

Research Article

Sliding mode control of the two-phase interleaved DC-DC converter

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ABSTRACT

Background: In systems where the bidirectional exchange of power is necessary, the topology of a bidirectional DC-DC converter is usually critical. Microgrids and composite energy storage systems commonly employ this topology. Interleaving the architecture reduces input-side ripple current, boosts power handling capacity, and increases the power density of the converter by enabling current sharing across multiple phases, which reduces the size of the input and output capacitors and filter inductors.

Methods: This publication presents the design and generalized phase shift parameters for a two-phase non-isolated bidirectional DC-DC converter. The sliding mode control method was adapted for controlling this specialized DC-DC converter. Simulations were performed in MATLAB/Simulink, taking into account both the boost and buck modes of operation.

Results: The results show that equal phase-to-phase current sharing minimizes input current ripple, reduces filter element size, and improves heat distribution within the converter. Compared to the PID standard control approach, the sliding mode control (SMC) method achieves a minimization of more than 0.15 V.

Conclusion: The results of the SMC simulation, recommended for this type of converter, demonstrate stable output voltage and current, as well as precise and consistent performance within the converter's limitations.

Introduction

DC-DC converters are an important class of energy conversion devices widely used in various electrical and electronic applications. Their architecture is based on two conversion branches that operate alternately to provide continuous and regulated output power. This approach reduces current and voltage ripples, improving overall system efficiency and reducing energy loss. Control of these converters can be achieved via various modulation techniques, such as PWM or FM, as well as advanced control strategies, such as predictive control or sliding mode, to optimize dynamic performance and control accuracy. Due to their advantages in terms of power distribution, energy efficiency, and voltage regulation, these converters are widely used in a range of applications, such as data center power supplies, electric propulsion systems, and industrial equipment. Despite their advantages, challenges remain, particularly with regard to switching loss management and system stability, requiring continuous research to improve their performance and reliability (1). A well-designed control system not only ensures stable and reliable operation but also facilitates efficient power transfer, precise voltage regulation, and seamless integration into larger power conversion systems. In addition, an effective control strategy can improve the flexibility of the converter, allowing it to adapt to dynamic load conditions and optimize the overall efficiency of the system (2, 3). The integration of Sliding Mode Control (SMC) with two-phase interleaved DC-DC converters represents a dynamic research area aimed at improving the performance of these energy conversion systems. The SMC is known for its robustness against parameter variations and disturbances, making it an attractive candidate for controlling converters that are demanding in terms of stability and accuracy. The application of the SMC to these converters makes it possible to design regulators capable of guaranteeing accurate monitoring of the voltage or current reference while ensuring good regulation of the output. The sliding surfaces are designed to guide the system to desired trajectories, while the control algorithms adjust the system parameters in real time to keep the system on these surfaces despite disturbances. This approach also offers the flexibility to adapt to different operating conditions, such as load variations or

quick reference changes. Recent studies in this field have explored different slip surface design strategies and control algorithms, as well as advanced techniques such as multi-sliding surface control, to improve system performance and robustness. In summary, the integration of the SMC with the intertwined two-phase DC-DC converters represents a promising avenue for the development of robust and efficient regulators able to meet the increasing demands of energy conversion in various applications (4).

These challenges underscore the critical importance of implementing a well-designed control strategy tailored to the specific requirements of the converter. The importance of a good control topology cannot be overstated in the context of the two-phase interleaved converter. (A well-designed control system not only ensures stable and reliable operation but also facilitates efficient power transfer, precise voltage regulation, and seamless integration within larger power conversion systems. Moreover, an effective control strategy can enhance the converter's flexibility, enabling it to adapt to dynamic load conditions and optimize overall system efficiency. In summary, the two-phase interleaved converter represents a significant advancement in power electronics, offering improved efficiency, reduced component stress, and enhanced reliability. However, realizing the full potential of this converter architecture hinges on the implementation of a robust control topology. By addressing the challenges associated with control, engineers can unlock the full capabilities of the two-phase interleaved converter and usher in a new era of efficient and reliable power conversion technology. The two-phase interleaved converter plays a crucial role in advancing the integration and utilization of renewable energy sources, thereby contributing significantly to the growth and sustainability of renewable energy systems. Its importance in this context stems from several key factors: Enhanced Efficiency: Renewable energy sources such as solar and wind exhibit inherent variability in their power output due to factors like weather conditions and time of day.

The two-phase interleaved converter's ability to efficiently convert and manage variable input power helps maximize the overall energy capture from renewable sources.

By reducing losses and optimizing power conversion, the converter improves the efficiency of renewable energy systems, making them more economically viable. **Grid Integration:** Integrating renewable energy sources into the existing electrical grid requires converters capable of converting the variable DC output of solar panels or wind turbines into stable AC power compatible with the grid. The two-phase interleaved converter offers high-quality power conversion with reduced harmonic distortion and an improved power factor, facilitating seamless grid integration of renewable energy systems. This ensures reliable operation and minimizes grid disturbances, enhancing the overall stability and reliability of the electrical grid. **Power Quality Improvement:** Renewable energy systems often suffer from fluctuations in output power, leading to issues with power quality such as voltage variations and harmonic distortion. The two-phase interleaved converter can mitigate these challenges by providing efficient and precise voltage regulation, reducing ripple currents, and improving power factor correction. This helps maintain a stable and high-quality electrical supply, meeting the stringent grid requirements and ensuring compatibility with sensitive loads (5).

Scalability and Modularity: The modular design of the two-phase interleaved converter allows for scalability, enabling renewable energy systems to be easily expanded or upgraded to accommodate increasing power demands. This flexibility is essential for the integration of distributed renewable energy resources, such as rooftop solar panels and small wind turbines, into both residential and commercial applications. Additionally, the modular nature of the converter facilitates maintenance and servicing, reducing downtime and operational costs. **Energy Storage Integration:** With the growing adoption of energy storage systems, such as batteries, for storing excess renewable energy and smoothing out fluctuations in power output, the two-phase interleaved converter plays a crucial role in managing energy flow between renewable sources and storage devices. Its efficient power conversion capabilities ensure optimal charging and discharging of energy storage systems, maximizing their effectiveness in enhancing renewable energy utilization and grid stability.

Methods

The related control method of this study is based on the Implementation of a robust control topology, such as sliding mode control (SMC), is paramount for the effective operation of the two-phase interleaved converter due to several critical reasons: The dynamic nature of renewable energy systems requires converters to respond swiftly and accurately to changes in input conditions, such as variations in solar irradiance or wind speed. Sliding mode control offers fast transient response and robust stability characteristics, allowing the converter to quickly adjust its output to maintain system stability and performance under varying operating conditions. Also, for a Load Regulation and Tracking, Renewable energy systems often encounter dynamic load variations, necessitating precise control over the output voltage and current of the converter to ensure optimal power delivery to the load. Sliding mode control provides excellent load regulation capabilities, allowing the converter to track desired refer-

ence signals accurately and maintain stable operation even in the presence of significant load disturbances (9). From the other side, a sliding mode control can enhance the Robustness to Parameter Variations and Uncertainties: Renewable energy systems are subject to uncertainties and variations in operating conditions, such as changes in temperature, component aging, and fluctuations in renewable resource availability. Sliding mode control exhibits inherent robustness to parameter variations and uncertainties, making it well-suited for controlling the two-phase interleaved converter in such dynamic and uncertain environments. **Minimization of Ripple and Disturbances:** The interleaved operation of the converter aims to reduce ripple currents and disturbances, improving overall system efficiency and reliability. Sliding mode control allows for effective ripple suppression and disturbance rejection, ensuring smooth operation and minimizing the impact of transient disturbances on the converter's performance. And basically, it is possible to Optimize the Power Conversion Efficiency: Maximizing power conversion efficiency is essential for enhancing the profitability and sustainability of renewable energy systems. Sliding mode control can optimize the converter's operating point in real-time, ensuring efficient power transfer and minimizing losses, thereby maximizing the overall energy conversion efficiency of the system.

Sliding mode control (SMC) is a non-linear discontinuous control technique. SMC can continue to operate as intended even in the face of outside shocks and uncertainty. The system converges to the sliding surface and tries to slide on it for continuous stability in order to minimize error. The chattering effect is an inaccuracy that occurs throughout this operation (10). In Figure 1, the DC-DC converter design and the SMC control technique are integrated for maximum performance across a range of load conditions (11).

The sliding surface in this converter control system is determined by combining the output capacitor voltage (V_c) and input inductor current (I_l) of each buck boost DC DC converter linearly, namely:

$$S(I_l, v_c) = k_1 e_1 + k_2 e_2 \quad (1)$$

Where the coefficients k_1 and k_2 are appropriate gain, while e_1 and e_2 are the state variables' output overshoots I_l and v_c respectively has given by Eq:

$$e_1 = I_{lref} - I_l \quad (2)$$

$$e_2 = v_{cref} - v_c \quad (3)$$

v_{cref} Is the reference voltage of the output capacitor,

I_{lref} is the reference waveform of the input inductor current.

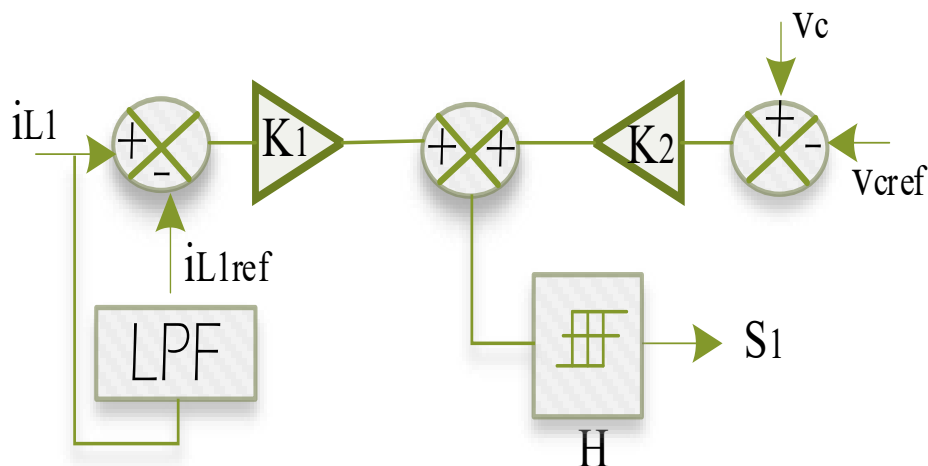


Figure 1. The sliding mode control scheme for one of the two phases

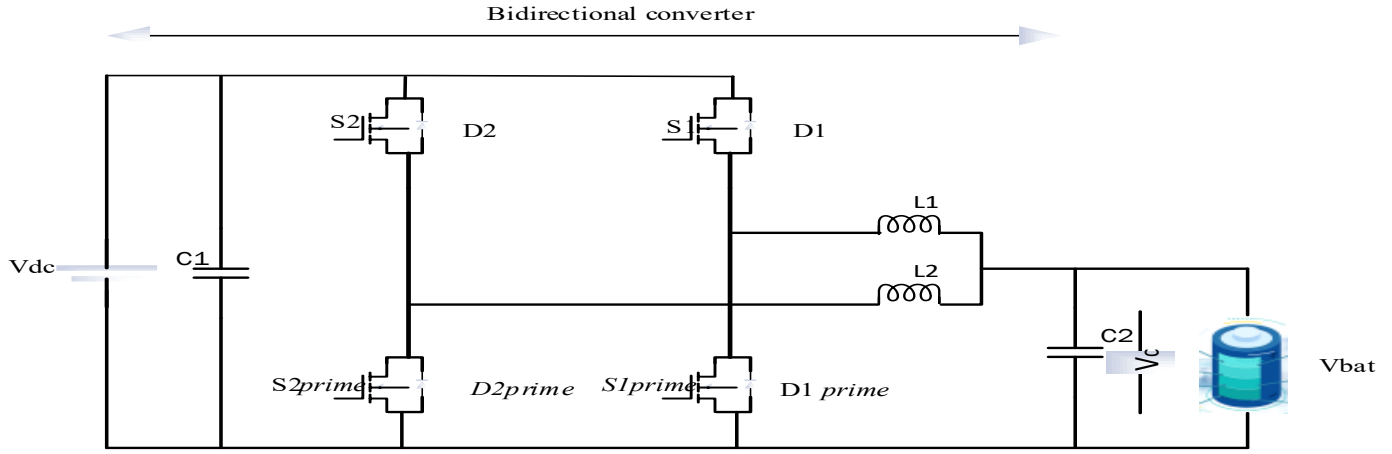


Figure 2. Two-phase Interleaved Bidirectional Converter design

Two-phase Interleaved Bidirectional Converter Control

The Two-phase Interleaved Bidirectional Converter represents a sophisticated power electronics solution designed for efficient energy transfer in bidirectional power flow applications. Its architecture consists of two interleaved converter phases operating in parallel, allowing for enhanced power handling capabilities and improved current ripple reduction. In its design, each phase typically comprises a combination of switches, such as MOSFETs or IGBTs, coupled with passive components like inductors and capacitors. The interleaved operation ensures that the workload is distributed evenly between the phases, minimizing current ripple and reducing stress on individual components. This design not only enhances the converter's power handling capacity but also improves its reliability and efficiency. Moreover, the bidirectional capability of the converter enables seamless energy transfer between different energy storage elements or power sources, such as batteries, renewable energy systems, or the electrical grid, making it well-suited for applications like energy storage systems, electric vehicles, and grid-tied inverters. Overall, the Two-phase Interleaved Bidirectional Converter presents a versatile and efficient solution for bidirectional power conversion, offering benefits such as reduced component stress, improved power quality, and enhanced system reliability (6, 7).

A two-phase interleaved bidirectional converter Figure 2. is linked in parallel to two power modules, and gate signals undergo a 180° phase shift. Here, the source current is split into two flow paths that are parallel to one another (8).

The converter's state variables (currents in the coil, i_{L1} , i_{L2} , and voltage in the output capacitor, v_{dc}) are represented by the differential equations (4), (5), and (6), which show the fluctuations with time:

$$v_{dc} = \frac{i_{L1}(1 - v_{S1}) + i_{L2}(1 - v_{S2}) - i_{bus\ dc}}{C_1} \quad (4)$$

$$i_{L1} = \frac{d}{dt} \left(\frac{v_{bat} - v_{dc}(1 - v_{S2})}{L_1} \right) \quad (5)$$

$$i_{L2} = \frac{d}{dt} \left(\frac{v_{bat} - v_{dc}(1 - v_{S1})}{L_2} \right) \quad (6)$$

Equation 4 provides the value of each phase inductance

$$L_1 = L_2 \dots \dots = L_n = \frac{v_{bat} D}{\Delta I F_{sw}} \quad (7)$$

Equation 5 provides the value of the DC link capacitance.

$$C1 = \frac{D v_{dc}}{R_{dc} \Delta v_{dc} F_{sw}} \quad (8)$$

Results

The measurements were carried out utilizing a battery-linked DC source in order to verify the functionality of the interlaced bidirectional converter and the comparison between the two control strategies examined in the preceding sections.

The simulation was made through Matlab simulink model and by fixing the DC bus voltage $V_{DC} = 48V$ and a battery voltage $V_{bat} = 24V$.

The simulation is run to compare a PID control and an SMC control of an interleaved DC DC converter.

A resistive charge of 4.4Ω is connected as part of this operation, which simulates the converter under boost (discharge mode) of the low-voltage side of a 24V, 50Ah battery, which is thought to be supplied by direct current 48V bus voltage.

It can be seen that the output current with the PID control correctly follows the reference current. The voltage controller is capable of maintaining a constant output of 25 V during the transient charge of the battery and reducing the discharge as shown in Figure 3. The stability of the SMC loop is enough clear face the PID specialty in the transition points as the point 2.5 seconds, where some perturbation exists in that instant. This point is the discharge appliance point. This why the voltage moves from a negative region (charge phase) to the positive voltage (discharge phase).

Discussion

Conversely, the provided simulation results demonstrate that, in the charging mode, the inductor current is inversely proportional to the battery current, whereas in the unloading mode, it is equal to i_{L1} . As seen in the figures, on the other hand, we can observe that the SMC command causes the reverse battery current for each inductor current to decrease in value without the need for reference current regulation in order to maintain a steady voltage with less losses and disturbances.

Table 1. gives a statistical result about this comparison. It can be seen that even the PID is faster, but a large overlap exists in transition phases. Which is not the case for the SMC, where the stability is good enough. The given statistics was given basing on the Figure 3 c and d.

Table 1. Comparison between the performances of the SMC and the PID control loop

	Overlap (V)	Delay for stability (sec)
SMC	0.35	1.5 (Max)
PID	5	1.5 (Max)

Conclusion

The control and modeling of a bidirectional DC-DC modulation converter were covered in this paper. Both control topologies were spoken about. The stability of the control strategies for the two-phase non-isolated DC-DC converter topologies is also covered in the study. The outcomes of the SMC simulation suggested for such a type of converter demonstrate accurate and dependable performance within the converter's bounds as well as stability in current and voltage outputs. The simulation results were depicted through the Matlab Simulink software.

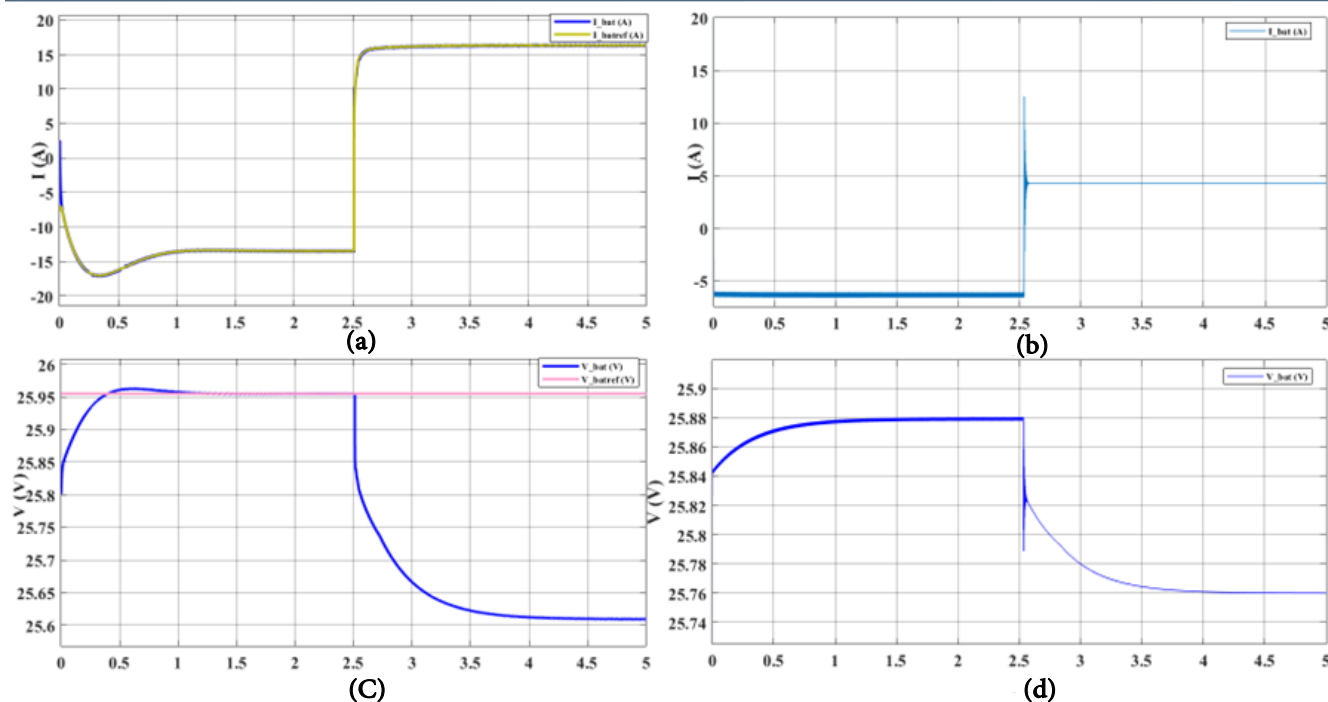


Figure 3. Performance of the SMC control topology face the PID standard control method. (a) I batterie with PID, (b) I batterie with SMC, (c) V batterie with PID, (d) V batterie with SMC.

Competing interests

The authors declare no competing interest.

Authors contributions

A Flah, H. Gaied, developed the research concept; and designed the data collection process; analysis of the data, and drafted the study reports. A. Flah provided academic guidance and continuous supervision, reviewed the study.

Data information:

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