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Research on a Control Strategy for Dual Active Bridge Converters Combining Super-Twisting Sliding Mode and Model Predictive Control

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Abstract: Against the backdrop of the “dual-carbon” strategy and the rapid development of renewable energy, Dual Active Bridge (DAB) converters have attracted wide application in energy storage systems and electric vehicles due to their high-efficiency bidirectional power transfer and galvanic isolation. Traditional PI control shows limited dynamic performance under complex operating conditions. Model Predictive Control (MPC), while forward-looking, depends heavily on model accuracy and is prone to steady-state errors under light load or parameter variations. This paper proposes a hybrid control strategy that integrates Super-Twisting Sliding Mode Control (ST-SMC) with MPC. The output of ST-SMC is employed as an error compensation term for MPC, combining predictive optimization with strong robustness. First, a mathematical model of the DAB converter is established and the control law is derived. Next, system stability is verified using the Lyapunov method. Finally, MATLAB/Simulink simulations compare the performance of traditional PI control, standalone MPC, and the proposed hybrid strategy. Simulation results demonstrate that the proposed method outperforms conventional approaches in terms of dynamic response and disturbance rejection, confirming its effectiveness and practical value in renewable energy power systems.

1. Introduction

Against the backdrop of the “dual carbon” strategy, the goals of carbon peaking and carbon neutrality have become central to global energy transition and economic development. With the large-scale integration of renewable sources such as wind and solar power into the grid, power systems now face greater fluctuations, more frequent bidirectional energy flows, and increasingly complex voltage and current dynamics [1-2]. These trends place higher demands on power electronic converters, which must not only achieve high efficiency and power density but also ensure stability and robustness under challenging operating conditions. Such capabilities are essential for maximizing the utilization of clean energy and safeguarding the reliable operation of the grid [3-4].

The Dual Active Bridge (DAB), a high-frequency isolated DC converter, has been widely adopted in renewable generation, energy storage systems, electric vehicle charging, and flexible DC grids, owing to its compact topology, strong bidirectional power transfer capability, and suitability for modular integration [5-6]. However, under complex operating conditions, conventional control methods such as proportional–integral (PI) controllers often suffer from slow dynamic response, significant steady-state errors, and limited disturbance rejection, making them inadequate for the high-performance requirements of modern renewable power systems [7].

In recent years, Model Predictive Control (MPC) has been increasingly applied to DAB converters due to its ability to exploit system models and anticipate future behavior [8]. MPC offers fast dynamic response and superior steady-state performance within a rolling optimization framework, yet its effectiveness relies heavily on model accuracy [9]. When system parameters deviate or the converter operates under light load and other non-ideal conditions, steady-state errors and output oscillations may arise. Complementing MPC, Sliding Mode Control (SMC) has been widely adopted in power electronics for its robustness and adaptability to nonlinear systems [10]. In particular, the Super-Twisting SMC (ST-SMC) [11], which avoids reliance on error derivatives, can effectively suppress the chattering associated with traditional SMC and is well suited to scenarios with discontinuous or rapidly varying voltage and current signals [12-13].

Building on this context, this paper proposes a hybrid control strategy that integrates ST-SMC with MPC. Specifically, the output of ST-SMC is employed as an error compensation term for MPC, combining the predictive accuracy of MPC with the robustness and disturbance rejection of ST-SMC. The proposed method aims to enhance the dynamic response and stability of DAB converters in renewable power applications, particularly under challenging conditions such as rapid operating changes and light-load scenarios, thereby demonstrating improved performance and broader application potential.

2. Fundamental Principles and Operating Characteristics of the DAB under Single-Phase-Shift Control

2.1 Topology of the DAB Converter

The topology of the Dual Active Bridge (DAB) converter is shown in Figure 1. As a high-efficiency isolated DC–DC conversion device, the DAB consists of two full-bridge circuits, one on the high-voltage side and the other on the low-voltage side. These two bridges are interconnected through a high-frequency transformer, which provides galvanic isolation and enables energy transfer. By precisely controlling the phase shift between the two bridges, the DAB achieves bidirectional power flow, thereby regulating both the magnitude and direction of power transfer. The voltage across the inductor L is determined by the difference between V_1 and the reflected secondary-side voltage nV_2. Based on this, the equivalent circuit of the DAB can be derived, as illustrated in Figure 2.

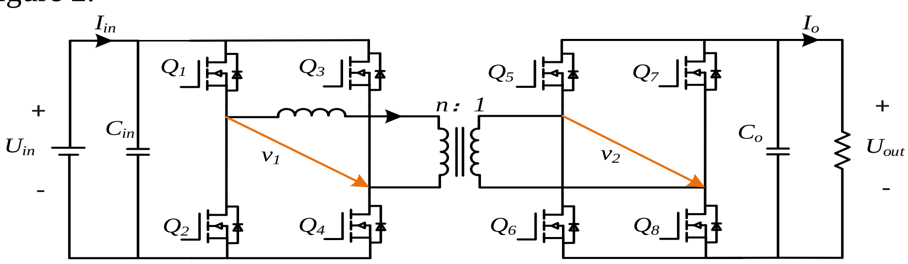

Figure 1 Topology diagram of DAB

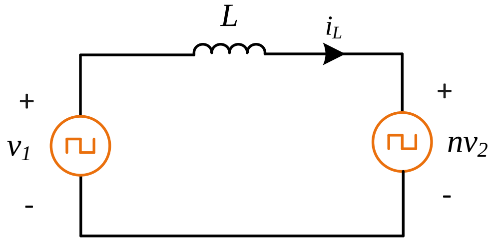

Figure 2 Equivalent circuit of DAB converter

2.2 Principle of Single-Phase-Shift (SPS) Control

Figure 3 illustrates the operating waveforms of the DAB converter under SPS control. Here, QI and QII represent the gate signals of the switches on the two bridges. V_1 denotes the output voltage of the primary-side full bridge, while nV_2 represents the secondary-side bridge voltage reflected to the primary through the transformer. The inductor current is denoted as iL, T_s is the switching period, and D is the normalized phase shift expressed as a fraction of half the switching cycle. When $0 \leq D \leq 1$, power flows from the primary side to the secondary side. Conversely, when $-1 \leq D < 0$, power flows from the secondary to the primary side. Thus, by adjusting D, the direction and amount of power transfer can be effectively controlled.

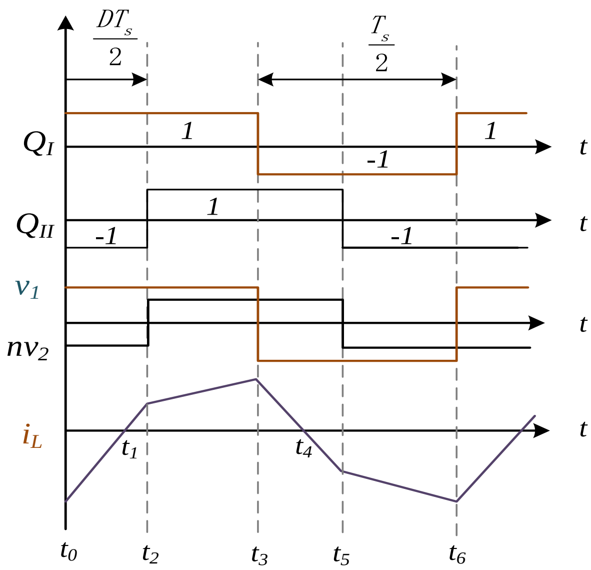

Figure 3 Operating waveforms under SPS control

3. Controller Design

3.1 Traditional Model Predictive Control (MPC)

This study develops a model predictive control (MPC) strategy for the Dual Active Bridge (DAB) converter operating under single-phase-shift (SPS) modulation. Building on the analysis of the DAB topology and operating modes presented in Chapter 2, the system model is formulated as follows:

$$C_o \frac{dU_o}{dt} = \frac{nU_{in}}{2f_s L} D(1-|D|) - I_o \tag{1}$$

The continuous-time model is discretized using the Euler method, resulting in the following discrete mathematical model:

$$C_o \frac{U_o(k+1) - U_o(k)}{T_c} = \frac{nU_{in}(k)}{2f_s L} D(1-|D|) - I_o(k) \tag{2}$$

To achieve stable tracking of the output voltage with respect to its reference value and to guarantee non-negativity of the cost function, the cost function is defined in quadratic form:

$$J = \left[U_o(k+1) - U_{oref}(k)\right]^2 = \left[U_o(k) + \frac{nU_i(k)}{2LCf_s^2} D(1-D) - \frac{U_o(k)}{RCf_s} - U_{oref}(k)\right]^2 \tag{3}$$

Where represents the reference output voltage (V). When the cost function reaches its minimum, the deviation between the actual and reference output voltages is minimized, thereby ensuring optimal control performance.

Taking the derivative of the cost function yields:

$$\frac{dJ}{dD(k)} = -\frac{nU_{in}(k)}{f_s^2 LC_o}\left[U_{oref}\left(1 - U_o^*(k+1)\right)\right]\left[1 - 2D(k)\right] \tag{4}$$

Where the normalized form of the output prediction function is expressed as:

$$U_o^*(k+1) = \frac{U_o(k+1)}{U_{oref}} \tag{5}$$

When Uoref = U₀(k+1), the cost function reaches its minimum regardless of the value of D(k):

$$D_o(K) = \frac{1 - \sqrt{1 - 4\alpha}}{2} \tag{6}$$

$$\alpha = \frac{2LCf_s^2\left[\frac{I_o(k)}{Cf_s} - U_o(k) + U_{oref}(k)\right]}{nU_i(k)} \tag{7}$$

To improve the prediction accuracy, a voltage error compensation term △U0(k) is introduced, and the optimal phase shift ratio D0(k) is further obtained:

$$D_o(k) = \frac{1}{2} - \sqrt{\frac{1}{4} - \frac{2LCf_s^2}{nU_i(k)}\left[\frac{i_o(k)}{Cf_s} - U_o(k) + U_{oref}(k) + \Delta U_o(k)\right]} \tag{8}$$

3.2 Design of Super-Twisting Sliding Mode Control

Sliding mode control (SMC) has been widely applied in power electronics because of its simple structure and strong robustness. However, conventional SMC suffers from inherent chattering due to the discontinuous nature of its control law.

The super-twisting sliding mode algorithm introduces a continuous function into the traditional SMC framework by shifting the discontinuous sign function into the second derivative. This approach effectively suppresses chattering, ensures continuity, and enhances overall system performance. To further improve system robustness, this study proposes replacing the conventional error compensation term △U0(k) with the output of the super-twisting sliding mode controller (ST-SMC).

The voltage error and sliding surface are defined as follows:

$$e(k) = U_{oref}(k) - U_o(k) \quad s(k) = \alpha e(k) + \beta \sum_{j=0}^{k} e(j) T_s, \alpha, \beta > 0 \tag{9}$$

s is a “PI-type” sliding surface, where the proportional term αe accelerates the response, and the integral term β∑e eliminates steady-state error while suppressing deviations caused by load disturbances.

The discrete form of the super-twisting sliding mode can be expressed as:

$$\begin{cases} u_{st}(k) = -k_1 \, | \, s(k) \, |^{\frac{1}{2}} \, sgn\left(s(k)\right) + U_1\left(k\right) \\ U\left(k+1\right) = -k_2 sgn\left(s(k)\right) \end{cases} \tag{10}$$

With k1, k2>0, the sliding surface s(k) converges to zero in finite time under suitable conditions.

The nonlinear term ensures that the rate of change in the control input decreases smoothly as the error diminishes, while the integral channel of U realizes a second-order sliding mode, significantly reducing chattering.

By integrating ST-SMC into the model predictive controller, a hybrid control strategy is developed:

$$D_o(k) = \frac{1}{2} - \sqrt{\frac{1}{4} - \frac{2LCf_s^2}{nU_i(k)}\left[\frac{i_o(k)}{Cf_s} - U_o(k) + U_{oref}(k) + u_{ST}(k)\right]} \tag{11}$$

3.3 Stability Analysis of ST-SMC

The stability of the super-twisting sliding mode control is verified based on Lyapunov stability theory. A candidate Lyapunov function is selected:

$$V(s, v) = a \, | \, s \, |^{3/2} + \frac{1}{2} b v^2, a > 0, b > 0 \tag{12}$$

When s=0 and v=0, V=0; in all other cases, V>0, so V is a positive - definite function.

By differentiating the Lyapunov function and combining it with the system dynamic equation (10), we can obtain:

$$\dot{V} = \frac{3a}{2} \, | \, s \, |^{1/2} \, d(t) - \frac{3a}{2} k_1 \, | \, s \, | + sgn(s) \cdot v \left(\frac{3a}{2} \, | \, s \, |^{1/2} - bk_2 \right) \tag{13}$$

Let $k_1 > \frac{d(t)}{|s|^{\frac{1}{2}}}$ and $\frac{3a}{2}|s|^{\frac{1}{2}} = bk_2$. At this time, the remaining term $-\frac{3a}{2}k_1|s| < 0$, satisfying $\dot{V}<0$. Since the Lyapunov function V(s, v) is positive - definite and its time derivative $\dot{V}<0$, according to the Lyapunov stability theorem, the continuous - time ST - SMC system converges to the sliding mode surface s=0 in finite time, and the system is stable.

The control flow chart is shown in Figure 4:

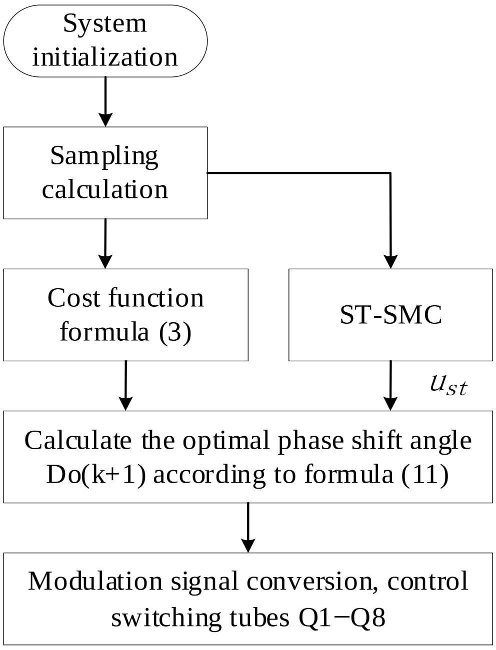

Figure 4 Control system block diagram

4. Simulation Results and Analysis

To evaluate the effectiveness of the proposed control strategy that integrates ST-SMC with MPC, a simulation model was developed in the MATLAB/Simulink environment. The load voltage performance of the proposed method was compared with that of conventional PI control and standard MPC. The simulation parameters are summarized in Table 1.

Table 1 Main Circuit Parameters

Parameter	Value
Input voltage / V	100
Load voltage reference / V	60
Inductance/μH	50
Output capacitance/μF	1000
Load resistance/Ω	15
Switching frequency/kHZ	1
K_p	0. 01
K_i	5

4.1 Initial Dynamic Response

Figure 5 shows that under conventional PI control, the output voltage exhibits an overshoot of 10 V and requires 96 ms to stabilize. Since parameter tuning cannot simultaneously ensure fast response and stability, its initial performance is limited. In contrast, Figure 6 shows MPC achieves stable output within 13 ms without noticeable overshoot, benefiting from rolling optimization based on the predictive model. Figure 7 shows the hybrid ST-SMC–MPC method achieves voltage stabilization in only 1. 5 ms, combining the strong robustness of the super-twisting sliding mode with the optimization capability of MPC, thus delivering the fastest initial response.

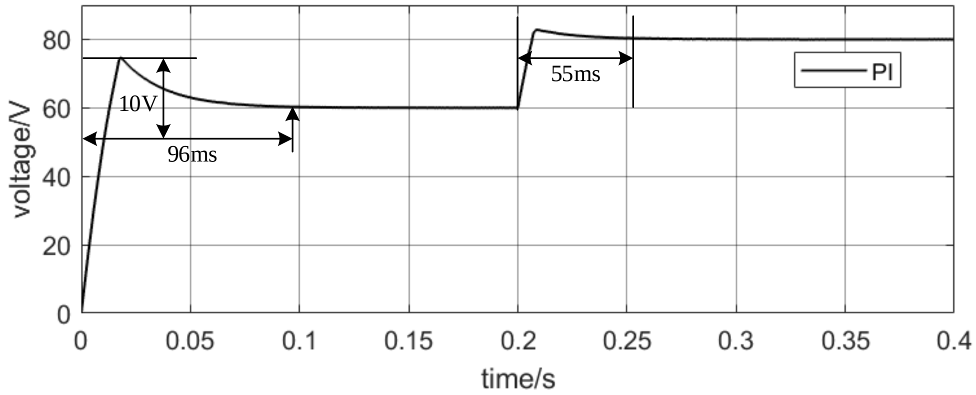

Figure 5 PI

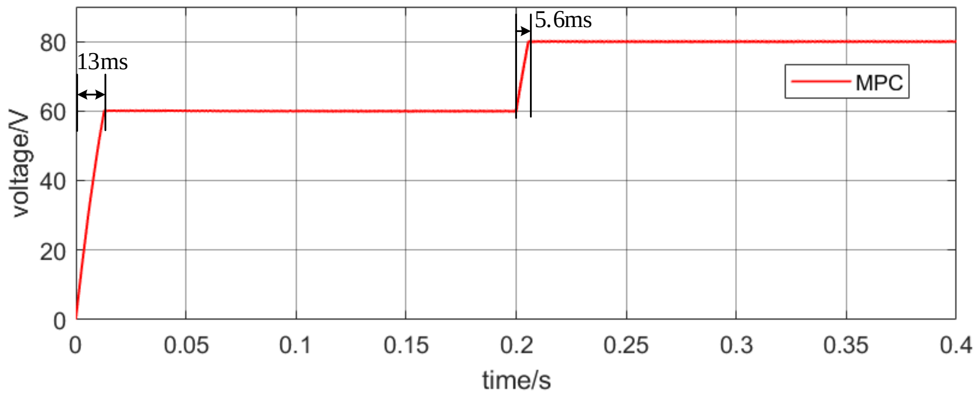

Figure 6 MPC

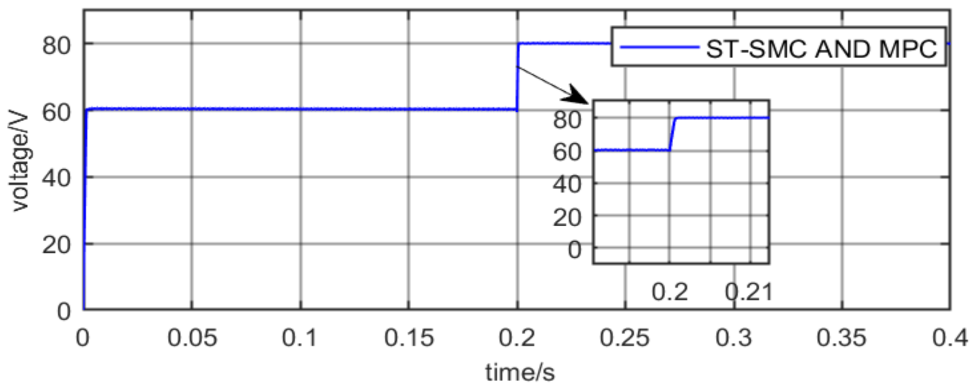

Figure 7 ST-SMC and MPC

4.2 Voltage Disturbance Test

As shown in Figure 8, traditional PI control exhibits large voltage fluctuations under disturbances and requires 55 ms to return to stability, indicating limited disturbance rejection capability. Figure 9 shows that MPC achieves recovery within 5. 6 ms, demonstrating stronger disturbance rejection than PI. By predicting and optimizing control actions in real time, it responds more effectively to disturbances, though there remains room for improvement. As shown in Figure 10, the combined ST-SMC and MPC method restores voltage stability within only 0. 92 ms. The synergy between the strong disturbance resistance of sliding mode control and the optimization capability of MPC delivers the fastest and most stable disturbance suppression.

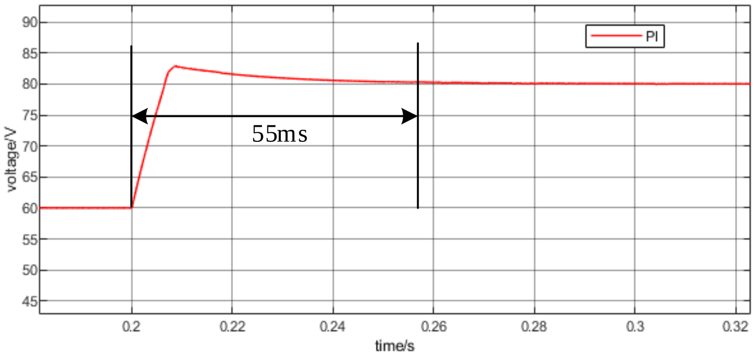

Figure 8 PI

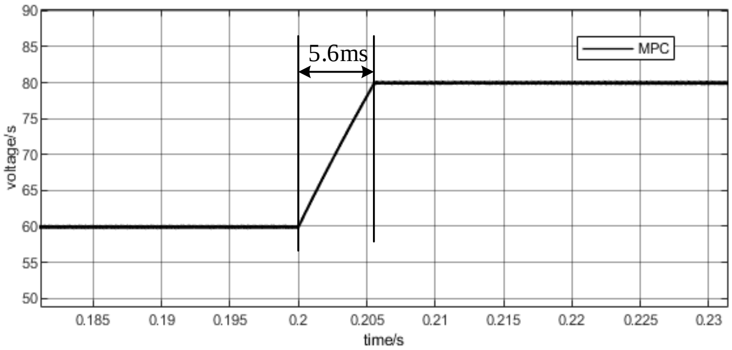

Figure 9 MPC

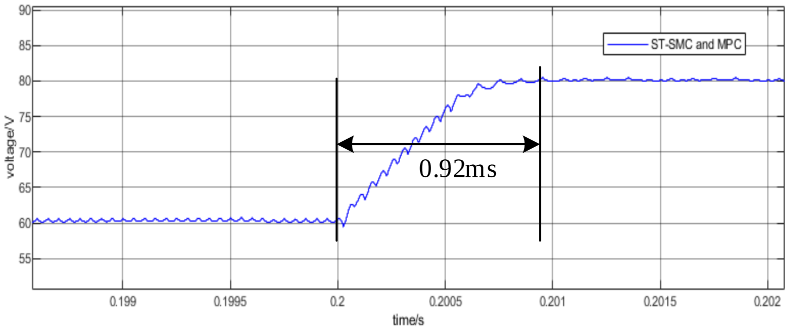

Figure 10 ST-SMC and MPC

5. Conclusion

This paper presents a model predictive controller (MPC) enhanced with super-twisting sliding mode control (ST-SMC) for phase-shift control of dual active bridge (DAB) converters. The proposed method preserves the predictive accuracy and foresight of MPC while incorporating the strong robustness and disturbance rejection capability of ST-SMC. Both theoretical analysis and simulation results demonstrate that the hybrid strategy outperforms conventional PI and standalone MPC in terms of rapid initial dynamic response and fast recovery under disturbances. These findings highlight the advantages of the hybrid control strategy in achieving both fast response and strong resilience to disturbances. The method is particularly well suited to scenarios involving severe operating condition variations or significant modeling uncertainties, showing promising potential for practical engineering applications.

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