Integral backstepping control design for enhanced stability and dynamic performance of VSC-HVDC systems

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ABSTRACT

The increasing demand for efficient and reliable high-voltage direct current (HVDC) transmission systems has underscored the necessity for advanced control strategies to augment system performance. This article presents the design and implementation of an integral backstepping control approach customized for voltage source converter (VSC)-based HVDC systems. The proposed methodology primarily concentrates on tackling the inherent nonlinearities, uncertainties, and disturbances that typically impede the stability and efficiency of VSC-HVDC systems. By incorporating integral action into the backstepping control framework, two key objectives are accomplished: i) precise regulation of the direct voltage at the rectifier station and accurate control of the active power at the inverter station, and ii) effective power factor correction (PFC) at both stations within the HVDC system. These objectives contribute to robust tracking performance, enhanced dynamic stability, and improved overall system efficiency. The theoretical design has been verified through extensive numerical simulations conducted in the MATLAB/Simulink environment, showcasing the efficacy of the proposed control strategy in ensuring stability and performance under varying conditions.

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1. INTRODUCTION

High-voltage direct current (HVDC) technology has become an indispensable component of contemporary electrical power transmission systems [1]. It plays a critical role in facilitating the efficient transmission of electricity over substantial distances, thereby significantly mitigating transmission losses and enabling the seamless integration of renewable energy sources into the primary grid [2]. In comparison to traditional alternating current (AC) transmission systems, HVDC offers a multitude of advantages in the context of long-distance power transmission [3]. Specifically, HVDC systems possess the ability to transmit greater power using the same conductor size as AC systems, resulting in reduced transmission losses [4]. This characteristic renders HVDC systems particularly well-suited for the transportation of electricity from remote renewable energy sources. Furthermore, HVDC systems facilitate the interconnection of asynchronous grids operating at varying frequencies, permitting the exchange of electricity between different countries and regions. This capability serves to enhance the reliability and efficiency of the overall power system [5].

The stability and dynamic performance of voltage source converter (VSC)-HVDC systems play a crucial role in guaranteeing dependable and effective power transmission [6], [7]. However, the integration of VSC-HVDC systems into power grids presents numerous challenges. These challenges encompass the necessity for robust control strategies that can ensure stable operation under various operating conditions, inaccuracies in tracking desired output variables such as direct current (DC) voltage [8] which can have an impact on the overall stability of the grid and the quality of power [9], and slow responses to disturbances [10]. All of these factors have the potential to compromise grid stability and power quality.

Several control strategies have been proposed for VSC-HVDC systems in order to ensure stable operation and improve dynamic performance. These strategies include proportional-integral-derivative (PID) controllers [11], model predictive control (MPC) [12], and sliding mode control (SMC) [13], [14]. PID controllers are commonly used due to their simplicity and ease of implementation, but they may not be capable of handling complex dynamics and disturbances. On the other hand, MPC and SMC are more advanced control strategies that can handle complex dynamics and disturbances, but their utilization requires a comprehensive understanding of the system dynamics and may require significant computational resources. Additionally, adaptive [15] and observer control [16] methods have been explored to address the variability and uncertainties in system parameters. Additionally, fault ride-through (FRT) techniques to manage faults and guarantee system stability [17]. The fuzzy logic methodology is utilized in [18] to assess the performance and precision of the proportional-derivative (PD) control approach. This approach is employed to improve system responses and performance, as well as to enable DC power recovery, specifically in the context of severe faults. Moreover, damping controllers are implemented to mitigate oscillation risks and enhance small signal stability [19]. Another very serious problem that can arise when connecting such a converter to the grid is the synchronization between voltages. This issue is discussed in [20] and resolved by using a PI-based phase-locked loop (PLL) and 24-sector control. Despite these advancements, there still exists a significant gap in achieving optimal performance under a wide range of operating conditions, highlighting the need for innovative control approaches.

This paper presents a hybrid technique, which incorporates an integral backstepping control design approach, aiming to address the inherent limitations of VSC-HVDC systems and enhance their stability and dynamic performance. Backstepping is a well-established nonlinear control technique that enables the systematic design of control laws. This approach involves the consideration of a sequence of virtual control signals and the design of feedback controllers to guide the actual system states towards the desired trajectories. The main contribution of this research is the integration of integral action into the backstepping framework. This integration addresses steady-state errors that may occur in conventional backstepping controllers, ensuring accurate tracking of reference signals. The proposed methodology for controller design provides a systematic and robust approach to achieve superior stability and dynamic performance in VSC-HVDC systems.

The remaining sections of this paper are structured as follows: Section 2 presents the control design of VSC-HVDC. Section 3 provides practical simulations and results to validate the theoretical analysis. Finally, section 4 concludes the paper by summarizing the key findings and contributions, and highlighting the main insights and implications of the study.

2. METHOD

2.1. System description and modeling

In this section, we will explore the description and modeling of an HVDC system, focusing specifically on the dynamics of the voltage source converter (VSC). Figure 1 illustrates a two-level VSC-HVDC transmission system, which includes an AC grid connected to a converter through a phase reactor. This system comprises two converters: one functioning as a rectifier and the other as an inverter. These converters are interconnected via a lengthy HVDC cable.

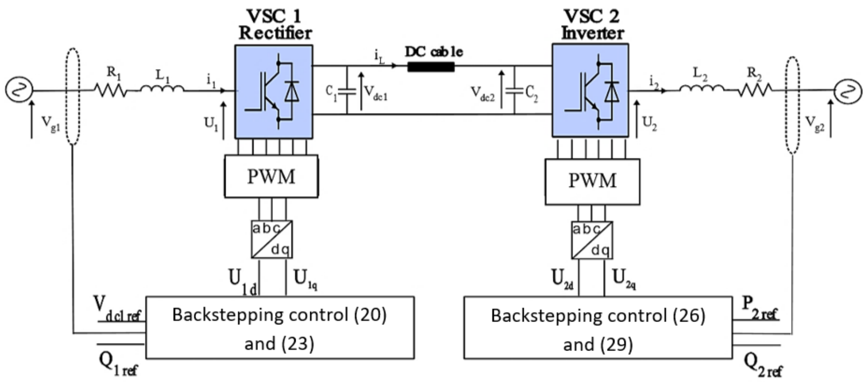


Figure 1. VSC-HVDC transmission system

2.1.1. Mathematical model

The d-q transformation is employed in order to streamline the analysis and control of the dynamics of the VSC-HVDC system [21]. The model of the rectifier station (VSC 1) in the rotating d-q reference frame is expressed as (1) and (2).

$$\frac{di_1^d}{dt} = -\frac{R_1}{L_1} i_1^d + w_1 i_1^q + \frac{1}{L_1} V_{g1}^d - \frac{1}{L_1} U_1^d \tag{1}$$

$$\frac{di_1^q}{dt} = -\frac{R_1}{L_1} i_1^q - w_1 i_1^d + \frac{1}{L_1} V_{g1}^q - \frac{1}{L_1} U_1^q \tag{2}$$

The mathematical representation of the inverter station (VSC 2) in the d-q reference frame is as (3) and (4).

$$\frac{di_2^d}{dt} = -\frac{R_2}{L_2} i_2^d + w_2 i_2^q + \frac{1}{L_2} V_{g2}^d - \frac{1}{L_2} U_2^d \tag{3}$$

$$\frac{di_2^q}{dt} = -\frac{R_2}{L_2} i_2^q - w_2 i_2^d + \frac{1}{L_2} V_{g2}^q - \frac{1}{L_2} U_2^q \tag{4}$$

The equivalent electrical model of the HVDC cable and its mathematical representation is described by:

$$\frac{dV_{dc1}}{dt} = \frac{V_{g1}^d . i_1^d}{C.V_{dc1}} - \frac{i_L}{C} \tag{5}$$

$$\frac{dV_{dc2}}{dt} = -\frac{i_{inv}}{C} + \frac{i_L}{C} \tag{6}$$

$$\frac{di_L}{dt} = -\frac{R_L}{L_L} i_L - \frac{V_{dc1}}{L_L} + \frac{V_{dc2}}{L_L} \tag{7}$$

U_k^d, U_k^q, and V_{gk}^d, V_{gk}^q are the VSC input voltage in the Park transform and the AC network voltage (k=1.2), respectively. i_k^d and i_k^q are the AC network currents in the Park transform (k=1.2). C is the equivalent capacitor of the DC link, while R_k and L_k are the resistance and inductance of the phase reactor, respectively (k=1.2). R_L and L_L are the resistance and inductance of the DC line, respectively. Considering that the reference of the system dq0 is chosen so that its d axis is in phase with the voltage U_g, $U_g^q = 0$.

2.1.2. Average model

The instantaneous model provides a detailed representation of the system's behavior at every instant. However, this approach is not conducive to directly designing a control law. For that purpose, the common approach is to resort to average models, where the average values of the variables replace their instantaneous values in the model. The state variables are defined as follows: $[V_{dc1}, i_1^d, i_1^q, i_2^d, i_2^q] = [x_1, x_2, x_3, x_4, x_5]$. The average representation of the system, obtained from the system model, is described by (8)-(12).

$$\dot{x}_1 = \frac{V_{g1}^d}{C.x_1} x_2 - \frac{1}{C} i_L \tag{8}$$

$$\dot{x}_2 = -\frac{R}{L} x_2 + w_1 x_3 + \frac{1}{L} V_{g1}^d - \frac{1}{L} U_1^d \tag{9}$$

$$\dot{x}_3 = -\frac{R}{L} x_3 - w_1 x_2 - \frac{1}{L} U_1^q \tag{10}$$

$$\dot{x}_4 = -\frac{R}{L} x_4 + w_2 x_5 - \frac{1}{L} V_{g2}^d + \frac{1}{L} U_2^d \tag{11}$$

$$\dot{x}_5 = -\frac{R}{L} x_5 - w_2 x_4 + \frac{1}{L} U_2^q \tag{12}$$

2.2. Controller design

In this paper, our objective is to develop a nonlinear control strategy based on backstepping control for VSC-HVDC transmission systems. This approach aims to simultaneously achieve the following two control objectives: i) controlling the DC voltage to track its reference and the active power at station 2 and ii) ensuring a sinusoidal grid current that is in phase with the grid voltage by strategically addressing reactive power at both stations. By addressing these objectives, the proposed nonlinear control strategy is expected to provide a more effective and efficient solution for VSC-HVDC transmission systems, improving their overall performance and stability.

2.2.1. Integral backstepping control

Integral backstepping control is a highly effective nonlinear control technique that combines the backstepping method with integral action in order to attain robust tracking performance and eliminate steady-state errors [22], [23]. The fundamental concept behind this technique is to augment the plant dynamics with an integral state, which increases the vector relative degree and necessitates additional backstepping steps [24]. This method employs Lyapunov-based design principles to guarantee system stability and performance, while also displaying remarkable ability in handling uncertainties, disturbances, and parameter variations within systems. Consequently, it can be classified as a versatile and reliable control approach.

2.2.2. The rectifier station control

The rectifier station serves a pivotal function within the VSC-HVDC system, facilitating stable operation through the simultaneous management of DC voltage and reactive power. Its primary objective is to maintain alignment with the reference value of the DC voltage VDC, thereby ensuring the desired stability of the system across varying operational conditions. Furthermore, the control of the rectifier station enhances overall power quality by correcting the power factor, a critical component for the efficient transmission of electrical energy.

a) DC voltage control

To implement the backstepping strategy for controlling DC voltage, follow these steps while utilizing (8)-(12).

- Step 1: First, we take into consideration the tracking error $\varepsilon_1 = x_1 - x_{1ref}$, (with $x_{1ref} = V_{\mathrm{d}cref}$ and its derivative, which remains constant, equals zero). The derivative of ε_1 is given by (13).

$$\dot{\varepsilon_1} = \dot{x}_1 - \dot{x}_{1ref} = \frac{V_{g1}^d}{C.x_1} x_2 - \frac{1}{C}\, i_L - \dot{x}_{1ref} \tag{13}$$

In (13), the term x_2 is identified as a virtual control signal. Assuming this to be the actual control signal temporarily, we proceed to consider the Lyapunov function candidate.

$$V_1 = \frac{1}{2}{\varepsilon_1}^2 \Rightarrow \dot{V_1} = \varepsilon_1 \dot{\varepsilon_1} \tag{14}$$

The time derivative of V_1 can be transformed into a negative definite function of ε_1, as:

$$\dot{V_1} = \varepsilon_1 \left(\frac{V_{g1}^d}{C.x_1} x_2 - \frac{1}{C}\, i_L - \dot{x}_{1ref} \right) = -k_1 {\varepsilon_1}^2 \tag{15}$$

by defining $x_2 = \delta_1$ where:

$$\delta_1 = \frac{C.x_1}{V_{g1}^d} \left(\frac{1}{C} i_L - k_1 \varepsilon_1 \right) \tag{16}$$

k_1 represents a positive design parameter. Since the actual control input is not δ_1. We define a new tracking error:

$$\varepsilon_2 = x_2 - \delta_1 \tag{17}$$

- Step 2: Stabilizing the system $(\varepsilon_1, \varepsilon_2)$. It follows from (17) that the derivative of ε_2 is (18).

$$\dot{\varepsilon_2} = \dot{x}_2 - \dot{\delta}_1 = -\frac{R}{L} x_2 + w_1 x_3 + \frac{1}{L} V_{g1}^d - \frac{1}{L} U_1^d - \dot{\delta}_1 \tag{18}$$

The positive Lyapunov function V_2 is used. We utilize the positive Lyapunov function $V_2 = V_1 + \frac{1}{2}{\varepsilon_3}^2 + \frac{1}{2}\not{f}_1 {\psi_1}^2$. The time derivative of V_2 can be made a negative definite function of ε_2. It is expressed as (19).

$$\dot{V_2} = \dot{V_1} + \varepsilon_2 \dot{\varepsilon}_2 + \not{f}_1 \psi_1 \varepsilon_2 = -k_2 {\varepsilon_2}^2 \tag{19}$$

Where ψ_1 is the integral term of ε_2 as $\psi_1 = \int \varepsilon_2$. In (18), δ_1 is the actual control input for the VSC1 station. To stabilize the system $(\varepsilon_1, \varepsilon_2)$. We suggest the following control law:

$$U_1^d = L_1 [k_2 \varepsilon_2 + \frac{V_{g1}^d}{C.x_1} \varepsilon_1 - \frac{R_1}{L_1} x_2 + w_1 x_3 + \frac{1}{L_1} V_{g1}^d - \dot{\delta}_1 + \not{f}_1 \psi_1] \tag{20}$$

where $k_2, \not{f}_1$ are any positive design parameters.

b) Reactive power control

The objective of this subsection is to ensure that the reactive power follows a specified reference signal. To achieve this, we introduce a new tracking error $\varepsilon_3 = x_3 - x_{3\text{ref}}$, (with $x_{3ref} = Q_{1ref}$). The derivative of ε_3 is defined as (21).

$$\dot{\varepsilon_3} = \dot{x}_3 - \dot{x}_{3\text{ref}} = -\frac{R_1}{L_1}x_3 - w_1x_2 - \frac{1}{L_1}U_1^q - \dot{x}_{3\text{ref}} \quad (21)$$

We utilize the positive Lyapunov function $V_3 = \frac{1}{2}{\varepsilon_3}^2 + \frac{1}{2}\text{ƀ}_2{\psi_2}^2$. The time derivative of V_3 can be made a negative definite function of ε_3. It is expressed as (22).

$$\dot{V_3} = \varepsilon_3\dot{\varepsilon}_3 + \text{ƀ}_2\psi_2\varepsilon_3 = -k_3{\varepsilon_3}^2 \quad (22)$$

Where ψ_2 is the quantity that is obtained by integrating ε_3, as expressed in the equation $\psi_2 = \int \varepsilon_3$. Therefore, by employing the derivatives of (21) and (22), we can establish the input control low.

$$U_1^q = L_1[k_3\varepsilon_3 - \frac{R_1}{L_1}x_3 - w_1x_2 - \frac{1}{L_1}U_1^q - \dot{x}_{3\text{ref}} + \text{ƀ}_2\psi_2] \quad (23)$$

Where k_3, ƀ_2 are any positive design parameters.

2.2.3. The inverter station control

The inverter station is responsible for regulating both active and reactive power within the system. By meticulously tracking their respective reference values, it guarantees precise power delivery to the interconnected AC grid or load. This control strategy not only optimizes the efficiency of power transmission but also contributes to grid stability by responding adeptly to dynamic system requirements.

a) Active power control

To implement the backstepping strategy for active power control and track its reference value, we follow these steps. We define a tracking error $\varepsilon_4 = x_4 - x_{4\text{ref}}$, (with $x_{4ref} = P_{2ref}$). Whose derivative is expressed as (24).

$$\dot{\varepsilon}_4 = \dot{x}_4 - \dot{x}_{4\text{ref}} = -\frac{R_2}{L_2}x_4 + w_2x_5 - \frac{1}{L_2}V_{g2}^d + \frac{1}{L_2}U_2^d - \dot{x}_{4\text{ref}} \quad (24)$$

The positive Lyapunov function $V_4 = \frac{1}{2}{\varepsilon_4}^2 + \frac{1}{2}\text{ƀ}_3{\psi_3}^2$ is used. The time derivative of V_4 can be formulated as a negative definite function of ε_4, presented as (25).

$$\dot{V_4} = \varepsilon_4\dot{\varepsilon}_4 + \text{ƀ}_3\psi_3\varepsilon_4 = -k_4{\varepsilon_4}^2 \quad (25)$$

Where ψ_3 is the quantity obtained by integrating ε_4, as $\psi_3 = \int \varepsilon_4$. By utilizing the derivatives of (24) and (25), we suggest the following control law:

$$U_2^d = L_2[-k_4\varepsilon_4 + \frac{R_2}{L_2}x_4 - w_2x_5 + \frac{1}{L_2}V_{g2}^d + \dot{x}_{4\text{ref}} - \text{ƀ}_3\psi_3] \quad (26)$$

$k_4, \text{ƀ}_3$ represents a positive design parameter.

b) Reactive power control

In this section, the objective is to ensure that the reactive power aligns with a specified reference signal. We define a tracking error $\varepsilon_5 = x_5 - x_{5\text{ref}}$, (with $x_{5ref} = Q_{2ref}$). Whose time derivative is expressed as (27).

$$\dot{\varepsilon}_5 = \dot{x}_5 - \dot{x}_{5\text{ref}} = -\frac{R_2}{L_2}x_5 - w_2x_4 + \frac{1}{L_2}U_2^q - \dot{x}_{5\text{ref}} \quad (27)$$

We employ the positive Lyapunov function $V_5 = \frac{1}{2}{\varepsilon_5}^2 + \frac{1}{2}\text{ƀ}_4{\psi_4}^2$. It is time derivative V_5 is made a negative definite function and its derivative is given by (28).

$$\dot{V_5} = \varepsilon_5\dot{\varepsilon}_5 + \text{ƀ}_4\psi_4\varepsilon_5 = -k_5{\varepsilon_5}^2 \quad (28)$$

Where ψ_3 is the quantity obtained by integrating ε_5, as $\psi_4 = \int \varepsilon_5$. Hence, by using the derivatives of (27) and (28). Then we get the control law of the inverter station as (29).

$$U_2^q = L_2[-k_5\varepsilon_5 + \frac{R_2}{L_2}x_5 + w_2x_4 + \dot{x}_{5\text{ref}} - \text{ƀ}_4\psi_4] \quad (29)$$

$k_5, \oint_4$ denotes a positive design parameter.

Based on the LaSalle-Yoshizawa theorem, ε_1, ε_2, ε_3, ε_4, and ε_5 are bounded and converge to zero as t approaches infinity. Since $\varepsilon_1 = x_1 - x_{1\text{ref}}$, $\varepsilon_3 = x_3 - x_{3\text{ref}}$, $\varepsilon_4 = x_4 - x_{4\text{ref}}$, $\varepsilon_5 = x_5 - x_{5\text{ref}}$, and (x_1, x_3, x_4, x_5) are also bounded and converge to the desired equilibrium point $x_{1\text{ref}}$ the boundedness of x_2 follows the boundedness of δ_1. From $\varepsilon_2 = x_2 - \delta_1$, shows that regulating x_1 will imply the regulation of x_2. Additionally, according to (20), (23), (26), and (29), the control rules U_1^d, U_1^q, U_2^d, and U_2^q are also bounded.

3. RESULTS AND DISCUSSION

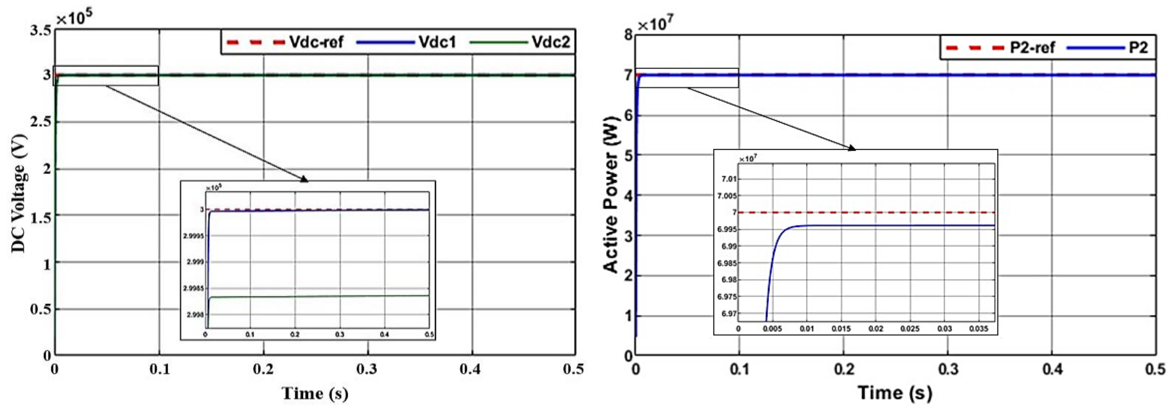
To validate the performance of the suggested controller, the complete control system depicted in Figure 1 is implemented via the MATLAB/Simulink software. The system and control parameters are intricately described in Table 1. The active and reactive power reference values are established as 70 MW and 0 Var, respectively. Additionally, the V_{dcref} value is set to 300 kV.

Table 1. System and control parameters

	Parameter	Value
System parameters	AC voltage	200 kV
	DC voltage	300 kV
	Frequency: f_1 in grid 1, f_2 in grid 2	50 Hz, 60 Hz
	Inductance	40 mH
	Resistance	0.4 Ω
	Capacitance	160 µF
	Length of transmission line	200 Km
	Cable inductance, resistance, and capacitance	0.06 mH/Km, 7 mΩ/Km, 0.3 µF/Km
Controller parameters	k_1, k_2, k_3, k_4, k_5, k_6, k_7	1000, 2000, 1500, 3000, 4000, 2000, 5000

3.1. Standard results

In this case, the performance evaluation is conducted under normal conditions. A rigorous analysis of the controller performance, as illustrated in Figures 2 and 3, highlights the robustness and efficiency of the system. The DC voltage tracks its reference with high accuracy, providing a quick dynamic response. Additionally, the nonlinear backstepping controller was shown to be able to maintain exceptional steady-state behavior, as depicted in Figure 2(a). Simultaneously, the active power demonstrates a commendable ability to quickly converge toward its maximum reference following a short transition period, as established in Figure 2(b).



(a) (b)

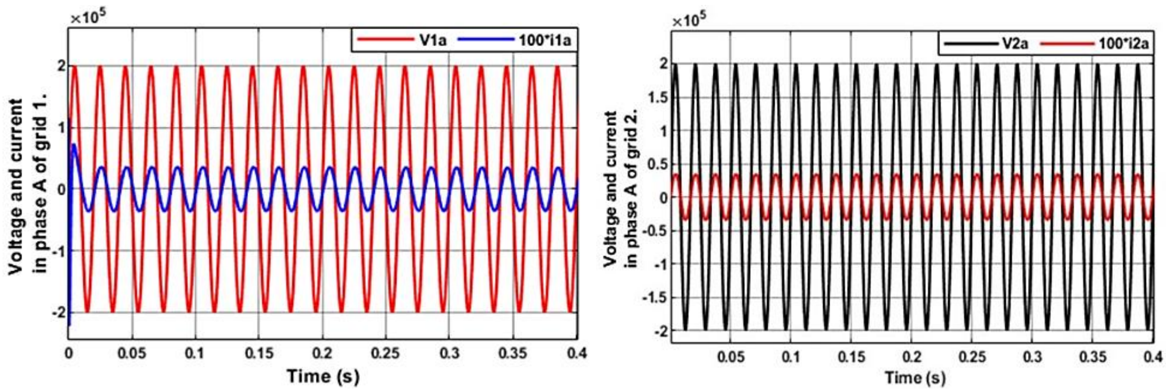
Figure 2. The DC voltage tracks and power fluctuations at two stations: (a) DC voltages at station 1 and (b) active power at station 2

The source voltage remains synchronized with the grid current in Figure 3. This discovery validates a fundamental element of the system's coherence and stability in an asynchronous VSC-HVDC system operating between grid 1 with a frequency of 50 Hz and grid 2 with a frequency of 60 Hz. This synchronization denotes the achievement of unity power factor correction (PFC), which plays a crucial role in enhancing system efficiency and optimization. These results demonstrate the effectiveness and robustness of the proposed control strategy for achieving high-performance VSC-HVDC systems.

3.2. Validation of resilience

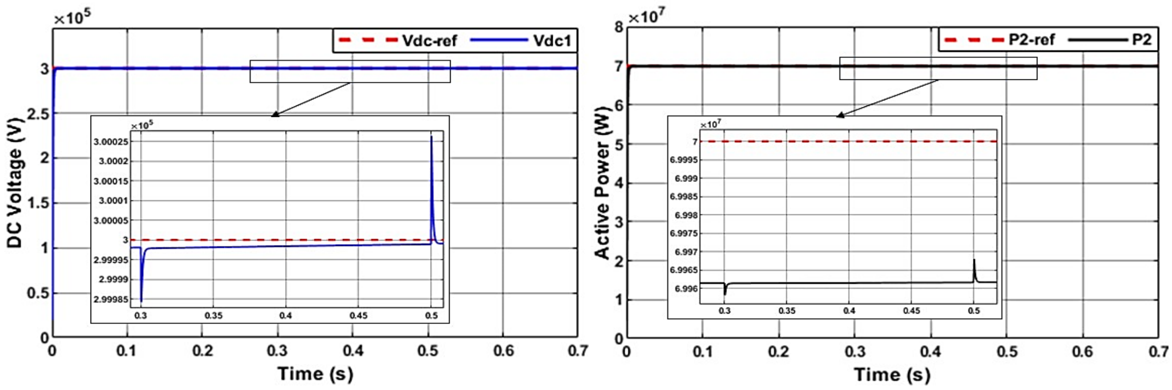
HVDC transmission systems are susceptible to disturbances that can affect their behavior. To assess the robustness of the control system, tests were conducted to evaluate its performance under a simulated disturbance scenario. The DC voltage undergoes a rapid decline of 50% from its initial value in 0.3 seconds and subsequently restores its original value within 0.5 seconds.

Figure 4 depicts the achieved performances of the proposed controller when subjected to disturbances. With the proposed control, the DC voltage and active power quickly reach their maximum reference values after a short transient period during the disturbance. In contrast, the PI controller exhibits significant deviations from the reference value, accompanied by pronounced oscillations and overshooting of the designated reference point [25]. The inclusion of integral parameters enables faster recovery to the setpoint in cases of line break failures compared to conventional backstepping control. By effectively ensuring system stability and performance in the face of various challenges, the proposed controller establishes itself as a robust and reliable solution for regulating HVDC transmission systems, thereby offering significant advantages over conventional methods.



(a) (b)

Figure 3. Voltage and current in phase a of (a) grid 1 and (b) grid 2



(a) (b)

Figure 4. Robustness of (a) DC voltages at station 1 and (b) active power at station 2

4. CONCLUSION

This paper examines VSC-HVDC system control using an integral backstepping method for two converter stations linked via a DC network. This approach takes into account variations in system parameters and enhances dynamic behavior. Simulation results demonstrate that the adopted control strategy significantly improves system performance compared to conventional PI control. It also successfully achieves our control objectives in both stations, even in the presence of disturbances and potential defects arising from the complexity of the power transmission system and unmeasurable random disturbances. In future research, our objective is to incorporate renewable energy sources into multi-terminal direct current (MTDC) systems through the exploration of novel control methods, aiming to optimize their utilization and enhance the reliability of HVDC systems in light of the evolving grid conditions and challenges.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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