



Charging of Supercapacitor Banks Using a Four Switch Buck-Boost Converter: A Literature Review

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Abstract—Supercapacitor systems are gaining more and more usage in transport, renewable energy and pulsed power applications because of their high-power density and long cycle life. One major issue with uncharged supercapacitors directly connected to a high-voltage D.C. Supply is the high inrush current and increased component stress. This paper presents a literature review of pre-charging control strategy for a four-switch buck-boost (FSBB) converter supplying a high-voltage supercapacitor stack. Unlike conventional design approaches that focus on steady-state ripple constraints and hardware-oriented component sizing, the proposed framework explicitly exploits time-scale separation between switching dynamics, inductor current evolution, and supercapacitor energy storage. A reduced-order energy-based model is derived to show that the pre-charging process can be governed by a quasi-linear voltage evolution independent of switching ripple.

Using this knowledge, a state-machine based control algorithm is presented, which is able to transition seamlessly between the buck and buck-boost states and keeps the charging current constant over the entire range of the output voltage. Implementation details are given to generate the PWM and duty saturation limits, while simulations confirmed that a continuous and linear constant current charging with smooth supercapacitor voltage increasing is achieved, with a continuous transition. A simple and physical intuitive algorithm for high voltage supercapacitor pre-charging.

Keywords— Constant-Current (CC) Control, Duty-Ratio, Energy-Based Modelling, Four-Switch Buck-Boost Converter (FSBB), and Supercapacitor (SC)



I. INTRODUCTION

The need for energy storage solutions, especially with a stronger presence of electrified transport systems, renewable energy interfaces, and high-power pulsed loads, has heightened. At the same time, supercapacitors have emerged as an attractive solution among the range of energy storage solutions. Despite advantages like high-power density, long cycle life, and enhanced charge/discharge efficiency, a major operating complication has been posed during the supercapacitor banks' incorporation into a high-voltage DC system: the charging process.

A notable distinction in comparison with batteries is that supercapacitors have an extremely low internal resistance and behave like an ideal capacitive load during the charging period. If an uncharged supercapacitor bank is directly connected to a stiff DC voltage supply, an extremely high inrush current can flow, resulting in electrical stress on semiconductor devices and DC voltage supply sources. It is therefore emphatically necessary to have a controlled pre-charging process for practical supercapacitor-based systems. Among different possible pre-charging methods, it is generally agreed upon that the constant current method is more effective.

Among the topologies, one of the most attractive options for a high-voltage operating regime is the Four Switch Buck-Boost Converter, mainly because it constitutes a unifying hardware structure for seamless operation at both Buck and Boost conditions.

Even though the FSBB converter topology is highly flexible, controlling the FSBB converter for a supercapacitor charging application has its own set of difficulties. While operating during the pre-charging transient, the FSBB converter crosses a wide range of operating points as the voltage level is increasing for the supercapacitor. Conventional converter analysis techniques, which are based on quasi-linear small-signal models, are not sufficient for energy-dominated systems.

A further complication arises from the fact that the dominant dynamics of the charging process are governed not by the switching frequency or output filter characteristics, but by the energy storage capability of the supercapacitor itself. When the supercapacitor capacitance is large relative to intermediate filter components, the system exhibits

strong time-scale separation: switching dynamics occur on the order of microseconds, inductor current dynamics evolve over milliseconds to seconds, and supercapacitor voltage changes unfold over hundreds of milliseconds or longer.

Motivated by these considerations, this paper presents a constant-current charging strategy for supercapacitor banks using a four-switch buck-boost converter, with a primary focus on energy-dominant transient behaviour and implementation-oriented control design. Rather than treating the pre-charging process as a sequence of steady-state operating points, the proposed approach explicitly recognizes that the supercapacitor voltage evolution is governed by a simple energy balance relationship when appropriate time-scale separation is enforced.

Furthering the development of this idea, a framework for state machine-based control is proposed to regulate the operating regimes of the FSBB converter over the entire charging period. This proposed controller will enable constant current charging to both low and high output voltages in a smooth and physically consistent manner while transitioning between buck and buck-boost operating regimes.

The main objectives of this study can be summarized as follows:

1. Development of a mathematical representation of the supercapacitor charging process by using FSBB converter and emphasizing the importance of time-scale separation.
2. To outline a constant current control charging technique with excellent control accuracy throughout a wide output voltage operating range and with smooth switching between buck and buck-boost modes of operation.
3. Develop a presentation of a state machine-driven duty ratio scheduling mechanism that mimics actual operating states of the switch-mode power converter and is easily implementable in discrete-time control regimes.
4. To further provide a detailed mathematical rationale for the determination of the inductance, intermediate capacitance, and supercapacitor parameter selections, closing the gap between the steady-state design equations and dynamic control requirements.



II. LITERATURE REVIEW

This article is imparting information on the importance of the FSBB Converter in modern power electronics systems, particularly in areas such as electric vehicles, renewable energy systems, and portable energy storage systems. It has been proved that this topology is crucial in certain areas of power electronics application, due to its remarkable characteristic of providing output voltage greater or less than the input while maintaining a positive polarity.

A. Control Strategies and Transition Smoothing

The biggest challenge with such an architectural setup of FSBB is the non-linear and unstable behaviour at the boundary between buck, boost, and buck-boost modes. Toward that end, various control techniques have been proposed for smooth operation in each mode. One such control technique that effectively reduces passive component sizes by providing continuous voltage conversion ratio is employing a dual duty ratio scheme using fixed and variable duty cycles for smooth voltages and hence suitable for supercapacitor pre-charger circuits [1]. In addition, QPCC techniques that facilitate smooth control with constant off-time are integrated into such circuits, thereby greatly reducing region selection logic complexity and providing advantages in terms of reduced inductor ripple currents for wide-range voltage operation [5].

Another technique that has been investigated to bypass the disadvantages of the traditional PI technique is Model Predictive Control (MPC). By using an optimal criterion to meet the condition of regulation and limit the flow of the currents, the MPC technique attains smooth transition and a maximum efficiency of 93.5% [9]. Similarly, the passivity-based control (PBC) technique, using the principle of damping injection, has been reported to regulate the output voltage without using complex mode detection.

B. Advanced Modulation and Soft Switching

Efficiency optimization, especially at fluctuating conditions, is still an area of primary research interest. While hard-switching control schemes for multi-mode control are easier to implement, they are associated with discontinuities due to dead zones caused during control. Similarly, soft-switching control methods like

Zero-Voltage Switching (ZVS) greatly reduce switching losses [2]. PWM PPS control with a single-carrier approach is proposed for easier implementation and to enhance ZVS performance during load fluctuations [6].

Further efficiency improvements are claimed in the form of Variable Frequency Quasi-Resonant Boundary Conduction Mode, which is said to attain peak efficiencies of up to 99.6% [7]. In the case of light loads, the use of multi-frequency pseudo-continuous conduction mode is applied to reduce circulation losses, achieving a reduction of 15% in losses compared to traditional methods [14].

C. Modelling, Optimization, and Analytical Frameworks

Precise modelling is essential for both control design and efficiency mapping. Traditional time-domain approximations are increasingly being replaced by frequency-domain analysis to minimize total power losses-conduction and switching analytically [8]. Other non-linear average models based on inductor energies have also been developed for representing the dynamics of FSBB under phase shift modulation [4].

The move to digital control has likewise been evaluated, with comparative modelling showing that dynamic responses can be better for mobile applications compared to analog controllers [11]. The ability of such software tools like Micro-Cap and PSIM has equally performed admirably, with the possibility of detailed analysis of electromagnetic processes performed without pre-linearization of the state space averaging process [10]. With regard to intelligent adaptation, the implementation of BP neural network controllers for auto-tuning of the PID controller parameters has seen reaching times much faster compared to conventional controllers [3].

D. Emerging Applications and Research Gaps

The integration of FSBB converters with supercapacitor technology is becoming an emerging trend. Although supercapacitors have good power density and life cycles, their lower density and voltage make them demand higher balancing and control solutions [13]. Apart from the progress made on soft-switching and transition smoothing, certain research gaps have been identified. There is a recorded need for unified multi-physics models that cover non-

linearity and thermal limitations, especially when it comes to high-voltage applications [2]. In addition, despite the effectiveness of most of these strategies in maintaining stability in the transitions, there are still other issues that have been identified, such as transitions dealing with extreme loads and/or the use of digital predictive solutions and thermal stability when dealing with phase-shifting at high frequencies [5,6,8]. Future research is expected to focus on collaborative optimization mechanisms and the application of these strategies in aviation power systems and smart-city sensor networks.

TABLE I
LITERATURE REVIEW OF DSM AND EV INTEGRATION

Authors	Methodology	Key Findings	Research Gap
Hyeon-Jun Kwon, Ku-Yong Kim, Jun-Ho Kim (2024)	New control scheme to a FSBB converter for a Super Capacitor Pre-Charger in H-EV.	It reduces ripple of voltage across the boundaries from conventional schemes.	Focus in robustness of the controller to different thermal environment, is missing.
Guanzhen Lin, Yan Li, Zhaoyun Zhang (2025)	FSBB converters with application of 400V/800 V systems.	Noted that the interaction optimization among multi-control aims are unsystematic	Forecasted that a more advanced EMI control method will be needed on the future platforms.
Luoyao Ren (2024)	Established a new adaptive PID control using an optimized BP neural network.	Under varying voltage reference and power disturbance (from 20% to 80%),	The computational cost on a low-cost microcontroller, is not taken into consideration
Ezio Gallo,	A non-linear	The energy-	Without a comprehensive

Davide Biadene, Filip Cvejić, Giorgio Spiazzi (2024)	average model and a linearized small-signal model were developed for the FSBB converters.	based mathematical models are very consistent with the results.	sive approach towards all extreme parasitic issues and complicated temperature dependencies of devices.
Quadrat Ullah, Xuanlyu Wu, Umar Saleem (2021)	Proposed a current-controlled robust FSBB DC-DC converter using half-bridge topology.	The current-controlled FSBB can solve the issues of computational burden.	The real prototypes is necessary for further work.
O.V. Vasylenko, G.V. Snizhnoi (2025)	Developed adaptive universal models for the FSBB converter in software simulation (using Micro-Cap, PSIM).	The adaptive models provided accurate and economic means of investigating operating regions using PWM control.	In the future there is a need for experimental verifications with different thermal patterns to check the applicability.
W. Vermeer, M. Wolleswinkel, J. Schijffelen Al. (2024)	Closed-loop control algorithms are developed and demonstrated on 10kW prototype.	So decided that QR-BCM has similar to better efficiency (up to 99.6%) compared to TCM.	The potential future work would be the effects of component tolerance, investigate more on



			magnetic core roll off.
Z. Hao, Y. Xu, J. Bai (2025)	Designed an optimal control algorithm based on the Whale Migration Optimization Algorithm for FSBB.	WMA shows faster convergence rate where the optimal solution was obtained.	Real-time hardware implementation of WMA is suggested to determine practical constraints and dynamic boundaries.
X. Li, Y. Liu, and Y. Xue (2021)	Derived a control strategy to enhance the output voltage transient responses.	Improvements over the classical PI-based control for a faster output voltage transient response and better tracking of the reference voltage.	In the paper very little theoretical description is provided regarding the stability limits of the used algebraic-differential equations.
A. Benlafkih, S. Krit, M. C. Elidrissi (2013)	Compared analog and digital controllers on FSBB converter to be used on mobile devices, using MATLAB/Simulink.	Showed that, digital controller performance in terms of transient response is better compared to analog controller.	Future research would need to address fabrication in an IC, analysis of real parasitics, thermal management and practical operation of the controller.

H. Komurcu, S. Bayhan, N. Guler, R. Guzman (2022)	It has presented a passivity-based control (PBC) methodology for FSBB DC-DC converter.	It controlled the inductor current and capacitor voltage stably and smoothly, reducing steady-state errors.	Future works must include sophisticated state observer to deal with unknown disturbance, and the high power system with the PBC scheme.
Z. Stevic, I. Radovanovic (2022)	Reviewed application of FSBB converter for PV systems and electric vehicle.	Supercapacitors contribute significantly to dynamic disturbance elimination, energy regeneration for EVs.	Further scope comprises the extensive researches to decrease the material cost, and to decrease the converter thermal loss.
S. Gao, F. Zhang, H. Mei (2024)	Presented an optimum control scheme of light load efficiency of FSBB converters.	This multi-frequency PCCM-ZVS control resulted in better efficiency.	2-D lookup table has the high memory requirement and difficulty in handling random dynamic load changes.
B. Ma, J. Jiao, Z. Ye (2024)	Adaptive Global Fast Integral Terminal Sliding Mode	ATSMC provided much better robust stability	The inherent chattering of sliding mode control in

	Control (ATSMC) for FSBB converter.	and convergence than the conventional approach.	hardware implementations is not taken into account.	Z. Ma, Q. Yu 2022	Developed control law of Boost converter by adaptive integral terminal sliding-mode control.	Drove the output voltage toward the designated trajectory with no steady-state error.	Future work could consist of Hardware-in-the-Loop simulation and implementation on a full-bridge.
Q. Ullah, T. D. C. Busarello, D. I. Brandao, M. G. Simões 2023	Designed and experimented the SMC (Sliding Mode Control)-based DC-DC converter system.	Regulation of voltage and current transition on step-up and step-down processes was successfully controlled with the help of SMC algorithm.	In future versions, a sliding surface with adaptation should be proposed to decrease the high frequency chattering and a physical test.	D. Zhang, Y. Gu, D. Zhang, X. Zhang, H. Li, A. Li 2024	Designed two efficient three mode control methods for the FSBB converter and gave theoretical analysis.	Both bias control methods decreased the dead-zone voltage mismatches and switching actions for the transition mode.	The proposed two-edge and interleaved bias controls are not easy to implement with low-cost digital signal processors.
Texas Instruments 2018	Included a technical application note and block diagram of a typical FSBB Converter design.	Outlined the necessary operating procedure for effective management of inductor current and feedback voltage.	This is an application note, so, advanced non-linear control optimization and total loss modelling are not covered rigorously.	K. Kitazoe, K. Natori, Y. Sato 2024	Investigated the use of FSBB converter as BPFC in DC power network.	The experimental waveform verified it has steady and smooth switching direction.	Does not address sophisticated fault tolerance and short-circuit protection for large scale DC grids.
F. Zhang, J. Li, G. Zhu, R. Hu, Y. Qu, Y. Zhang 2023	It presented a general Passivity-Based Control (PBC) strategy applied to the FSBB converter.	The PBC scheme improved the current overshoot 14.29% and the current ripples more than 50%.	The current design of the PBC doesn't treat the small signal and large signal disturbance equally.	O. Akin, Ç. Bilgin, S. Celik, M. O. Gülbahçe 2023	A design algorithm for an FSBB converter used in LEVs, which analyzes both cost and	Two optimized design sets were produced; a cost-constrained one and one with an efficiency constraint.	The next phase of development will be to build actual converters to test the database driven algorithm.

	efficiency was given.		
A. Malou, B. Allard, X. Lin-Shi, A. Hijazi, B. L. Men 2018	Performed mode transition between continuous conduction mode (CCM) and discontinuous conduction mode (DCM).	Suppressed instabilities and enlarged the stability limit, proving effective during transients.	The non-linear stability models need to be tested with wide band gap semiconductors operating at very high switching frequencies.
X. Ma, Q. Xu, Y. Jiao 2024	ZVS control strategy was presented for FSBB converters aimed at reducing the peak inductor current.	The simplified analytical algorithm minimized the inductor current RMS value and provided ZVS.	This work is focused only on analytical optimization and does not explain about dynamic transient.
L. Tian, H. Liu, Y. Zhang, X. Wu 2025	This paper is a small-signal model, reduced-order, developed for FSBB converter.	This lower-order model rendered the multi-variable FSBB control design significantly less complicated.	The small-signal model has been extremely linearized, and may not be able to account for very severe large-signal transients.

III. MATHEMATICAL MODELLING OF FSBB CONVERTER

The modelling is developed with a specific focus on transient energy transfer rather than steady-state ripple characteristics. The objective is to derive a

physically transparent representation that directly supports the proposed constant-current control strategy.

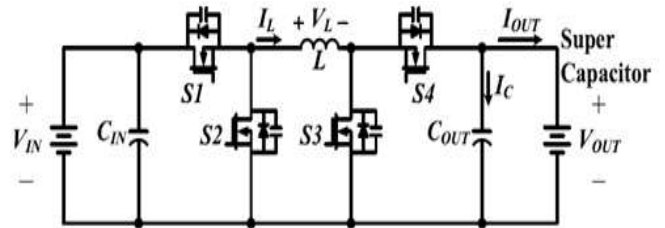


Fig. 1 FSBB converter-based supercapacitor charger

Fig. 1 illustrates the FSBB converter-based supercapacitor charger considered in this study. The converter comprises two half-bridge legs that are connected together through the common inductor LL , with the DC source $V_{in}V_{in}$ being filtered through the input capacitor $C_{in}C_{in}$. The output port of the converter is connected to an intermediate capacitor $C_{out}C_{out}$ and a supercapacitor bank modelled by an equivalent capacitance $C_{sc}C_{sc}$. The inductor LL , carrying current i_Li_L , works as the only energy transfer component between the input and output ports.

Four-switch buck-boost converter structure is composed of two half-bridge structures coupled in common with an inductor. The front-end structure connects to DC, while the rear-end structure connects to a port in which the supercapacitor bank is connected as a load.

Let S_1S_1 and S_2S_2 represent the high-side and low-side switches of the input leg, and S_3S_3, S_4S_4 be the switches of the output leg. At any time, the switches will be in a position to determine the voltage that is applied across the inductor and, therefore, the dynamics of the inductor currents.

Assuming ideal switches and neglecting parasitic effects for clarity, the inductor voltage v_Lv_L depends on the instantaneous switching configuration. Over one switching period, the converter operates in two dominant energy transfer states.

When the high side switch of an input leg is active and the low side switch of an output leg is conducting, the inductor is connected to the input source. At this instant, the inductor voltage is defined as,

$$v_L = V_{in} - V_o \tag{1}$$

Here, $V_{in}V_{in}$ is the input DC voltage and V_oV_o is the output voltage across the supercapacitor bank. In the complementary state, in which the low side

switch of the input leg and the high side switch of the output leg are in conduction, the inductor releases its stored energy to the output, showing,

$$v_L = -V_o v_L = -V_o \quad (2)$$

With a proper sequence of states within a switching period, a regulated power transfer is facilitated. Let D_F denote the duty ratio associated with the input-side active state and $D_R D_R$ denote the duty ratio associated with the output-side active state. These duty ratios play a central role in the subsequent modelling and control formulation.

IV. PROPOSED CONSTANT CURRENT CHARGING CONTROL

The fundamental objective of the controller is to regulate the inductor current to a prescribed reference value throughout the entire charging interval, thereby enforcing a predictable and nearly linear supercapacitor voltage trajectory.

A. Operating Mode Definition

During the process of charging the supercapacitor, there are two working modes of the FSBB converter based upon the instantaneous relationship between the output voltage and the input voltage.

Mode 1: Buck Mode

If the output voltage $V_o V_o$ is sufficiently lower than the input voltage $V_{in} V_{in}$, then the buck mode is obtained. In this mode, power transfer is only controlled by switching on the input side and is disabled for the output side. This mode is characterized by:

- Active modulation of the input-side duty ratio D_F
- Output side duty ratio, $D_R D_R$ at 0

Mode 2: Boost-Buck mode

At this stage, as the output voltage is near to the input voltage, buck-boost operation is employed. In this region:

- The duty ratio for the input side is fixed at a pre-defined maximum value
- Power transfer is controlled by regulating the duty ratio on the output side $D_R D_R$

This mode facilitates the continuation of the current regulation even when the pure buck operation is not adequate to maintain the desired charging current.

The transition between these operating modes follows a structure based on voltage conditions in

physically consistent operation without discontinuity in the normal power flow.

E. Mode Transition Criterion

To ensure a smooth and deterministic transition between operating modes, the mode selection logic is defined as

$$\begin{aligned} \text{Mode} &= \text{Buck for } V_o < V_{trans} \\ \text{Mode} &= \text{Buck for } V_o < V_{trans} \end{aligned} \quad (3)$$

$$\begin{aligned} \text{Mode} &= \text{Buck - Boost for } V_o \geq V_{trans} \\ \text{Mode} &= \text{Buck - Boost for } V_o \geq V_{trans} \end{aligned} \quad (4)$$

Where, $V_{trans} V_{trans}$ denotes the transition voltage.

In this work, the transition voltage is selected as

$$V_{trans} = D_F, \max V_{in} V_{trans} = D_F, \max V_{in} \quad (5)$$

Where, $D_F, \max D_F, \max$ is the maximum allowable input-side duty ratio. This choice ensures that the buck operating region is fully exploited before engaging buck-boost operation and avoids premature activation of the output-side switching.

F. Current Control Strategy

The basic component of the suggested control strategy is a discrete-time current regulator that follows a constant current reference signal denoted as $I_{ref} I_{ref}$. The error is defined as

$$e_{I(k)} = I_{ref} - i_{L(k)} e_{I(k)} = I_{ref} - i_{L(k)} \quad (6)$$

Where, k is a discrete-time index.

A proportional-integral (PI) controller is used to produce an intermediate signal:

$$\begin{aligned} u(k) &= K_p e_{I(k)} + K_i \sum_{j=0}^k e_{I(j)} T_s \\ u(k) &= K_p e_{I(k)} + K_i \sum_{j=0}^k e_{I(j)} T_s \end{aligned} \quad (7)$$

Where $K_p K_p$ and $K_i K_i$ are the proportional and integral gains, respectively, and $T_s T_s$ is the control sampling period.

G. Duty-Ratio Scheduling Strategy

The intermediate control signal, denoted by $u(k)$, is then transferred to the duty ratios of the respective power converter according to the active operating mode.

1. Buck Mode Duty Scheduling

In buck mode, the input side duty ratio is actively controlled, whereas on the output side, switching is disabled:

$$D_{F(k)} = D_{F(k-1)} + u(k) D_{F(k)} = D_{F(k-1)} + u(k) \quad (8)$$

$$D_{R(k)} = 0D_{R(k)} = 0 \quad (9)$$

This incremental update of duty cycle will enable the present controller to smoothly regulate the inductor voltage, thus keeping any abrupt changes in current low.

2. Buck-Boost Mode Duty Scheduling

In Buck-Boost mode, the duty ratio of the input side is fixed at its maximum value to provide continuous power transfer:

$$D_{F(k)} = D_{F,max}D_{F(k)} = D_{F,max} \quad (10)$$

Current regulation is then accomplished with the modulated duty ratio of the output side.

$$D_{R(k)} = D_{R(k-1)} + u(k)D_{R(k)} = D_{R(k-1)} + u(k) \quad (11)$$

This distribution of tasks is determined by the physical characteristics of the FSBB converter and allows for only one duty variable to be actively managed in each mode.

The intermediate control signal $u(k)u(k)$ is mapped to the converter duty ratios according to the active operating mode.

H. Duty-Ratio Constraints and Saturation

To ensure safe and physically realizable operation, the duty ratios are constrained as

$$0 \leq D_F \leq D_{F,max}0 \leq D_F \leq D_{F,max} \quad (12)$$

$$0 \leq D_R \leq D_{R,max}0 \leq D_R \leq D_{R,max} \quad (13)$$

These saturation limits prevent overmodulation, reduce switching stress, and ensure compatibility with practical PWM generation. Importantly, duty saturation is applied after the PI computation, allowing the integrator to reflect actual operating constraints without destabilizing the control loop.

I. End of Charge Behaviour

Once the voltage of the supercapacitor attains the desired final value $V_{final}V_{final}$, the reference charging current is set to zero:

Instead of forcing the converter or its internal states to shut down or reset, the controller simply continues operating in Buck mode using the identical control law for the current. This allows for a natural decay of the inductor current to zero.

In this terminal condition:

- The output side duty ratio is kept at a fixed value
- The input side duty ratio will change based on the controller's current.

- The integrator state is preserved, thereby avoiding artificial discontinuities

Such a design choice facilitates a smooth transition between active charging and idle state.

J. Discrete-Time Implementation

The controller is implemented in discrete time with an explicit carrier-based PWM scheme. A normalized sawtooth carrier signal is generated internally:

$$carrier(k) \in [0, 1]carrier(k) \in [0, 1] \quad (14)$$

which is compared against the computed duty ratios to produce the gate signals:

$$S_1 = I(D_F > carrier)S_1 = I(D_F > carrier) \quad (15)$$

$$S_2 = 1 - S_1S_2 = 1 - S_1 \quad (16)$$

$$S_3 = I(D_R > carrier)S_3 = I(D_R > carrier) \quad (17)$$

$$S_4 = 1 - S_3S_4 = 1 - S_3 \quad (18)$$

This explicitly specified PWM formulation makes the entire link between the control logic and switching operation transparent, both in simulation and in actual implementation.

V. CONCLUSIONS

This paper presented a constant-current charging strategy for high-voltage supercapacitor banks using a four-switch buck-boost converter, with a primary focus on the large-signal transient behaviour encountered during the pre-charging process. Unlike conventional converter studies that emphasize steady-state operation and ripple-based component design, the proposed work addressed the fundamentally energy-dominant nature of supercapacitor charging and its implications for modelling and control.

A mathematical model based on the notion of energy has been formulated over the process of voltage evolution of the supercapacitor under the control of a constant current source, which shows that the charging process can be simplified as a first-order dynamic phenomenon dominated by the capacitance of the supercapacitor and the set-point current reference signal when a proper time-scale separation principle is adopted.

Based on this model, a new state machine-based control framework was developed to manage the operation modes of the four-switch buck-boost converter throughout the voltage range. In the control strategy, a structured duty ratio scheduling was used



to manage the inductor current while transitioning between the buck mode and buck-boost mode.

A key contribution of this work lies in the rigorous justification of component selection from a control-oriented perspective. By deliberately selecting inductance, intermediate capacitance, and supercapacitor parameters to enforce time-scale separation, the proposed approach achieved predictable and stable charging behaviour.

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