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Enhancing the Performance of Super-Twisting Sliding Mode Control Techniques for Dual Active Bridge DC-DC Converters

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Abstract

The Dual Active Bridge (DAB) DC-DC converter has become a fundamental topology in modern power electronics because of its ability to handle bidirectional power flow, high efficiency, galvanic isolation, and suitability for medium- to high-power applications such as renewable energy systems, electric vehicles, and smart grids. However, maintaining high performance under varying conditions remains a challenge due to nonlinear behavior, parameter variations, and external disturbances. This study addresses these issues by developing and applying advanced sliding mode control (SMC) techniques to improve the dynamic performance, robustness, and reliability of DAB converters. A simplified mathematical model is created to support control design while capturing the essential dynamics of the system. This model is then used to implement and evaluate various control strategies aimed at enhancing voltage regulation and power transfer. To overcome the limitations of traditional control methods, a sliding mode based direct power control (DPC) strategy is proposed. This method directly controls the power transfer and output voltage by defining an appropriate sliding surface, enabling fast dynamic response and robustness against disturbances. However, the classical sliding mode control often suffers from chattering, a high-frequency oscillation that can lead to switching losses and stress on components. To resolve this issue, a more advanced Super-Twisting Sliding Mode Control (ST-SMC) technique is introduced. To further improve system reliability and reduce the need for physical sensors, a current observer-based sensorless control approach is developed and integrated with the sliding mode framework. This observer estimates the inductor current using available measurements, eliminating the need for direct current sensing. This lowers system cost and complexity and enhances fault tolerance and noise immunity.

The proposed observer-based SMC approach is accurately estimating system states and compensating for disturbances, the controller ensures stable operation and consistent performance even under varying load dynamics. The Overall, this work contributes to the advancement of high-performance control strategies in power electronics, offering practical solutions for efficient and reliable operation of DAB DC-DC converters in next-generation energy systems.

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Keywords: *Dual Active Bridge (DAB), Direct Power Control (DPC), Sliding Mode Control (SMC), Super-Twisting Algorithm, Constant Power Load (CPL), Current Observer (ZVS).*

1. Introduction

The rapid development of renewable energy systems, electric vehicles, and modern power electronics has significantly increased the demand for highly efficient, reliable, and controllable DC-DC power converters. Among various converter topologies, the Dual Active Bridge (DAB) converter has attracted considerable attention due to its bidirectional power flow capability, high power density, galvanic isolation, and suitability for high-frequency operation. These features make the DAB converter a highly suitable choice for applications such as renewable energy integration, battery energy storage systems, electric vehicle charging infrastructure, and smart grid technologies. However, despite its advantages, maintaining stable operation and achieving high performance under varying load conditions, parameter uncertainties, and external disturbances remains a challenge. Therefore, advanced control strategies are essential to ensure optimal performance, efficiency, and robustness of DAB converters. Figure 1 shows Dual active bridge basic structure.

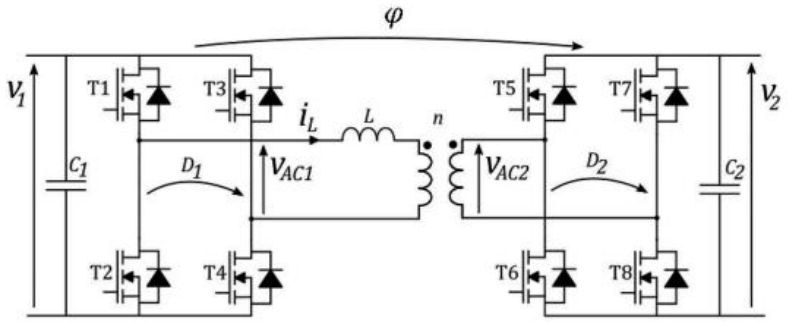


Figure 1 Dual active bridge basic structure.

The DAB converter consists of two active full-bridge circuits connected through a high-frequency transformer and an inductor that facilitates energy transfer between two DC sources. Power transfer in this converter is primarily controlled by adjusting the phase shift between the switching signals of the two bridges. Traditional control methods such as proportional-integral (PI) controllers are often used for regulating the output voltage or current. However, these linear control strategies may not provide satisfactory performance in nonlinear systems like DAB converters, especially when the system experiences rapid load changes, component variations, or switching nonlinearities. Consequently, modern nonlinear control techniques have been explored to overcome these limitations and enhance the converter's dynamic response and robustness. One of the most promising nonlinear control approaches in power electronics is Sliding Mode Control (SMC). Sliding mode control is a variable structure control technique known for its robustness against system uncertainties and disturbances. Due to its inherent robustness and simple implementation, SMC has been widely adopted in various power electronic converters, motor drives, and renewable energy systems. However, classical sliding mode control methods suffer from certain drawbacks, most notably the phenomenon known as chattering. Chattering refers to high-frequency oscillations around the sliding surface caused by the discontinuous control action. In power electronic

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converters, chattering can lead to increased switching losses, electromagnetic interference, and potential damage to switching devices. To address this issue, several advanced sliding mode control techniques have been developed, including higher-order sliding mode control, adaptive sliding mode control, fuzzy sliding mode control, and super-twisting algorithms. Advanced sliding mode control techniques provide several advantages when applied to DAB converters. First, they enhance the robustness of the system against uncertainties such as transformer parameter variations, load fluctuations, and input voltage disturbances. Second, they improve the transient response of the converter by enabling faster convergence to the desired operating point. Third, these techniques can maintain stable operation across a wide range of operating conditions, which is particularly important for applications involving renewable energy sources and battery systems where the operating environment is highly dynamic. Another important aspect of applying advanced sliding mode control in DAB converters is the design of appropriate sliding surfaces and control laws. In recent years, researchers have also explored hybrid control strategies that combine sliding mode control with other intelligent control techniques such as fuzzy logic and neural networks. These hybrid methods aim to further improve system performance by leveraging the strengths of multiple control paradigms. For example, fuzzy sliding mode control can lessen chattering and enhance the smoothness of control, while neural network-based sliding mode controllers can offer adaptive learning features. These intelligent control methods are becoming more widely studied for use in high-performance power electronic systems, such as DAB converters found in renewable energy and smart grid applications. The assessment of advanced sliding mode control methods for DAB converters usually includes examining factors like output voltage regulation, dynamic response, efficiency, robustness, and stability across different operating conditions. Tools like MATLAB/Simulink are often used to create models of the converter system and test the performance of the controller prior to building the actual hardware.

2. Literature Review

The body of literature on structured DAB DC-DC converters and advanced control strategies shows a consistent trend towards the use of nonlinear and robust techniques to manage the dynamic conditions of microgrids. Batool et al.(2024) conducted a thorough review of control methods in DC microgrids, highlighting that advanced approaches such as Model Predictive Control (MPC) and Sliding Mode Control (SMC) are essential for effective energy management. Similarly, Ataullah et al.(2022) found that DAB topologies combined with high-frequency toroidal transformers and optimized control methods are crucial for reducing leakage inductance and improving efficiency.

In the field of Direct Power Control, several innovations have aimed to separate active and reactive power. Mujammal et al.(2024) introduced a Grid Voltage Modulated-Neural Network Control (GVM-NNC) to address the strict tuning needs of traditional PI controllers in conventional DPC, significantly lowering Total Harmonic Distortion (THD). Sayeh et al.(2024) proposed an F12-DPC (Fuzzy Logic-based 12-sector DPC) that reduced power fluctuations by up to 72.7% without relying on complex mathematical models. Hamza and Krim (2012) further showed that fuzzy inference systems can replace hysteresis comparators, resulting in smoother power regulation.

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However, DPC techniques on their own often fall short when dealing with the severe nonlinearities of DAB converters.

As a result, sliding mode-based approaches have become increasingly popular. Utkin (2013) demonstrated that SMC ensures system stability against unmodeled dynamics by restricting the state evolution to a switching manifold. Nevertheless, the issue of chattering has led researchers to explore higher-order sliding modes. Bagheri et al.(2023) developed an adaptive ST-SMC for DAB converters under Extended Phase Shift (EPS) modulation, using online optimization to minimize backflow power. Sami et al.(2024) applied a Double Integral Super Twisting Sliding Mode Control (DI-STSMC) on a 230 W DAB setup, achieving zero steady-state error without chattering. Gu and Pan (2024) investigated the use of hyperbolic tangent functions (HTF) as a continuous substitute for the discontinuous switching component, enabling precise voltage tracking while reducing buffeting effects. The integration of observers has also proven essential for sensorless control. Yang and Liu (2023) combined a Linear Extended State Observer (LESO) with SMC for distributed electric propulsion systems, achieving fast dynamic performance while detecting and canceling total disturbances. Yan et al.(2023) used a damping torque observer to enhance transient performance and reduce switching coefficients in double-controlled DFIG systems. Esteban et al.(2021) examined control methods for DAB converters interacting with DC microgrids, focusing on maintaining zero mean current in high-frequency transformers. Despite these advancements, there remains a gap in research regarding the complete integration of ST-SMC, Direct Power Control, and nonlinear current observers to manage Constant Power Loads (CPLs) simultaneously under real-world hardware constraints. Many existing models rely solely on ideal simulations. This research bridges that gap by physically implementing various strategies on a 2-kW hardware prototype.

3. Modeling and Modulation of DAB Converters

3.1 Topology and Operating Principle

The DAB converter features a symmetrical architecture comprising a primary H-bridge, a secondary H-bridge, a high-frequency isolating transformer (with a turns ratio of 1:n), and an equivalent series inductance (L_k), which includes the transformer's leakage inductance.

The primary H-bridge functions as an inverter, converting the input DC voltage (V_in) into a high-frequency AC square wave (V_p).The secondary H-bridge acts as an active rectifier, converting the secondary AC voltage (V_s) back into a regulated DC output voltage (V_o).

3.2 Modulation Strategies

Power transfer in the DAB converter is controlled by the relative timing between the switching signals of the two H-bridges.

3.2.1 Single Phase-Shift (SPS) Modulation:

This is the simplest and most widely used method. All switches operate at a 50% duty cycle, and the only variable is the phase shift angle (δ) between the primary and secondary AC voltages. Power flows from the primary bridge to the secondary bridge.

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3.2.2 Double Phase-Shift (DPS) Modulation:

Introduces an inner phase shift (duty ratio variations D_1 and D_2 within the bridges along with an outer phase shift (δ). DPS expands the ZVS (Zero Voltage Switching) range and minimizes circulating currents, especially under high voltage conversion ratios.

3.2.3 Extended Phase-Shift (EPS) Modulation:

Keeps the primary bridge at a 50% duty cycle but modulates the secondary bridge's duty cycle (D_2) and the phase shift (δ) to optimize ZVS under varying load conditions.

3.2.4 Triple Phase-Shift (TPS) Modulation:

Utilizes three independent variables (D_1, D_2, and δ) for maximum flexibility, although it requires complex control calculations. This study primarily focuses on SPS modulation due to its practical implementation benefits for high-speed dynamic control. Through Fourier series analysis, the total power transferred (P_t) in SPS is the sum of all harmonic powers (P_h):

3.3 Reduced-Order Mathematical Model

Because DAB state-based variables include both AC (inductor current) and DC (terminal voltages) components, generalized average modeling here is highly complex. A reduced-order model ignores here as the high-frequency internal dynamics natured of the inductor current, assuming it reaches steady state within a single switching cycle. The dynamic structured natured energy balance at the output terminal is governed by the DC-link capacitor C_o:

$$\frac{d}{dt}\left(\frac{1}{2}C_o V_o^2\right) = P_t - P_o$$

Rearranging this relationship yields here as the first-order differential equation for the output voltage:

$$\frac{dV_o}{dt} = \frac{P_t}{C_o V_o} - \frac{I_o}{C_o}$$

This simplified system based equation serves as the basis here for the advanced nonlinear control synthesis.

4. Conventional Direct Power Control (DPC) strategies

They are used to regulate the output voltage by converting voltage tracking errors into instantaneous active power references.

4.1 PI-Based Direct Power Control

In PI-DPC, the required active power reference P^* is calculated from the output voltage error $e = V_o^* - V_o$ using a Proportional-Integral (PI) controller. Once P^* is calculated, the required natured phase shift based ratio δ is determined here by solving the inverted power equation:

$$\delta = 0.5 - \sqrt{0.25 - \frac{f_s L_k P^*}{n V_{in} V_o}}$$

While PI-DPC simplifies control, it shows exhibits here more with significant overshoot natured during load changes as well as in here becomes severely unstable here as if system parameters (such as L_k or C_o) drift from their nominal values.

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4.2 Fuzzy Logic-Based Direct Power Control

To reduce reliance here as on exact mathematical parameters, a Fuzzy Logic Controller (FLC) can replace the PI loop. The FLC structured takes the voltage error (e) as well as its integral ($\int e$) as linguistic inputs (Negative, Zero, Positive). The rule here to be in base is synthesized using a Sugeno-type fuzzy inference system.

Error (e) \ Integral ($\int$e)	**Negative (N)**	**Zero (Z)**	**Positive (P)**
Negative (N)	N	N	Z
Zero (Z)	N	Z	P
Positive (P)	Z	P	P

Table 1: Fuzzy Controller Rule Base

The output is a more of a single-valued constant that updates the power reference P^*. While Fuzzy-DPC demonstrates marginally better than settling times than PI-DPC, both natured methods fail to converge effectively when facing large parameter mismatches.

5. Advanced Super-Twisting Sliding Mode Control (ST-SMC)

To fully take advantage of the natural behavior here in order to eliminate the chattering effect while maintaining the robustness of sliding mode control, the Super-Twisting Algorithm—a complex second-order sliding mode method—is applied.

5.1 Concept of Higher-Order Sliding Modes

First-order sliding modes force the system to reach and maintain s=0 by using discontinuous functions. Second-order sliding modes go a step further by ensuring that both s=0 and its derivative $\dot{s}$=0 are satisfied. The "Twisting Algorithm" is a well-known method for achieving second-order sliding modes, but it requires the calculation of the first derivative of the sliding variable ($\dot{s}$), which can be affected by measurement noise. The Super-Twisting Algorithm addresses this issue by focusing primarily on the sliding variable s and its integral, resulting in a control signal that is continuous over time.

5.2 ST-SMC Formulation

The ST-SMC replaces here as the discontinuous switching term in the power based reference equation with a continuous term u_{st}:

$$u_{st} = -\alpha|s|^{0.5}\text{sgn}(s) + u_2$$

$$\dot{u_2} = -\beta\text{sgn}(s)$$

Where α as well as with β are strictly positive control gains. The final phase-shift in this nature generating power command is thus entirely free of discontinuous based relays.

5.3 Lyapunov Stability for ST-SMC

To ensure that the ST-SMC can handle system disturbances such as unexpected input voltage changes or unaccounted capacitor degradation, the system dynamics are redefined to include a total bounded disturbance ζ, where the magnitude of its time derivative is bounded by φ. Stability is analyzed using a custom quadratic Lyapunov function.

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$$V(s) = \eta^T Q \eta$$

The state vector is $\eta = [|s|^{0.5} \cdot \text{sgn}(s), u_2]^T$, and here Q is a positive definite matrix. Taking the time derivative of V confirms that the system will reach the sliding surface in finite time if the gains are designed according to the constraints.

$$\alpha > \sqrt{2\varphi}$$

$$\beta > \alpha \frac{\alpha^2 + 2\varphi}{\alpha^2 - 2\varphi}$$

Because ST-SMC produces a smoother control variable, the DAB phase shift effectively follows power demands, specifically designed to significantly reduce steady-state voltage ripples and prevent transformer flux bias.

6. Hardware Setup

The control algorithms (PI-DPC, SMC, and ST-SMC) were primarily developed in MATLAB/Simulink and also directly

compiled onto a high-speed dSPACE-1104 controller board.

The power conversion stage used Semikron SKM50GB12T4 IGBT modules, which were driven by integrated SKHI22A circuits. Voltage and current levels were measured using LEM-LV-25-p and LEM-LA-55-p Hall-effect sensors.The high-frequency transformer and auxiliary inductor were both wound around an ETD 54 ferrite core.

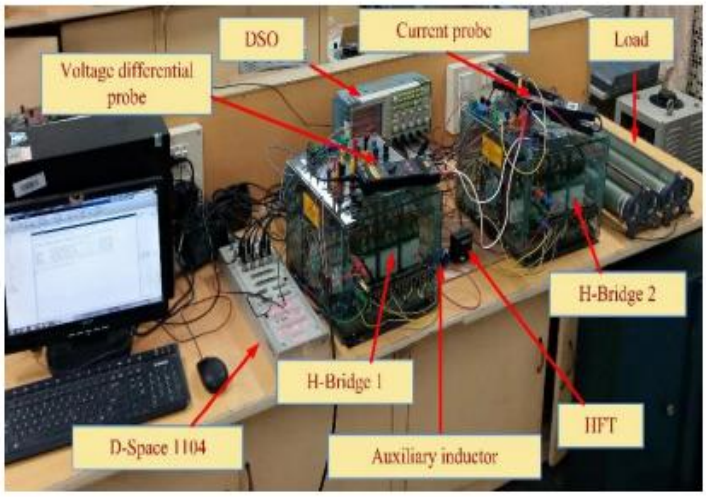


Figure 2 The hardware setup of the DAB with dSPACE-1104

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Parameter	Value
Nominal Input Voltage (V_{in})	150 V / 450 V
Regulated Output Voltage (V_o)	450 V
Transformer Turns Ratio ($1:n$)	1:3 / 1:1
Equivalent Inductance (L_k)	141 μH / 632 μH
Switching Frequency (f_s)	10 kHz
DC-link Capacitors (C_o, C_{in})	1.1 mF
Rated Power	2 kW / 3 kW

Table 2: Experimental DAB Converter Parameters

The controller gains were more to be established as follows: For PI-TVLC, $k_p = 8000$, $k_i = 2000$; for PI-DPC, $k_p = 5000$, $k_i = 800$; for more of ST-SMC + Observer, $k_1 = 1$, $k_2 = 10$, $k_s = 500$, observer gain $w = 50$.

7. Comprehensive Experimental Performance Summary

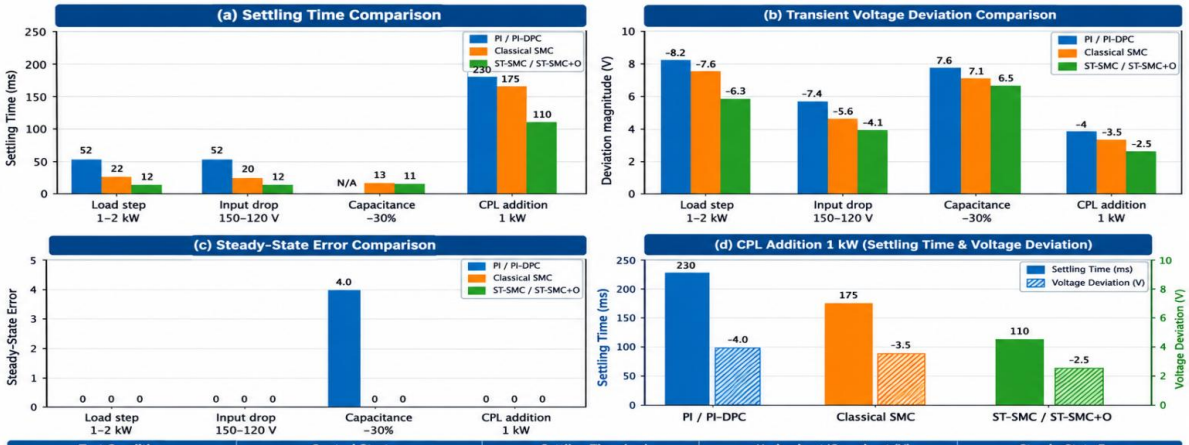
Test Condition	Control Strategy	Settling Time (ms)	Undershoot/Overshoot (V)	Steady-State Error
Load Step 1-2kW	PI	52	-8.2	0
	Classical SMC	22	-7.6	0
	ST-SMC	**12**	**-6.3**	**0**
Input Drop 150-120V	PI	52	-7.4	0
	Classical SMC	20	-5.6	0
	ST-SMC	**12**	**-4.1**	**0**
Capacitance -30%	PI	N/A	7.6	4.0 V
	Classical SMC	13	7.1	0
	ST-SMC	**11**	**6.5**	**0**
CPL Addition 1kW	PI-DPC	230	-4.0	0
	Classical SMC	175	-3.5	0
	ST-SMC+O	**110**	**-2.5**	**0**

Table 3: Comprehensive Experimental Performance Summary

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8. Simulation Graph Analysis



Test Condition	Control Strategy	Settling Time (ms)	Undershoot/Overshoot (V)	Steady-State Error
Load Step 1–2 kW	PI / PI-DPC	52	-8.2	0
	Classical SMC	22	-7.6	0
	ST-SMC / ST-SMC+O	12	-6.3	0
Input Drop 150–120 V	PI / PI-DPC	52	-7.4	0
	Classical SMC	20	-5.6	0
	ST-SMC / ST-SMC+O	12	-4.1	0
Capacitance -30%	PI / PI-DPC	N/A	7.6	4.0
	Classical SMC	13	7.1	0
	ST-SMC / ST-SMC+O	11	6.5	0
CPL Addition 1 kW	PI / PI-DPC	230	-4.0	0
	Classical SMC	175	-3.5	0
	ST-SMC / ST-SMC+O	110	-2.5	0

9. Conclusion

The control of Dual Active Bridge (DAB) DC-DC converters in modern microgrid systems faces challenges due to nonlinear behaviors, parameter variations, and the destabilizing effect of Constant Power Loads. This research clearly shows that traditional linear methods, such as Proportional-Integral (PI) control and basic Direct Power Control (DPC), are not sufficient for handling significant uncertainties, as they often fail to perform well when there are mismatches in system parameters.

Although classical Sliding Mode Control (SMC) is theoretically robust, its real-world application leads to issues like high- frequency chattering, excessive voltage ripple, and switching stress.

The advanced Super-Twisting Sliding Mode Control (ST-SMC) algorithm effectively addresses these problems. By incorporating the integral of the sliding variable, ST-SMC generates a smooth and continuous phase-shift modulation command. Experimental results on a 2 kW hardware setup show that ST-SMC reduces settling times by up to 75% compared to PI controllers, eliminates steady-state voltage ripple, and ensures accurate reference tracking even when capacitance values degrade by 30%. Additionally, the use of a nonlinear disturbance observer removes the need for physical current sensors.

This observer accurately estimates rapid changes in Constant Power Load transients, allowing ST-SMC to dynamically introduce virtual positive impedance. The combination of the observer-based ST-SMC framework offers a reliable, chattering-free, and fault-tolerant control system, making it an ideal solution for next-generation electric vehicles, renewable energy storage, and smart grid systems.

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