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A Comparative Review of Advanced Control Strategies for VSC-HVDC Transmission Systems

Mohammed Amine RHONDALI[1,*], Abdelmounime EL MAGRI[1], Ilyass EL MYASSE[2], and Lhoussain BAHATTI[1]

[1]EEIS Laboratory, ENSET Mohammedia, Hassan II University of Casablanca, Morocco.
[2]LSIB Laboratory, FST of Mohammedia, Hassan II University of Casablanca, Morocco.

Abstract. This paper presents a comparative review and simulation-based analysis of control strategies for Voltage Source Converter-based High Voltage Direct Current (VSC-HVDC) transmission systems. Conventional approaches such as PID controllers remain widely adopted due to their simplicity and ease of implementation, yet they face inherent limitations when dealing with nonlinear dynamics and parameter uncertainties. To address these challenges, advanced strategies such as nonlinear, predictive, and intelligent control have been proposed in the literature. Building on this foundation, the paper provides a comprehensive review of control strategies for HVDC systems and develops a detailed case study comparing a conventional PI controller with a backstepping controller, applied to a two-terminal VSC-HVDC system interconnecting two AC grids through a 100 km cable. Simulation results demonstrate that the backstepping controller significantly outperforms the PI controller, achieving superior DC-link voltage regulation, faster active power tracking, and effective reactive power compensation. Quantitative performance indices confirm the robustness and precision of the nonlinear scheme. The findings highlight the growing importance of advanced and hybrid control methods in ensuring reliable and efficient operation of future HVDC networks.
keywords: VSC-HVDC, Conventional Control Schemes, Nonlinear control, Multi-terminal DC (MTDC), Power factor correction, Active and reactive power regulation, Offshore wind integration, Advanced control strategies, Renewable energy transmission

1 Introduction

High-Voltage Direct Current (HVDC) technology based on Voltage Source Converters (VSC) has become a cornerstone for long-distance power transmission, interconnection of asynchronous grids, and large-scale integration of renewables such as offshore wind. Compared with Line Commutated Converter (LCC) schemes, VSC-HVDC offers independent control of active and reactive power, black-start capability, and robust operation with weak grids, making it well suited to modern, highly dynamic power systems [1, 2]. At the same time, these advantages come with stringent control requirements: tight DC-link voltage regulation across long cables, fast power set-point tracking, power-factor correction at the AC terminals, and resilience to parameter variations, disturbances, and grid events.

In practice, conventional linear controllers, notably PI and PID, remain the most widely deployed in VSC applications because they are simple, transparent, and easy to tune within the familiar double closed-loop structure (inner current control in the dq frame and outer voltage/power loops). Numerous studies report satisfactory performance with such schemes under nominal conditions and for point-to-point links [3–5]. Enhancements such as vector PI, harmonic compensation, and improved tuning rules have further extended their utility [6–8]. Nevertheless, inherent limitations persist: parameter sensitivity, restricted adaptability across operating points, and difficulty addressing the pronounced nonlinearities and couplings in VSC-HVDC during large steps, faults, or weak-grid operation [9–12].

These challenges have catalyzed growing interest in nonlinear and intelligent control strategies. Sliding-Mode Control (SMC) variants mitigate modeling uncertainty and disturbances while improving transient behavior [13–19]. Backstepping leverages Lyapunov-based recursive designs to coordinate inner/outer loops and guarantee global asymptotic stability with explicit performance shaping [20–22]. Feedback linearization and hybrid FL–SMC schemes offer additional decoupling and robustness for MMC/VSC control [23, 24]. Alongside nonlinear methods, advanced and data-driven approaches—fuzzy logic, metaheuristic optimization (GA/PSO/ABC/Mayfly), and predictive control (hierarchical MPC, DeePC)—have been explored to improve tuning, multi-objective performance, and model uncertainty handling [25–33]. Robust H_∞ formulations remain attractive when worst-case guarantees and communication imperfections must be considered [34–39].

Against this backdrop, modern HVDC deployments are trending from point-to-point links toward multi-terminal DC (MTDC) networks with Modular Multilevel Converters (MMCs), tighter voltage coordination, and increasingly ambitious ancillary-service roles (frequency support, oscillation damping, synthetic inertia). The resulting control landscape is richer—but also more demanding—in terms of model fidelity, stability margins, and interaction with grid codes. Literature surveys indicate a clear shift toward strategies that explicitly account for nonlinearities and uncertainties, particularly in weak-grid and renewable-dominated scenarios [12, 19, 29, 40, 41].

This article makes two complementary contributions.

1. A comparative review of control strategies for VSC-HVDC has been presented, covering conventional PI/PID, advanced methods (SMC, backstepping, feedback linearization), and intelligent approaches (fuzzy logic, metaheuristics, MPC, H_∞). The review organizes recent results by control objective (DC-link regulation, PFC, active/reactive power coordination) and by application context (MMC, MTDC, weak grids), highlighting strengths, limitations, and implementation considerations.

2. A case study is conducted as a comparative analysis between a well-tuned PID baseline and a Lyapunov-based backstepping controller on a representative two-grid/two-VSC, 100-km HVDC system. Using identical plant parameters and reference programs, we evaluate DC-link regulation, active-power tracking, and reactive-power control. Results show that backstepping delivers markedly shorter transients, reduced overshoot, and improved steady-state accuracy, with superiority quantified by standard indices (ISE/ITSE/IAE/ITAE).

The remainder of the paper is organized as follows: Section 2 reviews linear controllers and their enhancements, emphasizing practical tuning and known limitations. Section 3 surveys SMC, backstepping, and feedback linearization and synthesizes recent advances. Section 4 summarizes fuzzy, metaheuristic, predictive, and H_∞ controllers for VSC-HVDC. The section 5 integrates insights from the literature, offering guidance on method selection for present and future HVDC applications. Section 6 describes the test system, controller implementations, and simulation protocol, followed by results and quantitative metrics. Finally, Section 7 presents the concluding remarks and outlines promising directions for future research in the integration of transmission technologies for large offshore wind farms.

2 Conventional control schemes (PI and PID)

Conventional control schemes, particularly PI and PID controllers, remain widely adopted in VSC applications due to their simplicity and ease of implementation. Despite their widespread use, these methods face several challenges related to parameter sensitivity, limited adaptability under varying operating conditions, and difficulty in handling nonlinear dynamics inherent in HVDC systems. Recent research efforts have focused on enhancing these traditional controllers to address such limitations through advanced strategies and hybrid approaches. Table 1 summarizes key studies that explore these conventional control techniques, their limitations, and the corresponding improvements proposed in recent literature.

Table 1. Overview of Conventional PI and PID Control Strategies for VSC-HVDC Systems

Refs	Control Type	Problematic and Contribution	Strategy	Results
[1–5, 40, 42]	PI and PID	Control of Voltage Source Converters (VSC)	Double-closed loop PI control structure (inner current and outer power loops)	Simplicity, robustness, management of stabilization, active/reactive power, and overall VSC performance.
[6, 7]	PI	Sensitivity to parameters and operational condition changes	Strategy combining PI and vector PI controllers	Suppression of low-order harmonics in VSC-HVDC systems and improved waveform quality.
[9]	PI	DC-side stabilizing conditions for hybrid HVDC links	Stability criterion based on dominant frequency model reduction	DC-side stability worsens with low DC voltage, heavy loads, small DC-link capacitors, and slow inner-loop dynamics.
[10]	PI	Improvement of power quality and small-signal stability for VSC-HVDC systems	Fractional Order Proportional Integral (FPI) controller	Uses fractional calculus for real-number integral orders, offering improved resilience to uncertainties and handling nonlinear system dynamics.
[11]	PI	Voltage regulation and power sharing in MMC-based multi-terminal HVDC systems	PI consensus-based Integrated Distributed Control (IDC) strategy	Reduces communication requirements and offers a simpler, more robust structure.
[12]	PI	Harmonic suppression for HVDC wind power systems	Modular N*-three-phase Permanent Magnet Synchronous Generator (PMSG) with harmonic suppression strategy	Modular design, electrical isolation, and fault tolerance.
[8]	PI	Improved closed-loop control performance and robustness in VSC-based HVDC systems	Vector control method with symmetric optimum PI tuning	Enhanced closed-loop control performance and robustness.
[43, 44]	PID	Limited performance when conditions change (designed for a single operating point)	Use of intelligent algorithms (fuzzy logic, PSO, neural networks) for dynamic parameter tuning	Improved VSC stability.

While these developments demonstrate meaningful advancements, PI and PID controllers still face fundamental limitations in highly dynamic and nonlinear environments. Challenges in VSC-HVDC control include structural complexity, nonlinear dynamics, time-varying parameters, and uncertainties, highlighting the need for advanced control methods to ensure optimal performance.

3 Nonlinear Control Schemes

Nonlinear control strategies have gained significant attention in the context of VSC-HVDC systems due to their ability to handle complex dynamics, uncertainties, and disturbances that traditional linear controllers struggle with [45]. These methods, including SMC, Backstepping, and Feedback Linearization (FL), offer improved robustness, stability, and dynamic response. Table 2 summarizes recent contributions in this domain, highlighting the key challenges addressed, control strategies employed, and outcomes achieved.

Table 2. Overview of Nonlinear Control Strategies for VSC-HVDC Systems

Refs	Control Type	Problematic and Contribution	Strategy	Results
[13]	SMC	Addresses nonlinearities and disturbances in MMC systems.	Partitioned state space control using switching functions.	Superior transient response and robustness compared to PI.
[15]	Super-Twisting SMC	Enhances stability and reduces chattering.	Hyperbolic tangent sliding surface and flower pollination algorithm.	Faster response than PI and conventional SMC.
[16]	SMC	Stabilizes converter operation during faults.	Robust SMC design.	Improved signal quality, stability, and settling time over PI.
[17]	Hierarchical Fractional-order SMC	Reduces chattering in MTDC systems with wind farms.	Exponential reaching laws and saturation functions.	Effective damping of oscillations in DC lines.
[18]	SMC	Handles unbalanced grid conditions.	Flexible instantaneous power model-based SMC.	Suppresses frequency ripples, robust to disturbances.
[19]	SMC	Improves stability with short circuit ratio uncertainty.	Robust model and control design.	Better dynamic response and robustness than vector PI control.
[46]	SMC	Enhances frequency stability in low inertia systems.	Robust sliding mode design.	Stable performance regardless of disturbance size.
[20]	Backstepping + DSC	Coordinates active/reactive power without complex derivatives.	Subsystem decomposition and dynamic surface control.	Efficient power regulation, minimal errors, fast response.
[21]	Backstepping (abc frame)	Ensures stability and avoids extra loops.	Control of key MMC variables with virtual input.	Improved transient performance and robustness.
[22]	Integral Backstepping	Improves current control bandwidth and decoupling.	Inner current loop controller.	Outperforms PI under normal and fault conditions.
[47]	Nonlinear Backstepping	Implements GFM converter control with inertia support.	Feedback linearization and energy-based design.	Superior energy and frequency control over PI.
[48]	Backstepping Output Feedback	Regulates power and voltage with robustness.	Nonlinear output feedback with backstepping.	Maintains stability under grid disturbances.
[24]	Hybrid FL-SMC	Suppresses subsynchronous oscillations.	Combination of FL and SMC.	Enhanced decoupling and robustness over PI.
[23]	FL	Manages d-q axis and circulating currents.	Nonlinear decoupling with zero-dynamics stability.	Improved transient and dynamic performance.
[49]	FL with Lyapunov	Achieves stability and voltage balance.	Lyapunov-compensated FL.	Validated stability and performance in simulations.

Despite these advances, practical deployment of nonlinear controllers in VSC-HVDC systems still face limitations, such as chattering, high implementation complexity, and sensitivity to modeling inaccuracies. Challenges in VSC-HVDC control include structural complexity, nonlinear dynamics, time-varying parameters, and uncertainties, highlighting the need for advanced control methods to ensure optimal performance.

4 Other Control Techniques

Beyond classical and nonlinear control strategies, various advanced techniques have been introduced to enhance the control and stability of VSC-HVDC systems. These include fuzzy logic, metaheuristic optimization, model predictive control, and H-infinity control. Each method addresses specific challenges such as uncertainty, computational efficiency, dynamic performance, and robustness. The following Table 3 summarizes key contributions, highlighting their control type, addressed issues, adopted strategies, and achieved results.

Table 3. Summary of other advanced control techniques used in VSC-HVDC systems.

Refs	Control Type	Problematic and Contribution	Strategy	Results
[50]	Fuzzy Logic	Frequency control in VSC-multi-terminal DC systems without communication.	Uses frequency deviation and its rate of change for power adjustment.	Improves frequency stability in AC systems.
[51]	Fuzzy-Adaptive Droop Control	Balances DC voltage regulation and frequency support in MTDC systems.	Dynamically adjusts droop gains based on local measurements.	Robust to parameter variation; efficient fuzzy rule base.
[52]	Neural Fuzzy Virtual Inertia	Enhances frequency stability at the receiving end of VSC-HVDC.	Adaptive adjustment of inertia and damping coefficients.	Improves dynamic frequency response.
[25]	MH Optimization (e.g. GA, PSO)	Optimizes controller parameters in VSC/MT-HVDC systems.	Uses GA and PSO to enhance robustness and mitigate SMC chattering.	Improves stability, efficiency, and reliability.
[26]	Multi-objective MH (e.g. ABC)	Addresses multi-objective control design for stability and robustness.	Applies multi-objective optimization techniques.	Achieves robust and stable control.
[27]	MH Algorithms	Optimizes VSC-HVDC converter control.	Employs various metaheuristic techniques.	Demonstrates improved converter performance.
[28]	Mayfly Algorithm	Optimizes PI controller parameters.	Applies multi-objective MA.	Demonstrates superior stability.
[29]	PSO-optimized PI	Tuning PI controllers for HVDC Light systems.	PSO algorithm embedded in Simulink.	Improves tuning and stability.
[30]	Folding MPC	Reduces computational complexity in MMCs.	Introduces FMPC with sorting algorithm.	Unifies control objectives and enhances dynamic response.
[31]	Hierarchical MPC	Coordinates AC/DC power and energy control in grid-forming MMCs.	Develops hierarchical structure.	Efficient power exchange and energy regulation.
[33]	Data-enabled Predictive Control (DeePC)	Model-free prediction and control of power oscillations.	Uses input-output data for control.	Enhances damping and optimality.
[32]	DHOVC (MPC + ADMM)	Mitigates reactive power fluctuations in offshore wind farms.	Uses adaptive droop and ADMM in MPC.	Improves voltage control and power sharing.
[34, 35]	H-infinity Control	Minimizes worst-case gain for robust performance.	Standard H_∞ setup with disturbance shaping weights.	Improves disturbance rejection and stability.
[37]	H-infinity + Passivity	Handles communication loss in GFM converters.	Uses GPS sync and virtual impedance; LMI-based design.	Ensures autonomous operation and robust control.
[38]	H-infinity Sliding Mode	Load frequency control with stochastic delays.	LMI toolbox used for gain synthesis.	Achieves high performance index and stability margin.
[39]	H-infinity (4-stage)	Enhances droop control in islanded MGs.	PMU-based control using `hinfsyn` algorithm.	Improves voltage, frequency regulation, and power sharing.

These advanced control techniques offer promising improvements in the reliability and performance of VSC-HVDC systems. However, challenges such as real-time implementation complexity, parameter sensitivity, and integration into large-scale systems remain active areas of research. Continued development and hybridization of these methods are crucial for meeting the growing demands of modern power systems.

5 Comparison of control techniques

Literature shows that linear control techniques are the most widely used in HVDC converter systems, particularly for Voltage Source Converters (VSC). Their popularity stems from their simplicity, ease of implementation, and reliable performance across a wide range of operating conditions. In many cases, linear controllers such as PI or droop-based schemes meet system requirements effectively. However, in scenarios involving significant uncertainties or where enhanced robustness is required, nonlinear control methods become essential [21]. Techniques like Sliding Mode Control (SMC), feedback linearization, fuzzy logic, (H_∞), and backstepping are increasingly being adopted to handle more complex dynamics and ensure better fault tolerance. These methods are particularly useful in systems with varying parameters, such as offshore wind farms where conditions change rapidly and unpredictably. SMC, in particular, is often selected when equivalent control laws are feasible, due to its robustness against parameter variations. Likewise, advanced and intelligent control strategies such as fuzzy logic, metaheuristic (MH) optimization, Model Predictive Control (MPC), and backstepping have gained significant traction in recent years. Their ability to adapt to dynamic conditions and meet multiple control objectives simultaneously makes them attractive for emerging multi-terminal HVDC (MT-HVDC) systems.

As HVDC systems evolve from simple point-to-point topologies to multi-terminal configurations, control complexity inevitably increases. Notably, around 70% of the reviewed papers focus on multi-terminal systems—where VSC and Modular Multilevel Converters (MMC) dominate. In fact, only a few studies include Line Commutated Converters (LCC), and those are typically in hybrid setups with LCC rectifiers and VSC inverters. This shift reflects the growing preference for VSC and MMC technologies, especially given the limitations of LCCs in interfacing with weak systems [19]. Controlling power flow, sharing, and ensuring system-wide voltage stability remain key objectives across all configurations [41]. Droop control, in particular, is widely used to manage DC voltage and voltage stability among multiple converters [40], while more complex strategies—such as H_∞, SMC, and MH techniques—are often employed when precision and robustness are paramount. Additionally, HVDC systems are increasingly being used to provide ancillary services such as frequency stabilization, power oscillation damping, and dynamic stability enhancement. Several studies address these challenges directly , highlighting the growing importance of these capabilities in offshore and renewable-integrated systems [12].

As systems become more complex, the shift from conventional linear methods toward nonlinear and intelligent control strategies becomes more apparent. These advanced approaches are often based on more accurate system models and can handle multi-objective optimization and real-time control under uncertain conditions. Each control method offers unique advantages depending on the use case:

- Linear control is best suited for systems operating near nominal conditions, where implementation simplicity and predictability are priorities.
- Nonlinear methods provide enhanced robustness and transient response but come with increased design complexity and computational cost.
- Metaheuristic approaches, such as those involving particle swarm optimization (PSO) or genetic algorithms, offer a flexible middle ground—balancing robustness and adaptability, though often at the expense of interpretability and longer setup or training times.

Ultimately, selecting the right control strategy depends on the system's specific needs, including its topology, reliability requirements, and tolerance to parameter uncertainty. Extensive simulation remains the standard practice for validating performance. A practical approach is to start with linear control methods, validate them through simulations, and then assess whether more advanced strategies are needed based on how well they handle variability and nonlinearities.

6 Comparative Study

6.1 System under study

The system under consideration is a point-to-point VSC–HVDC transmission link that interconnects two independent AC grids. As shown in Fig. 1, the configuration consists of two VSC stations—VSC1 operating as a rectifier at the sending end and VSC2 functioning as an inverter at the receiving end—connected through a long HVDC cable of 100 km length. Each converter station is interfaced with its respective AC grid through $L\check{}R$ filters in order to attenuate harmonics and limit current ripple. DC capacitors are placed at both ends of the HVDC cable to provide energy buffering and ensure voltage stability along the transmission line.

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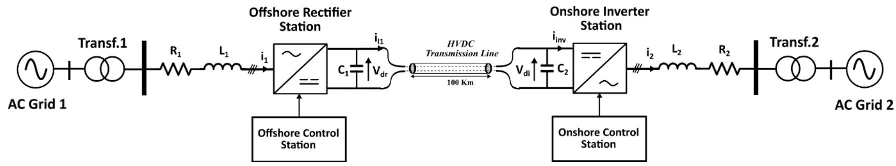

Figure 1. General configuration of the two-terminal VSC–HVDC system under study

This architecture is representative of modern HVDC transmission systems deployed for interconnecting asynchronous grids, transmitting bulk power over long distances, or integrating renewable generation units into existing power networks. Its flexibility in controlling both active and reactive power at each converter station makes it particularly suitable for demanding operational environments where dynamic stability and robustness are critical.

In the context of this study, the system is controlled to achieve three fundamental objectives:

- **CO1: DC voltage regulation** The primary task of the rectifier station (VSC1) is to regulate the DC-link voltage across the HVDC cable. The voltage must be tightly controlled around a constant reference value.
- **CO2: Power Factor Correction (PFC)** Both VSC stations are also responsible for maintaining sinusoidal grid currents that are in phase with the corresponding grid voltages to improve the efficiency of power exchange.
- **CO3: Active and reactive power regulation at the inverter side (VSC2)** The VSC2 is operated in power control mode, where it regulates the active and reactive power at the Grid 2 according to a prescribed reference trajectory.

The simultaneous fulfillment of these three objectives ensures that the HVDC system delivers reliable power transfer between the two grids while preserving voltage stability, maintaining high power quality, and enhancing the operational flexibility of the interconnected networks.

6.2 Conventional PID Controller

In the present system, the conventional PID-based scheme is organized in a double closed-loop structure. This structure consists of:

- **Inner current control loop:** operating in the synchronous dq reference frame, it directly regulates the $d-$ and $q-$-axis converter currents. The purpose of this loop is to ensure fast dynamic response and to decouple the control of active and reactive power. By acting on the converter switching signals through pulse width modulation (PWM).
- **Outer voltage/power control loop:** this loop supervises the slower dynamics of the system. At the rectifier side, it regulates the DC-link voltage to a prescribed reference value. At the inverter side, the outer loop is dedicated to controlling the active power injected into Grid 2. The outputs of the outer loops serve as current references for the inner loops.

This hierarchical arrangement has been proven effective for basic HVDC operation and has long been used in commercial installations. Its main advantages include straightforward tuning, low computational burden, and well-established design procedures.

However, the PID controller also suffers from inherent limitations when applied to modern VSC–HVDC systems. Its performance is highly sensitive to parameter variations such as line inductance, cable resistance, and converter dynamics, all of which may vary significantly in practice. As a result, PID-based schemes may exhibit overshoot, longer settling times, and reduced robustness compared to nonlinear or advanced control strategies.

6.3 Backstepping Controller

To overcome the limitations of conventional PID control, a **nonlinear backstepping controller** is designed. The backstepping approach is based on the recursive construction of Lyapunov functions and stabilizing functions, which guarantees global asymptotic stability of the closed-loop system. Unlike linear controllers, backstepping explicitly considers the nonlinear dynamics of the converters, thereby enabling superior transient response, robustness against parameter uncertainties, and effective decoupling of active and reactive power dynamics.

The backstepping design is applied separately to the two converter stations, with each controller tailored to its respective objectives.

Rectifier station (VSC1): The rectifier is primarily responsible for regulating the DC-link voltage and ensuring power factor correction at the sending end. Starting from the DC voltage dynamics, the Lyapunov-based recursive design yields the following control laws for the rectifier, as detailed in [53]:

$$\begin{cases} U_{d1} = \dfrac{L_1}{\beta}\left[z_5 + k_6 z_6 + \beta\left(-\dfrac{R_1}{L_1}x_7 + \omega_1 x_8 + \dfrac{1}{L_1}V_{d1}\right) - \dot{\alpha}_5\right] \\ U_{q1} = L_1\left[k_7 z_7 - \omega_1 x_7 - \dfrac{R_1}{L_1}x_8\right] \end{cases} \tag{1}$$

Here, the variables x_i denote system states (voltages and currents in dq frame), z_i are the defined tracking errors at each recursive step, k_i are positive design gains, and β is a constant related to system parameters. These laws ensure that the DC-link voltage tracks its reference (CO1) while the quadrature current tends to zero, enforcing unity power factor (CO2).

Inverter station (VSC2): The inverter regulates the active and reactive power delivered to the receiving grid. By defining the active power $P_2 = V_{d2} i_{d2}$ and the reactive power $Q_2 = V_{d2} i_{q2}$, the following control inputs are derived, as detailed in [53]:

$$\begin{cases} U_{d2} = L_2\left[-k_8 z_8 + \dfrac{R_2}{L_2}x_9 - \omega_2 x_{10} + \dfrac{1}{L_2}V_{d2} + \dot{i}_{d2}^{ref}\right] \\ U_{q2} = L_2\left[-k_9 z_9 + \dfrac{R_2}{L_2}x_{10} + \omega_2 x_9\right] \end{cases} \tag{2}$$

In these expressions, $i_{d2}^{ref} = \dfrac{P_2^{ref}}{V_{d2}}$ is the reference direct current computed from the active power command, while i_{q2}^{ref} is set to zero to enforce $Q_2 = 0$. The error terms z_8 and z_9 represent the deviations of the actual currents from their references, and k_8, k_9 are stabilizing gains chosen to guarantee exponential convergence.

Stability analysis: By combining the recursive Lyapunov functions from each design step, the overall closed-loop error dynamics of the HVDC system can be expressed as:

$$\dot{x} = Bz$$

where $z = (z_1, z_2, \ldots, z_9)^T$ is the vector of error states and B is a lower triangular matrix with negative diagonal elements determined by the design gains k_i. The global Lyapunov function given as $V_z = \frac{1}{2}\sum_{i=1}^{9} z_i^2$, yields the derivative :

$$\dot{V}_z = -\sum_{i=1}^{9} k_i z_i^2 < 0$$

for all positive k_i, proving that the error states converge to zero globally and asymptotically. This ensures that the controller fulfills all three objectives simultaneously: (i) DC-link voltage regulation, (ii) unity power factor operation, and (iii) accurate active/reactive power control.

Remark: *The control laws used in this work are adopted from [53]; however, for brevity, only the main expressions are presented here without detailed derivation.*

6.4 Simulation Results and Analysis

In order to evaluate and compare the performance of the conventional PID controller and the proposed nonlinear backstepping controller, time-domain simulations were carried out on the two-terminal VSC–HVDC system. The references of the controlled outputs were selected as follows: DC-link voltage Vi = 300 kV, reactive power of Grid 1 Q1 = 0 MVAr, active power of Grid 2 P2 = 100 MW, and reactive power of Grid 2 Q2 = 0 MVAr. Step changes were applied to the active power reference P2 at t = 2 s and t = 4 s, where the trajectory followed P2: 100 → 130 → 70 MW*. These tests allow assessment of both voltage regulation and power control objectives under realistic operating conditions.

The responses of the system are illustrated in Figs. 2, 3, 4 and 5, which present the evolution of the DC-link voltage, the active power of Grid 2, and the reactive powers of both grids under the two control strategies.

Analysis of the results

Fig. 2 presents the response of the DC-link voltage under both controllers when subjected to reference tracking at 300 kV. It can be observed that the PID controller exhibits a significant overshoot and oscillatory behavior during the transients, particularly around the instants of power step changes. In contrast, the backstepping controller regulates the voltage more effectively, converging rapidly to the reference with negligible error and shorter settling time. This confirms the superior robustness of the nonlinear approach in handling the system's nonlinear dynamics.

Fig. 3 illustrates the active power tracking of Grid 2 when the reference P2* is varied from 100 MW to 130 MW at t = 2 s, and then reduced to 70 MW at t = 4 s. While the PID controller shows delayed convergence and transient deviations, the backstepping controller achieves an almost instantaneous response with minimal overshoot and excellent steady-state accuracy. The zoomed views highlight the capability of the proposed scheme to follow abrupt power variations without oscillations.

Figs. 4 and 5 display the regulation of reactive power at Grid 1 and Grid 2, respectively, where the references were both set to zero to enforce power factor correction. In both cases, the two controllers succeed in maintaining the reactive powers around zero. However, the backstepping controller enforces stricter decoupling and eliminates residual fluctuations more effectively than the PID scheme, ensuring that the grid currents remain fully in phase with the corresponding grid voltages.

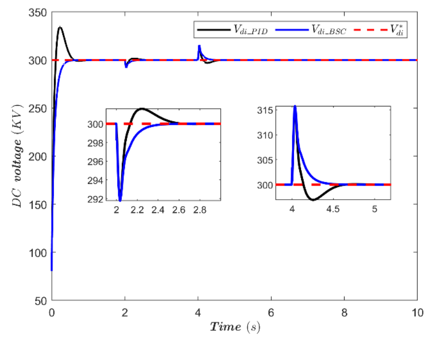

Figure 2. DC-link voltage response

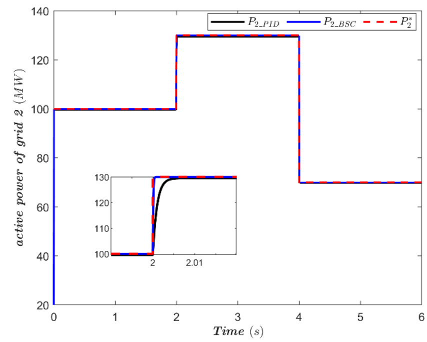

Figure 3. Active power tracking of Grid 2 under

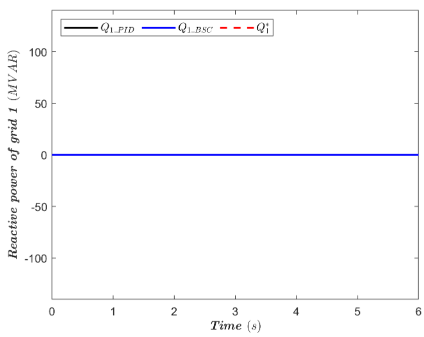

Figure 4. Reactive power regulation of Grid 1

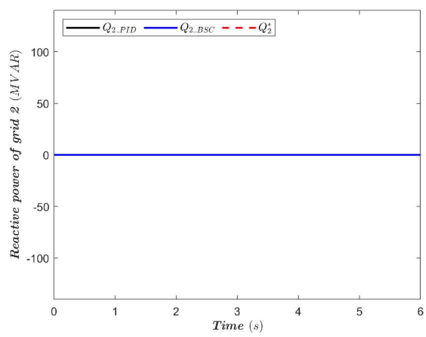

Figure 5. Reactive power regulation of Grid 2

The overall closed-loop performances clearly demonstrate that the backstepping controller outperforms the conventional PID approach. It delivers faster transient responses, reduced overshoot, and superior steady-state precision, thereby confirming its effectiveness and robustness for VSC–HVDC applications.

Specifically, the results show that the reference tracking is significantly improved when using the proposed backstepping controller. The transient responses are much shorter, and steady-state accuracy is markedly superior compared to the PID scheme. The supremacy of the nonlinear controller is further emphasized by the quantitative indices presented in Table 4, where the performances are expressed in terms of standard quality control criteria, namely the Integral of Squared Error (ISE), the Integral of Time Squared Error (ITSE), the Integral of Absolute Error (IAE), and the Integral of Time Absolute Error (ITAE). These indices are computed for both the DC-link voltage error $e_V = V_{di}^* - V_{di}$ and the active power error $e_P = P_2^* - P_2$.

It is evident from these results that the backstepping controller (BSC) significantly reduces the tracking errors in both DC voltage and active power regulation. For instance, the ITAE value for the active power error is reduced from 5.14 (PID) to 1.01 (BSC), while the ISE and ITSE values for the DC-link voltage are several orders of magnitude smaller under the backstepping control. These quantitative metrics confirm the observations made in the time-domain simulations: the backstepping controller ensures superior dynamic performance, improved robustness, and higher accuracy, making it a more suitable solution for advanced VSC–HVDC applications than the conventional PID approach.

Table 4. Performance evaluation criteria of both control strategies

Approach	$e_v = V_{dc} - V_{dc}^{ref}$				$e_p = P - P^{ref}$			
	ISE	ITSE	IAE	ITAE	ISE	ITSE	IAE	ITAE
BSC	$4.5e^{-6}$	$7.2e^{-6}$	$8.0e^{-5}$	$1.2e^{-4}$	0.012	0.09	0.28	0.95
PID	$9.1e^{-4}$	$1.4e^{-3}$	$4.6e^{-4}$	$6.2e^{-4}$	1.42	3.05	1.62	5.47

7 Conclusion and Perspectives

This paper has presented a comprehensive review and comparative study of control strategies for VSC-HVDC systems, with particular attention to the limitations of conventional PID-based schemes and the superior performance of nonlinear approaches such as backstepping. Through simulation studies on a two-terminal HVDC link, the backstepping controller was shown to provide faster transients, improved robustness, and higher accuracy in DC voltage regulation, active power tracking, and reactive power compensation, thereby confirming its suitability for modern applications.

Looking ahead, the rapid expansion of large offshore wind farms will continue to drive the need for advanced control strategies in VSC-HVDC transmission. Future research should focus on scalable and adaptive control methods capable of supporting multi-terminal DC (MTDC) networks, ensuring stable operation under weak-grid conditions, and enhancing the provision of ancillary services such as frequency support and synthetic inertia. Hybrid approaches that combine nonlinear control, optimization, and data-driven techniques also hold promise for addressing the increasing complexity of renewable-integrated power systems.

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