{1}{2}S^2 \tag{11}$$

The time derivative $\dot{P}$ of P must be negative definite $\dot{P} < 0$ to ensure system stability and make the surface S attractive. Such condition leads to the following inequality:

$$\dot{P} = S \cdot \dot{S} < 0 \tag{12}$$

To satisfy the condition given by Inequality (12), the nonlinear control component is defined as follows:

$$d_n = K_3 \cdot sign(S) \tag{13}$$

where K_3 is negative, and K_1 and K_2 are chosen to be positive. The establishment of these parameters are stated in [27]. However, the major drawback of SMC is the chattering phenomenon, which is a consequence of the discontinuity of the nonlinear component. To overcome the disadvantage of the sliding mode control, FSMS is proposed in the next section.

4. Fuzzy Sliding Mode Strategy Design

The combination of SMC with the fuzzy logic control aims to improve the robustness and the performance of controlled nonlinear systems [13], [15], [16], [22]. The proposed FSMS buck-boost DC-DC converter control strategy scheme for the electric vehicle propulsion system is given in Fig. 2.

Let us consider the sliding surface defined by Equation (7). The proposed fuzzy sliding mode controller forces the derivative of the Lyapunov function to be negative definite. Thus, the rule base table is established to satisfy Inequality (12).

Intuitively, suppose that $S > 0$ and $\dot{S} > 0$, the duty cycle must increase; if $S < 0$ and $\dot{S} < 0$, the duty cycle must decrease. Thus, the surface S and its variation $\dot{S}$ are the inputs of the proposed controller. The output signal is the control increment $\Delta U(k)$, which is used to update the control law. The control signal is defined as follows:

$$U(k) = \Delta U(k) + U(k-1) \tag{14}$$

The proposed fuzzy sliding mode controller is a zero-order Sugeno fuzzy controller, which is a special case of the Mamdani fuzzy inference system. Only the antecedent part of the Sugeno controller has the "fuzziness" and the consequent part is a crisp function. In the Sugeno fuzzy controller, the output is obtained through the weighted average of consequents [17], [18], [28].

Trapezoidal and triangular membership functions denoted by N (negative), Z (zero), and P (positive) are used for both the surface and surface changes. They are presented in Figs. 3 and 4 in the normalized domain. For the output signals, five normalized singletons denoted by NB (negative big), NM (negative middle), Z (zero), PM (positive middle), and PB (positive big) are used for the output signal (Fig. 5). The surface plot presentation relationship between the input and output parameters of the rule table given in Table 1 is visualized in Fig. 6.

Fig. 7 illustrates the block diagram of an FSMS buck-boost DC-DC converter control for electric vehicles.

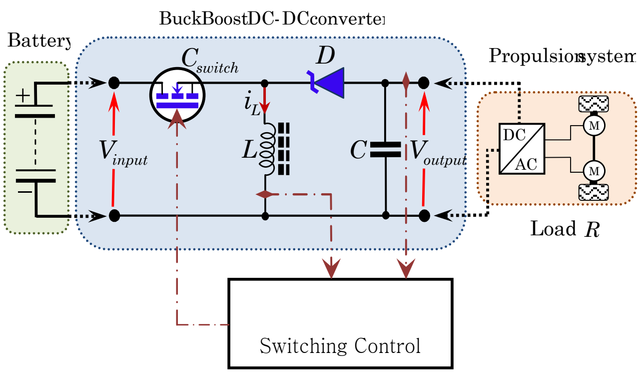

Fig. 2. FSMS buck-boost DC-DC converter control strategy scheme.

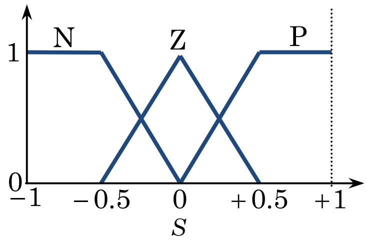

Fig. 3. Surface S membership functions.

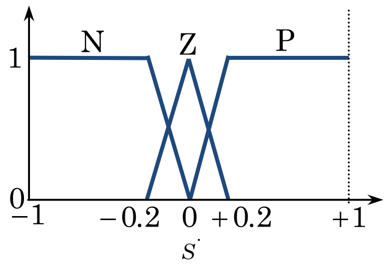

Fig. 4. Surface change $\dot{S}$ membership functions.

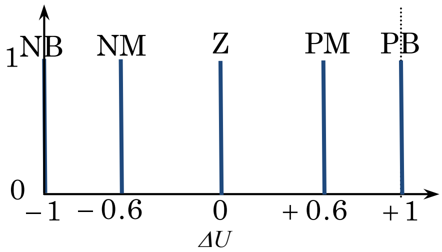

Fig. 5. Output singletons ΔU membership functions.

Table 1. Proposed FSMS Rules Base

ΔU		S		
		P	**Z**	**N**
$\dot{S}$	**P**	PB	PM	Z
	Z	PM	Z	NM
	N	Z	NM	NB

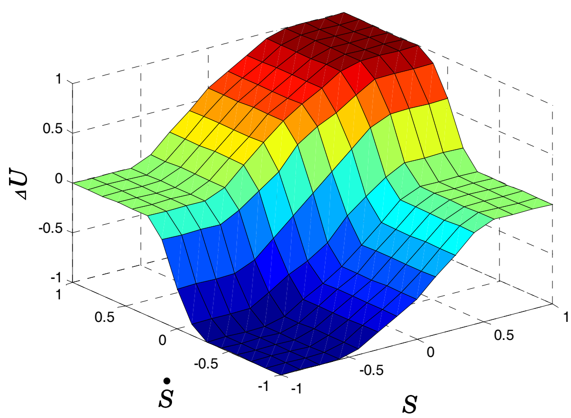

Fig. 6. Surface plot showing the relationship between the input and output parameters.

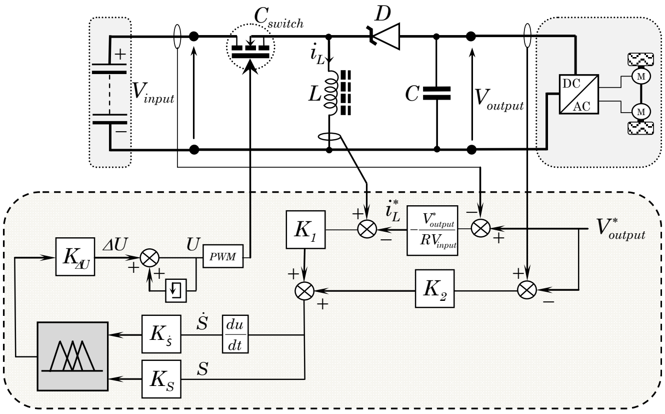

Fig. 7. Block diagram of an FSMS buck-boost DC-DC converter control for electric vehicles.

5. Simulation Results

The buck-boost DC-DC converter is designed for an input voltage of 10-72 V and an output voltage of 10-600 V to supply a 3.5 kW, 300 V load. The electrical parameters of the simulated buck-boost converter are as follows: C = 10 mF, L = 0.69 mH, resistance loss = 0.07 Ω.

The simulated results identified by Figs. 8a and 8b show the open loop of the output voltage and load current responses, respectively.

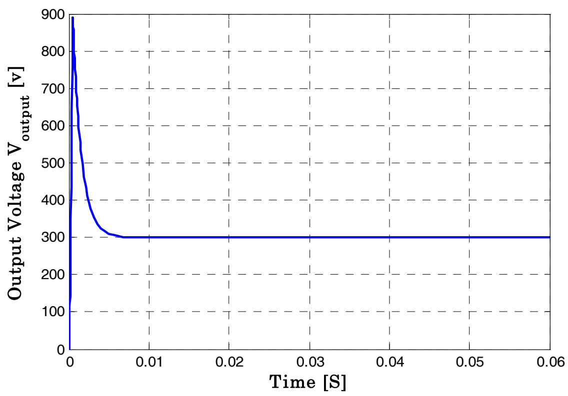

Fig. 8a. Output voltage and load current open-loop responses.

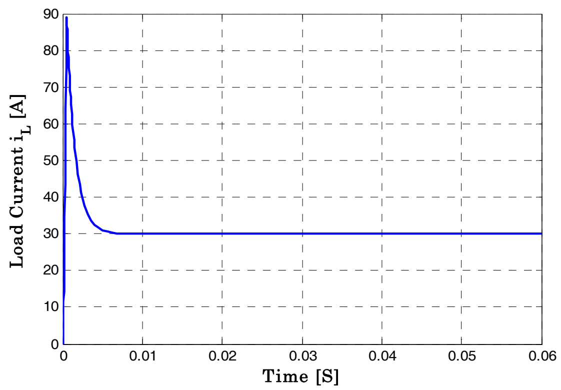

Fig. 8b. Output voltage and load current open-loop responses.

The classical SMC solution, described above, is compared to the proposed FSMS law and the proportional integral (PI) controller. Fig. 9 gives the simulated step responses of the studied buck-boost converter for a settling voltage of 300 V when the input voltage is 48 V. Fig. 10 proves that the two controllers can also regulate the load current at any desired value.

From the two figures, the dynamic behavior of the transient state of responses for the voltage and the current obtained by FSMS differ. The advantage of this control is its robustness, its capacity to maintain ideal reference trajectories for output voltage buck-boost DC-DC converter control, its assurance of good disturbance rejections with no overshooting, its DC-DC converter stability ensured with output voltage variations, and its less error output voltage.

The simulated results, shown in Figs. 11 and 12, prove that the chattering phenomenon is reduced from the output voltage response and the load current of the buck-boost DC-DC converter using FSMS. Moreover, the next simulations test the robustness of FSMS in the case of load current and input voltage variations. Fig. 13 presents current variations from 30 A to 45 A at 0.02 s. As shown in Fig. 14, FSMS rejects such perturbation.

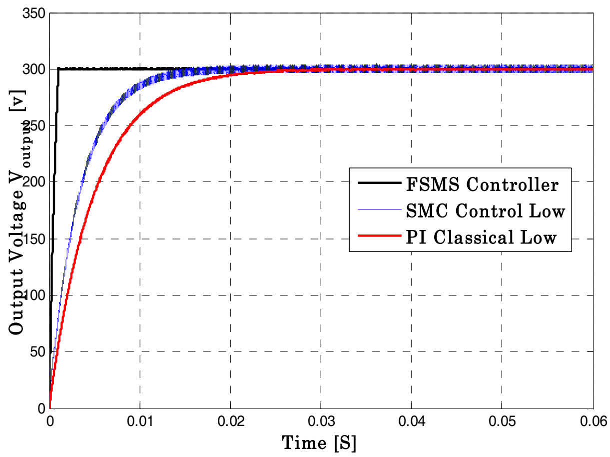

Fig. 9. Step voltage responses of the buck-boost DC-DC converter using SMC, FSMS, and PI controller.

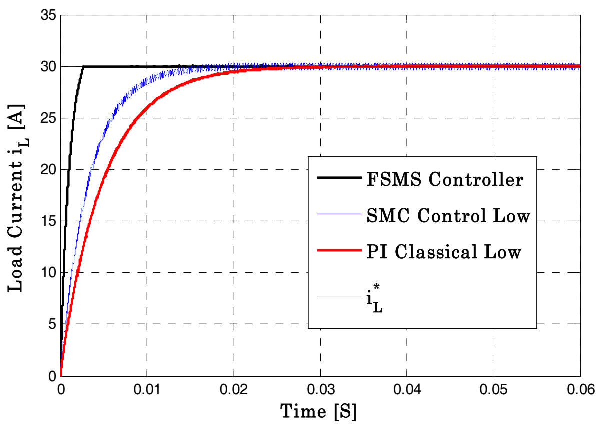

Fig. 10. Step current responses of the buck-boost converter using SMC, FSMS, and PI controller.

From Figs. 15 to 23, the buck-boost DC-DC converter is tested by varying the input voltage (varying the battery charge state). Fig. 15 illustrates variations in input voltage from 48 V to 35 V at 0.02 s. In this case, the output voltage is always at the desired value (300 V) and the converter works as a boost.

In Fig. 18, the input voltage varies from 61 V to 48 V at 0.02 s. Fig. 19 proves that the output voltage still remains

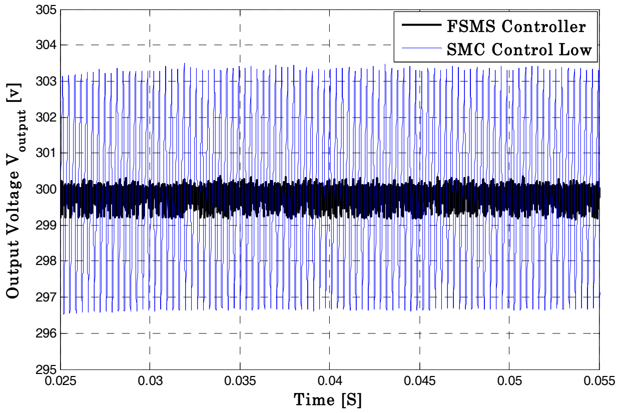

Fig. 11. Chattering phenomenon reduction from the output voltage response.

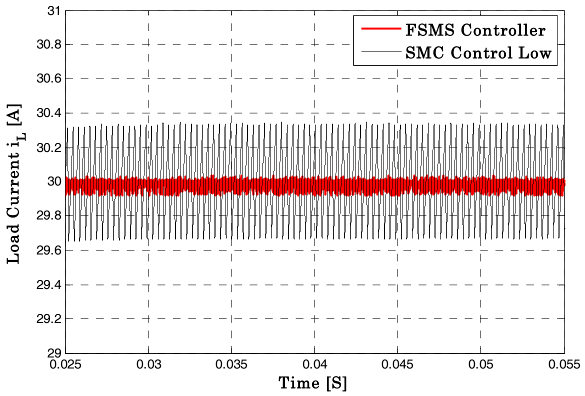

Fig.12. Chattering phenomenon reduction from the load current response.

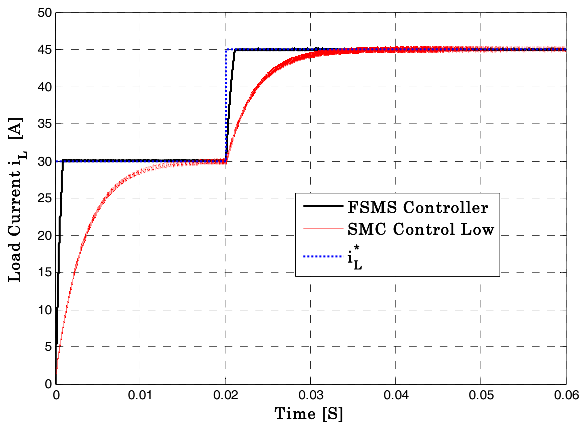

Fig. 13. Variations in load current from 30 A to 45 A.

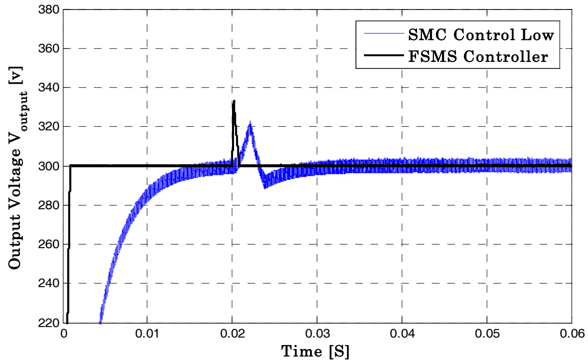

Fig. 14. Robustness test of FSMS for variations in load currents from 30 A to 45 A.

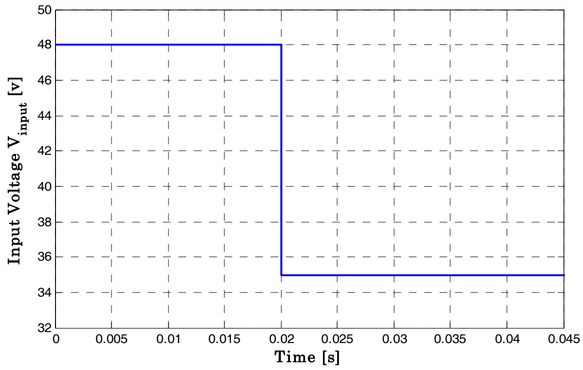

Fig. 15. Evolution of the input voltage from 48 V to 35 V.

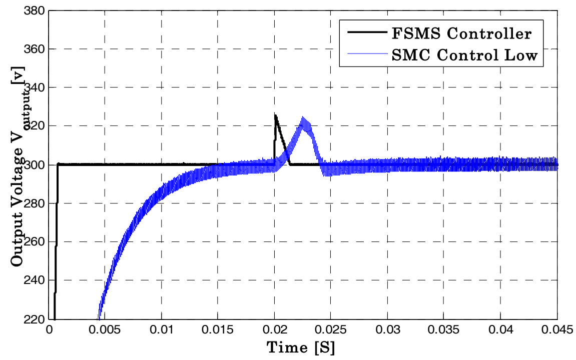

Fig. 16. Robustness test of FSMS for variations in input voltage from 48 V to 35 V.

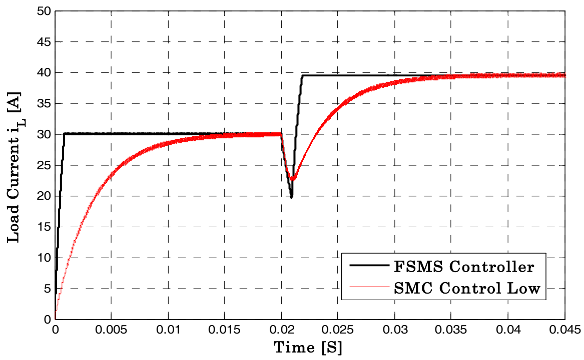

Fig. 17. Evolution of the load current when the input voltage changes from 48 V to 35 V.

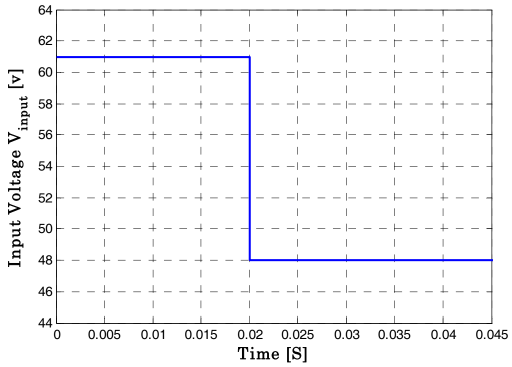

Fig. 18. Evolution of the input voltage from 61 V to 48 V.

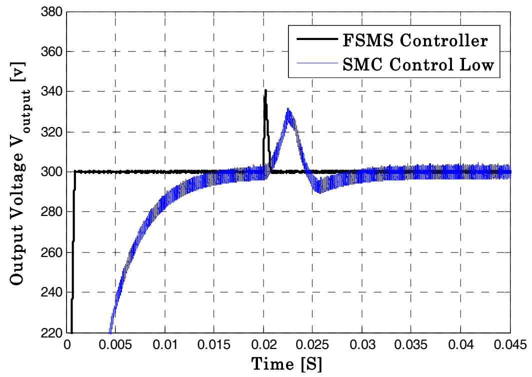

Fig. 19. Robustness test of FSMS for variations in input voltage from 61 V to 48 V.

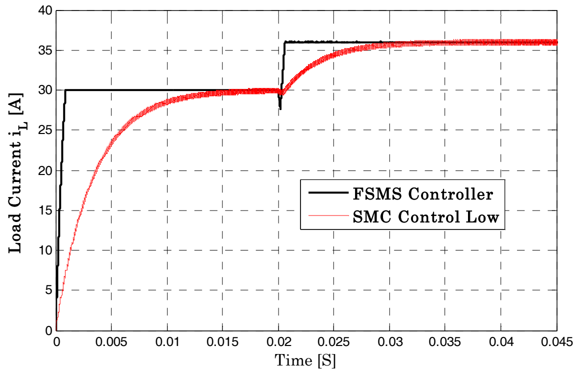

Fig. 20. Evolution of the load current when the input voltage changes from 61 V to 48 V.

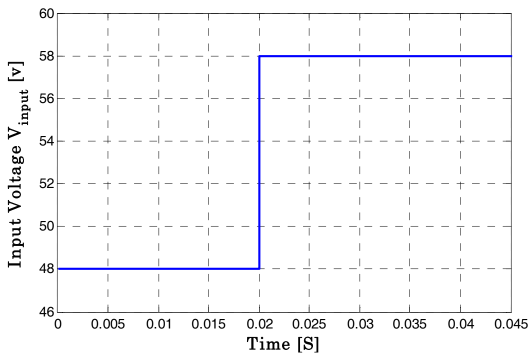

Fig. 21. Evolution of the input voltage from 48 V to 58 V.

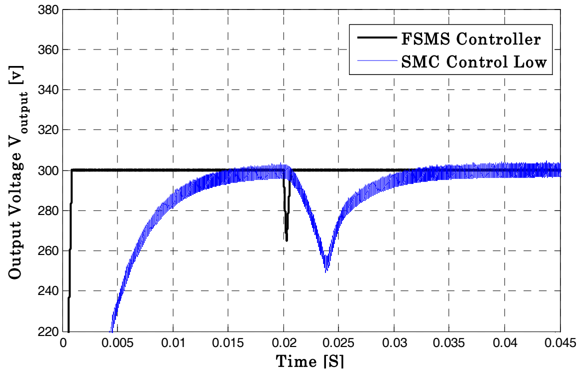

Fig. 22. Robustness test of FSMS for variations in input voltage from 48 V to 58 V.

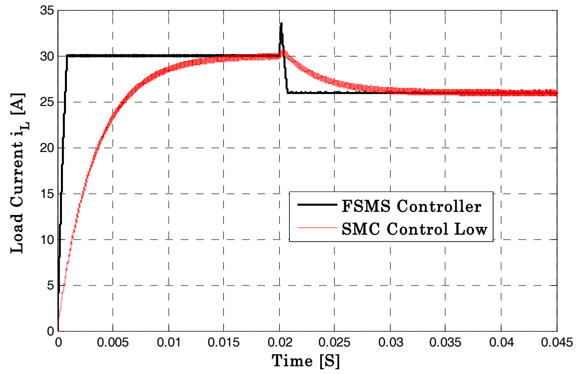

Fig. 23. Evolution of the load current when the input voltage changes from 48 V to 58 V.

at the same desired value (300 V). For this simulation, the converter working mode changes from buck to boost. Fig. 22 presents the robustness test results using FSMS for variations in input voltage from 48 V to 58 V at 0.02 s, in which the converter working mode changes from boost to buck.

6. Conclusion

This study demonstrates the robustness and the dynamic performance of the electric vehicle buck-boost DC-DC converter using FSMS. In the present study, FSMS is proposed to improve control robustness. The proposed fuzzy logic controller has a sliding surface and its variations as inputs. It also defines the control signal to satisfy the stability and the attraction condition of the sliding surface. The proposed FSMS simulation results show that the proposed controller overcomes the chattering problem. Moreover, the proposed controller is robust in case of variations in the desired output current caused by propulsion system load variations in the electric vehicle and input voltage variations caused by charge/discharge battery effects. The disturbances do not affect the performance of the buck-boost DC-DC converter output voltage. Thus, the control strategy results in the good dynamic characteristics of the electric vehicle propulsion system load.

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Boumediène ALLAOUA received his diploma in Electrical Engineering from Bechar University, Algeria. He took his master’s degree from the same university and his PhD from the Faculty of Sciences and Technology, Bechar University. Currently, he teaches electrical engineering at Bechar University. His research interests include power electronics robust control for electric vehicles and propulsion systems, power electronics development, electric drives robust control, modern control techniques, and artificial intelligence and its applications.

Abdellah LAOUFI received his state engineer degree in Electrical Engineering from the University of Sciences and Technology of Oran (USTO), Algeria. He took his MSc and PhD from the Electrical Engineering Institute of the University of Djillali Liabes, Algeria. He is currently a professor of electrical engineering at Bechar University.
His research interests include power electronics, electric drives control, and electric vehicle propulsion system control and its applications.