Advanced Strategies for Chattering Reduction in Sliding Mode-Controlled Bidirectional Cuk Converters

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***Abstract*—Sliding Mode Control (SMC) is a robust control technique widely used for managing nonlinear systems with uncertainties and disturbances. It has many advantages like Robustness to System Uncertainties, Simple Implementation, Finite-Time Convergence, Insensitivity to Nonlinearities, Stability and Robust Performance. Despite its advantages significant challenge in SMC is the phenomenon of chattering, characterized by high-frequency oscillations of the control signal around the desired sliding surface. This paper provides a comprehensive investigation into the chattering issues associated with HOSMC and ASMC in power converters, examining the causes, consequences, potential mitigation techniques. Comparative analysis explains that, both HOSMC and ASMC improve the dynamic response and stability of bidirectional converters, ensuring efficient and reliable operation.**

Keywords— Sliding mode control, chattering, bidirectional DC DC converter, HOSMC, ASMC.

I. INTRODUCTION

SMC is a popular control approach that entirely neutralizes the effect of matching disturbances on the system [1], [2]. The use of digital platforms for controller implementation has resulted in the discrete-time sliding mode [3], which updates the control on a regular basis. The discrete time implementation of the SMC is explored in [4] which discusses the implementation of discrete time terminal SMC.

In industrial processes, time delays due to nonlinearities are common in control systems, making stable controller design is challenging because of the after effect, which can degrade performance [5]. Various control strategies for Time Delay Systems (TDS) have been developed to address this issue. During the 1990s, robust control for TDS gained prominence, especially through techniques like Linear Matrix Inequality (LMI) and the Lyapunov-Krasovskii functional method, which are effective for handling both matching and mismatching uncertainties in time delay systems [6].

Sliding Mode Control (SMC) is a popular control method that provides optimal system performance even in the presence of large uncertainties [7]. However, because of the discontinuous character of the SMC law, it can induce the chattering effect [8], which is defined as high-frequency oscillations of the controlled variable which can shorten the life cycle of the actuators and it limits the usage of SMC in robotics.

Using a continuous approximation of discontinuous control to operate robotic systems could only guarantee the tracking error was uniformly and finally confined. This reduces the efficacy of SMC by generating a pseudo-sliding mode rather than an ideal sliding mode. Despite this, the literature has demonstrated the application of SMC to mechanical systems through a range of instances, including control and state observation [9].

A widely accepted approach for reducing chattering involves confining the control discontinuity to the derivative of the control variable, ensuring finite-time convergence of the sliding variable. This leads to a continuous control signal being applied to the system. After an initial transient phase, this method, called higher order sliding mode (HOSM) control, establishes a sliding mode that includes both the sliding variable and its temporal derivatives up to the order $\rho-1$ making it a ρ-sliding mode [10].

Sliding Mode Control (SMC) is particularly important in bidirectional converters for several reasons. These converters are used in applications where power flow needs to be controlled in both directions, such as in battery charging systems, electric vehicles, renewable energy systems, and UPS (Uninterruptible Power Supply) systems. Bidirectional converters often face varying load conditions and input voltage variations. SMC is robust to these changes and uncertainties, ensuring stable operation without the need for precise system modeling. This robustness makes SMC ideal for applications where the operating conditions can change dynamically.

Bidirectional converters require fast and accurate response to changing power demands**.** SMC ensures quick correction of errors and deviations from the desired trajectory with finite convergence to sliding surface. This leads to improved dynamic performance and stability, which is crucial for maintaining power quality and system reliability. SMC can effectively reject external disturbances**,** such as input voltage fluctuations and load changes, which are common in bidirectional converter applications. This ability to maintain performance despite external disturbances is essential for applications like renewable energy systems, where input power can be highly variable.

Sliding Mode Control is crucial for bidirectional converters due to its robustness to parameter variations and uncertainties, improved dynamic response, effective disturbance rejection, simplified control design, insensitivity to nonlinearities, enhanced efficiency, improved control of bidirectional power flow, stability and robust performance, versatility, and reduced harmonic distortion. These advantages make SMC an ideal choice for ensuring the efficient, reliable, and robust operation of bidirectional converters in various applications.

Bidirectional converters exhibit nonlinear behaviours, especially during mode transitions from charging to discharging. SMC is inherently capable of handling such nonlinearities without requiring linearization of the system model, making it a robust choice for these converters. SMC can help optimize the switching behavior of the power devices, minimizing switching losses and improving overall efficiency. This is particularly important in bidirectional converters, where efficiency directly impacts the performance and energy savings of the system.

Accurate and stable control of power flow in both directions is critical for bidirectional converters. SMC provides precise control over the power flow, ensuring efficient and reliable operation in both charging and discharging modes. This is crucial for applications like battery energy storage systems and electric vehicle chargers. SMC ensures stable operation even under adverse conditions, such as sudden load changes or fault conditions. This stability is critical for maintaining continuous operation and protecting the system from damage. SMC can help to reduce harmonic distortion in the output voltage and current, improving power quality. This is important for applications that are sensitive to power quality issues, such as grid-tied inverters and sensitive electronic loads.

In this paper, A bidirectional Cuk converter topology is used which has the advantage of low ripple current both on the input and output sides as compared to Buck-boost converter, making it suitable for battery applications. sliding mode control is used to manage the converter and ensure a constant current at the input or output side of the converter during battery charging and discharging.

II. Bidirectional Cuk Converter Design

A Bidirectional Cuk Converter is a modified conventional Cuk converter that allows bidirectional current flow. In order to achieve bidirectional operation, a MOSFET is used in place of the diode as shown in Fig.1. The bidirectional Cuk converter output is an inverted version of the Buck-boost converter output, with the added advantage of low current ripple at both the input and output. Various operational modes of proposed converter are explained in four modes as follows.

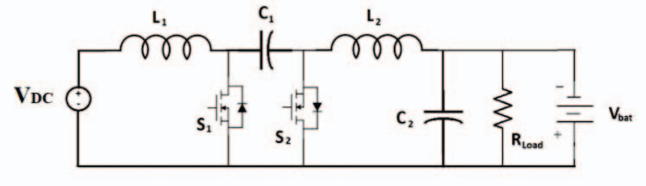

Fig. 1. Bidirectional Cuk Converter with battery load

A. Mode 1:

When MOSFET S_1 is turned on and MOSFET S_2 is turned off, inductor L_1 charges and no current flows through the load or battery, as shown in Fig.2, resulting in a zero output voltage.

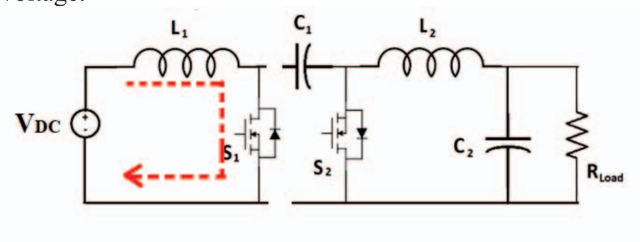

Fig. 2. Mode 1 operation with S_1 ON and S_2 OFF

And the inductor current is given by

$$I_{L1} = \frac{P_S}{V_S} \quad (1)$$

B. Mode 2:

When MOSFET S_1 is switched off and MOSFET S_2 is turned on, inductor L_1 starts discharging through S_2 and charges the capacitor C_1 to the voltage equal to V_s+V_0. Fig,3 shows that no current flows through the load or battery in this mode, hence the output voltage is zero.

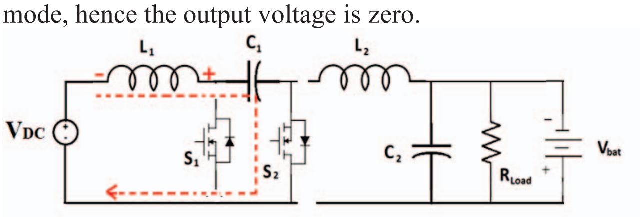

Fig. 3. Mode 2 operation with S_1 OFF and S_2 ON

C. Mode 3:

When MOSFET S_1 is turned on and MOSFET S_2 is turned off again, inductor L_1 charges, capacitor C_1 starts discharging through S_1 and current passes through the load and battery, charging the inductor L_2, as illustrated in Fig.4.

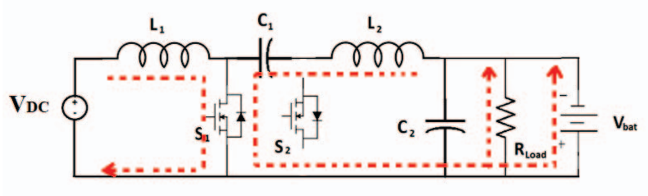

Fig. 4. Mode 3 operation with S_1 ON and S_2 OFF

The value of inductor current is given by,

$$I_{L2} = \frac{P_0}{-V_0} \quad (2)$$

D. Mode 4:

When MOSFET S_1 is switched off and MOSFET S_2 is turned back on, inductor L_1 begins discharging through S_2, charging the capacitor C_1, and inductor L_2 discharges through S_2, as illustrated in Fig. 5.

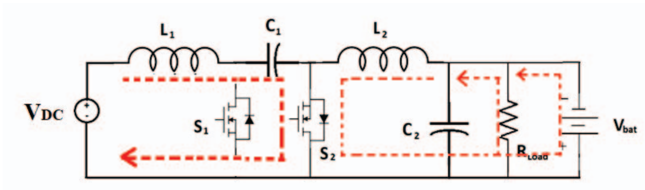

Fig. 5. Mode 4 operation with S_1 OFF and S_2 ON

E. Sliding Mode Control

Implementation of sliding mode control requires State space model of bidirectional Cuk converter. A bidirectional Ćuk converter allows power flow in both directions. The key components include two inductors, two capacitors and two switches. Two inductor currents i_{L1}, i_{L2}, two capacitor voltages V_{C1} and V_{C2} are considered as state variables of the converter.

This method involves various steps in implementation. The system can be represented as:

Step 1:

$$\begin{cases} \dot{x_1} = \frac{V_{in}-v_c}{L_1} \\ \dot{x_2} = \frac{i_L-i_{L1}}{C_1} \\ \dot{x_3} = \frac{v_c-V_{out}}{L_2} \\ \dot{x_4} = \frac{i_{L2}}{C_2} \end{cases} \quad (3)$$

Where

V_{in} is the input voltage,

V_{out} is the output voltage and

L_1, L_2, C_1, C_2 are the inductance and capacitance values.

Step 2:

Defining a sliding surface that reflects the desired behavior of the system:

$$S = K_1\left(i_L - i_{L_{ref}}\right) + K_2\left(v_C - V_{C_{ref}}\right) + K_3\left(i_{L2} - i_{L2_{ref}}\right) + K_4\left(v_{C2} - V_{C2_{ref}}\right) \quad (4)$$

where K_1, K_2, K_3 and K_4 are the weighting coefficient.

Step 3:

Design the SMC law to ensure the system states reach and remain on the sliding surface.

The equivalent control u_{eq} maintains the system on the sliding surface:

$$u_{eq} = \frac{\dot{S}}{\left(\frac{\partial S}{\partial u}\right)} \quad (5)$$

The switching control u_{sw} ensures the system reaches the sliding surface.

$$u_{sw} = -K * sign(S) \quad (6)$$

The overall control law is:

$$u = u_{eq} + u_{sw} \quad (7)$$

The control signal u determines the switching state of the converter and pulse-width modulation (PWM) approach is used to implement the control.

III. CHATTERING ISSURES

Chattering in Sliding Mode Control (SMC) refers to the high-frequency oscillations that occur around the sliding surface. This phenomenon is caused by the discontinuous nature of the control law, which switches rapidly between different control values to keep the system on the sliding surface. While this switching is the source of SMC's robustness, it can lead to practical issues in real-world implementations. Various causes of chattering are discontinuous control law, finite switching frequency, noise in the measurement of state variables and high frequency unmodeled dynamics of the system. The effects of chattering includes excessive wear and tear due to the rapid switching, increased energy dissipation, which reduces the efficiency of the system, introduces high-frequency noise and can destabilize the system, making it difficult to achieve the desired control objectives.

Various chattering reduction methods available in SMC which can improve the behavior of the converter. Most popular methods includes Boundary Layer Method in which a thin boundary layer is introduced around the sliding surface, and a continuous control law is applied within this layer. This makes the control signal smoother and reduces high-frequency switching. Higher order Sliding mode control (HOSMC) which extends the conventional first-order sliding mode to higher-order derivatives of the sliding variable. This approach can reduce chattering by smoothing the control action. Adaptive sliding mode control method adjusts the control gain based on the system's state to minimize chattering. Most commonly used methods are HOSMC and adaptive SMC.

A. Higher Order Sliding Mode Control

Higher Order Sliding Mode Control (HOSMC) is an advanced form of Sliding Mode Control (SMC) designed to address the chattering issue and improve the performance of control systems. Unlike classical SMC, which operates based on the first derivative of the sliding surface, HOSMC involves higher-order derivatives of the sliding variable, allowing for smoother control action and better performance.

To design an HOSMC, the sliding variable and its derivatives need to be defined.

define the sliding variable as the output voltage error

$$S(x) = V_{ref} - V_{out} \quad (8)$$

Defining Sliding Surface and Derivatives

$$\dot{S(x)} = -\frac{dV_{out}}{dt} \quad (9)$$

$$\ddot{S(x)} = -\frac{d^2V_{out}}{dt^2} \quad (10)$$

Design a control law that ensures the sliding variable and its derivatives converge to zero. The Super-Twisting Algorithm with second-order sliding mode control method applied as:

$$u = -K_1 * sign(S) + K_2 * sign(\dot{S}) \quad (11)$$

Where, K_1 and K_2 are positive constants

Based on the control input u, switches S1 and S2 of the converter will be operated towards the sliding surface.

B. Adaptive Sliding Mode Control

The adaptive sliding mode control law involves adjusting the control gains based on system states and performance. The control law can be split into the equivalent control u_{eq} and the adaptive switching control u_{sw}. A bidirectional Ćuk converter, the state-space representation can be expressed as follows:

$$\dot{x} = f(x) + g(x) * u \quad (12)$$

Where,

x is the state vector, u is the control input, f(x) represents system dynamics without control input and g(x) represents how the control input affects the system.

$$x = [i_{L1} \quad v_{c1} \quad i_{L2} \quad v_{c2}]^T \quad (13)$$

f(x) captures the natural dynamics of the converter without the switching control, and g(x) represents the influence of the control input (the switching states) on the converter's dynamics. These matrices are essential for designing the sliding mode control law. The actual forms of f(x) and g(x) depend on the specific operating mode of the converter and the state of the switches. The equivalent control maintains the system on the sliding surface.

$$u_{eq} = -\left(\frac{\partial S}{\partial x} * g(x)\right)^{-1} * \left(\frac{\partial S}{\partial x} * f(x) + \frac{d}{dt}\frac{\partial S}{\partial x}\right) \quad (14)$$

The adaptive switching control drives the system states to the sliding surface and compensates for disturbances. The control gain k is adjusted in real-time.

$$u_n = -K(t) * sign(S) \quad (15)$$

The gain k(t) is adapted based on the system performance. For instance, it can be adjusted using the following adaptation law:

$$\dot{K(t)} = \gamma * |S| \quad (16)$$

Where, γ is the positive adaptation rate.

precise measurement of state variables and proper tuning of control parameters γ and initial k is necessary to achieve the desired performance. The block diagram of control algorithm is shown in figure 6.

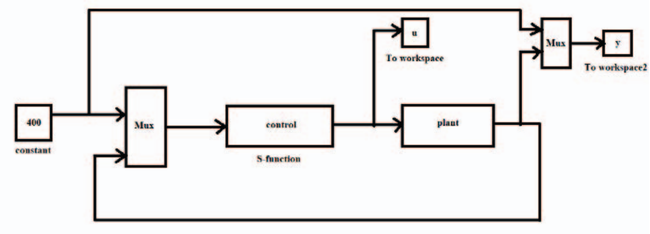

Fig. 6. Block diagram of control algorithm

IV. Results and Discussion

Design specifications of bidirectional Cuk converter and given in table 1. DC bus voltage and input inductor current are analyzed with respect to the changes in load ranging from 1kW to 5 kW with both HOSMC and ASMC control methods. The result shows that, input inductor current increases and ripple free with respect to the load variations and DC bus voltage is maintained constant with both HOSMC and ASMC methods.

TABLE I. Circuit Parameters of Cuk Converter

Circuit Parameter	*Specification*
DC Bus refernce voltage	400V
Nominal Battery Voltage	300V
Energy storage Inductor L1	1.714mH
Energy storage Inductor L2	1.714mH
Energy storage capacitor C1	7.143µF
Energy storage capacitor C2	7.143µF
Swiching frequency	100 kHz
Inductor current ripple (P-P)	20%
Capacitor voltage ripple (P-P)	1%

DC bus voltage of Bidirectional Cuk converter with HOSMC and ASMC for 1KW load is given in figure 7 and the input inductor current. The result in figure 7 shows that, HOSMC gives faster response and accurate bus voltage as compared to ASMC and figure 8 shows that, ripple at input current is very less.

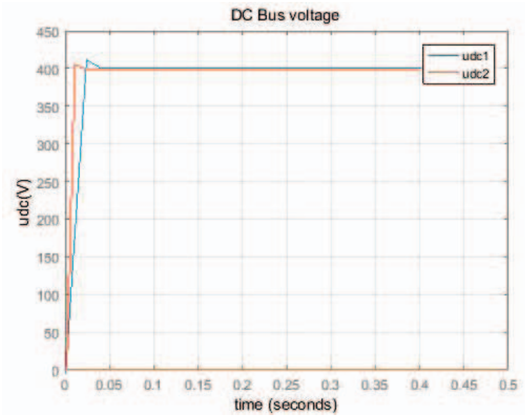

Fig. 7. DC Bus voltage with HOSMC and ASMC for 1kW load

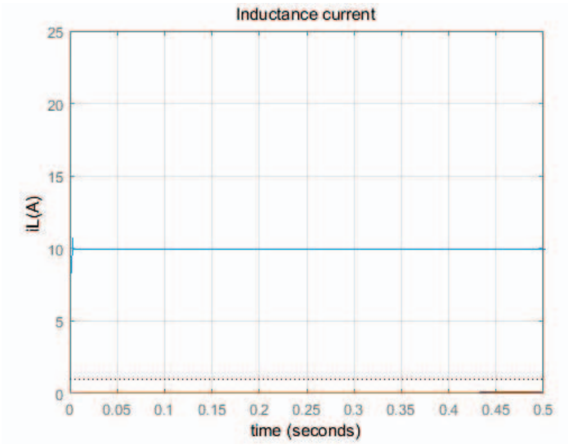

Fig. 8. Input Inductor current with 1kW load

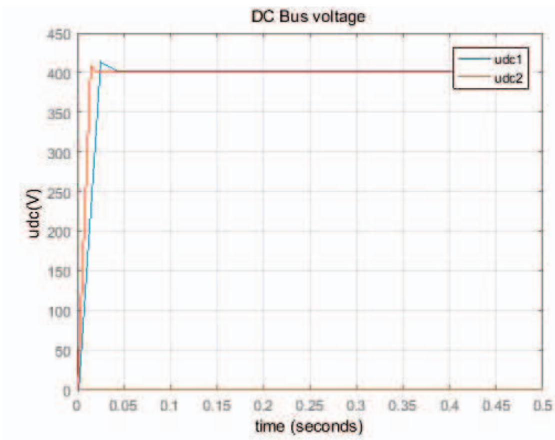

Fig. 9. DC Bus voltage with HOSMC and ASMC fro 5kW load

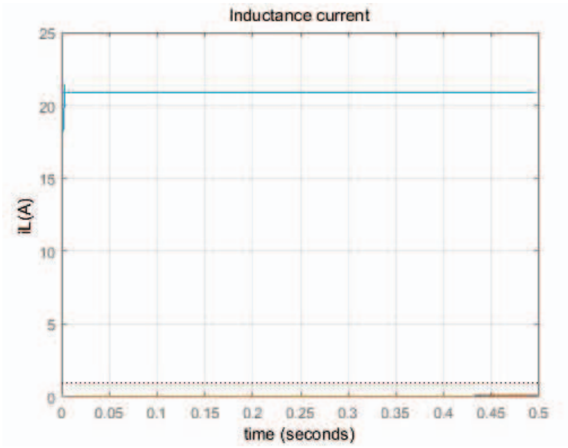

Fig. 10. Input Inductor current with 5kW load

V. Comparative analysis of HOSMC and ASMC

The comparative analysis of higher order sliding mode control (HOSMC) and adaptive sliding mode control (ASMC) of bidirectional Cuk converter are provided in table 2.

HOSMC is more suitable for applications requiring very high precision and where chattering must be minimized to an extremely low level. It is more complex to design and implement due to the involvement of higher-order derivatives whereas ASMC offers a balance between performance and complexity. It is effective in reducing chattering and enhancing robustness through adaptive gain mechanisms, making it suitable for systems with varying parameters and uncertainties.

TABLE II. Comparison of HOSMC and ASMC

Features	***HOSMC***	***ASMC***
Chattering Reduction	Excellent	Good
Robustness	High	High
Finite-time Convergence	Yes	Yes
Complexity	High	Moderate
Control Law	Super-Twisting Algorithm, other higher-order methods	Adaptive gain laws based on system performance
Implementation	More complex, requires accurate derivative computation	Less complex, requires adaptation mechanism

In practice, the choice between HOSMC and ASMC depends on the specific requirements of the application, including the acceptable level of complexity, the need for precision, and the nature of system uncertainties.

Conclusion

The paper concludes that HOSMC and ASMC are effective in mitigating chattering and enhancing the performance of the bidirectional Cuk converter. HOSMC, in particular, offers superior chattering reduction and robustness but is more complex to implement. ASMC provides a balance between performance and implementation complexity, making it suitable for systems with varying parameters and uncertainties. Both HOSMC and ASMC improve the dynamic response and stability of bidirectional converters, ensuring efficient and reliable operation. The choice between these methods depends on the specific requirements of the application, including the acceptable level of complexity and the need for precision. The study emphasizes the importance of selecting appropriate control strategies to ensure the optimal performance of bidirectional converters, particularly in applications requiring high precision and robustness against parameter variations and external disturbances. The comparative analysis of HOSMC and ASMC highlights the trade-offs between chattering reduction, complexity, and robustness, guiding the selection of the most suitable control method for specific applications. Further, Combining HOSMC or ASMC with other control techniques like fuzzy logic or neural networks could enhance adaptability and reduce complexity and focusing on the development of fault-tolerant HOSMC or ASMC to ensure system reliability in the event of component failures in power converters.

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