

DISTURBANCE COMPENSATED ROBUST SLIDING MODE VOLTAGE CONTROL STRATEGY FOR DUAL ACTIVE BRIDGE CONVERTER

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ABSTRACT. *To address lumped disturbances caused by load variations, parameter uncertainties, and unmodeled dynamics, this paper proposes a novel reaching-law-based sliding mode control strategy incorporating an improved third-order extended state observer (ST-TESO-NSMC) for output voltage regulation of dual active bridge (DAB) converters. First, an improved third-order extended state observer is introduced to replace the conventional physical model, and the estimated disturbances are actively compensated in a feedforward manner, thereby reducing the dependence of the control system on parameter uncertainties. Second, to overcome the slow convergence and severe chattering associated with conventional reaching laws, a novel reaching law is developed, in which the control gain gradually decreases as the system states evolve along the sliding surface, effectively suppressing chattering. Finally, based on the Lagrange multiplier method (LMM), the optimal phase-shift combination that minimizes current stress under a fixed power constraint is derived and integrated with the proposed control strategy. Experimental results demonstrate that the proposed method achieves fast voltage tracking, effective current stress optimization, strong disturbance rejection capability, and enhanced system robustness.*

Keywords: DAB, Observer, Robustness, Current stress optimization, LMM

1. Introduction. Dual active bridge (DAB) converters have been widely applied in electric vehicles, DC microgrids, and energy storage systems due to their bidirectional power transfer capability, galvanic isolation, and high power density [1]. However, owing to the strong nonlinearity, time-varying parameters, and multiple operating modes of the DAB converter [2], its output voltage is highly susceptible to load disturbances, component parameter uncertainties, and unmodeled dynamics, which poses significant challenges to high-performance voltage regulation and stable system operation [3].

Conventional proportional-integral (PI) control strategies are widely adopted for DAB converter voltage regulation due to their simple structure and ease of implementation. Under high switching frequency conditions, PI controllers can ensure satisfactory steady-state

tracking performance. Nevertheless, during load transients or rapid operating condition changes, PI controllers generally exhibit slow transient responses [4]. Moreover, improving dynamic performance often requires increasing the control gain, which may induce steady-state oscillations or even compromise system stability. To overcome the limitations of fixed-parameter PI controllers, a proportional-integral-derivative self-tuning (PID-ST) control strategy has been further proposed. By adjusting the controller parameters online, this method enhances the adaptability of the system under varying operating conditions [5]. Sliding mode control (SMC) has been introduced into DAB converter control owing to its strong robustness against parameter uncertainties and external disturbances. However, the discontinuous switching term in its control law often causes chattering, which not only degrades steady-state performance but also increases the stress on power devices. In [6], a super-twisting sliding mode control scheme was proposed to regulate the output voltage of a dual active bridge converter by calculating the phase-shift ratio according to the converter voltage dynamics and power transfer characteristics, thereby improving robustness and reducing chattering compared with conventional SMC. However, the aforementioned control methods generally rely on accurate mathematical models to achieve system performance optimization and require additional sensors for state information acquisition and feedback, thereby increasing the hardware cost and implementation complexity of the system. To reduce the dependence on sensors, related studies have further introduced observers, in which load variations and input voltage fluctuations are uniformly modeled as equivalent disturbances for online estimation and compensation. Based on this idea, [7] designed a linear extended state observer (LESO) within the active disturbance rejection control framework. By estimating and compensating generalized disturbances in real time, the voltage regulation performance and robustness of the system were improved. Nevertheless, the performance of the LESO is highly sensitive to the bandwidth parameter. Although increasing the bandwidth can accelerate disturbance tracking, it may simultaneously amplify measurement noise and introduce high-frequency oscillations, thereby degrading system stability and control accuracy [8].

From the perspective of modulation strategies, phase-shift modulation plays a crucial role in determining the current stress and efficiency of DAB converters. Traditional single phase-shift (SPS) modulation achieves power transfer solely through outer phase shift [9]. When the voltage transfer ratio deviates from the transformer turns ratio, the inductor current stress increases significantly [10], making SPS modulation unsuitable for wide operating ranges [11, 12]. Dual phase-shift (DPS) modulation simultaneously introduces the same internal phase-shift ratio D_1 into the primary and secondary H-bridges, thereby enlarging the power regulation range of the converter [13]. However, as pointed out in [14], this modulation method inevitably narrows the soft-switching operating range. [15] further studied the triple phase-shift (TPS) modulation strategy. By introducing an additional phase-shift variable D_3 , TPS modulation provides enhanced capability in current stress reduction and circulating power optimization. Nevertheless, the increased control degrees of freedom considerably complicate the operating mode analysis and parameter optimization process, which poses challenges for practical engineering implementation. In contrast, extended phase-shift (EPS) modulation introduces an inner phase-shift ratio D_1 into the primary-side bridge, thereby providing greater flexibility for current stress optimization without excessively increasing the modulation complexity [16].

Inspired by the advantages of sliding mode control and observer-based methods, this paper proposes a robust sliding mode control strategy based on EPS modulation for output voltage regulation of the DAB converter without requiring additional current sensors. First, a novel sliding mode control (NSMC) strategy is developed to achieve fast convergence and chattering suppression without increasing system complexity. Second,

to reduce the dependence on sensors, a super-twisting third-order extended state observer (ST-TESO) is proposed. By incorporating super-twisting terms into the conventional third-order linear extended state observer (TLESO), the disturbance estimation speed is improved, and the extended states are introduced into the control law as feedforward compensation terms to enhance system robustness. Finally, the Lagrange multiplier method is employed to derive the optimal current stress solution under the corresponding power constraints [17, 18]. Through the proposed strategy, the current stress of the converter is effectively reduced, the power transfer efficiency is improved, and the fluctuations of the DC bus voltage and load are significantly suppressed, thereby enhancing system robustness while simultaneously improving the dynamic performance and efficiency of the converter.

The remainder of this paper is organized as follows. Section 2 introduces the topology of the dual active bridge converter and analyzes the operating waveforms under extended phase-shift (EPS) modulation. Section 3 presents the controller design and derives the optimal phase-shift ratio for minimizing current stress based on the Lagrange multiplier method (LMM). Section 4 validates the effectiveness of the proposed method through simulations from both steady-state and dynamic perspectives. Finally, Section 5 concludes the paper and discusses its limitations as well as directions for future research.

2. Preliminaries.

2.1. Topology of the DAB converter. The topology of the DAB converter is shown in Figure 1. The converter consists of two full-bridge circuits, denoted as H_1 and H_2 , which are interconnected through a high-frequency transformer $TX1$ and an equivalent series inductance L_r . The output voltages of bridges H_1 and H_2 are represented by U_{ab} and U_{cd} , respectively. The dc-side voltages of the primary and secondary bridges are denoted as U_1 and U_2 , respectively. An input-side capacitor C_1 and an output-side capacitor C_2 are employed to stabilize the dc-link voltage. The load is modeled as a resistive element R_2 connected to the secondary side. Switches Q_1 - Q_4 form the primary-side full bridge H_1 , while switches Q_5 - Q_8 form the secondary-side full bridge H_2 .

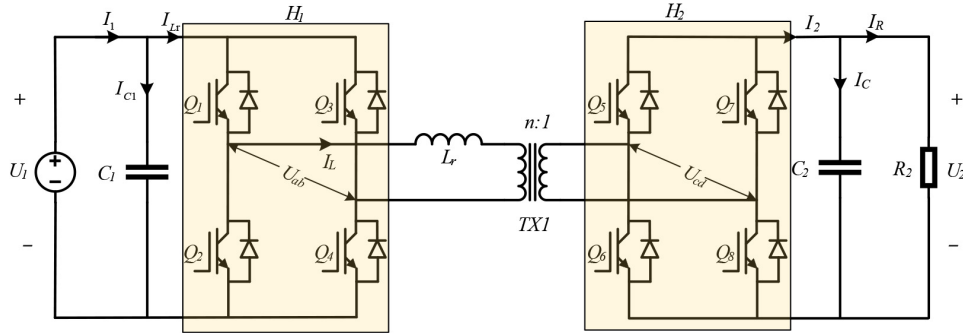


FIGURE 1. Topology of the DAB converter

2.2. Extended phase-shift modulation. EPS modulation is a phase-shift control strategy for the dual active bridge converter. Unlike single phase-shift modulation, EPS introduces not only an outer phase-shift ratio D_2 between the two full bridges, but also an inner phase-shift ratio D_1 on the primary-side H-bridge. The voltage conversion ratio is defined as $r = U_1/(nU_2)$, where n denotes the transformer turns ratio. By properly adjusting the internal phase shift D_1 and the external phase shift D_2 , bidirectional power transfer can be achieved. In this paper, forward power transfer is taken as an example for analysis, while reverse power transfer can be analyzed in a similar manner. The

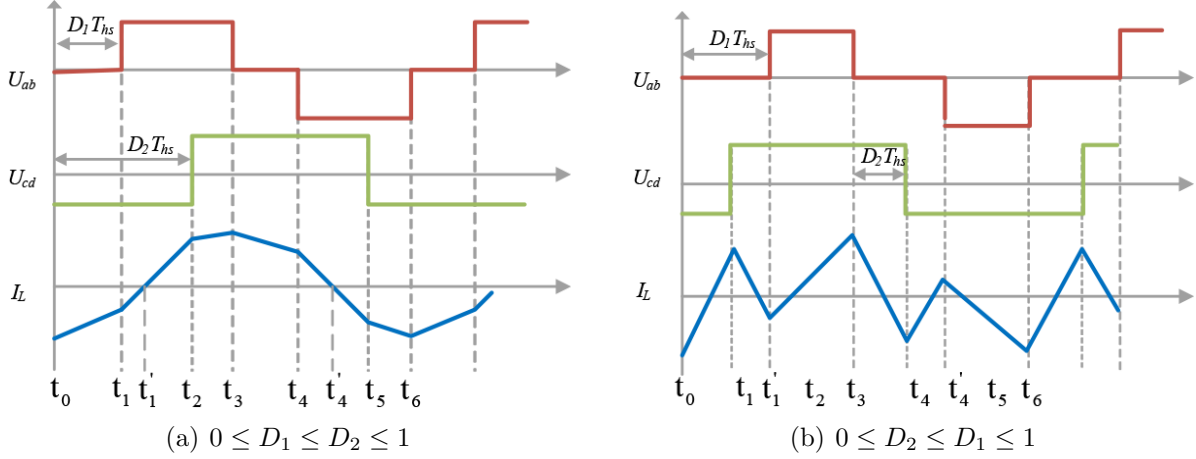


FIGURE 2. Operating waveform

corresponding voltage and current waveforms under EPS modulation are illustrated in Figure 2.

When $0 \leq D_1 \leq D_2 \leq 1$, the maximum inductor current occurs at t_3 . When $0 \leq D_2 \leq D_1 \leq 1$, the maximum inductor current may occur at either t_3 or t_1 . Accordingly, the inductor current stress I_L is normalized as

$$I_E^* = \frac{I_L}{I_B} = \begin{cases} 2(r(1-D_1) + 2D_2 - 1) & 0 \leq D_1 \leq D_2 \leq 1 \\ \max(2(r(D_1-1) + 1), 2(r(1-D_1) + 2D_2 - 1)) & 0 \leq D_2 \leq D_1 \leq 1 \end{cases} \quad (1)$$

where $I_B = \frac{nU_2}{8L_r f_s}$ denotes the base value of the inductor current, used as a normalization reference for evaluating current stress. f_s denotes the switching frequency.

The transmission power P_E is normalized as

$$P_E^* = \frac{P_E}{P_B} = \begin{cases} 2(2D_1D_2 - D_1 - D_1^2 - 2D_2^2 + 2D_2) & 0 \leq D_1 \leq D_2 \leq 1 \\ 2(2D_2 - D_1 + D_1^2 - 2D_1D_2) & 0 \leq D_2 \leq D_1 \leq 1 \end{cases} \quad (2)$$

where $P_B = \frac{nU_1U_2}{8L_r f_s}$ denotes the base value of the transmitted power, used as the normalization reference.

3. Control Design.

3.1. Ultra-local model of the DAB converter. Considering the secondary side of the transformer as the output side, the equivalent circuit of the DAB converter output stage is shown in Figure 1. Let U_2 denote the output voltage, I_2 the average output current, I_C the capacitor current, and I_R the load current. By Kirchhoff's current law, $I_C = I_2 - I_R$. Thus, the output voltage dynamics can be expressed as

$$C_2 \frac{dU_2}{dt} = \frac{P_E}{U_2} - I_R \quad (3)$$

Consequently, the output voltage dynamics are obtained as

$$\dot{U}_2 = \frac{nU_1}{8L_r f_s C_2} P_E^* - \frac{I_R}{C_2} \quad (4)$$

In order to mitigate the reliance on accurate system parameters, the nonlinear system in Equation (4) is substituted by an ultra-local model. This replacement enhances robustness of the converter under disturbances and parameter uncertainties.

$$\dot{U}_2 = b_1 u + f_r \quad (5)$$

where $b_1 = \frac{nU_1}{8L_r f_s C_2}$ is the nominal control gain, $u = P_E^*$, which is the control input of the system, and f_r denotes lumped disturbances including load variation and modeling errors.

3.2. Design of ST-TESO. Load variations, parameter mismatches, and external disturbances can cause fluctuations in the converter output voltage. To estimate and compensate for these effects, an observer is designed. The LESO introduces an extended state $\mathbf{x} = [U_2, f_r]^T$ to represent the lumped disturbance, while the TLESO further augments the state with $\dot{f}_r$, $\mathbf{x} = [U_2, f_r, \dot{f}_r]^T$, improving disturbance rejection by predicting disturbance trends.

However, a fixed linear injection gain limits the observer's ability to quickly handle abrupt or highly nonlinear disturbances: increasing the gain accelerates convergence but amplifies noise and induces chattering. To address this, a super-twisting term is added to make the injection gain error-dependent, enabling fast convergence for large errors while maintaining high precision and robustness near the equilibrium.

Consider the following third-order observer with both linear and super-twisting terms:

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 + b_1 u + l_1 e_1 + k_1 |e_1|^{1/2} \text{sgn}(e_1) \\ \dot{\hat{x}}_2 = \hat{x}_3 + l_2 e_1 + k_2 |e_1|^{1/2} \text{sgn}(e_1) \\ \dot{\hat{x}}_3 = l_3 e_1 + k_3 \text{sgn}(e_1) \end{cases} \quad (6)$$

where $e_1 = x_1 - \hat{x}_1$ is the output estimation error, and l_i, k_i are positive observer gains. The observer states $\hat{x}_1, \hat{x}_2$, and $\hat{x}_3$ are used to estimate the output voltage U_2 , the lumped disturbance f_r , and its time derivative $\dot{f}_r$, respectively.

The plant is assumed to be described by $\dot{x}_1 = b_1 u + x_2, \dot{x}_2 = x_3, \dot{x}_3 = \xi(t), \xi(t) \leq \Delta$.

Error dynamics are given by

$$\begin{cases} \dot{e}_1 = e_2 - l_1 e_1 - k_1 |e_1|^{1/2} \text{sgn}(e_1) \\ \dot{e}_2 = e_3 - l_2 e_1 - k_2 |e_1|^{1/2} \text{sgn}(e_1) \\ \dot{e}_3 = \xi(t) - l_3 e_1 - k_3 \text{sgn}(e_1) \end{cases} \quad (7)$$

Choose the Lyapunov function:

$$V = \frac{1}{2} e_1^2 + \frac{1}{2} e_2^2 + \frac{1}{2} e_3^2 \quad (8)$$

$$\begin{aligned} \dot{V} = & -l_1 e_1^2 - k_1 |e_1|^{3/2} + e_1 e_2 + e_2 e_3 - l_2 e_1 e_2 - k_2 |e_1|^{1/2} e_2 \text{sgn}(e_1) + \xi(t) e_3 \\ & - l_3 e_1 e_3 - k_3 e_3 \text{sgn}(e_1) \end{aligned} \quad (9)$$

Using Young's inequality, for any $\epsilon > 0$, $ab \leq \frac{\epsilon}{2} a^2 + \frac{1}{2\epsilon} b^2$, and collecting like terms, we obtain

$$\begin{aligned} \dot{V} \leq & -\left(\frac{3l_1}{4} + \frac{l_2 + l_3}{2}\right) e_1^2 + \left(\frac{1}{l_1} - \frac{l_2}{4}\right) e_2^2 + \left(\frac{1}{l_2} - \frac{l_3}{2} + \frac{1}{2}\right) e_3^2 \\ & - k_1 |e_1|^{3/2} - k_2 |e_1|^{1/2} |e_2| - k_3 |e_3| + \frac{1}{2} \Delta^2 \end{aligned} \quad (10)$$

If the gains satisfy $l_2 > \frac{4}{l_1}, l_3 > \frac{2}{l_2} + 1$, then there exists $\alpha > 0$ such that

$$\dot{V} \leq -\alpha \|e\|^2 - k_1 |e_1|^{3/2} - k_2 |e_1|^{1/2} |e_2| - k_3 |e_3| + \frac{1}{2} \Delta^2 \quad (11)$$

Therefore, the estimation error system is stable in the Lyapunov sense. In particular, when $\Delta = 0$, the error dynamics are finite-time stable and e_1, e_2 , and e_3 converge to the origin in finite time. When $\Delta > 0$, the estimation errors are uniformly ultimately bounded, and the size of the ultimate bound is proportional to the disturbance magnitude Δ .

3.3. Design of the novel reaching law. In sliding mode control, exponential reaching laws are widely used due to their simple structure and fast convergence. The core idea is to drive the sliding variable toward the sliding surface at a preset rate through an exponential reaching term, thereby improving transient performance. However, conventional exponential reaching laws typically employ fixed gains, so the reaching dynamics remain unchanged throughout the control process. Under load steps, parameter mismatch, or strong disturbances, a large reaching gain is often required to achieve fast response, which inevitably amplifies chattering and increases sensitivity to sensor noise. Conversely, using a small gain to improve steady-state performance significantly slows convergence in the large-error phase, making it difficult to balance speed and precision.

To address this issue, a novel reaching law is proposed by introducing an error-dependent nonlinear modulation mechanism into the exponential reaching framework. Instead of relying on constant gains, the reaching speed is continuously adjusted based on the sliding variable and system state, such that the control action is strengthened when the error is large and reduced when the error is small. As a result, the proposed reaching law achieves fast transient response while effectively suppressing chattering.

$$u_{sw} = -\frac{k_{1,sw} \text{sat}(s)}{1 + \gamma \left[\beta + \left(1 + \frac{1}{|x|^2 + \varepsilon} - \beta \right) e^{-\alpha|s|} \right]} - \frac{k_{2,sw} s}{1 + |s|^\eta} \quad (12)$$

where s is the sliding variable, $k_{1,sw}$ and $k_{2,sw}$ are positive switching gains, and $\text{sat}(\cdot)$ denotes the saturation function. The parameters α , β , γ , η , and ε are positive design constants.

The reaching law consists of a state-dependent reaching term and a nonlinear damping term. The denominator of the reaching term varies exponentially with $|s|$: when $|s|$ is large, $e^{-\alpha|s|}$ approaches zero, so the denominator tends to $1 + \gamma\beta$, resulting in a larger effective gain and enabling fast convergence under large errors or severe disturbances. As $|s|$ decreases, $e^{-\alpha|s|}$ increases, and the denominator approaches $1 + \gamma\left(1 + \frac{1}{|x|^2 + \varepsilon}\right)$, which continuously reduces the effective gain and weakens the control action, thus suppressing chattering near the sliding surface. The state-dependent term $\frac{1}{|e_v|^2 + \varepsilon}$ scales the control gain with the voltage tracking error $e_v = \hat{U}_2 - U_{ref}$. When the error is large, the term decreases, leading to a larger effective gain for faster correction; when the error is small, the term increases, thus avoiding excessive gain and reducing chattering. The second term is a nonlinear damping component: it provides strong dissipation when $|s|$ is large to suppress overshoot, while it vanishes as $|s| \rightarrow 0$, which benefits steady-state accuracy.

The sliding surface is designed as

$$s = k_p E + k_i \int E dt \quad (13)$$

Here, $E = U_2 - U_{ref}$, and $k_p, k_i > 0$ are the sliding surface gains determining the convergence rate of the tracking error. The integral term is introduced to eliminate steady-state error.

By differentiating Equation (13) and substituting Equation (5), the equivalent control input is obtained as

$$u_{eq} = \frac{1}{b_1} \left(-\frac{k_i}{k_p} E - f_r \right) \quad (14)$$

Sliding-mode control is generally implemented using the equivalent sliding-mode approach, and the resulting control law is given by

$$u = \frac{1}{b_1} \left(-\frac{k_i}{k_p} E - f_r \right) - \frac{k_{1,sw} \text{sat}(s)}{1 + \gamma \left[\beta + \left(1 + \frac{1}{|x|^{2+\varepsilon}} - \beta \right) e^{-\alpha|s|} \right]} - \frac{k_{2,sw} s}{1 + |s|^\eta} \quad (15)$$

3.4. Stability proof. The Lyapunov function is selected as $V = \frac{1}{2}s^2$.

Therefore, it can be obtained that

$$\dot{V} = -k_p b_1 s \left(\frac{k_{1,sw} \text{sat}(s)}{1 + \gamma \left[\beta + \left(1 + \frac{1}{|x|^{2+\varepsilon}} - \beta \right) e^{-\alpha|s|} \right]} + \frac{k_{2,sw} s}{1 + |s|^\eta} \right) \quad (16)$$

It can be obtained that $\beta + \left(1 + \frac{1}{|x|^2} - \beta \right) e^{-\alpha|s|} > 0$, and $\text{sat}(s) > 0$. Therefore, $\dot{V} \leq 0$ holds, which implies that the proposed exponential reaching law satisfies the Lyapunov stability condition, ensuring the asymptotic stability of the system.

3.5. Hybrid control of sliding mode control and current stress optimization.

Based on the analysis of current stress characteristics under EPS modulation presented in Section 2.2, it is shown that, under a given power transfer constraint, minimizing the inductor current stress by optimizing the inner and outer phase shifts constitutes an equality-constrained optimization problem. The Lagrange multiplier method, as a well-established technique for equality-constrained optimization, is therefore adopted to solve the minimum current stress problem under EPS modulation. Compared with conventional analytical differentiation approaches, LMM offers clear advantages in terms of computational complexity and solution efficiency.

Using this method, the optimization problem is transformed into a polynomial-solving problem. In this study, the equality constraint corresponds to the power transfer requirement, the inequality constraint enforces the zero voltage switching (ZVS) condition, and the objective function is defined as the normalized current stress. Accordingly, the Lagrangian function under the Karush-Kuhn-Tucker (KKT) conditions can be generally expressed as

$$L(D_1, D_2, \lambda_i, \mu_j) = I_E^*(D_1, D_2) + \sum_{i=1} \lambda_i h_i(x) + \sum_{j=1} \mu_j g_j(x) \quad (17)$$

In Equation (17), λ_i denotes the Lagrange multiplier associated with the equality constraint $h_i(x)$, which enforces constant power transfer and satisfies $\lambda_i \neq 0$, while μ_j represents the multiplier corresponding to the inequality constraint $g_j(x)$ for achieving ZVS, with $\mu_j \geq 0$.

By taking the partial derivatives of Equation (17), the optimal phase-shift combination (D_1, D_2) can be obtained.

$$(D_1, D_2) = \begin{cases} \begin{cases} D_1 = (r-1) \sqrt{\frac{1-P_E^*}{r^2-2r+2}} \\ D_2 = \frac{1}{2} + \frac{r-2}{2} \sqrt{\frac{1-P_E^*}{r^2-2r+2}} \end{cases} & \frac{2r-2}{r^2} \leq P_E^* \leq 1 \\ \begin{cases} D_1 = 1 - \sqrt{\frac{P_E^*}{2(r-1)}} \\ D_2 = \frac{1}{2} + \frac{r-2}{2} \sqrt{\frac{P_E^*}{2(r-1)}} \end{cases} & \frac{2r-2}{(3r-2)^2} \leq P_E^* < \frac{2r-2}{r^2} \\ \begin{cases} D_1 = \frac{4r-3-\sqrt{1-(4r-2)P_E^*}}{4r-2} \\ D_2 = \frac{3r-2-r\sqrt{1-(4r-2)P_E^*}}{4r-2} \end{cases} & 0 \leq P_E^* < \frac{2r-2}{(3r-2)^2} \end{cases} \quad (18)$$

As illustrated in Figure 3, the proposed control strategy comprises three modules: (i) the ST-TESO observer; (ii) a sliding mode controller based on the improved exponential reaching law, providing fast response and producing the control signal $u = P_E^*$; and (iii) current stress optimization, where the optimal phase-shift pair is derived from the preceding control output. The obtained phase-shift signals are then fed into a PWM module to generate the switching signals for the DAB converter.

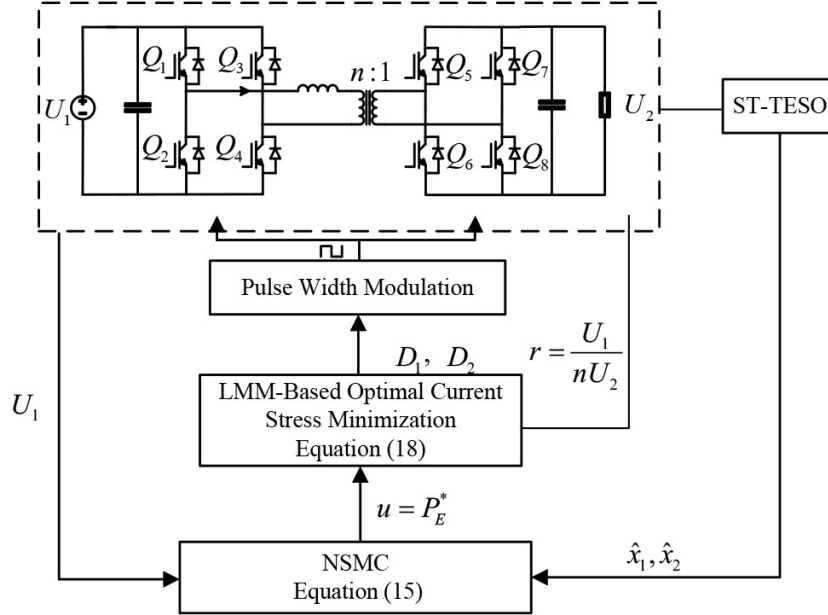


FIGURE 3. Control block diagram

4. Simulation Analysis. In this paper, a simulation model of the DAB converter is developed in MATLAB/Simulink. Taking the buck operating mode with forward power transfer as an example, simulation studies are conducted. The parameters in Table 1 include both DAB circuit parameters and controller parameters. The DAB circuit parameters are selected according to the typical operating requirements of a 400 V/48 V bidirectional DC conversion system in energy storage and DC microgrid applications, while considering the power transfer capability, current stress, and soft-switching performance of the converter. In addition, the controller parameters are determined based on the convergence speed, chattering suppression, and disturbance rejection requirements of the proposed control strategy, and are further fine-tuned through simulation studies.

TABLE 1. System parameters

Parameter	Value
Input voltage/V	400
Output voltage/V	48
Switching frequency/Hz	20000
Output-side capacitor/ μF	6800
Inductance/ μH	40
Transformer turns ratio n	8.33
$k_{1,sw}, k_{2,sw}, \gamma, \beta$	15, 25, 0.5, 0.8
η, k_p, k_i, α	0.5, 0.008, 0.005, 10

4.1. Real-time estimation performance of the ST-TESO. A comparative analysis between the TLESO and the ST-TESO is conducted. Compared with TLESO, the ST-TESO incorporates nonlinear error injection terms and a super-twisting correction mechanism, enabling the observer gain to adaptively vary with the magnitude of the estimation error. Specifically, a larger gain is applied to accelerating convergence when the error is significant, whereas the correction strength is automatically attenuated as the error approaches zero, thereby effectively suppressing high-frequency chattering and transient overshoot. As a result, the estimated trajectory of the ST-TESO closely coincides with the actual value during the initial stage, demonstrating superior fast-tracking capability and enhanced dynamic smoothness.

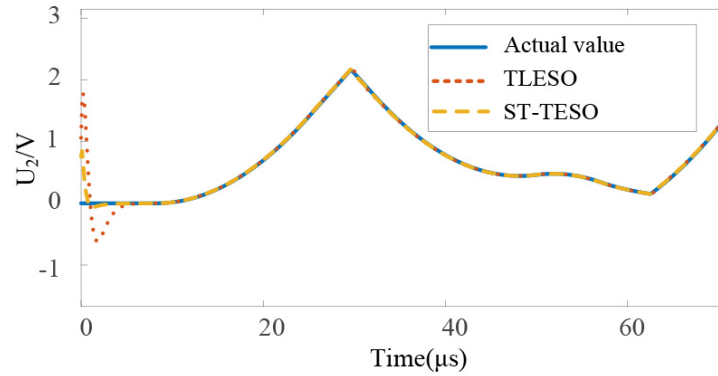


FIGURE 4. Real-time observation performance

4.2. Steady-state performance study. A comparative study of current stress was conducted between the proposed EPS-modulated ST-TESO-NSMC combined with the LMM-based current stress optimization strategy and a conventional control scheme under SPS modulation. Figure 5 and Figure 6 show the inductor current waveforms under voltage ratios of $r = 1.2$ and $r = 1.8$, respectively.

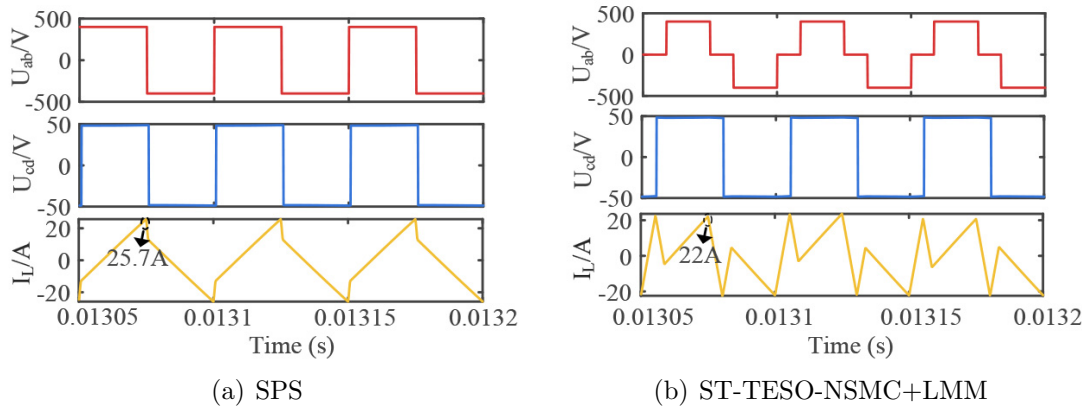
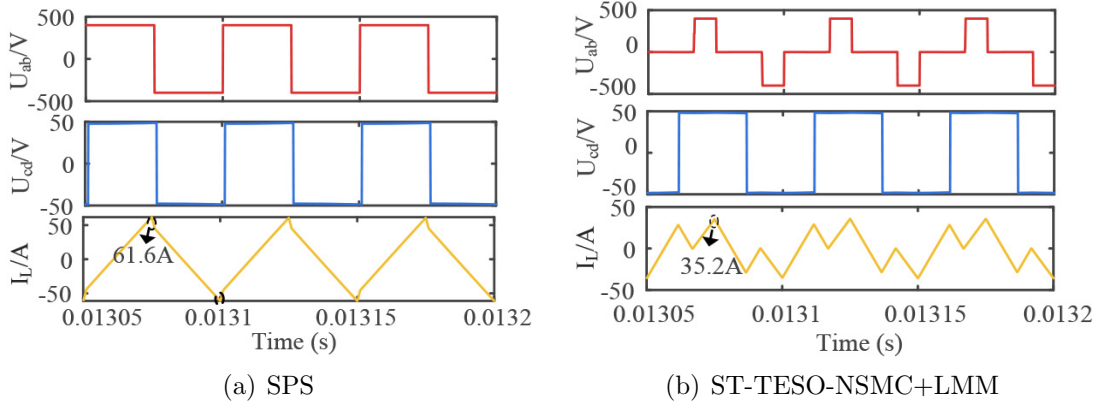


FIGURE 5. Current stress comparison of two control strategies ($r = 1.2$)

For $r = 1.2$, the SPS-based scheme yields a current stress of 25.7 A, while the proposed method reduces it to 22 A, corresponding to a reduction of 14.4%. For $r = 1.8$, the current stress under SPS modulation is 61.6 A, whereas the proposed strategy achieves 35.2 A, resulting in a reduction of 42.9%.

These results indicate that the current stress increases as the voltage ratio deviates further from the transformer turns ratio. Moreover, due to the limited control freedom of

FIGURE 6. Current stress comparison of two control strategies ($r = 1.8$)

SPS modulation, its ability to suppress current stress is inherently constrained. In contrast, the proposed EPS-modulated ST-TESO-NSMC with LMM optimization effectively exploits the additional phase-shift degree of freedom, enabling significant current stress reduction under wide operating conditions.

4.3. Dynamic characteristics analysis. To further validate the superiority of the proposed algorithm, comparative simulations under load step changes, inductance parameter mismatches, sudden output voltage variations, and input voltage disturbances were conducted among the proposed strategy, PID-ST, and STSMC. The corresponding experimental waveforms are shown in Figure 7, while the quantitative comparison results are summarized in Table 2. It can be observed that the proposed ST-TESO-NSMC achieves

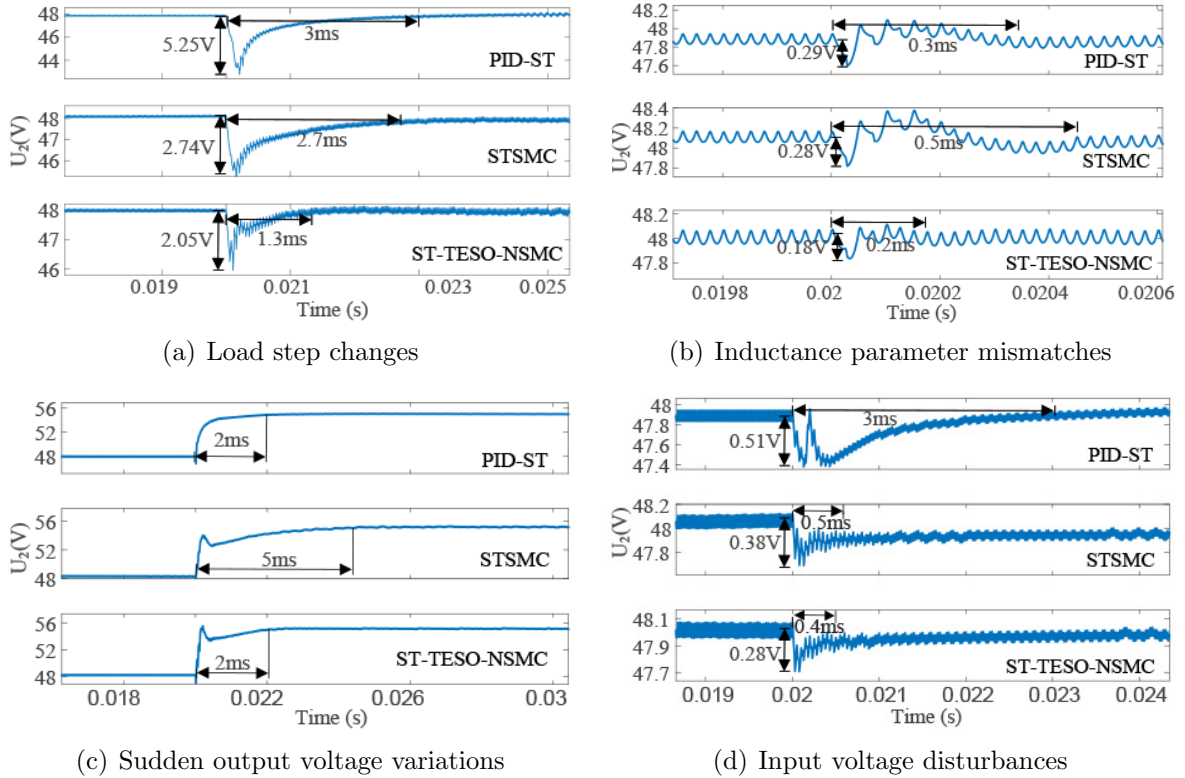


FIGURE 7. Disturbance experiment

TABLE 2. Performance comparison under different disturbance conditions

Condition	Method	Overshoot (V)	Settling time (ms)
Load step changes	PID-ST	5.25	3.0
	STSMC	2.74	2.7
	Proposed	2.05	1.3
Inductance parameter mismatches	PID-ST	0.29	0.3
	STSMC	0.28	0.5
	Proposed	0.18	0.2
Sudden output voltage variations	PID-ST	—	2.0
	STSMC	—	5.0
	Proposed	—	2.0
Input voltage disturbance	PID-ST	0.51	3.0
	STSMC	0.38	0.5
	Proposed	0.28	0.4

smaller overshoot and shorter settling time under different disturbance conditions. The improved dynamic performance mainly benefits from the coordinated action of the proposed nonlinear reaching law and the ST-TESO. The reaching law enhances the convergence speed when the system state is far from the sliding surface while weakening the switching action near the equilibrium point, thereby improving transient response and suppressing chattering simultaneously. In addition, the ST-TESO estimates generalized disturbances caused by load variations, parameter mismatches, and input voltage fluctuations in real time, and introduces them into the control law as feedforward compensation terms. Therefore, compared with PID-ST and STSMC, the proposed strategy achieves a better balance among convergence speed, robustness, and chattering suppression under wide operating conditions.

5. Conclusions. This paper proposes a novel control strategy for DAB converters to enhance dynamic performance and reduce current stress under complex operating conditions. By integrating a super-twisting-based extended state observer with an improved sliding mode control law, the proposed method achieves fast error convergence and strong robustness against input voltage fluctuations, load variations, and parameter uncertainties. The observer accurately estimates lumped disturbances and compensates them in a feedforward manner, effectively reducing model dependence. Furthermore, based on the Lagrange multiplier method, the optimal phase-shift pair is derived under the constraint of power transfer, enabling simultaneous voltage regulation and current stress minimization. The effectiveness of the proposed strategy is validated through stability analysis and simulation results, demonstrating superior performance compared with conventional control schemes in terms of dynamic response, disturbance rejection, and current stress suppression, indicating its potential for practical applications such as energy storage systems and DC microgrids.

Although the proposed strategy achieves stable voltage regulation and effective current stress reduction, several limitations still remain. Under abrupt load variations, transient current accumulation caused by volt-second imbalance across the leakage inductance may introduce additional current stress that is not explicitly constrained in this study. In addition, the bandwidth and nonlinear gains of the ST-TESO are selected empirically, and their influence on disturbance estimation and system stability requires further investigation. Therefore, future work will focus on transient current suppression and adaptive parameter coordination of the observer and controller.

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