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The Supplementary Damping Method for CLCC HVDC Based on Projective Control Theory

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Abstract: This paper proposes a design method for an additional damping reduced-order controller based on the projective control theorem. Improvements are made to the projective theorem to achieve additional damping control through Controllable-Line-Commutated Converter (CLCC)-based High Voltage Direct Current (HVDC), which suppresses low-frequency oscillations. Using small disturbance identification techniques, the system's linear model is first identified, and the state feedback control law of the system is then determined using the state-space pole assignment control method. Then, by retaining the dominant oscillation modes of the closed-loop system through the improved projective theorem, the state feedback is converted into output feedback. Ultimately, the sixth-order state feedback controller is reduced to a second-order one and applied in the CLCC HVDC additional damping strategy to suppress low-frequency oscillations. Simulation results based on the electromagnetic transient simulation software PSCAD demonstrate that the designed CLCC HVDC additional damping reduced-order projective control exhibits good suppression performance, strong robustness, and low order, which are of significant importance for engineering practice.

Keywords: HVDC; CLCC; projective control; damping control



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1. Introduction

The additional damping control of High Voltage Direct Current (HVDC) transmission systems is a unique resource in AC-DC hybrid power grids [1], which can have damping ability besides power transmission [2]. The Pacific DC in the United States designed a DC additional damping controller based on the frequency response method and root locus method of classical control theory, effectively suppressing low-frequency oscillations and increasing the transmission power of AC tie lines by 400 MW. This is one of the most successful cases of DC additional damping control [3].

Recently, some scholars have proposed an HVDC system based on Controllable-Line-Commutated Converter (CLCC) topology [4]. This topology is designed using the concept of a mixed connection of fully controlled and semi-controlled devices [5]. The current is transferred through fully controlled devices and awaits the restoration of the thyristor's turn-off capability before being utilized again [6]. The fully controlled device interrupts the current and swiftly completes commutation between bridge arms. In the event of an AC fault, the CLCC can forcibly interrupt the fault current in the bridge arm, effectively resolving the issue of commutation failure caused by AC system faults. While some research has been conducted to enhance the efficiency of CLCC operation, relatively little attention has been given to the design of its additional damping controller. As the CLCC is the potential development direction of the HVDC area, how to design its supplementary damping controller is important.

Actually, the CLCC's supplementary damping controller design can use the theory applied to traditional Line-Commutated Converter (LCC) HVDC, as its basic control

structure is similar. The design methods for HVDC additional damping control mainly focus on feedback linearization, pole assignment, LQR design, and robust control, etc.

The combination of differential geometry with the design of nonlinear control systems has led to the development of feedback linearization methods based on differential geometry theory. The main design methods include exact linearization design, zero dynamics design, and output decoupling from disturbances design [7]. Article [8] applies feedback linearization techniques for differential algebraic systems to the design of nonlinear controllers for AC-DC parallel systems, considering the actual load of power systems and the nonlinear characteristics of the DC system itself. It also conducts an in-depth study on generator excitation control and DC system rectifier-side constant current control laws in AC-DC hybrid systems. In the literature, article [9] combines linear optimal design methods with nonlinear control theory to design a nonlinear controller for High Voltage Direct Current transmission systems based on voltage source converters.

Pole assignment method is one of the basic methods for designing damping controllers in linear control systems [10]. In the field of modern control engineering, the pole assignment method can be applied not only in single-input single-output systems but also in multi-input multi-output systems. For different control objectives, power systems can be equivalent to single-input single-output systems or single-input multi-output system models in most cases, and the pole assignment method has a wide range of applications in power systems.

The Linear Quadratic Regulator (LQR) [11] is also an excellent design method in modern control theory. However, some state variables in actual systems are difficult to collect [12], so the controller can generally be designed as an observer-based linear quadratic optimal controller. Considering the nonlinearities and uncertainties of the system, a nonlinear SSO mitigation strategy is proposed in [13] based on the feedback linearization theory and sliding mode control (SMC), where the feedback linearization theory is used to eliminate the nonlinearities. Article [14] proposes a new control strategy for a line-commutated converter-based (LCC) HVDC system, wherein the DC-link voltage and current are optimally regulated to improve real-time GFR in both rectifier- and inverter-side grids, in which the linear quadratic Gaussian (LQG) controller is also designed for optimal secondary frequency control. Article [15] describes an optimal control scheme for robust frequency regulation (FR) in power networks that utilize Multi-Terminal High Voltage Direct Current (MT-HVDC) systems to interconnect AC grids, which involves the development of a Linear Quadratic Gaussian (LQG) controller to minimize FR in each grid.

Robust control can be divided into two categories: linear robust control [16] and nonlinear robust control [17]. For linear robust control, there are mainly two methods: H_∞ robust control and structured singular value analysis (μ analysis). In H_∞ robust control theory, the H_∞ norm is used to measure the amplitude of the transfer function and reduce the impact of input (or disturbance) on the output by reducing its H_∞ norm. Therefore, the linear robust control problem can be converted, in many cases, to finding a controller that satisfies the desired H_∞ norm conditions of the closed-loop system. For example, a robust coordination approach for the controller design of multiple High Voltage Direct Current (HVDC) and flexible AC transmission systems (FACTS) wide-area controls (WACs) are presented in [18].

Besides the above damping controllers design methods, which change the converters' control scheme themselves, other damping and coordinated strategies also enhance the stability of the system by more global readjustment. For example, article [19] proposes a methodology for tuning a supervisory and frequency-response outer loop control system of a multi-terminal direct current (MTDC) grid designed to transmit offshore wind energy to an onshore AC grid, and to provide frequency support during over-frequency events. Some researchers use the DC-link capacitor energy of offshore wind turbines (WTs) to reduce interactions between power oscillations and HVDC grid voltage when onshore grid-side VSCs (GSVSCs) modulate the active and reactive power injections [20]. Article [21] proposes a novel system identification method to handle that case when there is

no control input excitation, the control strategy that fully considers the real-time stability constraints of the HVDC. More specifically, the system matrix and the control matrix are separately estimated.

However, with the expansion of system scale and the enhancement of time-varying characteristics, HVDC controllers designed based on classical control methods mainly have the following two issues: large disturbance faults and high order. The first problem is that in cases of large disturbance faults or significant changes in the system model, the effectiveness of controllers designed based on classical control theory is not ideal. High order is another important issue commonly encountered in controller design. High order is a significant factor affecting the practicality and effectiveness of controllers. Direct order reduction methods for various controllers have a substantial impact on control quality and can introduce time delays.

Specifically, the pole assignment method is used in [22] to suppress inter-area low-frequency oscillations with weak damping through a fifth-order HVDC supplementary controller. Article [23] designs an HVDC supplementary controller based on LMI-based mixed H_2/H_∞ robust control, with the controller order reaching up to 10th order. A linear optimal (LQR) controller with an observer is used in [24] to suppress inter-area low-frequency oscillations in multi-infeed HVDC systems, and the reduced-order controller still has a high order of 8th.

Projective control [25] is a method for designing reduced-order controllers of systems. By taking the output of the given open-loop system under study as the control input and the control input as the output, a reference controller is established and combined with the original system to form a feedback control structure, thereby forming a closed-loop reference system. Projective control is based on state feedback control to design an output feedback control that is easy to implement in engineering and perform order reduction. While reducing the order, it retains the control effect of state feedback as much as possible.

Therefore, to utilize the CLCC HVDC's flexible controllability, and also make sure the supplementary damping controller can be used for practical projects, this paper proposes a design method for reduced-order controllers based on the projective theorem, and makes improvements to the projective theorem to achieve CLCC HVDC supplementary damping control for low-frequency oscillations suppression.

The novelties of this paper are as follows: (1) The projective control is used to design a low-order control for CLCC HVDC, where the projective theory is also improved by newly defined disturbance matrix to guarantee the control effect; (2) The additional damping control is design for the new type HVDC, namely the CLCC, where the low frequency oscillations can be suppressed. The structure of the paper is as follows: Section 2 introduces the pole assignment and projective control theory, Section 3 proposes the supplementary damping method for CLCC HVDC based on projective control, Section 4 presents the case study and simulation verifications, and Section 5 concludes the paper.

2. Pole Assignment and Projective Control Theory

2.1. Pole Assignment Based on the Ackermann Formula

Consider the controlled system with the state equation

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \quad (1)$$

In this formula, x represents the state vector, y represents the output vector, u represents the control vector, and A , B , and C respectively represent the state matrix, output matrix, and control matrix.

Then, pole assignment control in state space can be described as: finding a state feedback control law $u = Kx$, such that the closed-loop system is

$$\begin{cases} \dot{x} = (A + BK)x \\ y = Cx \end{cases} \quad (2)$$

where all the poles of the closed-loop system (2) are located at the desired positions: $s = u_1, s = u_2, \dots, s = u_n$. In other words, the characteristic equation of the closed-loop system is

$$|sI - (A + BK)| = (s - u_1)(s - u_2) \cdots (s - u_n) = s^n + \alpha_1 s^{n-1} + \cdots + \alpha_{n-1}s + \alpha_n = 0 \quad (3)$$

where $\alpha_1, \dots, \alpha_n$ are the correlation coefficients. Then, the required state feedback gain matrix K can be obtained using the Ackermann formula:

$$K = [0 \ 0 \ \cdots \ 0 \ 1] [B \ AB \ \cdots \ A^{n-1}B \ A^n]^{-1} \phi(A) \quad (4)$$

In Formula (4), $\phi(A) = A^n + \alpha_1 A^{n-1} + \cdots + \alpha_{n-1}A + \alpha_n I$, where I is the identity matrix.

2.2. The Projective Control Theory

The main idea of projective control theory is to map the state feedback controller to a lower-order output feedback controller while preserving the dominant eigenvalues of the reference closed-loop system. Under the action of the state feedback $u = Kx$, the system matrix of the closed-loop feedback system represented by Equation (2) is eigendecomposed to obtain $(A + BK)X = X\Lambda$. Here, Λ is an n -order eigenvalue triangular matrix, and X is an n -order eigenvector matrix.

Assume that the projective controller to be designed has a state equation.

$$\begin{cases} \dot{z} = A_c z + B_c y \\ u = C_c z \end{cases} \quad (5)$$

In this formula, z represents the state vector of the controller to be designed, and A_c , B_c , and C_c , respectively represent the state matrix, control matrix, and output matrix of the controller to be designed. Then, the closed-loop feedback system based on projective control in Equation (1) is

$$\begin{cases} \dot{x}_s = A_s x_s \\ y_s = C_s x_s \end{cases} \quad (6)$$

where

$$x_s = \begin{bmatrix} x \\ z \end{bmatrix} \quad (7)$$

$$y_s = \begin{bmatrix} y \\ u \end{bmatrix} \quad (8)$$

$$A_s = \begin{bmatrix} A & B C_c \\ B_c C & A_c \end{bmatrix} \quad (9)$$

$$C_s = \begin{bmatrix} C & 0 \\ 0 & C_c \end{bmatrix} \quad (10)$$

Perform eigenvalue decomposition on the system matrix A_s :

$$\begin{bmatrix} A & B C_c \\ B_c C & A_c \end{bmatrix} \begin{bmatrix} X_p \\ W_p \end{bmatrix} = \begin{bmatrix} X_p \\ W_p \end{bmatrix} \Lambda_p \quad (11)$$

where Λ_p represents the dominant eigenvalues of the reference system (2) that are being retained, and X_p represents the corresponding retained eigenvectors, such that $(A + BK)X_p = X_p \Lambda_p$. W_p represents the vectors introduced due to the increase in the order of the closed-loop system, which represent the state-space transformation of the controller. From Equation (11), we can see that

$$B_c C X_p + A_c W_p = W_p \Lambda_p \quad (12)$$

$$\rightarrow A_c = W_p (\Lambda_p - W_p^{-1} B_c C X_p) W_p^{-1} \quad (13)$$

Definition: Given $P_0 = W_p^{-1} B_c$, then we have

$$A_c = W_p(\Lambda_p - P_0 C X_p) W_p^{-1} \quad (14)$$

$$B_c = W_p P_0 \quad (15)$$

Similarly, from Equation (11), we can deduce that

$$B C_c W_p + A X_p = X_p \Lambda_p \quad (16)$$

$$\rightarrow B_c C_c W_p + A X_p = (A + B K) X_p \quad (17)$$

Then

$$C_c = K X_p W_p^{-1} \quad (18)$$

Given that W_p only represents a state space transformation of the feature vector introduced by the controller, W_p can be any matrix. Let W_p be the identity matrix, so that Equations (14), (15) and (18) can be rewritten as

$$\begin{cases} A_c = \Lambda_p - P_0 C X_p \\ B_c = P_0 \\ C_c = K X_p \end{cases} \quad (19)$$

So far, we have obtained the state space matrices of the projective controller. It should be noted that although the projective controller preserves the dominant eigenvalues of the reference system, it also introduces other eigenvalues. The introduced eigenvalues are determined by the eigenvalues of the matrix $A_r = A - X_p P_0 C$, that is,

$$\lambda_s = \lambda_p \cup \lambda(A_r) \quad (20)$$

where λ_s represents the eigenvalues of the closed-loop system (6), λ_p represents the preserved dominant eigenvalues, and $\lambda_s(A_r)$ represents the eigenvalues of the matrix A_r .

Proof. Let

$$T = \begin{bmatrix} X_p & I_n \\ I_p & 0 \end{bmatrix} \quad (21)$$

Then

$$T^{-1} = \begin{bmatrix} 0 & I_p \\ I_n & -X_p \end{bmatrix} \quad (22)$$

In this formula, I_n and I_p represent the identity matrices of order n and order p , respectively. Therefore,

$$T^{-1} A_s T = \begin{bmatrix} A_c + B_c C X_p & B_c C \\ A X_p + B C_c - X_p (A_c + B_c C X_p) & A - X_p B_c C \end{bmatrix} \quad (23)$$

$$\Rightarrow T^{-1} A_s T = \begin{bmatrix} \Lambda_p & B_c C \\ 0 & A_r \end{bmatrix} \quad (24)$$

That is, $\lambda_s = \lambda_p \cup \lambda(A_r)$. $\square$

It can be seen that the closed-loop system is affected by the eigenvalues of the matrix A_r . Therefore, based on this observation, this paper further improves the projective control. We define the A_r as disturbance matrix. Noticing that $A_r = A - X_p P_0 C$, and P_0 is adjustable, we can control the range of eigenvalues of the disturbance matrix A_r through P_0 to reduce the impact on the original oscillation mode, which can enhance the control effectiveness. The principles for selecting the eigenvalues of the disturbance matrix are: (1) A relatively

large damping ratio; (2) The oscillation frequency is far away from the oscillation frequency of the preserved eigenvalues.

3. The Supplementary Damping Method for CLCC HVDC Based on Projective Control

3.1. The Basic Structure of CLCC HVDC

The Controllable-Line-Commutated Converter (CLCC) topology introduces fully controllable Insulate-Gate Bipolar Transistor (IGBT) devices into the traditional LCC converter station. By exploiting the controllable characteristics of IGBT, it transfers the current from the main branch, where the thyristor is located, to the auxiliary branch. This extension of the thyristor's turn-off time ensures its reliable recovery of forward blocking capability.

The basic structure of CLCC HVDC is shown in Figure 1. To prevent commutation failure, a recovery time of at least 400 microseconds must be provided for the thyristor after it ceases to conduct, ensuring reliable restoration of its forward blocking capability. Based on this principle, CLCC HVDC introduces an IGBT in series with the original thyristor branch and adds an auxiliary branch for commutation, as illustrated in Figure 1. In this setup, V11 and V14 are thyristors, while V12 and V13 are IGBTs. V11 is connected in series with V12, forming the main branch for carrying high currents, while V13 is connected in series with V14, creating an auxiliary branch for current transfer.

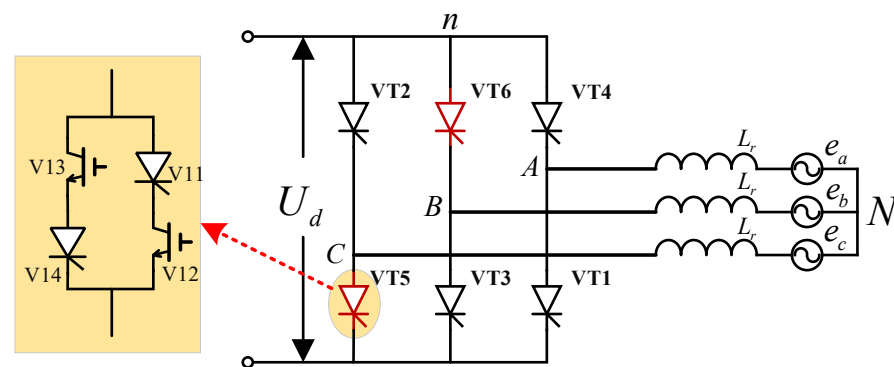


Figure 1. The structure of CLCC HVDC system.

During operation, the main branch initially conducts the current. V11, V12, and V13 are triggered simultaneously to conduct. After 120° , the bridge arm begins commutation. At this point, V12 is turned off, and simultaneously, V13 and V14 in the auxiliary branch are turned on, forcing the current to commute to the auxiliary branch. This process continues until V11 can reliably restore its forward blocking capability. Then, the auxiliary branch is shut down, awaiting the next commutation process. This topological structure allows independent control of the main and auxiliary branches, providing sufficient recovery time for the thyristors in the main branch.

3.2. The Main Control of CLCC HVDC

Under non-fault conditions, the main control strategy of CLCC HVDC is similar to that of conventional LCC. The system achieves control over DC power and current by regulating the trigger angle. Traditional control strategies include constant current control, constant voltage control, and constant extinction angle control. Among these, constant current control is typically employed on the rectifier side, while constant voltage control and constant extinction angle control are used on the inverter side.

The control process of constant current control is illustrated in the Figure 2 below. In the figure, I_d represents the DC current input value, and I_{dref} is the given DC current setting value. The current controller calculates the deviation by subtracting the given current reference value from the real-time current value during operation. Additionally, the figure shows ΔI_m , which represents the current margin and is typically used for setting the constant current on the inverter side. Finally, after passing through the PI adjustment

module and the limiting module, the current difference is output as the trigger angle control command for the converter. When the output value exceeds the defined amplitude limit, it will no longer be controlled, and the trigger angle output will remain constant.

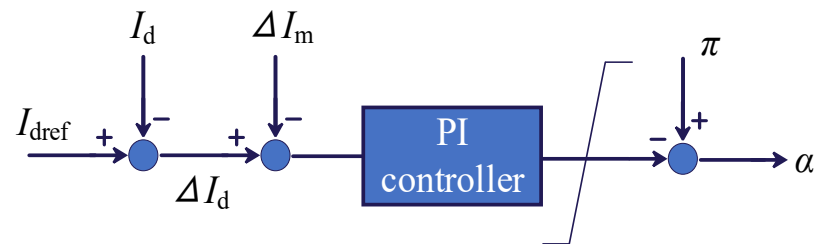


Figure 2. The constant DC current control diagram of CLCC HVDC.

The fundamental principle of constant voltage control is similar to that of constant current control. In High Voltage Direct Current (HVDC) transmission systems, it is essential to maintain a stable DC voltage by employing constant voltage control at one end, typically on the inverter side. The specific control process is illustrated in Figure 3. In the figure, U_d represents the DC voltage input value, while U_{dref} is the given DC voltage setting value. The voltage controller calculates the voltage deviation ΔU_d by subtracting the given voltage reference value from the real-time voltage value during operation. This deviation is then processed through a PI adjustment module and a limiting module, converting the voltage difference into trigger angle control commands for the converter, thereby maintaining the voltage at the reference value. When the output value exceeds the defined amplitude limit, it ceases to be controlled, and the trigger angle output remains constant.

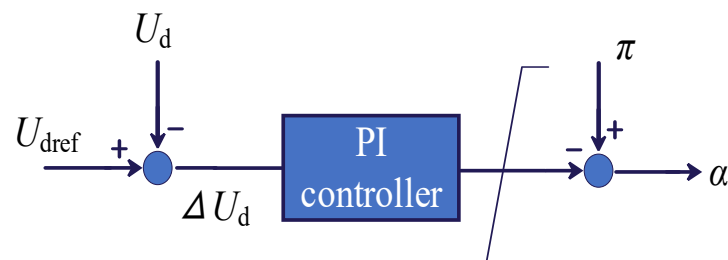


Figure 3. The constant DC voltage control diagram of CLCC HVDC.

3.3. The Supplementary Damping Control Strategy of CLCC HVDC

The additional damping control strategy based on CLCC HVDC is illustrated in the Figure 4. The controller, installed at the constant current position on the rectifier side, consists of three main components: the Time delay segment, the wash out segment, and the projective control segment. The Time delay segment, implemented using an approximate second-order process, simulates the delay incurred during wide-area signal acquisition. The wash out segment eliminates the DC component, ensuring that the controller only exerts control during system oscillations. When the system operates normally, the controller's output is zero. The projective control segment is a specifically designed controller based on the aforementioned theory. Its final output, an additional current deviation, is superimposed on the original system's constant DC current control to achieve the desired control effect. For the controller's input segment, generator frequency deviation is typically selected as the input to enhance control effectiveness.

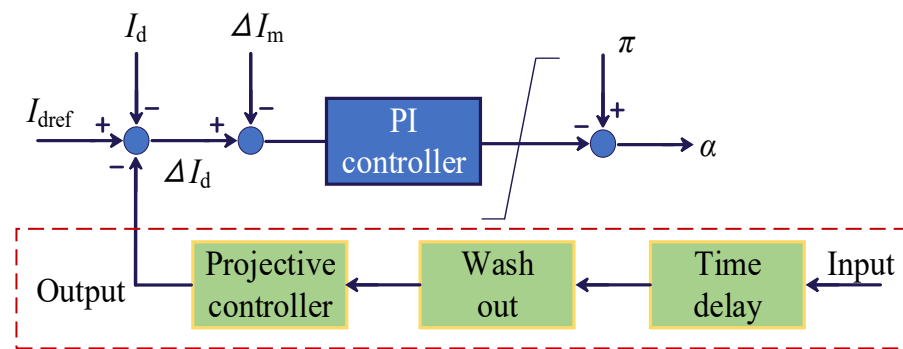


Figure 4. CLCC HVDC supplementary damping control diagram.

4. Case Study

4.1. Introduction to the Calculation System

To validate the aforementioned theory, simulation verification of the system was conducted using PSCAD v50 software. The simulation system employed a four-machine AC/DC system, with the network structure illustrated in Figure 5. The generator models G1, G2, G3, and G4 all include excitation and speed control systems. Under normal conditions, the DC system operates with constant current control on the rectifier side and constant extinction angle control on the inverter side. The DC system utilized a CLCC HVDC structure. Its basic information is shown in Table 1 below.

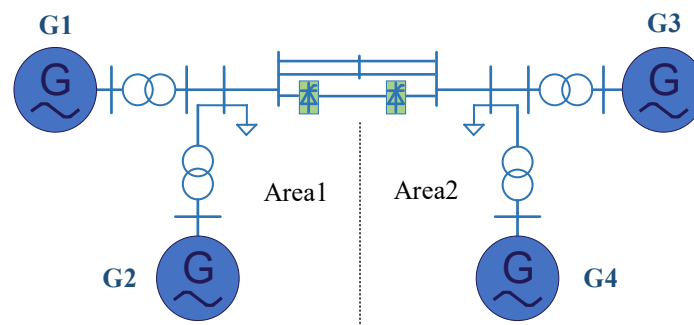


Figure 5. The test system for simulation verification.

Table 1. The information of the simulation system.

Devices	Names	Values	Units
G1	Rated Capacity	600	MW
G2	Rated Capacity	400	MW
G3	Rated Capacity	600	MW
G4	Rated Capacity	400	MW
CLCC HVDC	Rated Capacity	1000	MW
	Rated DC voltage	500	kV

Then the total least squares-estimating signal parameter via rotational invariance techniques (TLS-ESPRIT) method was employed to identify the low-frequency oscillation characteristics of each generator. The TLS-ESPRIT algorithm is a high-resolution signal analysis method based on subspace, which has stronger anti-noise and anti-interference capabilities compared to the traditional Prony algorithm. The core idea of the ESPRIT algorithm is to calculate the signal's rotation factor by forming an autocorrelation matrix and a cross-correlation matrix from sampled data. The frequency and damping factor of the signal can be derived from the rotation factor, and then the amplitude and phase of the signal can be obtained by combining TLS. It is suitable for oscillation characteristic analysis and model identification under small perturbations in large systems. After the

system reaches a steady state, small perturbations were applied as excitations, ensuring that these perturbations do not violate the conditions for system linearizability. The output was selected as the incremental rotor angular velocity of each generator. The oscillation frequencies and mode shapes of the system, as obtained, are presented in Table 2.

Table 2. Oscillation frequencies and mode shapes of the system.

Names	Devices	Values	Units
Mode Shapes	G1	$1.23\angle 33.6^\circ$	1×10^{-5} p.u.
	G2	$0.26\angle 17.3^\circ$	1×10^{-5} p.u.
	G3	$0.40\angle -146.5^\circ$	1×10^{-5} p.u.
	G4	$0.26\angle -123.4^\circ$	1×10^{-5} p.u.
The main Oscillation Frequencies	The whole system	1.20	Hz

From Table 2, it can be observed that the system exhibits a 1.20 Hz oscillation mode, where generators 1 and 2 swing in opposition to generators 3 and 4. Subsequently, the TLS-ESPRIT technique was once again employed to identify the linear model of this oscillation mode. Taking into account that the relevant signals collected are wide-area signals, an approximate second-order 80 ms time delay element was incorporated during the identification of the reduced-order transfer function. The transfer function for the *Pade'* delay is expressed as:

$$G_{pade'}(s) = \frac{s^2 - 75s + 1875}{s^2 + 75s + 1875} \quad (25)$$

Finally, the identified 1.20 Hz oscillation model, incorporating the time delay, is of 6th order.

4.2. The Projective Controller Design

To suppress the 1.20 Hz oscillation mode, an HVDC additional damping controller is employed. The speed difference between generators 2 and 4, namely ω_{24} , which have larger participation factors, is used as the input for the controller. The controller is installed at the constant current position on the rectifier side, and its structure is shown in Figure 4. In this setup, the 80 ms delay segment is implemented using the aforementioned approximate second-order transfer function, and the time constant for the DC isolation segment is set to 10 s.

Firstly, the optimal gain matrix for state feedback is determined. Ideal pole positions are selected, and the state feedback matrix is obtained using the Ackermann's formula for pole placement:

$$K = [-3.0 \quad -17.4 \quad -233.4 \quad -872.0 \quad -3469.3 \quad -5378.9] \quad (26)$$

Based on this, and according to the identified system model, eigenvalue decomposition is performed on the closed-loop system matrix. Referring to Table 3, which shows the eigenvalues and damping ratios of the closed-loop system, it can be seen that the damping ratio of the dominant 1.20 Hz oscillation mode in the closed-loop system has increased to 5.10%.

Table 3. Eigenvalues and damping ratios of the controlled system.

Eigenvalues	Damping Ratios (%)
$-0.6869 + 7.5185i$	5.10
$-0.6869 - 7.5185i$	5.10
$-1.2129 + 4.8182i$	24.41
$-1.2129 - 4.8182i$	24.41
$-2.5678 + 1.1489i$	91.28
$-2.5678 - 1.1489i$	91.28

Next, the eigenvalues of the obtained closed-loop system are evaluated to determine which should be retained. Typically, eigenvalues that play a dominant role in the system dynamics are selected. When choosing the dominant eigenvalues, both their distance from the imaginary axis and their damping ratios are taken into consideration. A pair of eigenvalues that are closer to the imaginary axis and have a relatively low damping ratio are chosen as the retained eigenvalues. It is important to note that if multiple closed-loop poles exhibit similar dominance, multiple pairs of eigenvalues can be selected, although this will increase the order of the projective controller. When n eigenvalues are selected, the order of the projective controller will be n . Additionally, to ensure the effectiveness of the calculated controller, eigenvalues corresponding to oscillation modes must be selected in pairs.

Finally, by selecting P_0 , the range of eigenvalues introduced by the disturbance matrix is limited, aiming to reduce its impact on the closed-loop system. The set limitations are: a damping ratio of eigenvalues greater than 20% and an oscillation frequency of eigenvalues less than 0.2 Hz. Based on these criteria, a 2nd-order projective controller is designed as

$$K_s = \frac{-3.742 \times 10^6 s - 2.571 \times 10^6}{s^2 + 1.45 \times 10^4 s + 9904} \quad (27)$$

4.3. The Simulation Verification

The projective controller K_s is integrated into the DC additional controller shown in Figure 4. Electromagnetic transient simulation software PSCAD is utilized for simulation verification, and the control effects under different perturbations are compared. For a better comparison, a traditional LQR damping controller are also designed.

(1) Case 1

At 2 s, a single-phase short-circuit ground fault was set at 1% of the AC bus side in Area 2, which disappeared after 0.1 s. The suppression effect on the rotor speed difference between G2 and G4, with different controls, are illustrated in Figure 6. Similarly, the suppression effect on the rotor speed difference between G1 and G3 is shown in Figure 7.

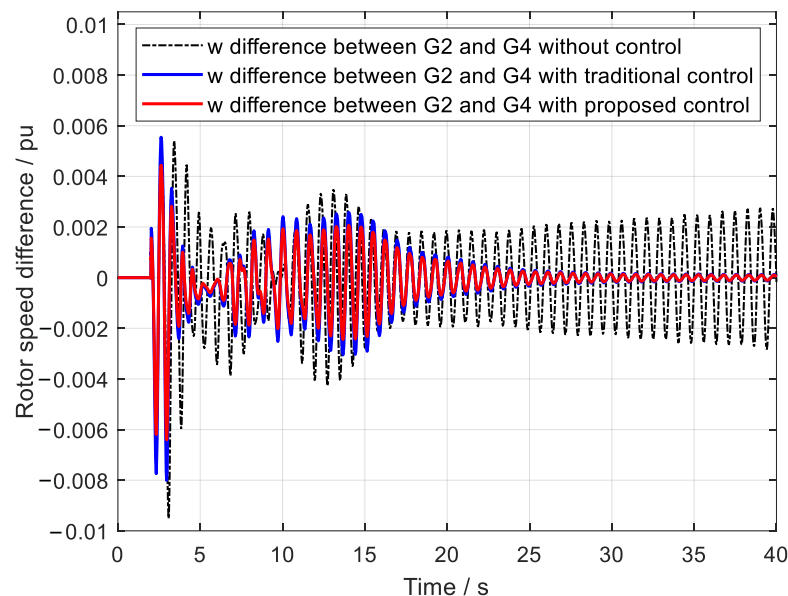


Figure 6. The rotor speed (ω) difference between G2 and G4 with different controls in Case 1.

It is evident that the controller based on the proposed projective control demonstrates effective performance during a single-phase short circuit. Controlled based on the speed difference between G2 and G4, it not only suppresses $\Delta\omega_{24}$ oscillations but also effectively mitigates $\Delta\omega_{13}$ oscillations. The primary reason for this is that projective control directly

converts state feedback into output feedback using retained eigenvalues, thereby preventing the accumulation and amplification of errors. Additionally, it can be seen that the traditional LQR control although has some effect compared with without control situation, the proposed projective can suppress the oscillation more quickly, which further prove the advantages of the strategy in this paper.

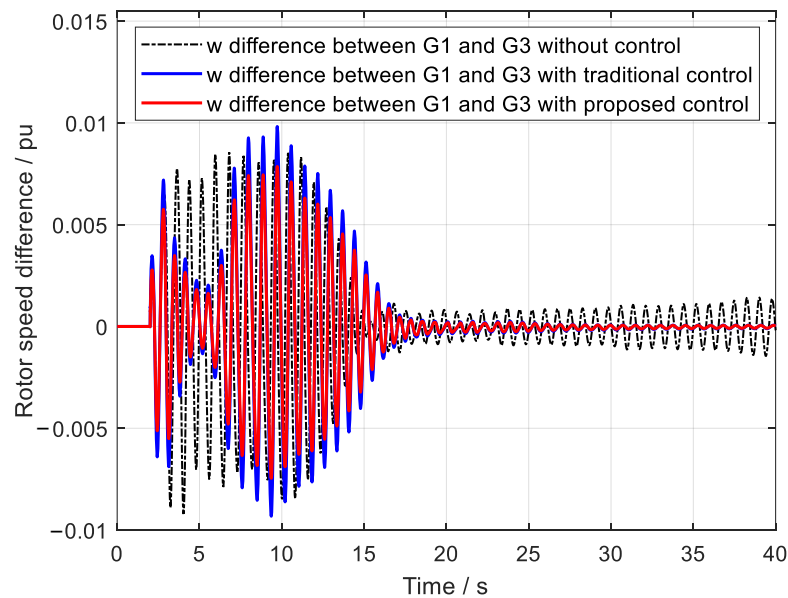


Figure 7. The rotor speed (ω) difference between G1 and G3 with different controls in Case 1.

(2) Case 2

At 2 s, a load of 400 MW was cut off from the AC bus in Area 1. The suppression effect on the rotor speed difference between G2 and G4, with different controls, are illustrated in Figure 8. Similarly, the suppression effect on the rotor speed difference between G1 and G3 is shown in Figure 9.

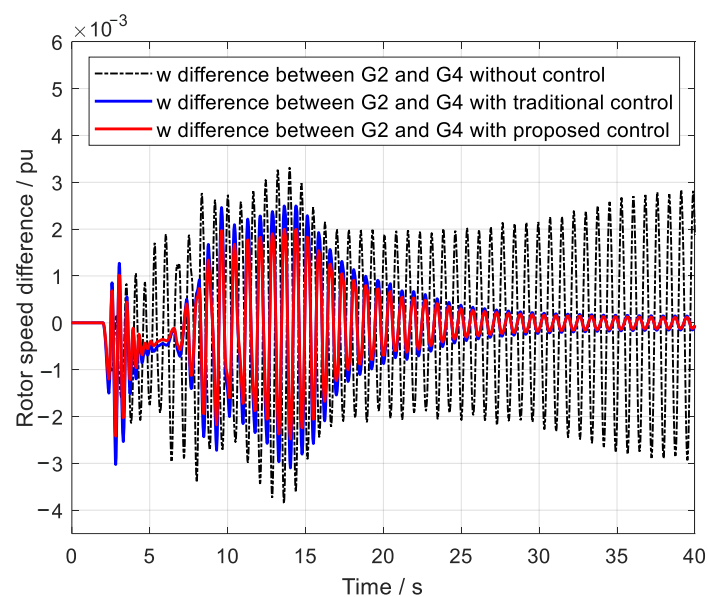


Figure 8. The rotor speed (ω) difference between G2 and G4 with different controls in Case 2.

Simulation results based on Case 2 indicate that the system experiences significant oscillation phenomena when a large amount of load is removed. This is due to a severe

fault that pushes the system beyond its stability margin, causing low-frequency oscillations to become more prominent. However, the controller based on projective control demonstrates effective performance even during severe faults, ensuring that the speed fluctuations between different generators stabilize. This verifies the robustness of the designed projective control.

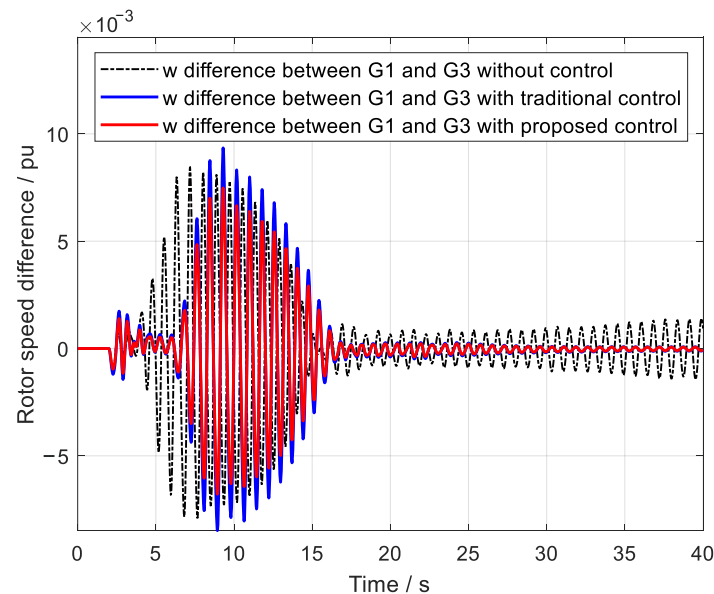


Figure 9. The rotor speed (ω) difference between G1 and G3 with different controls in Case 2.

5. Conclusions

In this paper, the additional damping control for CLCC HVDC is designed based on projection control theory. Utilizing the TLS-ESPRIT technique and building upon an enhanced projection control framework, a reduced-order HVDC additional controller is devised to mitigate low-frequency oscillations. The following conclusions are drawn:

- (1) The projection controller, designed under pole placement state feedback control, can suppress low-frequency oscillations, demonstrating the effectiveness of CLCC HVDC additional damping control.
- (2) The projection controller directly utilizes retained eigenvalues to reduce the controller's order, which not only better facilitates engineering practice compared to traditional high-order controllers but also adapts to various operating conditions, exhibiting strong control robustness.

It should be noted that the method proposed in this paper does not carry out a sensitivity analysis to explore resonance sources with our new branch. An additional resonance sources study will be conducted in future.

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