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Fuzzy sliding mode control for multilevel DC/DC converters in hybrid energy storage systems for EVs

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***Abstract*—Bidirectional DC/DC power converters are critical for managing energy flow within electric vehicles, ensuring coordination between, the energy storage system, the grid, and the high_voltage DC link. To achieve uniform load current distribution among multiple converter modules, a fuzzy sliding mode control technique is proposed. This control strategy is validated through simulations involving four interleaved DC/DC boost converters operating in parallel. The results confirm the effectiveness and robustness of the proposed method under various disturbance scenarios.**

Keywords— Electrical vehicle; control; robustness; DC-DC converter; Hybridization

I. INTRODUCTION

The limited energy efficiency of traditional utility vehicles, combined with ongoing global energy challenges, has fostered a favorable environment for the advancement of electric vehicles (EVs). EVs offer numerous advantages, particularly in reducing greenhouse gas emissions, minimizing environmental impact, and contributing to the resolution of worldwide energy concerns [1]. In response to the growing demand for sustainable transportation solutions, the scalability and widespread integration of EVs are closely tied to the development and deployment of advanced, high-performance energy storage systems capable of handling variable load conditions while maintaining consistent system efficiency and reliability [2].

Despite these advancements, the various components within an EV's powertrain require significant power, and subjecting the battery to frequent and rapid power fluctuations can degrade its performance and shorten its lifespan [3]. One effective approach to mitigate these issues is the integration of an auxiliary energy source designed to meet peak power demands when needed [4]. This method, referred to as source hybridization, involves combining two complementary energy sources within a single system to maximize overall performance.

To improve battery durability, extend the vehicle's range during startup, reduce battery stress during acceleration, and support regenerative braking, this study proposes the integration of a supercapacitor (SC) alongside the main traction battery [4]. The SC is interfaced with the DC bus through DC/DC converters to enable precise and efficient energy flow management.

In recent years, interleaved converter topologies have become increasingly popular in high-current DC/DC converter applications due to their ability to reduce total current ripple and improve thermal distribution. To further enhance power density in EV systems, this work presents an interleaved multiphase bidirectional DC/DC converter architecture [5]. Specifically, a four-phase interleaved converter is designed and controlled using a Fuzzy Sliding Mode Control strategy. The effectiveness and robustness of the proposed control approach are validated through simulations under predefined disturbance conditions [6–7].

II. HYBRIDIZATION OF TWO SOURCES BATTERY/SUPERCAPACITOR IN AN ELECTRIC VEHICLE

In an electric vehicle, to preserve the vehicle's battery, increase its range when starting, and relieve it during acceleration and braking. A supercapacitor (SC) is installed in parallel with the battery, as shown in figure 1. with the new fast-charging batteries, supercapacitors are economical, robust and non-polluting devices used to :

- extend battery life across the entire range of HEVs,
- relieve the load on batteries during power peaks for 100% electric vehicles.

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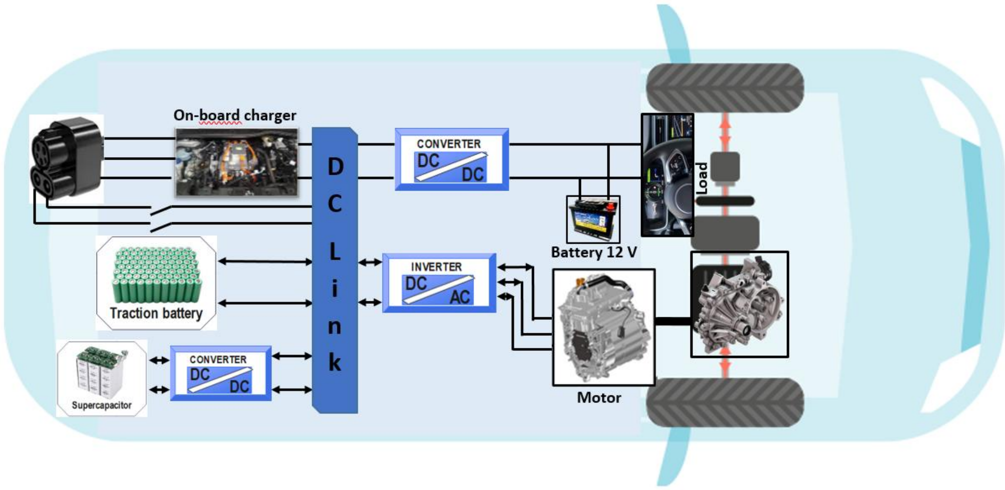

Figure 1. Schematic diagram of a hybrid electrical energy storage system with battery and supercapacitor

III. POWER CONVERTERS FOR ELECTRIC VEHICLES

As electric vehicle components require different voltage levels (high or low), DC/DC converters are used to maintain the voltage value for these components.

A. The benefits of paralleling converters for electric vehicles

In automotive applications such as EVs, energy losses in the conditioning converter (DC/DC converter) are more significant the further apart the source and DC bus voltage levels are.

Figure 2 shows the structure of a multiphase bidirectional DC/DC converter. The converter consists of 2N controlled switches (SW_{11}...SW_{N1} and SW_{12} ... SW_{N2}), 2N diodes (D_{11} ...D_{N1} and D_{12} ... D_{N2}), N inductors (L_1 , L_2 ... L_N) with their associated equivalent series resistors (r_1, r_2... r_N), as well as input and output filter capacitors.

The multiphase converter's structure distributes current across multiple elementary cells, reducing the current handled by each individual cell. This structure primarily minimizes current ripple while also reducing the converter's overall weight and volume. The individual converter is identical and the current through each converter is:

$$i_{Ln} = \frac{i_L}{q} \tag{1}$$

The current waveform in each phase presents a triangular ripple component, quantified by:

$$\Delta i_{Ln} = \frac{V_{sc}}{L}(1-d)d.\,T_s \tag{2}$$

Output current ripple is expressed by :

$$\Delta i_0 = \frac{V_0}{L}(1-Nd)dT_s \tag{3}$$

Figure (3) shows the characteristic of the current ripple as a function of duty cycle. It becomes zero for d/N, where :

- d is the duty cycle
- N is the number of phases in DC/DC converter.

For a four-phase interleaved DC/DC converter, the relative ripple of the input current cancels out for a cycle d ratio equal to 1/4, 2/4, 3/4 and 1.

Figure 3 shows that current ripple is reduced by increasing the number of cells in the bidirectional DC/DC converter.

In this paper, we have proposed an interleaved DC-DC boost converter with four parallel branches, as shown in figure 2.

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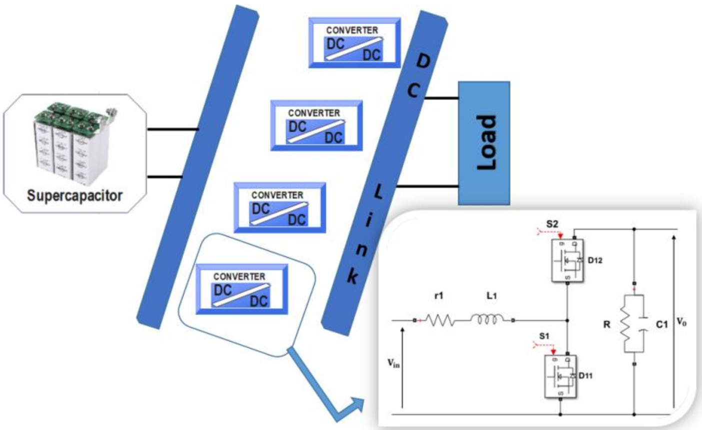

Figure 2. Structure of a bidirectional multiphase DC-DC converter

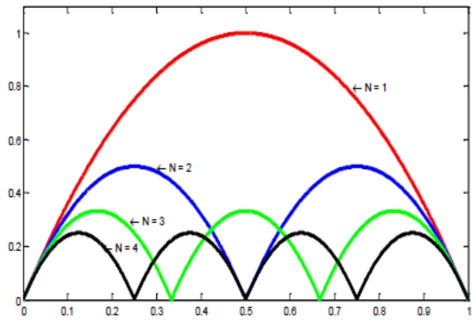

Figure 3. Current ripple [8]

B. Model of multiphase DC-DC converter

In this paper, four converters are associated in parallel, and the system of differential equations governing the operation of the system composed of these four converters is defined:

$$\begin{cases} \frac{di_{L_1}}{dt} = \frac{1}{L_1}\left(V_{in} - r_1 i_{L_1} - (1-d_1)V_0\right) \\ \frac{di_{L_2}}{dt} = \frac{1}{L_2}\left(V_{in} - r_2 i_{L_2} - (1-d_2)V_0\right) \\ \frac{di_{L_3}}{dt} = \frac{1}{L_3}\left(V_{in} - r_3 i_{L_3} - (1-d_3)V_0\right) \\ \frac{di_{L_4}}{dt} = \frac{1}{L_4}\left(V_{in} - r_4 i_{L_4} - (1-d_4)V_0\right) \\ \frac{dv_0}{dt} = \frac{1}{C_{eq}}\left((1-d_1)i_{L_1} + (1-d_2)i_{L_2} + (1-d_3)i_{L_3} + (1-d_4)i_{L_4}\right) - \frac{1}{RC_{eq}}V_0 \end{cases} \tag{4}$$

Hence the following matrix representation:

$$\begin{cases} \dot{x} = \begin{bmatrix} \dot{i}_{L_1} \\ \dot{i}_{L_2} \\ \dot{i}_{L_3} \\ \dot{i}_{L_4} \\ \dot{V}_0 \end{bmatrix} = A \begin{bmatrix} i_{L1} \\ i_{L2} \\ i_{L3} \\ i_{L4} \\ V_0 \end{bmatrix} + BU \\ v_0 = Cx \end{cases} \tag{5}$$

$$\text{where } x = \begin{bmatrix} i_{L1} \\ i_{L2} \\ i_{L3} \\ i_{L4} \\ V_0 \end{bmatrix};\quad A = \begin{bmatrix} -\frac{r_1}{L_1} & 0 & 0 & 0 & -\frac{1-d_1}{L_1} \\ 0 & -\frac{r_2}{L_2} & 0 & 0 & -\frac{1-d_2}{L_2} \\ 0 & 0 & -\frac{r_3}{L_3} & 0 & -\frac{1-d_3}{L_3} \\ 0 & 0 & 0 & -\frac{r_4}{L_4} & -\frac{1-d_4}{L_4} \\ \frac{1-d_1}{C_{eq}} & \frac{1-d_1}{C_{eq}} & \frac{1-d_1}{C_{eq}} & 0 & -\frac{1}{RC_{eq}} \end{bmatrix};\ B = \begin{bmatrix} \frac{1}{L_1} \\ \frac{1}{L_2} \\ \frac{1}{L_3} \\ \frac{1}{L_4} \\ V_0 \end{bmatrix},\ C = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

IV. Fuzzy sliding-mode control of the DC/DC converters examined

To increase and regulate the supercapacitor voltage from low to high voltage, a fuzzy sliding-mode control is proposed for the control of multiphase bidirectional interleaved DC-DC converters. This control method improves the performance of the high side voltage and ensures that the load current is evenly distributed between each converter module.

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In this paper, we propose a contribution to the control of parallel multi-cell Boost converters: an unconventional fuzzy sliding mode (FSM) control.

The proposed approach is based on the fuzzification of the sliding surface and its variation. The parallel multicell converter structure under study is composed of four Boost converters, figure 2.

For the fuzzy sliding mode controller, we propose the sliding surface represented by equation:

$$S_j = k_j e_{i_j} - \lambda e_v \qquad (6)$$

where k_j and λ are coefficients used for the sliding surface, j = 1,2,3,4.

e_v denotes the voltage error for the bidirectional DC/DC converter described as follows:

$$e_v = V_{ref} - v_0 \qquad (7)$$

V_{ref} and v_0 x and y are the reference voltage and output voltage, respectively, of the converter being studied.

$$e_{i_j} = I_{ref} - i_{L_j} \qquad (8)$$

where e_{i_j} denotes the current error of inductance L_j in the jth cell of the multiphase bidirectional interleaved DC/DC converter.

So, for the four converters, we have the following four surfaces:

$$\begin{cases} S_1 = k_1 e_{i_1} + \lambda e_v = k_1\left(I_{ref} - i_{L_1}\right) + \lambda(V_{ref} - v_0) \\ S_2 = k_2 e_{i_2} + \lambda e_v = k_2\left(I_{ref} - i_{L_2}\right) + \lambda(V_{ref} - v_0) \\ S_3 = k_3 e_{i_3} + \lambda e_v = k_3\left(I_{ref} - i_{L_3}\right) + \lambda(V_{ref} - v_0) \\ S_4 = k_4 e_{i_4} + \lambda e_v = k_4\left(I_{ref} - i_{L_4}\right) + \lambda(V_{ref} - v_0) \end{cases} \qquad (9)$$

We will then consider the Lyapunov function V_j defined as follows:

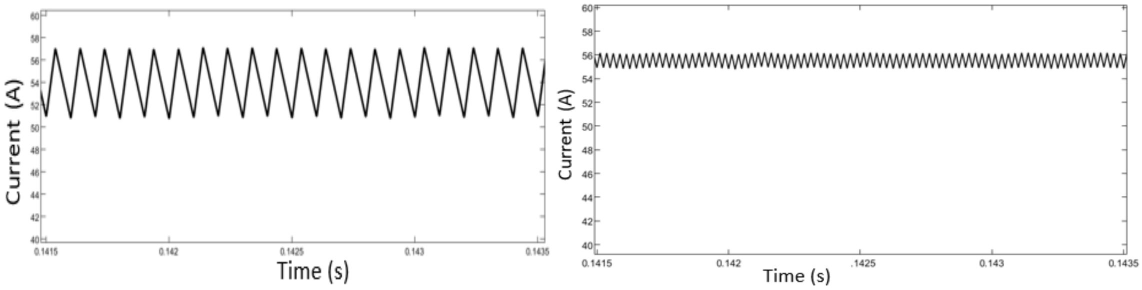
$$V_j = \frac{1}{2} S_j^2 \qquad (10)$$

The proposed fuzzy sliding mode control forces the derivative of the Lyapunov function to be negative definite. As a result, the rule base is set to satisfy the inequality $S_j \dot{S}_j < 0$ for each j=1, 2,3,4. The surface S_j and its derivative $\dot{S}_j$ are taken as the inputs to the fuzzy controller, the controller output being the control increment $\Delta U(k)$, used to adjust the duty cycle value according to equation (11).

$$U(k) = \Delta U(k) + U(k-1), \; j = 1,2,3,4 \qquad (11)$$

V. SIMULATIONS RESULTS

Figure 4 shows the variation of current in an inductor.



a. single-cell case b. case of 4 cells

Figure 4. Current variation in inductance L

Figure 5 shows the output voltage response for a reference voltage of 400V with the fuzzy sliding-mode controller designed in this way.

We note that the output voltage shows an overshoot of the order of 20%. This overshoot has been mitigated in the case of the fuzzy sliding mode controller applied to the multi-cell converter.

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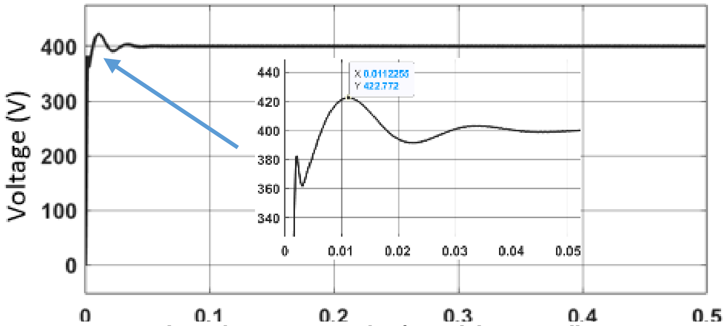

Figure 5. Voltage characteristics with a fuzzy sliding controller

To test the robustness of the proposed fuzzy sliding mode controller, we varied the system parameters, i.e. load and input voltage. Figure 6 shows the converter output voltage when the input voltage changes from 270V to 250V at t = 0.464s.

In the event of a change in input voltage (drop in voltage at the SC output), we note that the regulator attenuates the disturbance introduced. The results obtained show that the proposed controller can compensate for variations in input voltage and load. The proposed method exhibited robust performance under targeted disturbances

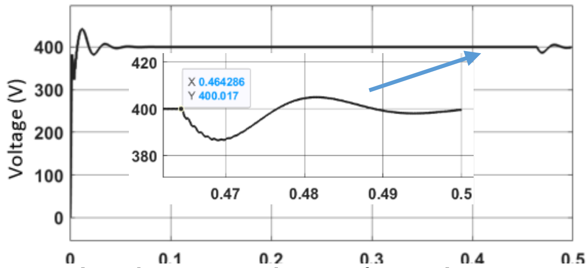

Figure 6. Voltage characteristic in the event of input voltage variation

VI. Conclusion

With the advent of fast-charging batteries, supercapacitors (SCs) have emerged as cost-effective, durable, and eco-friendly energy storage devices. To efficiently step up and regulate the voltage of supercapacitors from low to high levels, a fuzzy sliding mode control strategy has been applied to multiphase interleaved bidirectional DC-DC converters. This approach has enhanced the performance of the high-voltage side while ensuring balanced load current distribution across all converter modules.

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