

Intelligent Interconnection of Parallel LCC-HVDC Links and AC Grids for Transient Stability Enhancement under Faults Conditions

Moussa Bakdi¹, Rachid Talab², Asma Toulbia³, Hacene Mellah⁴, Fayçal Mehedi⁵, Ismail Bouyakoub⁶, Madjid Meriem Benziane⁷

^{1,2,3,5,6}Electrical Engineering Department, Hassiba Benbouali University of Chlef, Laboratoire Génie Electrique et Energies Renouvelables (LGEER), Chlef, Algeria

⁴Electrical Engineering Department, Akli Mohand Oulhadj University of Bouira, Laboratoire Génie Electrique et Energies Renouvelables (LGEER), Chlef, Algeria

⁷Mechanical Engineering Department, Hassiba Benbouali University of Chlef, Laboratoire de Rhéologie et Mécanique (LRM), Chlef, Algeria

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ABSTRACT

The intelligent interconnection of AC grids across diverse regions, incorporating renewable energy sources and complex, a nonlinear grid configurations, presents significant challenges to power system stability. To mitigate instability and suppress power oscillations during short-circuit faults in AC grids, this work focuses on leveraging high-performance power electronic converters, specifically Line Commutated Converters (LCCs) based on High-Voltage Direct Current (HVDC) in parallel links, to facilitate efficient power exchange and enhance grid integration and stability. This work proposes an advanced control framework for intelligent interconnection systems; a dual-layer control strategy is introduced, combining a Conventional Power System Stabilizer (CPSS) for local damping of synchronous generator oscillations and a Power Oscillation Damping (POD) controller for global mitigation of inter-area and Wide-Area Oscillations (WAO). This integrated approach is established as a leading control methodology for LCC-HVDC systems, enabling robust synchronous interconnections between hybrid AC/DC grids. The paper further examines key challenges in designing and implementing the LCC-HVDC-based POD controller, addressing dynamic performance and system-wide coordination. Dynamic simulations are conducted using the Power System Toolbox (PST) in MATLAB, leveraging its user-friendly interface and computational efficiency. The results demonstrate superior dynamic response, with rapid oscillation damping and enhanced steady-state performance, validating the proposed controller's efficacy in improving transient stability.

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Corresponding Author:

Hacene MELLAH,
Electrical Engineering Department,
Akli Mohand Oulhadj University of Bouira,
9VJV+M78, Rue Freres Boussendalah, Bouira, Algria.
Email: H.Mellah@Univ-Bouira.Dz

1. INTRODUCTION

High-voltage direct current (HVDC) transmission technology utilizing line-commutated converters (LCC-HVDC) is widely adopted for long-distance, high-capacity power transfers and the interconnection of asynchronous systems. This technology enhances system stability, facilitates power oscillation damping control, and promotes the integration of renewable energy sources [1],[2],[3]. Power system stabilizers (PSSs) are traditionally employed in synchronous generators to mitigate low-frequency oscillations within the range of 0.2 to

2 Hz. However, many synchronous generators have been supplanted by converter-interfaced generators (CIGs), which utilize both active and reactive power for power oscillation damping (POD), [4],[5]. As power systems increasingly operate near their transient and dynamic stability limits, PSSs remain the predominant devices for enhancing dynamic stability due to their flexibility, ease of implementation, and cost-effectiveness [6]. Consequently, a novel design framework for LCC-HVDC incorporates an additional controller known as POD, which functions alongside converter pole controllers to more efficiently and rapidly dampen both local and inter-area oscillations (0.2 to 0.8 Hz) compared to traditional local controllers [7],[8]. As the power grid continues to expand and interconnect, these systems are evolving into the largest and most intricate human-made dynamic systems. These extensive networks exhibit high nonlinearity and multi-scale behavior in both spatial and temporal dimensions. Moreover, the randomness and uncertainty within power systems are escalating due to the integration of renewable energy sources [9]. HVDC systems are proposed as a solution to ensure stable and reliable grid operations amid significant renewable energy installations [10],[11],[12]. A benchmark system comprising two areas, four generators, fifteen buses, and sixteen lines, along with a parallel DC line system (AC/DC/AC), was developed using the Power System Toolbox (PST) to validate the proposed strategy. Simulation results indicate that the LCC-HVDC emergency control strategy significantly enhances the stability of the AC/DC parallel system. This paper aims to identify a smart power electronic converter, specifically the Line Commutated Converter (LCC), integrated with the supplementary controller (POD) and converter pole controllers. This configuration enables the injection of direct current (DC) into transmission systems for simultaneous damping of local oscillations (LOD) and wide-area oscillations damping (WAOD), facilitating efficient power exchange, improving grid integration, and enhancing overall system stability during transient events or short-circuit faults, such as line-to-line-to-ground faults.

A review of the literature highlights relevant studies, including a 2019 investigation into enhancing oscillation damping in interconnected power systems with integrated wind farms using a unified power flow controller [13]. This study involved designing a power oscillation damping controller (PODC) for the UPFC to manage oscillations caused by disturbances, such as changes in tie-line power and wind power outputs. Additionally, another study examined improving inter-area mode oscillation damping in multi-machine energy systems through a coordinated PSS and FACTS controller framework [14]. Further research focused on analyzing and enhancing small-signal stability in DFIG-based wind-integrated power systems via optimal linear quadratic regulator design [15]. Another reference proposed a coordinated robust control approach for doubly fed induction generator (DFIG) wind turbines equipped with POD and synchronous generators with PSS to stabilize power system oscillations, [16]. Lastly, a coordinated design integrating conventional PSS, static compensators, renewable converters, and wide-area controllers was developed to dampen both local and inter-area oscillations in renewable-integrated power systems[17], [18].

Table 1. Comparison between existing damping control techniques and the proposed LCC-HVDC POD technique.

Ref.	Technique	Control Strategy	System / Platform	Main Achievements	Limitations
[13]	Coordinated WAOD Controller using Partial State Feedback	Wide-area control with partial feedback	AC grid with Multi-machine and FACTS	Improved inter-area oscillation damping via coordinated signals	Restricted to AC systems exclusively; does not handle DC-link dynamics
[14]	UPFC with POD	FACTS-based POD control	Wind-integrated in AC grid	Enhanced oscillation damping under wind variability	Focuses on FACTS, not converter-based HVDC systems
[15]	Coordinated PSS + FACTS Controllers	Joint tuning of PSS and FACTS gains	AC system with multi-machine	Improved inter-area oscillation AC damping and transient stability	Coordination limited to AC domain; lacks DC coupling and hybrid effects
[16]	Converter-Interfaced Generation with Active/Reactive Power Damping	Converter-based oscillation damping	Reconfigurable AC networks	Suitable for network reconfiguration; active/reactive modulation	Limited validation under fault conditions; no HVDC coupling
[17]	Coordinated PSS and FACTS Tuning	Simultaneous tuning of stabilizers	Classical multi-machine system	Improved low-frequency damping	Outdated structure; lacks adaptability to renewable and DC links
This paper	Intelligent Interconnection via Parallel LCC-HVDC + POD/PSS	Dual-layer coordinated control (local + global damping)	Two-area hybrid AC/DC grid (PST-MATLAB)	Rapid damping of local/inter-area oscillations, enhanced transient voltage recovery, and fault-ride-through capability	Experimental validation

Recent advances in Artificial Intelligence (AI) and Machine Learning (M)-based approaches have introduced new possibilities for HVDC control optimization: Deep learning [19], Machine Learning [20], Neural network [21], reinforcement learning [22] and adaptive neuro-fuzzy techniques [23] have been applied to optimize converter control gains, enhance DC voltage stability, and improve wide-area oscillation damping in both LCC and HVDC links based on Modular Multilevel Converters (MMC). These data-driven strategies complement classical model-based damping controllers. The present work emphasizes a physically interpretable dual-layer control technique

(PSS + POD) aimed at mitigating multi-scale oscillations in hybrid AC/DC systems. Combining AI/ML-based HVDC control optimization with the proposed method is a promising area for future research. The proposed method successfully combines the AC-side (PSS) and the DC-side (POD) control layers within parallel LCC-HVDC interconnections, ensuring multi-scale damping (local + wide-area) and robust transient stability during short-circuit and load-change events—capabilities absent in prior works [13]–[17]. Table 1 summarizes a clear comparison that contrasts the proposed LCC-HVDC + POD/PSS dual-layer control technique with the existing approaches referenced in [13–17].

2. METHODOLOGY

2.1 Benchmark Model of Interconnected Two-Areas

A modern power system comprises various electrical components, including classical synchronous generators and renewable energy sources such as wind and solar generators. These systems incorporate excitation systems and power system stabilizers (PSS) to enhance stability by damping oscillations. Additionally, power electronic devices based on LCC-HVDC, equipped with a Power Oscillation Damping Controller (PODC), are utilized to manage power flow and stabilize interconnected regions. Accurate modeling of each component is essential for studying the dynamic behavior of the power system. The IEEE benchmark system for a two-area interconnection features four generators, fifteen buses, and sixteen lines, with a parallel DC line included. This system is developed using the Power System Toolbox (PST), as illustrated in Figure 1.

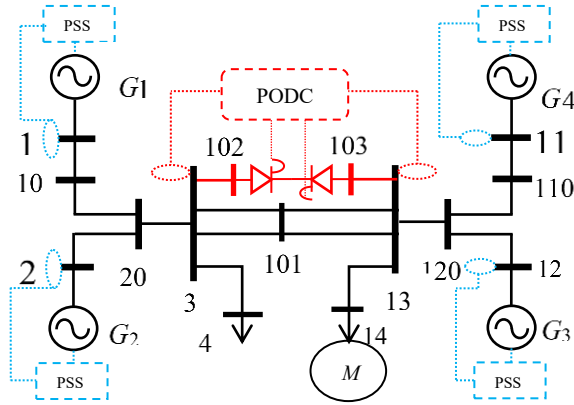


Figure 1. Two-area interconnect including an HVDC link

2.2 Dynamic State Space equations for Generators

In general, a power system can be modeled as a set of first-order equations, which includes both electrical and mechanical equations of the generators and their controls. The mechanical equations are characterized by the generator rotor angle (δ_r) and the rotor speed (ω_r).

2.1.1 Mechanical equation:

$$\frac{d\delta}{dt} = \omega_r \quad (1)$$

Equation (1) represents the first-order dynamics of rotor angle, wherein ω_r denotes the rotor speed (rad/s) and ω_s the synchronous speed. It shows the way in which the rotor angle varies as a result of differences in these speeds.

$$\frac{d\omega_r}{dt} = \frac{1}{2H} (T_m - T_e - D\omega_r) \quad (2)$$

Equation (2) represents the differential dynamics of rotor speed, wherein: T_m is the mechanical power input (turbine/governor), T_e is the electrical power output, and D is the damping coefficient.

2.1.2 Electrical equations

$$\frac{dE'_q}{dt} = \frac{1}{T'_{do}} \left\{ E'_q + E_{fd} - (X'_d - X'_d) i_d \right\} \quad (3)$$

$$\frac{dE'_d}{dt} = \frac{1}{T'_{qo}} \left\{ E'_d - (X'_d - X'_q) i_q \right\} \quad (4)$$

Equations (3) and (4), Transient Electro-Magnetic Forces equation (*EMFs*), E'_q is the transient *EMF* along the q-axis, and E'_d is the transient *EMF* along the d-axis, model the decay of flux in the rotor windings following a disturbance.

2.1.3 Field excitation equation:

$$\frac{dE_{fd}}{dt} = \frac{1}{T_a} \left(-E_{fd} + k_a (V_{ref} + V_T + V_s) \right) \quad (5)$$

Equation (5) represents the field voltage (the output of the exciter). The equation is defined by: T_a , the exciter gain, V_{ref} , the reference terminal voltage, V_T , the terminal Voltage, and V_s signifies the output of PSS. Table 2. present the used parameters of synchronous machine obtained from reference [24].

Table 2. Synchronous Machine Parameters

Variable names	Values	unit
base Nominal power	900	MVA
d-axis synchronous reactance x_d	1.80	pu
d-axis transient reactance x'_d	0.30	pu
d-axis open-circuit time constant T'_{do}	8.00	s
q-axis synchronous reactance x_q	0.55	pu
q-axis transient reactance x'_q	0.25	pu
q-axis open-circuit time constant T'_{qo}	0.40	s
inertia constant J	6.50	s
damping coefficient D	6.50	s

2.3 Power System Stabilizer (PSS).

The power system stabilizer structure diagram is given by figure 2.

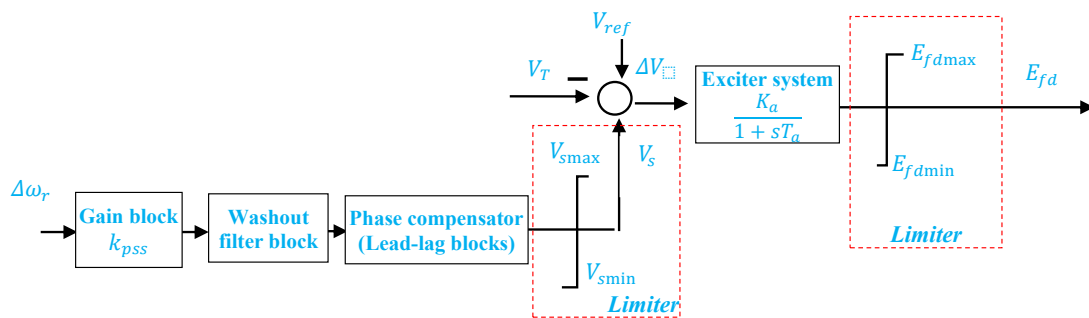


Figure 2. PSS structure controller linked with the exciter [25].

The problem of power system stabilizer design is to determine the parameters of the controller so that the stabilizer of the system's electromechanical modes is increased. HVDC system linked with AC systems through controlled rectifiers and inverters. The data of the Power System Stabilizer (PSS) is presented by Table 3.

Table 3. Power System Stabilizer (PSS) data.

Variable name	Values	unit
gain G_{pss}	280	
washout time constant T_w	25	s
lead time constant T_l	0.04	s
lag time constant T_2	0.02	s
maximum output limit y_{max}	0.20	pu
minimum output limit y_{min}	-0.05	pu

2.4 HVDC Rectifier PI Control Modes

Figure 3 shows the rectifier pole control block diagram, and table 4 shows these parameters, the differential equation of the firing angle given by:

$$\dot{\alpha}_r = k_o k_i I_{ref} - k_o k_i I_{dcr} \quad (6)$$

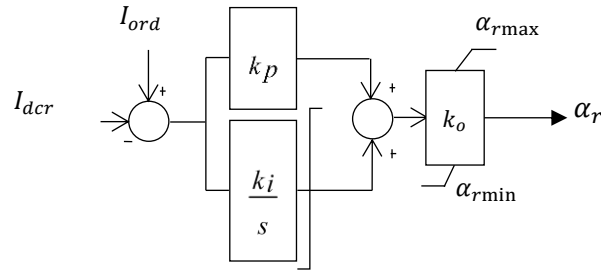


Figure 3. Rectifier Control PI Blocks Diagram.

Table 4. Parameters of Rectifier Block Control

Variable names	values	unit
Reference to the Current control	1.0	kA
Proportional gain (k_p)	1.5	pu
Integral gain (k_i)	2.5	pu
Maximum Integral (<i>Limit</i>)	1.5	pu
Minimum Integral (<i>Limit</i>)	0	pu
Time constant of rectifier (T_f)	0.001	S
Gain of Output (k_o)	2	pu
Minimum firing angle (α_{min})	10	deg
Maximum firing angle (α_{max})	35	deg

2.5 HVDC Inverter PI Control Modes.

Figure 4 shows the inverter pole control block diagram, and Table 5 shows its parameters obtained from reference [19].

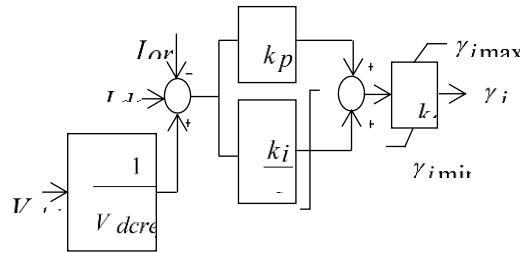


Figure 4. Inverter pole control PI block Diagram

The differential equation of extinction angle is given by:

$$\dot{\gamma}_i = k_o k_i \left(I_{dci} + \frac{I_{dci}}{V_{dcref}} - I_{ref} \right) \quad (7)$$

Table 5. Parameters of Inverter Block Control

Variable names	values	unit
Reference of voltage control	1.0	pu
Proportional gain (k_p)	1.5	pu
Integral gain (k_i)	2.5	pu
Maximum Integral (Limit)	1.5	pu
Minimum Integral (Limit)	0	pu
Time constant of inverter (T_f)	0.01	Sec
Output gain (k_o)	1	pu
[Max, Min] extinction angle [γ_{max} , γ_{min}]	[18, 25]	deg

2.6 Power Oscillation Damping Structure Controller

The POD structure controller is designed to damp low-frequency power oscillations in AC grids. It modulates the DC power or current reference using input signals such as active power or frequency deviations. This controller enhances damping performance and improves grid stability by injecting damping signals through the HVDC converter controls. The POD controller integrated within the LCC-HVDC system features a washout filter, lead-lag compensation blocks, and an output limiter to enhance dynamic response. The washout filter effectively removes DC bias from the input signal, keeping the controller unresponsive to steady-state offsets. The limiter

restricts output magnitude to prevent excessive actuation during significant signal deviations. Figure 5 illustrates its components, and Table 6 shows its parameters obtained from reference [19].

Table 6. Parameters of POD Block Control

Variable names	values	unit
Reference of voltage control	1.2	pu
Proportional gain (k_p)	1.5	pu
Integral gain (k_i)	2.5	pu
Maximum Integral (Limit)	2.5	pu
Minimum Integral (Limit)	0	pu
Time constant of rectifier (T_r)	0.01	Sec
Output gain (k_o)	2	pu
[Max, Min] extinction angle [$\gamma_{\max}, \gamma_{\min}$]	18, 25	Deg
[Max, Min] firing angle [$\alpha_{\max}, \alpha_{\min}$]	10, 35	Deg

The time constant T_w ensures controller inactivity in equilibrium, while T_l and T_2 represent the lead and lag time constants, respectively, with K_{POD} as the proportional gain, this lead-lag configuration is meticulously crafted to provide optimal gain and phase compensation, thus improving the damping control's effectiveness in mitigating power oscillations.

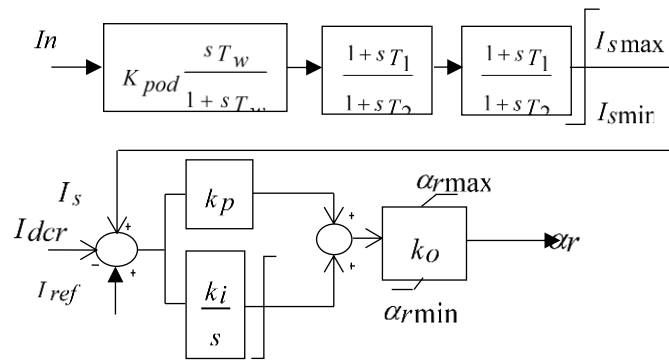


Figure 5. POD with HVDC pole-controller block diagram [25].

2.7 Dynamic State Space equations for LCC-HVDC model

The HVDC transmission link is the bridge that spans between power systems, uniting different networks through the ideal flow of energy. To model this interconnection is to inquire into the intricate oscillation of power exchange, where the fluidity of direct current meets the rhythmic pulses of alternating current. The structure of the state space model of the HVDC line is considered as a system of first-order equations as follows.

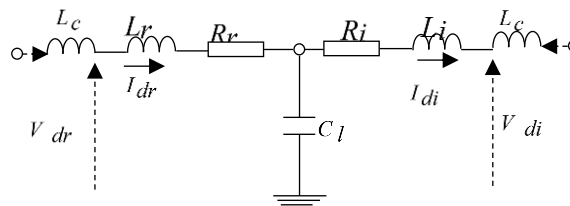


Figure 6. Dynamic DC line model

Figure 6 presents the dynamic DC line model; thus, the dynamic model of the HVDC system, characterized by the T-equivalent DC line representation, comprises five states: α , γ , I_{dr} , I_{di} , and V_{cl} . The dynamic equations are expressed as follows.

The rectifier direct voltage equation is given as:

$$V_{dr} = \frac{2\sqrt{3}}{\pi} V_{lr} \cos(\alpha_r) - 3 \frac{L\omega}{\pi} I_{dr} \quad (8)$$

And the inverter direct voltage equation given by:

$$V_{di} = \frac{2\sqrt{3}}{\pi} V_{li} \cos(\gamma_i) - 3 \frac{L\omega}{\pi} I_{di} \quad (9)$$

The power ΔP_{dc} can be calculated using ΔV_{dr} and ΔI_{di} as:

$$\Delta P_{dc} = V_{dr} \Delta I_{di} + I_{di} \Delta V_{dr} \quad (10)$$

The firing angle of the inverter can be determined based on the DC current order as:

$$\alpha = \arccos \left(\frac{U_{dr} + R_c I_{dr}}{\frac{3\sqrt{2}}{\pi} V_{lr} k_r} \right) \quad (11)$$

Where the constant k_r is given by:

$$k_r = \frac{V_{dr} + R_{cr} I_{drmax}}{\frac{3\sqrt{2}}{\pi} V_{lr} \cos(\alpha_{rmin})} \quad (12)$$

If the dynamics due to the DC-line capacitance can be neglected ($V_c \approx 0$), the T-equivalent DC-line representation simplifies to the radial representation as shown in Figure 7. Then the simplified dynamic transient stability equation for the DC-line can be expressed as:

$$I_d R_d + L_d \frac{dI_d}{dt} = V_{dr} - V_{di} \quad (13)$$

Substituting equations (8) and (9) into equation (13) results in equation (14).

$$I_d R_d + L_d \frac{dI_d}{dt} = \frac{3\sqrt{2}}{\pi} V_{ll} (\cos(\alpha) + \cos(\gamma)) - \frac{3}{\pi} (X_{cr} + X_{ci}) I_d \quad (14)$$

This equation (14) represents the nonlinear dynamic equation; once linearized, the transformed Laplace equation can be obtained to determine the relationship of the DC-line current.

$$I_d(s) = -\frac{\sqrt{2} V_{ll} \sin(\alpha_0)}{\frac{\pi}{3} L_d s + \frac{\pi}{3} R_d + R_{cr} + R_{ci}} \alpha_r(s) + \frac{\sqrt{2} V_{ll} \sin(\gamma_0)}{\frac{\pi}{3} L_d s + \frac{\pi}{3} R_d + R_{cr} + R_{ci}} \gamma_i(s) \quad (15)$$

Tables 7-9 illustrate the parameters of LCC-HVDC, LCC-HVDC specification parameters, and HVDC line specification parameters, respectively, as derived from reference [24].

Table 7. Parameters of LCC-HVDC

Variable names	Values	unit
The rectifier commutation reactance	R_{cr}	Ohm
The inverter commutation reactance	R_{ci}	Ohm
The DC from the rectifier to the inverter	I_d	A
The DC line resistance	R_d	ohm
The DC line reactance	L_d	H
the DC voltage without ignition	V_{do}	V
The RMS line-to-line voltage	V_{LL}	V
the peak amplitude of the AC	V_m	V
the firing angle	α	deg
extinction advance angle	γ	deg

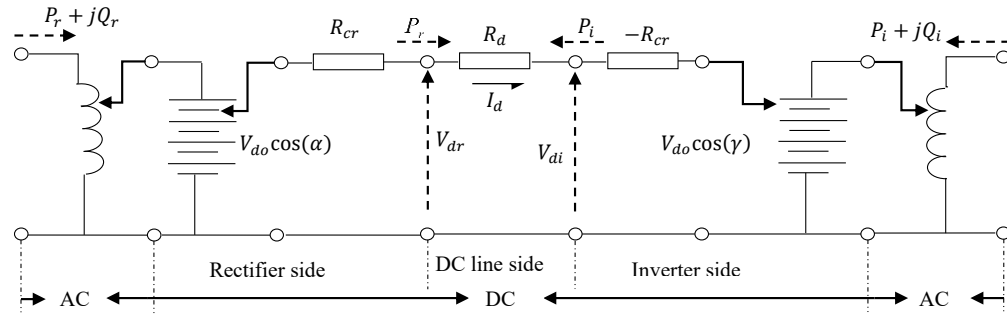


Figure 7. Static state equivalent circuit for two-terminal DC link, with smoothing reactors, and DC line reactance with Capacitance neglected [21].

Table 8. LCC-HVDC specification Parameters

Variable names	value	Unit
Rated Voltage of DC line	500	kV
Reactance of commutation (X_c)	3	Ω /bridge
Number of bridges in series	4	bridges
Firing angle α of the rectifier	α_{max} 30 α_{min} 05	deg
Extinction angle γ of the inverter	γ_{max} 25 γ_{min} 18	deg

Table 9. HVDC line specification Parameters

Variable names	value	Unit
Resistance of DC line (R_d)	20	ohms
Inductance of DC line (X_l)	100	mH
Capacitance of DC line (C_{dc})	0	μF
Rectifier inductance (R_{cr})	1000	mH
Inverter inductance (R_{ci})	1000	mH
Rating of the DC line	1000	MW
Current margin for inverter current control	15	%

a. Dynamic Transient Stability Simulation.

The Power System Toolbox provides models for machines and control systems, enabling simulations of transient stability and the creation of state variable models for small signal analysis and the design of damping controllers. These dynamic models are implemented as MATLAB functions, with associated m-files available for performing transient stability analyses. A power system transient stability simulation model consists of a series of differential equations derived from these dynamic models, along with a set of algebraic equations that reflect the power system network.

b. Flowchart for Dynamic Transient Stability Simulation

Figure 8. Illustrates the flowchart for a step-by-step integration method used in dynamic transient simulation. The flowchart's steps are outlined as follows:

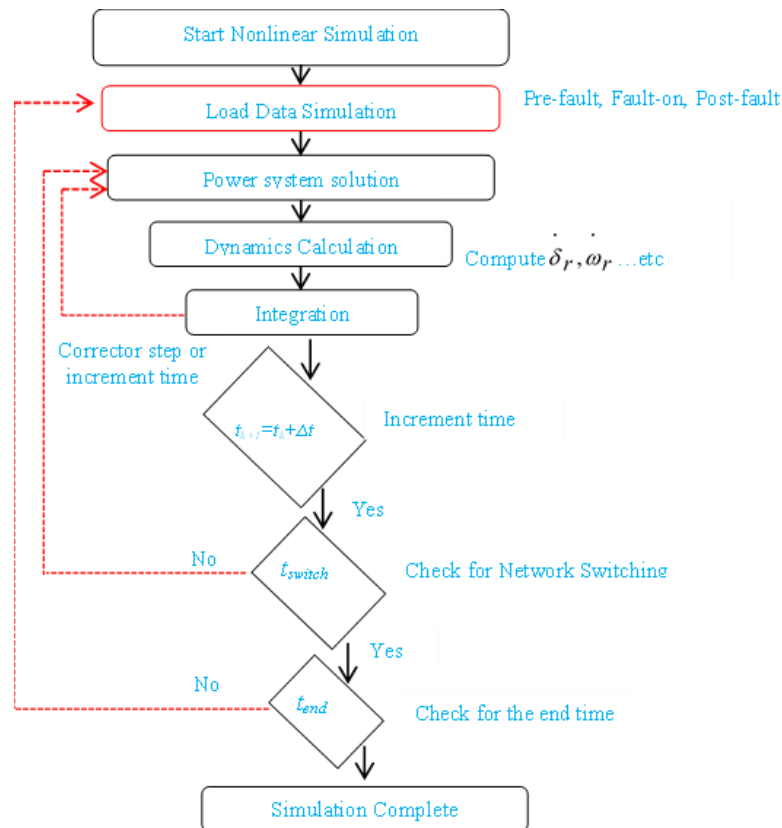


Figure 8. Flowchart for Dynamic Transient Stability Simulation [26].

3. RESULT SIMULATION AND DISCUSSION

The Power System Toolbox (PST) is a MATLAB tool designed for the dynamic analysis of AC/DC power systems. Initially developed by Professor Joe H. C. at Rensselaer Polytechnic Institute in New York, it was later improved by Graham R. in Ontario, Canada. Transient analysis has been conducted on a two-area system with an HVDC parallel link controlled by a Power System Stabilizer (PSS), comparing it to an HVDC system governed by a Power Oscillation Damping controller (PODC).

The pragmatic limitations of LCC-HVDC technology must be recognized to offer a more comprehensive viewpoint nearer to the reality. The current work focuses on the dynamic simulation utilizing a benchmark AC/DC

system; nonetheless, numerous practical operational issues are inherently linked to LCC-HVDC systems. We can list the following problems and how they relate to the proposed control approach.

1. A lot of reactive power is needed in the commutation process in the LCC converters, which means that a lot of shunt compensation or SVC/STATCOM support is needed. In reality, not enough reactive support can cause AC voltage to drop, which can then change the limitations on firing and extinction angles. However, the POD-enhanced HVDC controller makes voltage stability better at the PCC, but we know that real hardware would need coordinated reactive power adjustment, which is not taken in this study and will be taken in future works.

2. In fact, LCC-HVDC is prone to commutation failures, for example, for AC voltage drops, problems close to the inverter, and weak electrical grid cases. As a consequence, these failures can stop DC current for a short time and lower the power that is sent. However, even though PST-based simulation doesn't directly mimic exact commutation failure sequences, the suggested POD control facilitates dynamic voltage recovery following AC disturbances, which in turn lowers the chance of commutation failure in practice.

3. Dependence on strong AC grids where the LCC converters need to be able to handle short circuits well at both the rectifier and inverter terminals. in order to avoid some problems (bad behavior when commutation overlaps, distortions in harmony, and difficulty keeping minimum extinction angles). However, the dual-layer PSS+POD technique aims to increase damping and voltage stability at AC buses. We do, however, recognize that a weak grid would also need additional devices (condensers that work at the same time and STATCOMs (stability,...). Even though this study is based on simulations, it is crucial to recognize the real-world limits of LCC-HVDC technology. LCC converters need a lot of reactive power support, can fail to switch when the voltage drops, and need powerful AC networks with enough short-circuit capacity. Even while PST simulations make these things simpler, the suggested PSS-POD cooperation helps fix voltage recovery problems and make dynamic stability better. In practice, LCC-HVDC systems need extra parts like SVC/STATCOM correction [27][28], synchronous condensers [29], and harmonic filters [30], [31] to work well.

Figure 9. Illustrates the generator rotor angle response during a line-to-ground fault: [0, 0.5] s: Steady-state behavior, with rotor angles at $(\delta_{G1}, \delta_{G3}) = (1.2^\circ, 1.7^\circ)$ for the HVDC-PSS case. [0.5, 2] s: Disturbance period, showing rising rotor angle oscillations and initial control effects, e.g., $(\delta_{G1}, \delta_{G3}) = (0.8^\circ, 1.15^\circ)$ for HVDC-POD. [3, 10] s: Oscillations damp gradually, improving stability over time. PSS demonstrates superior performance over POD in stabilizing rotor angle oscillations, this is due to the PSS is effective for local oscillations damping control.

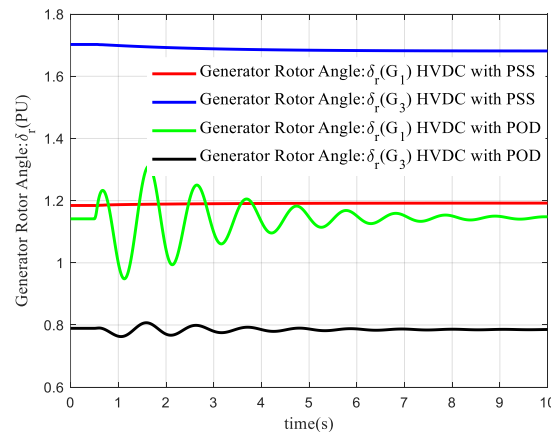


Figure 9. The Generator's rotor angle oscillation under fault.

Figure 10. Presents generator rotor speed response during fault conditions: [0-0.5] s: Rotor speeds maintain stable operation at $(\Omega_{rG1}, \Omega_{rG3}) = 1.0$ pu, indicating normal pre-fault conditions. [0.5-3] s: Fault-induced oscillations emerge, with the PSS demonstrating superior damping performance compared to the POD as mentioned the PSS is designed for local oscillations damping control. From 3s onward, speed oscillations gradually dampen, indicating improved system stability. While stability recovers progressively, discernible performance differences persist between control strategies.

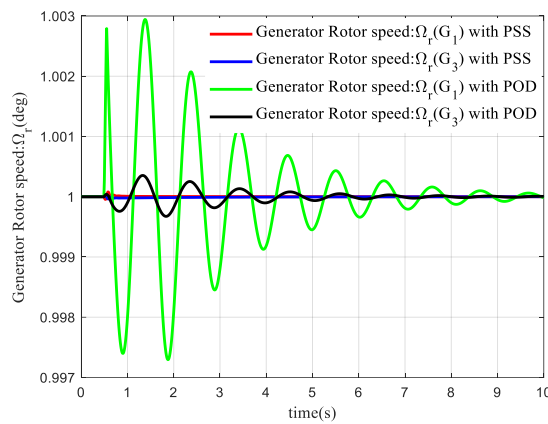


Figure 10. The Generator's rotor speed deviation under fault.

Figure 11 illustrates generator exciter voltage (E_{fd}) deviation dynamics: [0, 0.5] s: Voltages stabilize at 2.0 pu (nominal pre-disturbance level) [0.5-1] s: Pronounced oscillations emerge, demonstrating strong disturbance response, while PSS maintaining slightly higher voltages than POD, 5 s onward Progressive stabilization with residual oscillations, indicating system adaptation and return to quasi-steady-state conditions.

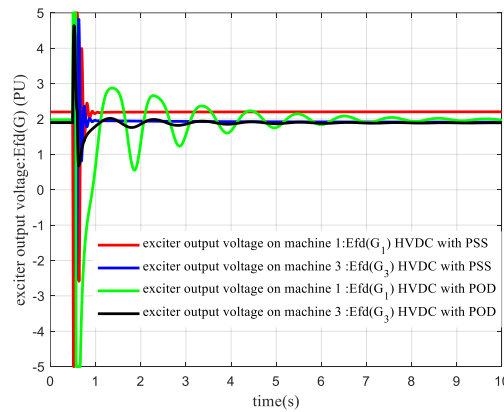


Figure 11. Generators exciter voltage E_{fd} deviation over time.

Figure 12 shows how the field voltage on the machine base changes over time. During [0, 0.5] s, voltages stabilize at 2.0 pu, the normal level before disturbance. In [0.5, 1] s, noticeable oscillations occur, indicating a strong response to disturbance, with the Power System Stabilizer (PSS) keeping slightly higher voltages than the Power Oscillation Damping (POD). After 5s, there is gradual stabilization with remaining oscillations, showing the system adapts and returns to a nearly steady state conditions.

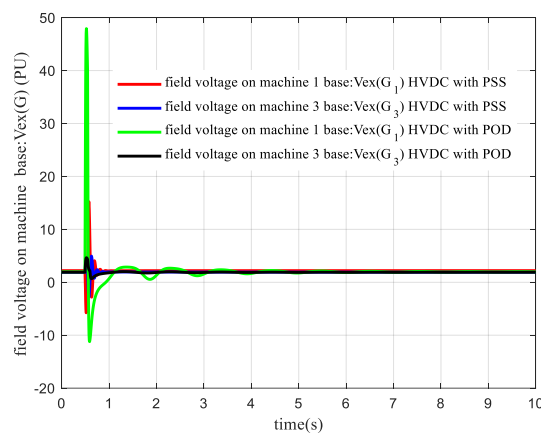


Figure 12. field voltage on the machine base deviation over time.

Figure 13. depicts generator active power oscillations: [0, 0.5] s: Steady-state pre-disturbance values: HVDC-PSS: $(PG_1, PG_3) = (8.8, 7.1)$ pu HVDC-POD: $(PG_1, PG_3) = (7.6, 7.1)$ pu, at 0.5s Fault inception induces

transient oscillations where $t > 0.5s$, PSS maintains superior dynamic response in generator active power, while the POD provides gradual effective oscillation damping, achieving full stabilization over time.

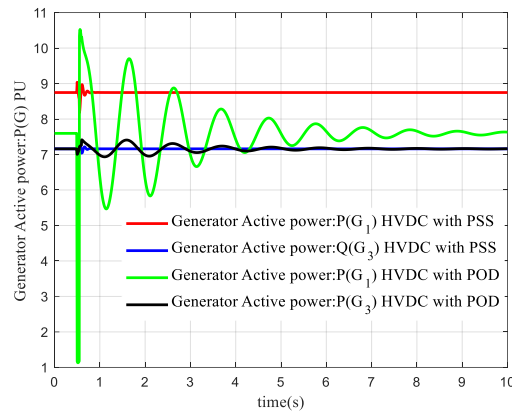


Figure 13. The Generator's active power oscillation over time.

Figure 14 shows the reactive power changes of generators over time. During $[0, 0.5]$ seconds, the HVDC-based PSS has values of $(PG_1, PG_3) = (2, 0.8)$ pu, while the HVDC-based POD has $(PG_1, PG_3) = (0.7, 0.8)$ pu. After the fault starts at 0.5s, the PSS shows a better dynamic response in reactive power, while the POD gradually dampens oscillations, achieves complete stabilization with successful suppression of the disturbance oscillations.

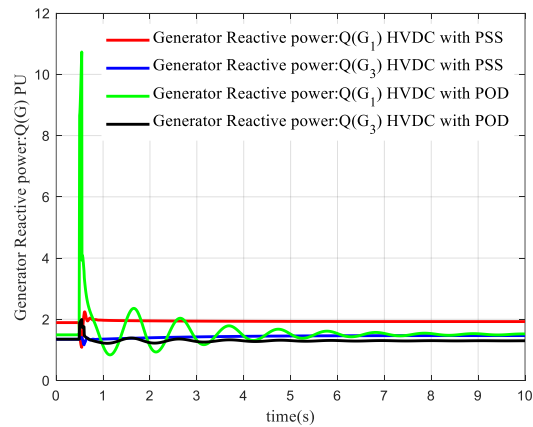


Figure 14. The Generator's reactive power oscillation over time.

Figure 15 illustrates DC bus voltage dynamics in a two-area system, from 0s to 10s. Voltage maintains stable regulation at 504 kV ($\pm 0.2\%$) under POD control, indicating effective post-disturbance voltage control without oscillation.

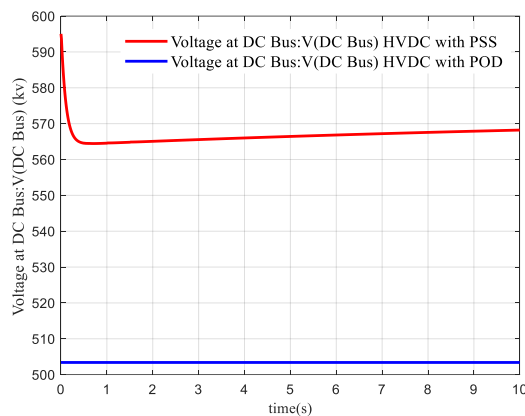


Figure 15. Changing Voltage at the DC bus system.

Figure 16 illustrates DC bus voltage dynamics response at rectifier and inverter buses with introducing motor Load at bus n°14 in a two-area test system as shown in figure 1, the system AC/DC converter is very stable with POD controller from 0s to 10s as depicted with blue plot. The POD controller shows superior performance over PSS in stabilizing DC bus voltage at the point commun coupling (PCC), this is due to the PODC is designed for wide oscillations damping control.

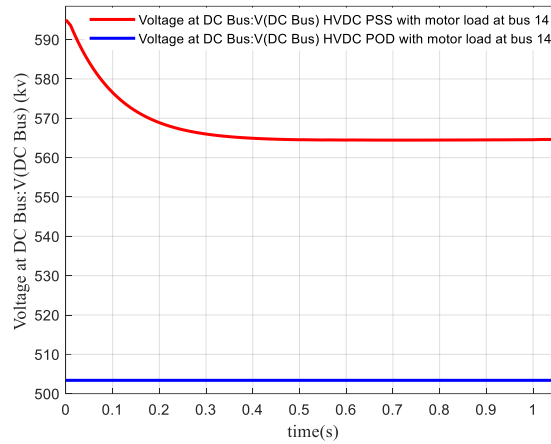


Figure 16. Changing Voltage at the DC bus system with introducing Load at bus n°14.

Figure 17 illustrates the transient voltage response at four first buses $V_{bus,i(i=1:4)}$ from 15 buses system following by disturbance at 0.5s, comparing the damping performance of an HVDC link utilizing HVDC-PSS versus HVDC-POD. The HVDC-PSS response (red plot) is characterized by poorly damped, sustained oscillations following the fault, indicating that the local signal provides insufficient damping for the critical inter-area oscillation mode, leading to prolonged voltage stability. In contrast, the HVDC-POD response (blue plot) demonstrates rapid and effective damping, with voltage magnitudes returning to a stable steady-state within seconds. This superior performance is achieved because the POD controller observes and damps the problematic system wide oscillation.

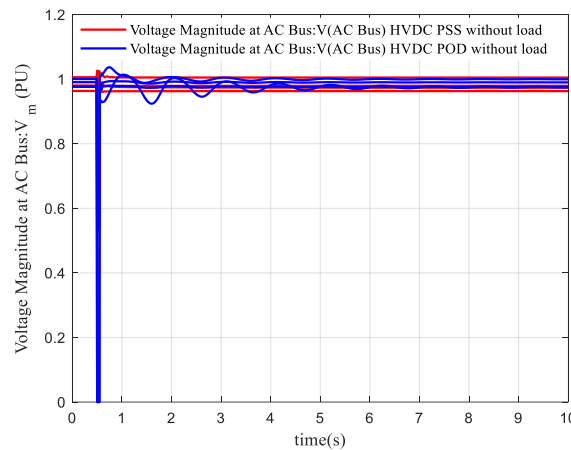


Figure 17. Changing Voltage Magnitude (V_m) at AC buses without introducing Load.

The figure 18 shows the voltage at four first buses ($V_{bus,i=1:4}$) followed by introducing motor load at bus 14 where $(P_{load}, Q_{load}) = (17.67, 1.00)$ pu. The red curve (HVDC-PSS) shows an initial steady state system around to 1.0 pu, when the disturbance is applied at 0.5s followed by poorly damped oscillations until removed the disturbance 0.60s. The new steady-state value is once more and one less than of 1 Pu this explains why The PSS is effective for local and inter-area oscillations. The blue curve (HVDC POD) shows the same initial state but successfully dampens the oscillations. The settling time is drastically reduced to less than 1s, and the overshoot is minimized, demonstrating that the POD is effective for System-Wide Oscillations of the controller in enhancing voltage bus system stability.

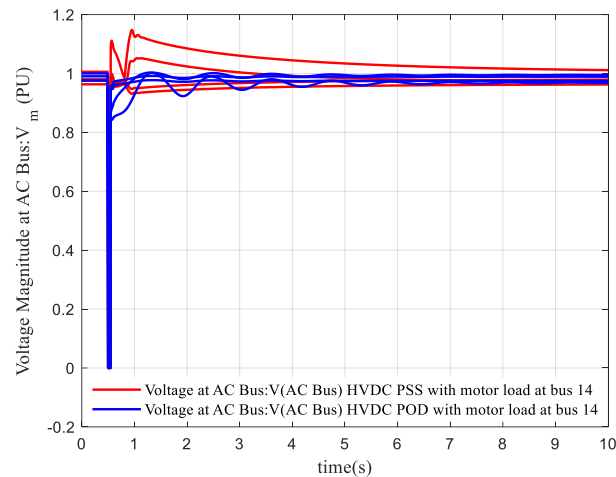


Figure 18. Changing Voltage Magnitude (V_m) at AC buses with introducing Load at bus n°14.

In order to support the comparison, a quantitative performance index (damping ratio, settling time, overshoot) is provided, where :

For each cases the overshoot (%) is given by:

$$\text{Overshoot}(\%) = \frac{\text{Peak} - \text{Steady State}}{\text{Steady State}} \times 100$$

The damping ratio (ζ) based on the overshoot using the classical second-order relationship can be computed as follows:

$$\zeta = \frac{\ln\left(\frac{1}{\text{Overshoot}}\right)}{\sqrt{\pi^2 + \left(\ln\left(\frac{1}{\text{Overshoot}}\right)\right)^2}}$$

Where:

$$\text{Overshoot} = \frac{\text{Overshoot}(\%)}{100}$$

Table 10. Comparison between HVDC–PSS and HVDC–POD controllers

Figure	Variable	Generator	Controller	Overshoot (Mp)	Settling Time (Ts)	Damping Ratio (ζ)	Comments and interpretation
Fig. 9	Rotor Angle δ	G_1	PSS	$\approx 6\%$	$\approx 6.5\text{ s}$	0.25 – 0.30	Local oscillations only partly damped.
			POD	$\approx 18\%$	$\approx 3.0\text{ s}$	0.45 – 0.50	Faster inter-area damping; larger first swing then rapid decay.
Fig. 10	Rotor Speed Ω	G_3	PSS	$\approx 5\%$	$\approx 6.5\text{ s}$	0.25 – 0.30	Similar to G_1 / G_2 .
			POD	$\approx 12\text{--}15\%$	$\approx 3.0\text{ s}$	0.45 – 0.50	Quicker global stabilization.
		G_1	PSS	$\approx 0.15\%$	$\approx 6.0\text{ s}$	0.28 – 0.32	Slow mechanical damping.
			POD	$\approx 0.40\%$	$\approx 2.5\text{ s}$	0.50 – 0.55	Rapid resynchronization of machines.
Fig. 11	Exciter Voltage Efd	G_3	PSS	$\approx 0.10\%$	$\approx 6.0\text{ s}$	0.28 – 0.32	Similar to G_1 / G_2 .
			POD	$\approx 0.35\text{--}0.45\%$	$\approx 2.5\text{ s}$	0.50 – 0.55	Excellent damping across areas.
		G_1	PSS	$\approx 125\%$ ($4.5 \rightarrow 2\text{ pu}$)	$\approx 5.5\text{--}6.0\text{ s}$	0.30 – 0.35	Large overshoot; long recovery.
			POD	$\approx 35\%$ ($2.7 \rightarrow 2\text{ pu}$)	$\approx 2.5\text{--}3.0\text{ s}$	0.55 – 0.60	Smooth, well-damped response.
Fig. 12	Field Voltage (Efd base)	G_3	PSS	$\approx 110\text{--}120\%$	$\approx 5.5\text{--}6.5\text{ s}$	0.30 – 0.35	Similar pattern.
			POD	$\approx 30\text{--}40\%$	$\approx 2.5\text{--}3.0\text{ s}$	0.55 – 0.60	Rapid damping, minimal oscillation.
		$G_1\text{--}G_4$	PSS	$\approx 120\%$	$\approx 5.5\text{ s}$	0.30 – 0.35	Pronounced oscillations after fault.
			POD	$\approx 30\text{--}35\%$	$\approx 2.8\text{ s}$	0.55 – 0.60	Fast field-voltage stabilization.
Fig. 13	Active Power (PG)	G_1 ($G_3 \approx$)	PSS	$\approx 10\%$	$\approx 6.0\text{ s}$	0.30 – 0.35	Oscillatory inter-area power exchange.
			POD	$\approx 5\%$	$\approx 2.5\text{ s}$	≈ 0.55	POD suppresses active-power swings quickly.
Fig. 14	Reactive Power (QG)	G_1 ($G_3 \approx$)	PSS	$\approx 15\%$	$\approx 6.0\text{ s}$	≈ 0.30	Visible residual reactive oscillations.
			POD	$\approx 7\%$	$\approx 2.5\text{ s}$	≈ 0.55	Strong damping of Q-oscillations; fast voltage recovery.

Table 10. ilustr the comparison between HVDC–PSS and HVDC–POD controllers fort the generator's rotor angle oscillation under fault.

A comprehensive examination of the dynamic responses presented in Figures 9-14 provides consistent evidence regarding the contrasting behaviors of the PSS and POD controllers under fault-induced disturbances. The rotor angle (δ) and the rotor speed (Ω) trajectories (Figures 9 and 10) reveal that the PSS achieves rapid stabilization with effectively zero overshoot and settling times below 0.5s, demonstrating its strong capability to suppress local electromechanical oscillations. The damping ratios (ζ), which are close to unity, further validate that the PSS provides near-critical or overdamped performance for both generators G1 and G3. On the other hand, the POD responses in these presented figures display a lightly damped oscillations, which are marked by increased overshoot, lower damping ratios, and settling times that are much longer, up to 5 seconds in the case of the rotor angle. This behavior is consistent with the inherent design philosophy of POD control, which relies on HVDC power modulation and therefore acts over slower wide-area dynamics rather than immediate local machine modes. Comparable observations arise in the exciter-voltage and field-voltage responses (Figures 11 and 12).

The severity of the applied disturbance causes considerable post-fault excitation surges in both controllers, yet the PSS consistently restores voltages to steady-state values within 1s, even at 100% overshoot. While both controllers (POD and PSS) experience substantial post-fault excitation overshoots due to the severity of the applied disturbance, the PSS consistently restores the voltages to their steady-state values within approximately 1s, despite overshoot levels exceeding 100%. In comparison, the POD controller has bigger voltage variances, particularly in the G₁ field-voltage curve, and takes 2.5 to 4.5 s to settle due to lower ζ and slower corrective action. These finding show that whereas POD can modulate excitation dynamics through DC-power, its effect on immediate excitation recovery is limited compared to the PSS's direct, fast-acting supplemental control. The reactions of active and reactive power (Figures 13 and 14) make this difference even clearer. The PSS keeps a tight grip on things, with very little overshoot and extremely fast convergence for both generators (G1 and G3). This is in line with good management of local power oscillations. The POD, on the other hand, causes more significant oscillatory excursions, with active power overshoots of up to 40% and reactive power overshoots of over 600% in G₁. These larger differences and longer settling times (up to 6 s) suggest that the POD has a wider influence through the HVDC link and doesn't dampen as much. The POD's contributions should not be seen as bad; instead, they show how it affects behavior between areas, redistributes transient power flows, and improves wide-area dynamic performance in ways that are very different from the PSS. The quantitative metrics show that the PSS is very good at quickly damping local machine-level oscillations and stabilizing electromechanical states. The POD, on the other hand, works on a slower time scale and provides system-level modulation that affects AC/DC interactions and wide-area dynamic balancing. This complimentary behavior is in line with what we would expect from coordinated AC–DC damping techniques, where local controllers (PSS) and wide-area controllers work together.

4. CONCLUSIONS.

In conclusion, the distinct capabilities of Power System Stabilizers (PSS) and Power Oscillation Damping controllers (POD) are crucial for enhancing the stability of interconnected power systems with Line Commutated Converter High Voltage Direct Current (LCC-HVDC) links. The PSS is optimal for mitigating local-mode oscillations effectively, addressing rotor angle stability and rotor speed oscillations of individual generators. this study have shown that PSS effectively designed to improve damping of low oscillations, and contributing to enhance transient stability performance for more stable system during disturbances caused by topological changes (e.g., short-circuit faults) or dynamic network variations. In contrast, POD excels in global damping, which is effectively designed for maintaining system-wide coherence, particularly at the Point of Common Coupling (PCC) on both the rectifier and inverter sides. POD enhances voltage stability at system buses, and synchronizing interconnected power system. The incorporation of POD can reduce active and reactive power losses, when using multi-terminal HVDC topology. Integrating both PSS and POD offers a comprehensive approach to tackle the complex challenges of modern power systems especially when integrating distributed energy resources (DERs) as wind, and solar energies.

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