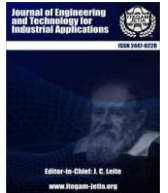




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RESEARCH ARTICLE

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A MODIFIED DROOP CONTROL FRAMEWORK FOR MULTI-TERMINAL VSC-HVDC SYSTEM WITH IMPROVED POWER SHARING AND VOLTAGE REGULATION

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ABSTRACT

In this paper an adaptive droop control strategy is proposed for voltage source converter based multi-terminal direct current (VSC-MTDC) systems to achieve a higher power-sharing accuracy, DC voltage regulation, and operating robustness during converter failures. The scheme integrates the robustness of voltage margin control with the distributed balancing capability of conventional droop regulation in a way that converters operating under constant power mode initially can switch automatically to droop mode at any time DC voltage differences exceed pre-set operating thresholds. Event-driven adaptability enhances synchronized inter-terminal response, enables equitable power readjustment, and mitigates voltage instability under heavy transient disturbances. A ± 400 kV four-terminal VSC-MTDC system was planned and rigorously simulated in PSCAD/EMTDC for comparing the proposed method with conventional fixed-slope droop control. Quantitative results confirm that the proposed method realizes 45–60% reduction of peak DC voltage excursions, 40–55% reduction of active power overshoot, and 35–50% improvement in voltage settling time. Additionally, the passive converters in conventional schemes deliver up to +65 MW of extra support, thereby preventing the remaining terminals from being overloaded and maintaining safe operating margins. The dynamic coordination with advanced capabilities allows solid post-fault operation for single as well as multi-converter outages without protection-led shutdowns and improves the entire system's resilience. The demonstrated voltage stability, fault tolerance, and converter utilization enhancements confirm the adaptive droop control as a viable approach for the next-generation resilient, large-scale HVDC microgrids with high-penetration renewable energy integration.



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I. INTRODUCTION

The imperative to decarbonise global energy systems has emerged as a primary strategy to combat climate change and reduce detrimental greenhouse gas emissions. In this context, renewable energy sources (RES), especially solar photovoltaic and offshore wind power, have emerged as viable alternatives due to their significant potential for sustainable and eco-friendly generation [1-3].

The swift proliferation of these technologies is transforming the architecture of contemporary electrical networks, steering them towards a more intricate, decentralised, and dynamic framework. This shift, however, presents new problems for transmission and distribution systems, which must now guarantee stable, dependable, and efficient operation under varied and frequently uncertain operating conditions. Most renewable energy producing facilities are generally situated at considerable distances from primary consumption centres, necessitating long-distance transmission [4], [5]. Moreover, their sporadic characteristics—dictated by climatic elements like wind velocity and sun radiation result in fluctuations and uncertainty in energy production. These oscillations necessitate sophisticated control and management systems to ensure real-time power balance, voltage stability, and power quality [6], [7]. Offshore wind farms are becoming pivotal to this transformation. They capitalise on optimal wind resources, diminished aerodynamic turbulence, and extensive areas distant from populous regions, resulting in enhanced generating potential with reduced environmental and noise effect [8], [9]. The notion of continental-scale Super Grids has gained prominence to properly utilise these remote and variable resources. Extensive infrastructures link geographically separated renewable locations with load centres using High Voltage Direct Current (HVDC) transmission networks [10], [11]. In contrast to conventional AC transmission, HVDC provides reduced losses, increased transfer capacity, and improved dynamic stability.

Conventional Line-Commutated Converter HVDC (LCC-HVDC) technology, although extensively utilised, is constrained by limited flexibility and inadequate grid-support capabilities. Conversely, Voltage Source Converter HVDC (VSC-HVDC) technology offers autonomous regulation of active and reactive power, black-start functionality, and uninterrupted bidirectional power flow, rendering it the favoured choice for contemporary grids [12], [13]. Leveraging these benefits, Multi-Terminal DC (MTDC) networks utilising VSC-HVDC are anticipated to serve as the foundation of future power transmission systems. MTDC facilitates the concurrent integration of various renewable sources, augments system redundancy, and improves operational flexibility. Nonetheless, the stability of these systems continues to be a significant problem, especially during severe disruptions such as converter failures or line faults. Sudden disparities in power distribution can provoke substantial DC voltage fluctuations, jeopardising the stable functioning of the entire grid [14-16]. To alleviate these challenges, sophisticated control frameworks are utilised in MTDC systems, generally organised into hierarchical tiers. At the network level, master control schemes are essential for coordinating power distribution among terminals. The Voltage Droop Method (VDM) is acknowledged as a superior decentralised strategy, surpassing the Master-Slave Method (MSM) and the Voltage Margin Method (VMM) in flexibility, scalability, and fault tolerance [16-18].

Nonetheless, traditional fixed-parameter droop control encounters constraints under extreme operating circumstances. The failure to dynamically adjust to system fluctuations or critical contingencies may jeopardise both stability and performance, therefore limiting the reliability of future MTDC grids. This work presents a revised adaptive droop control technique aimed at enhancing the resilience and performance of VSC-MTDC systems in various fault conditions. The suggested method, in contrast to existing methodologies, dynamically modifies droop parameters based on real-time operating conditions, hence ensuring adherence to the N-1 contingency criterion. A comprehensive four-terminal MTDC test system is constructed in PSCAD/EMTDC, simulating various fault scenarios, including single and multiple converter failures, to assess transient reactions, voltage stability, and power redistribution efficacy. Comparative investigations indicate that the suggested technique markedly enhances dynamic performance by diminishing DC voltage swings, expediting fault recovery, and ensuring equitable power distribution among terminals. The results underscore the promise of adaptive droop-based control as a viable and scalable approach for improving the stability and dependability of future MTDC networks functioning in increasingly complex and uncertain contexts.

II. RELATED WORKS

The swift incorporation of renewable energy into contemporary electricity systems has presented considerable issues concerning stability, regulation, and protection. Recent studies indicate that traditional protection strategies are inadequate in renewable-dominant networks, where intermittency and bidirectional power flows hinder fault identification and isolation [19], [20]. These situations threaten overall system reliability, requiring enhanced protection and control mechanisms specifically designed for high renewable penetration. The geographical distance between remote renewable generation sites and primary load centres necessitates the implementation of resilient long-distance transmission technologies and sophisticated control systems that can handle variable generation while guaranteeing secure and uninterrupted power delivery. High Voltage Direct Current (HVDC) transmission is acknowledged as a premier solution to these difficulties, facilitating efficient, long-distance power transfer with diminished electrical losses relative to traditional AC systems [21]. Among HVDC technologies, Voltage Source Converter-based HVDC (VSC-HVDC) has garnered significant interest due to its superior controllability, encompassing independent regulation of active and reactive power, black-start capability, and dynamic grid support, which are essential for the integration of substantial renewable generation.

Leveraging these benefits, Multi-Terminal DC (MTDC) networks enhance the functionality of VSC-HVDC by linking numerous nodes, thus augmenting redundancy, operational flexibility, and the scalability of renewable integration. Nonetheless, MTDC systems provide further hurdles in sustaining voltage stability and fault tolerance, necessitating hierarchical control frameworks and adaptive solutions to ensure secure operation amid various circumstances. To mitigate these issues, numerous control mechanisms have been investigated. The Voltage Droop Method (VDM) is acknowledged as an efficient decentralised strategy for power distribution and voltage regulation in MTDC systems. Nonetheless, conventional fixed-parameter droop methods sometimes struggle to adjust to severe disruptions or swiftly fluctuating operational conditions, resulting in potential instability hazards [22]. This constraint has spurred the advancement of adaptive droop control methods that adjust control parameters in real time, significantly enhancing transient response, fault ride-through capability, and fair power redistribution in multi-terminal HVDC grids [23], [21], [22]. Notwithstanding these developments, current methodologies continue to encounter challenges in reconciling practical simplicity with resilience in various fault circumstances, highlighting the necessity for innovative adaptive solutions specifically designed for large-scale MTDC applications.

III. MULTITERMINAL VSC-HVDC CONFIGURATION TYPE

The multi-terminal HVDC is modelled using many configurations, including radial, radial-ring, and meshed, as illustrated in Figure 1. In the radial layout seen in Figure 1 (a), numerous Voltage Source Converters (VSCs) are interconnected on the DC side to establish a string connection. This setup can be augmented from the current point-to-point links [24]. In radial networks, the failure of a DC transmission line segment would lead to a complete service disruption at the affected converter terminal; conversely, in meshed MTDC networks, as illustrated in Fig. 1 (b), rated operation remains feasible, albeit with increased transmission losses [25]. In comparison to radial topology, ring topology exhibits a reduced chance of malfunction, while its overall reliability is worse [26].

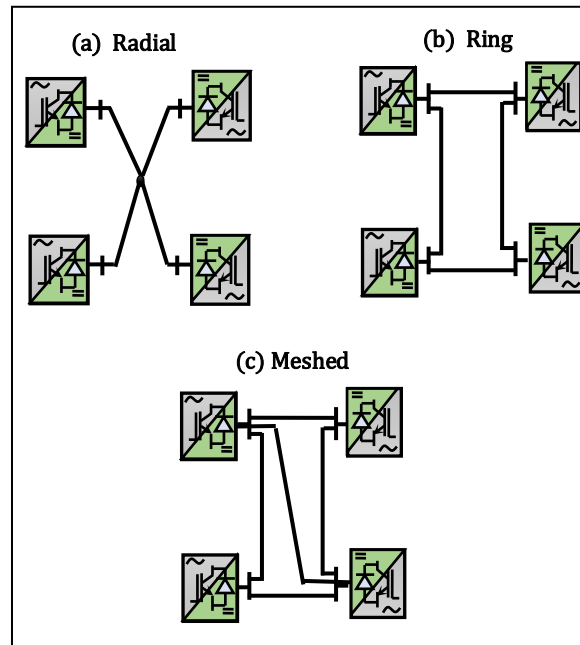


Figure 1: MTDC topologies (a) Radial (b) Ring (c) Meshed.
Source: Authors, (2026).

IV. PRINCIPLES CONTROLS OF VSC IN MULTI-TERMINAL HVDC

IV.1 BASIC CONTROL OF VSC-MTDC

VSC are becoming the core of future MTDC networks. The VSC technology playing a key role to enhance energy efficiency for power transmission. A basic VSC-HVDC system comprises of two converter stations built with VSC topologies is presented in Figure 2.

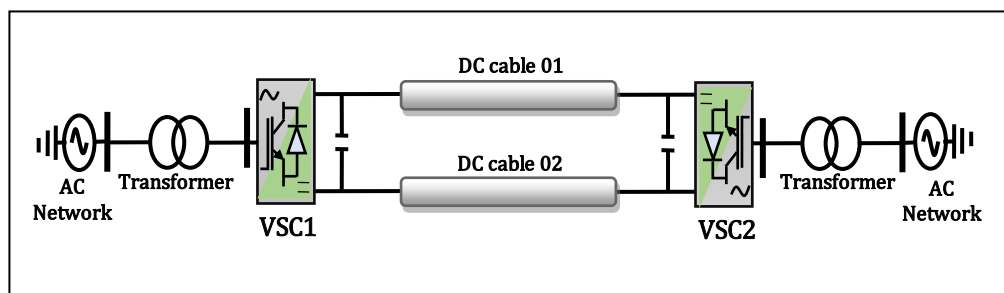


Figure 2: A basic point to point VSC-HVDC system.
Source: Authors, (2026).

Generally, the control system of each two level VSC converter connected to AC grid in VSC-HVDC point to point or multi-terminal has a cascade structure. The single line diagram of the VSC-HVDC converter utilising the vector control approach is depicted in Figure 3. This control strategies based on vector current control with Proportional integrator (PI) control algorithm in dq frame, it consists of the outer and inner loop. The outer controllers are part of the local controller of the VSC which defines the operation mode of the converter. The VSC station can operate in four distinct control modes based on the control philosophy: P/Q, P/Vac, Vdc/Q, and Vdc/Vac [27] (ENP ORAN). The inner current controller calculates the d and q-axis modulation indices from the reference (target) and actual (measured) values. The indices are then transferred to the abc reference frame for the PWM operation on all three phases [28]. The phase locked loop (PLL) is used to synchronize the VSC converter with the AC grid. It makes it possible to determine the instantaneous phase of a signal, as well as its frequency. The Phase-Locked Loop (PLL) is crucial for converting signals represented in phase values (abc) to direct quadrature-zero (dq0) coordinates, and vice versa [29].

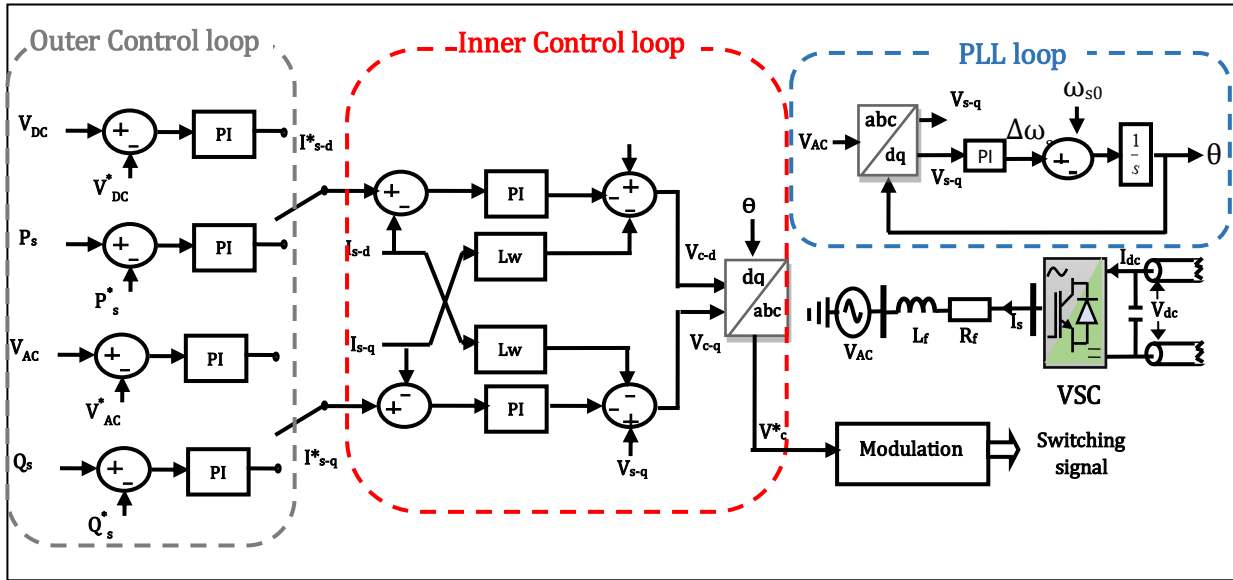


Figure 3: Control system model in VSC terminal.
Source: Authors, (2026).

IV.2 DC VOLTAGE MARGIN CONTROL STRATEGY IN MTDC NETWORK

In the paper [30], the philosophy of voltage margin method was the first proposed for VSC-HVDC system by Tatsuhiro Nakajima and Shoichi Irokawa. In MTDC grid, the VMM method could be combined both the DC voltage and active power as shown in Figure 4. Indeed, depending on the state of the system (in terms of operating limits) each converter can control either the DC voltage or the active power flow. In this method, only one master converter equipped with DC voltage control at each Time.

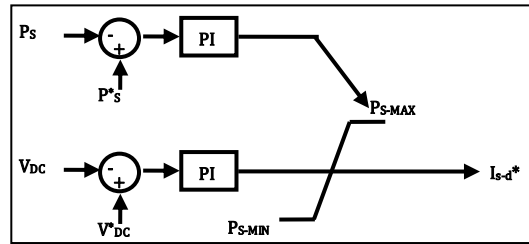


Figure 4: Voltage margin control scheme.
Source: Authors, (2026).

The VMM technique in three terminals MTDC works as follows (see Figure 5): In the first, let us assume that VSC1 converter it operates at DC voltage control with the reference value V_{DC1}^* (VDC control mode) as known as slack bus converter, while VSC2, VSC3 and VSC4 are adopting a constant active power with the value (P control mode). When the active power of VSC1 reaches the limits (P_{1upper} or P_{1lower}), this converter will change from VDC control mode to a P control mode. Therefore, the second converter VSC2

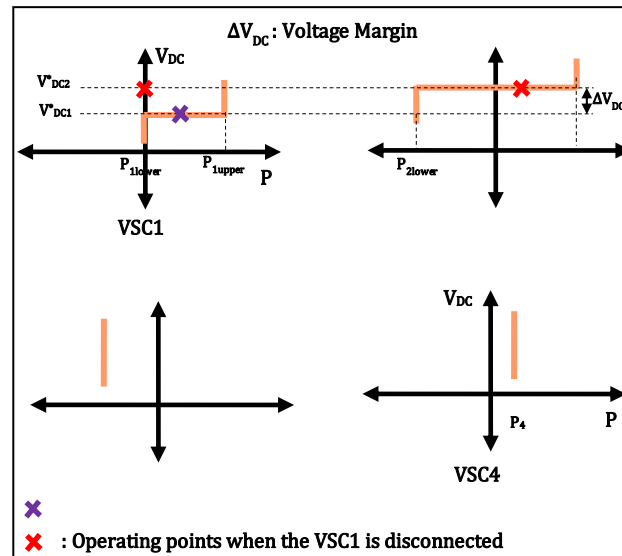


Figure 5: Characteristic of P, VDC of MTDC network using Voltage margin method.
Source: Authors, (2026).

Will change the control mode from a P control mode to a VDC control mode with the new set value V^*_{DC2} . The difference between the references of DC voltage for the two converters VSC1 and VSC2 is called the voltage margin (ΔV_{DC}) [31], [32].

IV.3 DC VOLTAGE POWER SHARING BASED ON DROOP CONTROL STRATEGY IN MTDC NETWORK

The principle voltage droop method for MTDC grid works similarly to the droop frequency control in conventional HVAC networks, where the balance between power generation and demand dependent frequency deviations, each production unit is equipped with a frequency controller which regulates their power generation according to power-frequency characteristic. In MTDC systems, the change in the DC voltage causes the VSC-MTDC converters to react with a change of their active-power. This method allows all VSC converters equipped with droop control to contribute in the power balancing following the lost any converter. The block diagram of droop control is illustrated in Figure 6, which is combined with VDC control and P control [33-36].

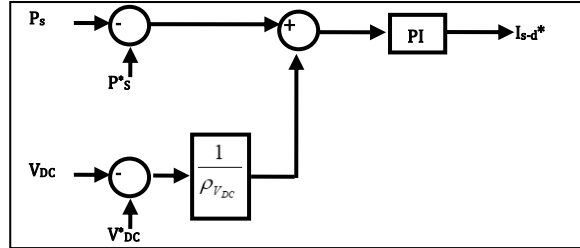


Figure 6: Voltage droop control scheme.

Source: Authors, (2026).

The relationship between the DC voltage and power of a converter terminal in an MTDC system is definite by:

$$(V^*_{DC} - V_{DC}) + \rho_{V_{DC}} (P_s - P_s^*) = 0 \quad (1)$$

$$\Delta P_s = P_s - P_s^* \quad (2)$$

$$\Delta V_{DC} = V^*_{DC} - V_{DC} \quad (3)$$

$$\Delta V_{DC} = \rho_{V_{DC}} \Delta P_s \quad (4)$$

The operating principles of voltage droop method in four terminals MTDC is illustrated in Figure 7, as Voltage/Power characteristic. The voltage droop method is applied in three terminals system. VSC1 VSC2, VSC4 converters are endowed with the voltage droop method while VSC3 is controlling its power flow. At the initial time, VSC1, VSC2 and VSC4 operate at active power P_1 and P_2 respectively. All VSCs have the same DC voltage level (V_{DC}). In this case, it is assumed that the converter equipped with VDM technique is lost. When the outage of VSC1, the power (P_2) of VSC2 stabilizes to a new set value (P_2'). Hence, the DC voltage of VSC2 stabilizes at V_{DC1} and the DC voltage of VSC1 stabilizes at the same V_{DC1} .

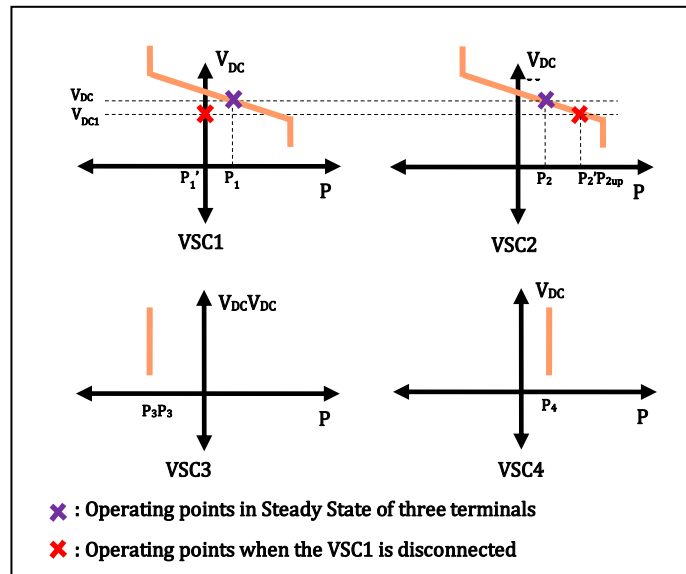


Figure 7: Characteristic of P, VDC of MTDC network using Voltage droop method.

Source: Authors, (2026).

IV.4 DC VOLTAGE POWER SHARING BASED ON MODIFIED DROOP CONTROL STRATEGY IN MTDC NETWORK

The proposed power sharing control combine the both technique voltage margin and droop control strategies to enhance the stability of MTDC system. Any variation of active power in conventional droop control of MTDC system will cause deviation of DC voltage. In the event of a small power sharing, the balancing operation will be assumed by the stations that are conventionally controlled by the droop method. However, in the event of a large power sharing, the DC voltage reaches a critical limit and the stations that were initially in constant power control mode switch to droop control mode in order to support the DC voltage and contribute to the balancing effort. Figure 8 shows the DC power/voltage characteristics of our four-terminal VSC-MTDC system equipped with modified voltage droop control [37-40]. In the initial state (green cross), the station VSC4 equipped with the modified droop operates in constant power mode. Once the VSC1 station is out of service (red cross), the DC voltage level exceeds the minimum voltage limit, and consequently the VSC1 station increases its power, in order to stabilize the system and reduce the DC voltage deviation. The VSC4 station changes its control mode to voltage droop and helps the VSC2 to balance the power transit in the MTDC system. Figure 9 shows a voltage droop controller.

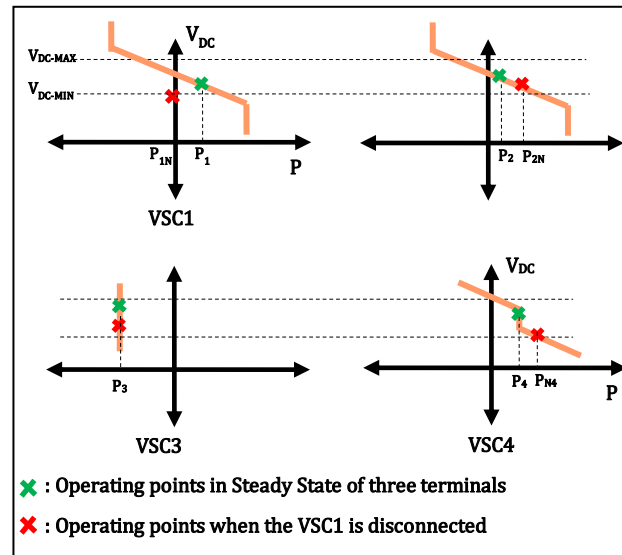


Figure 8: Characteristic of P, VDC of MTDC network using modified Voltage droop method.

Source: Authors, (2026).

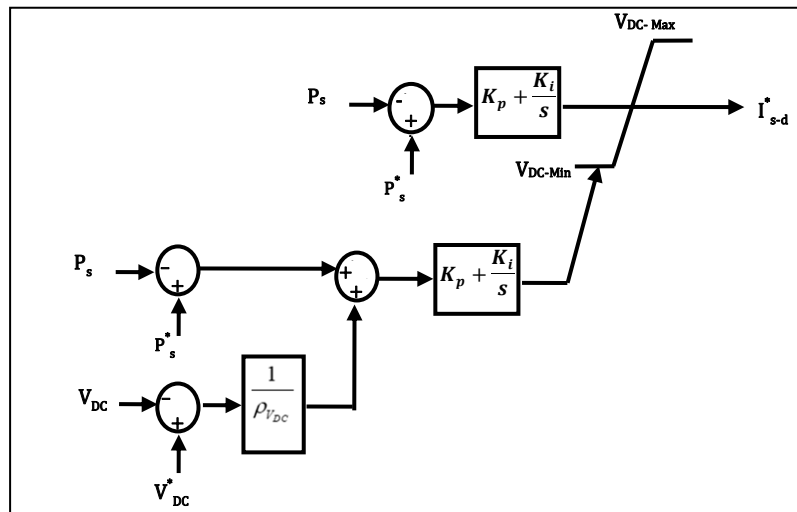


Figure 9: Voltage droop control scheme.

Source: Authors, (2026).

V. SIMULATION AND RESULTS ANALYSIS

Following the paper's aim, a four-terminal VSC-MTDC model is developed to verify the performance of the proposed droop control, as depicted in Figure 10. The three sending-end converter stations, VSC1 and VSC2, implement droop control, while VSC4 employs constant active power control within the conventional droop control, conversely, the proposed droop control applies a modified droop control. At the receiving-end converter station, VSC3 operates under constant active power control. The established VSC-MTDC model is implemented using PSCAD/EMTDC software. The different reference values (Active power, DC voltage) and droop coefficients for both the conventional and proposed droop control strategies are illustrated in Table 01 and Table 02.

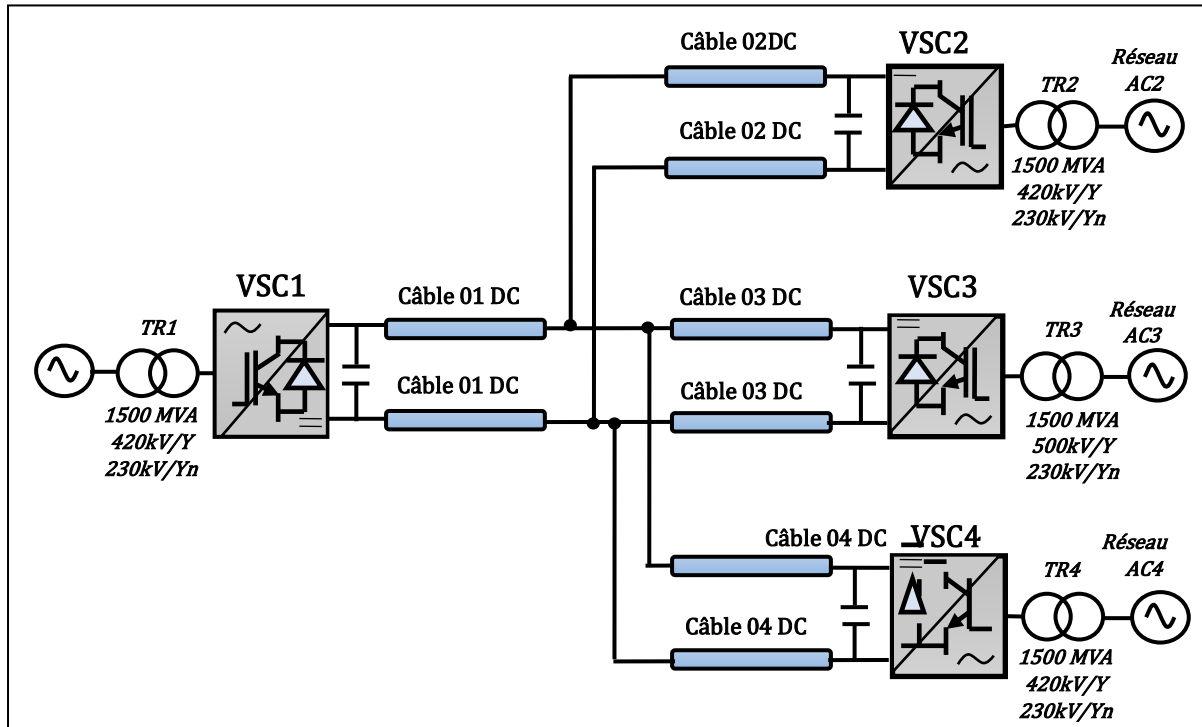


Figure 10: Investigated a VSC-MTDC with four terminals.
Source: Authors, (2026).

Table 1: MTDC grid parameters and droop coefficients.

Parameter system	Value
VSC rated power SVSC	1500 MVA
AC network rated power Sb	100 MVA
VSC nominal DC voltage VDC	400 kV
VSC nominal AC voltage Vs-c	230 kV
AC networks impedance	26.45 Ω
AC networks impedance phase angle	80°
SCR	2.5
AC frequency (VSC2, VSC3)	50 Hz
AC frequency (VSC1)	60 Hz
Switching frequency	1980 Hz
DC capacitor C	300 μ F
Droop coefficient ρ VDC	0.02 kV/MW
DC line resistance	7 Ω
DC line inductance	0.5968 H
DC line capacitance	26 μ F
Converters topology	2 level IGBT

Source: Authors, (2026).

Table 02: The different reference values of Active Power, DC Voltage, and droop coefficients for the MTDC system before and after the first outage (conventional droop control).

	Converters	VSC1	VSC2	VSC3	VSC4
Steady state	Mode control	Droop control	Droop control	Active power control	Modified droop control
	V*DC	400 kV	400 kV	-	-
	P*AC	80 MW	80 MW	-240MW	80 MW
	droop coefficients	0.02 kV/MW	0.02 kV/MW	-	-
After Converter outage	Mode control	-	Droop control	Active power control	Modified droop control
	V*DC	-	400 kV	-	410 kV
	P*AC	-	80 MW	-240 MW	80 MW
	droop coefficients	-	0.02 kV/MW	-	0.02 kV/MW

Source: Authors, (2026).

Two cases have been chosen as test cases for the four terminals VSC-MTDC system:

- 1) Case 1: Outage of converter equipped with droop control (VSC1) then variation of active power of VSC2.
- 2) Case 2: Outage of converter equipped with droop control (VSC1) then outage of converter equipped with droop control (VSC2).

V.1 CASE 1

This case evaluates the dynamic behavior of the VSC-MTDC system following the outage of VSC1, a power injection terminal operating under droop control. The objective is to assess how the remaining converter, VSC2, responds to the resulting power imbalance and how the system performs under both the conventional and proposed droop control strategies. Initially, VSC1 and VSC2 are configured to inject 80 MW each into the DC grid with identical droop coefficients (0.02 kV/MW). Simultaneously, VSC3 consumes -240 MW under constant power control, and VSC4 injects 80 MW using a modified droop control. At steady state, the system is fully balanced. Following the sudden disconnection of VSC1, the system experiences a power deficit of 80 MW. With VSC3 maintaining its fixed consumption and VSC4 holding its reference output, VSC2 becomes the primary converter tasked with rebalancing the system.

- Under conventional droop control, VSC2 reacts with a sudden and steep rise in active power output, leading to a significant overshoot and a noticeable DC voltage dip, as depicted in Figure 12(a). This rapid adjustment results in oscillations and a longer settling time. Furthermore, Figure 11(a) shows the sharp disturbance at the moment of VSC1's disconnection, with abrupt changes in current and power. The system lacks coordination, highlighting the rigidity of the fixed droop slope.
- In contrast, under the proposed droop control strategy, VSC2 demonstrates a more adaptive, smoother, and coordinated response. The increase in power output is gradual, with minimal overshoot, and the DC voltage deviation is significantly reduced, as shown in Figure 12(b). Moreover, Figure 11(b) confirms a controlled response in current and power after the disturbance. This behavior is attributed to the adaptive features of the proposed droop method, which allow real-time tuning of the droop coefficient or voltage reference depending on system conditions.
- Additionally, Figure 14(b) illustrates how VSC4 actively contributes to the power compensation through its modified droop control, further alleviating the burden on VSC2 and supporting DC voltage recovery. In contrast, Figure 14(a) shows that VSC4 remains passive under conventional setting.

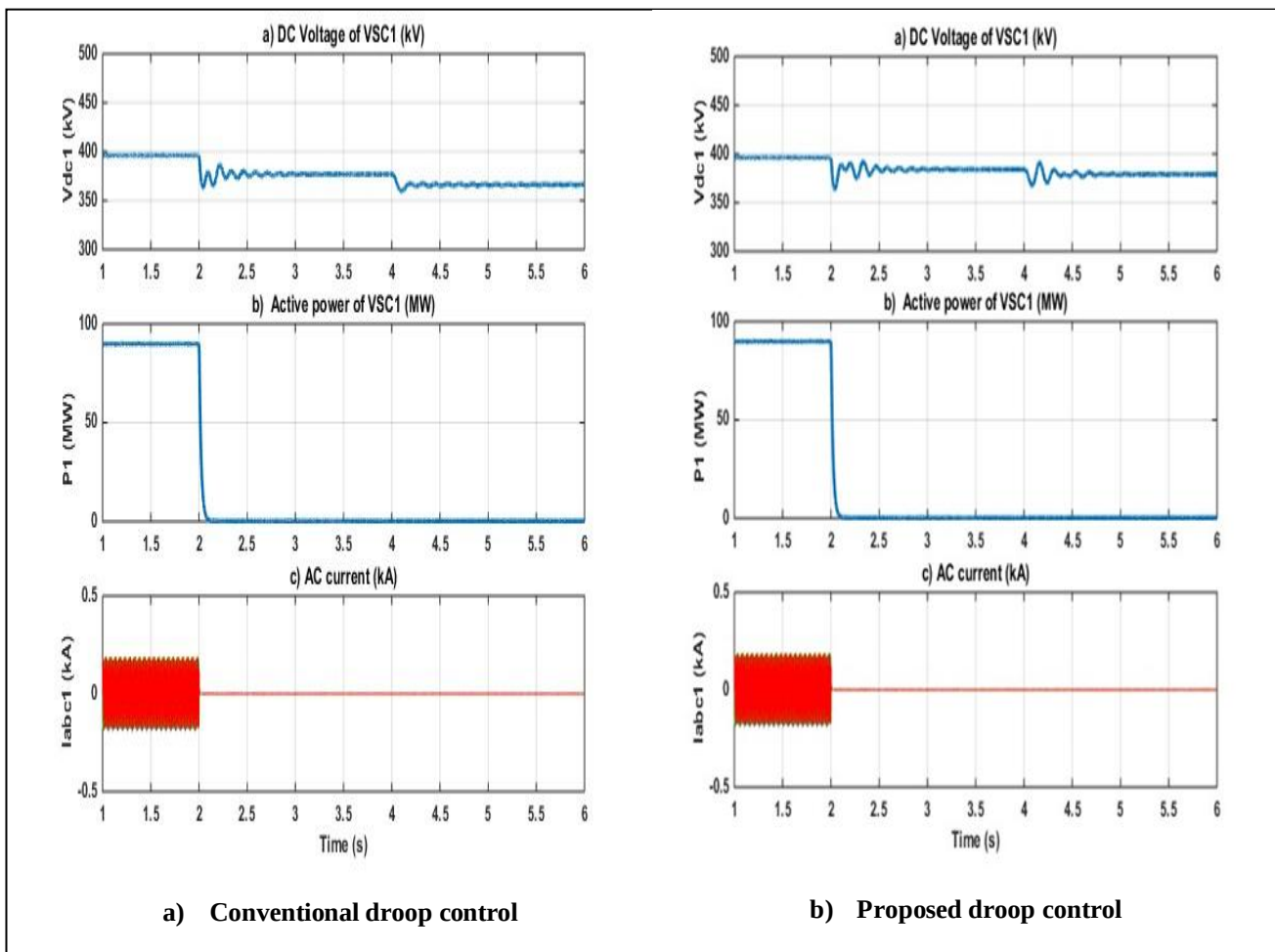


Figure 11: DC voltage, Active power and AC current of VSC1.

Source: Authors, (2026).

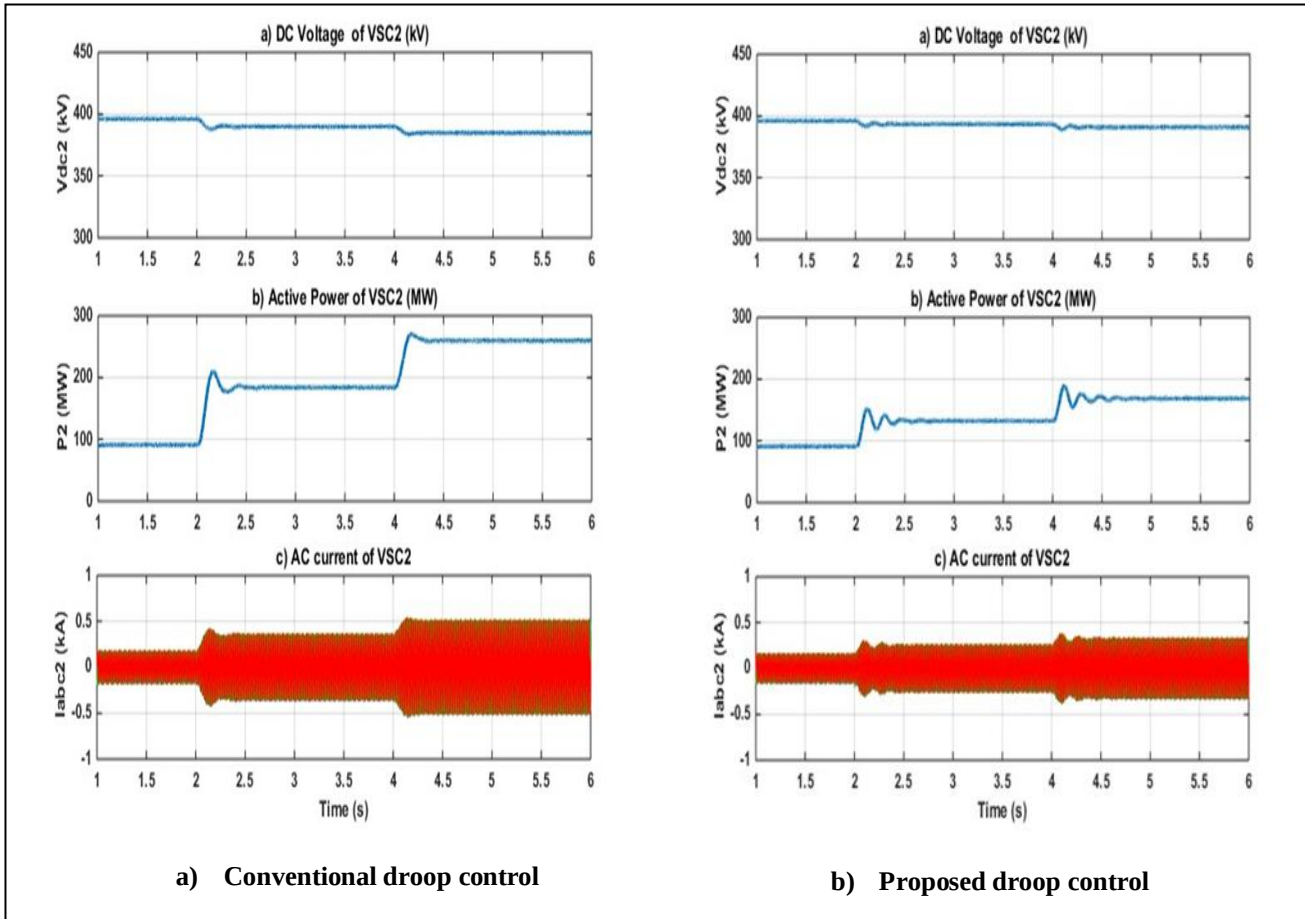


Figure 12: DC voltage, Active power and AC current of VSC2.
Source: Authors, (2026).

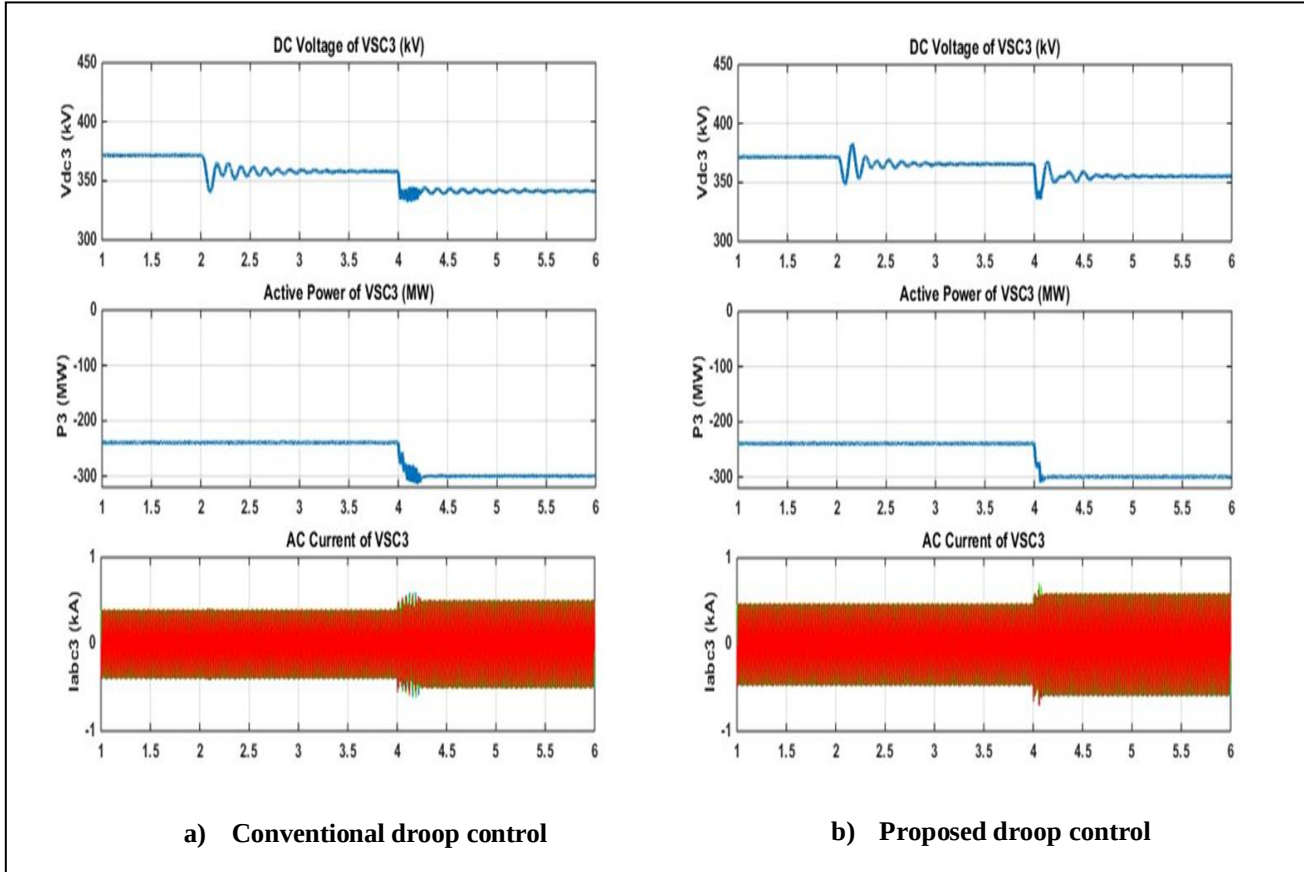


Figure 13: DC voltage, Active power and AC current of VSC3.
Source: Authors, (2026).

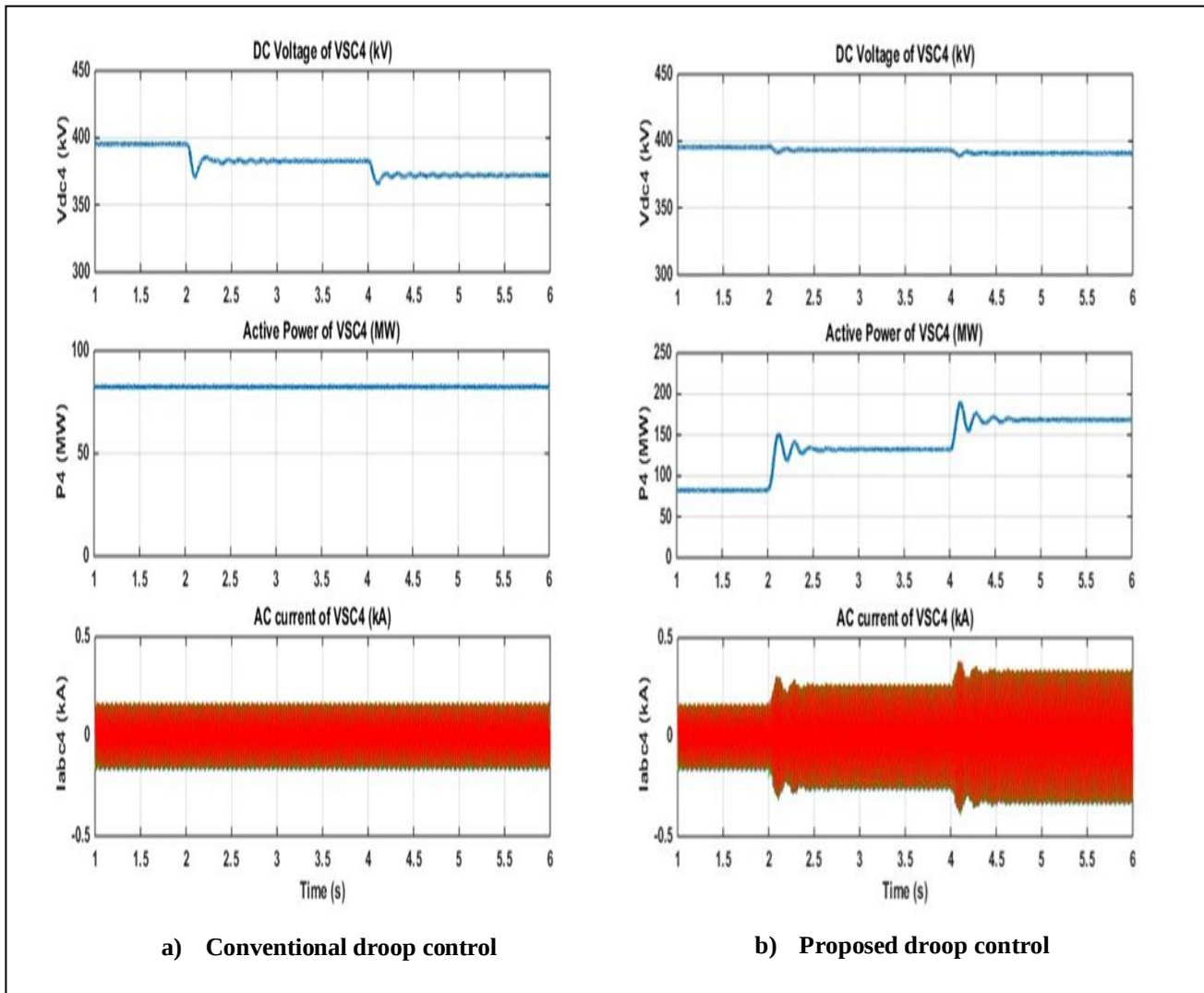
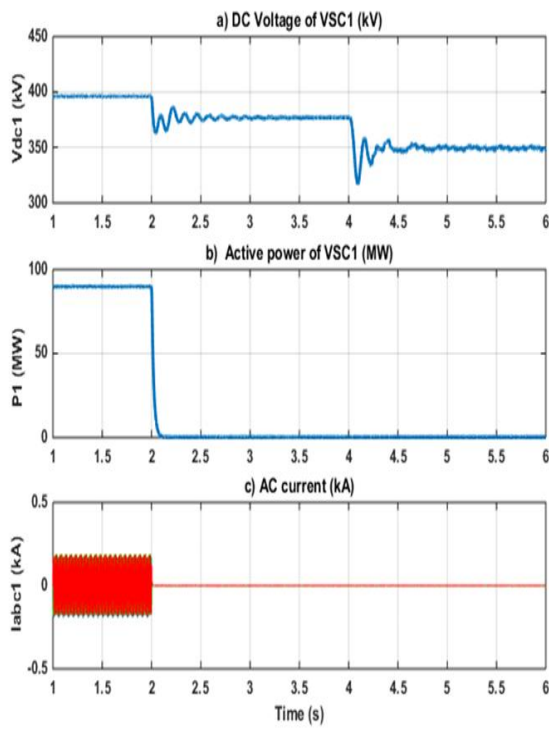


Figure 14: DC voltage, Active power and AC current of VSC4.

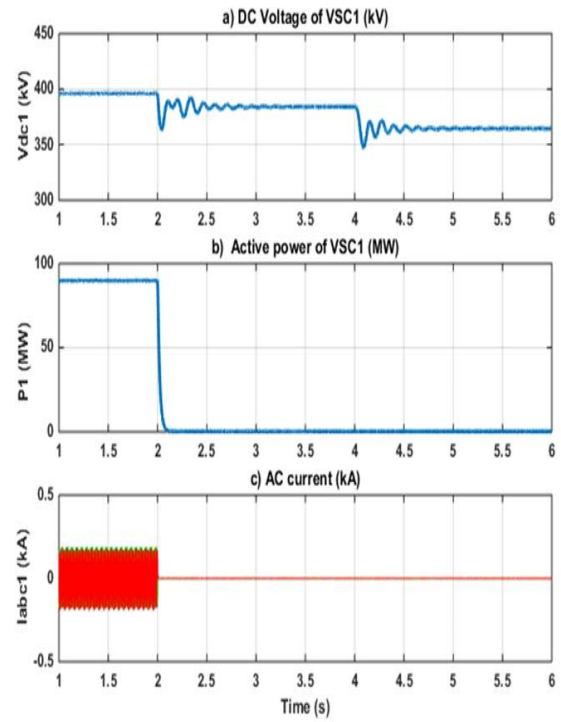
Source: Authors, (2026).

V.2 CASE 2

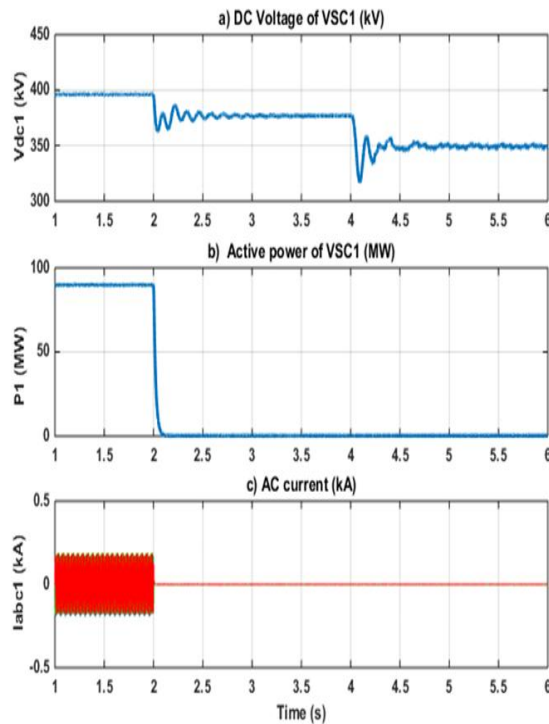
This case investigates the dynamic performance of the VSC-MTDC system under a severe disturbance caused by the sequential outage of VSC1 and VSC2, both operating under conventional droop control. The objective is to evaluate the system's ability to maintain power balance and voltage stability through the remaining terminals, VSC3 and VSC4, under both conventional and proposed droop control strategies. Initially, VSC1 and VSC2 each inject 80 MW using droop control, while VSC3 consumes -240 MW in constant active power control mode, and VSC4 operates with a modified droop control, injecting 80 MW. This setup ensures total power balance under normal conditions. Following the outage of VSC1, VSC2 initially increases its power output to compensate for the deficit. However, once VSC2 is also disconnected, a total of 160 MW of injected power is lost, while VSC3 continues to draw constant power and VSC4 maintains its reference. The system is left with only one remaining injection terminal (VSC4). Under the conventional droop control configuration, VSC4 is unable to adapt its output dynamically because it operates at a fixed setpoint. As a result, the system experiences a critical power imbalance. This leads to a sharp increase in DC voltage, caused by the excess unabsorbed power from VSC3. The system becomes unstable, with persistent voltage deviation and no convergence toward a new steady-state. This outcome reveals the inadequacy of conventional control in multi-terminal HVDC systems facing severe multi-converter outages. In contrast, with the proposed droop control strategy, VSC4 is capable of responding adaptively to the DC voltage deviation. Upon the loss of VSC1 and VSC2, VSC4 detects the voltage rise and gradually increases its power output, stabilizing the system. This dynamic response ensures that the power imbalance is progressively compensated, and the system achieves a new steady-state with minimal disturbance. Importantly, the proposed strategy significantly limits the rise in DC voltage, keeping it within operational thresholds and thereby preventing protection activation or converter shutdown. This improvement in voltage regulation is a direct result of the proposed droop mechanism's real-time adaptability, including the dynamic adjustment of droop slope or voltage reference. By enabling VSC4 to contribute flexibly to power balancing, the strategy also supports grid resilience and fault tolerance, even in the absence of two major power sources.



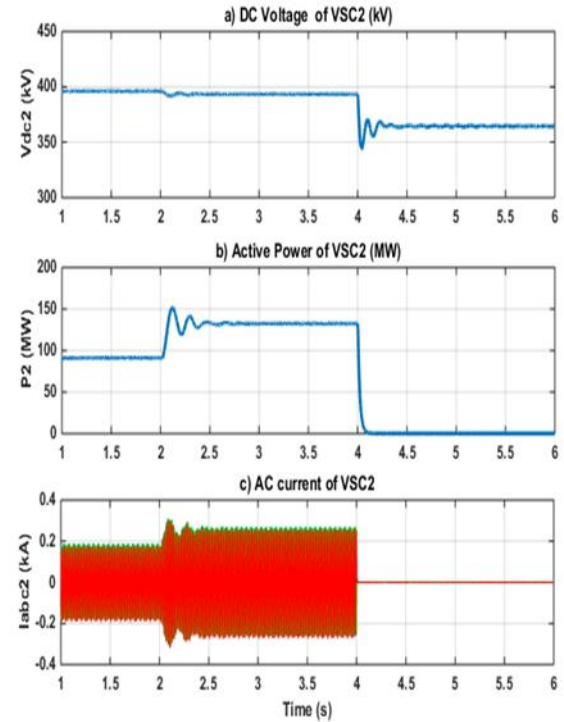
a) Conventional droop control



b) Proposed droop control

Figure 15: DC voltage, Active power and AC current of VSC1.
Source: Authors, (2026).

a) Conventional droop control



b) Proposed droop control

Figure 16: DC voltage, Active power and AC current of VSC2.
Source: Authors, (2026).

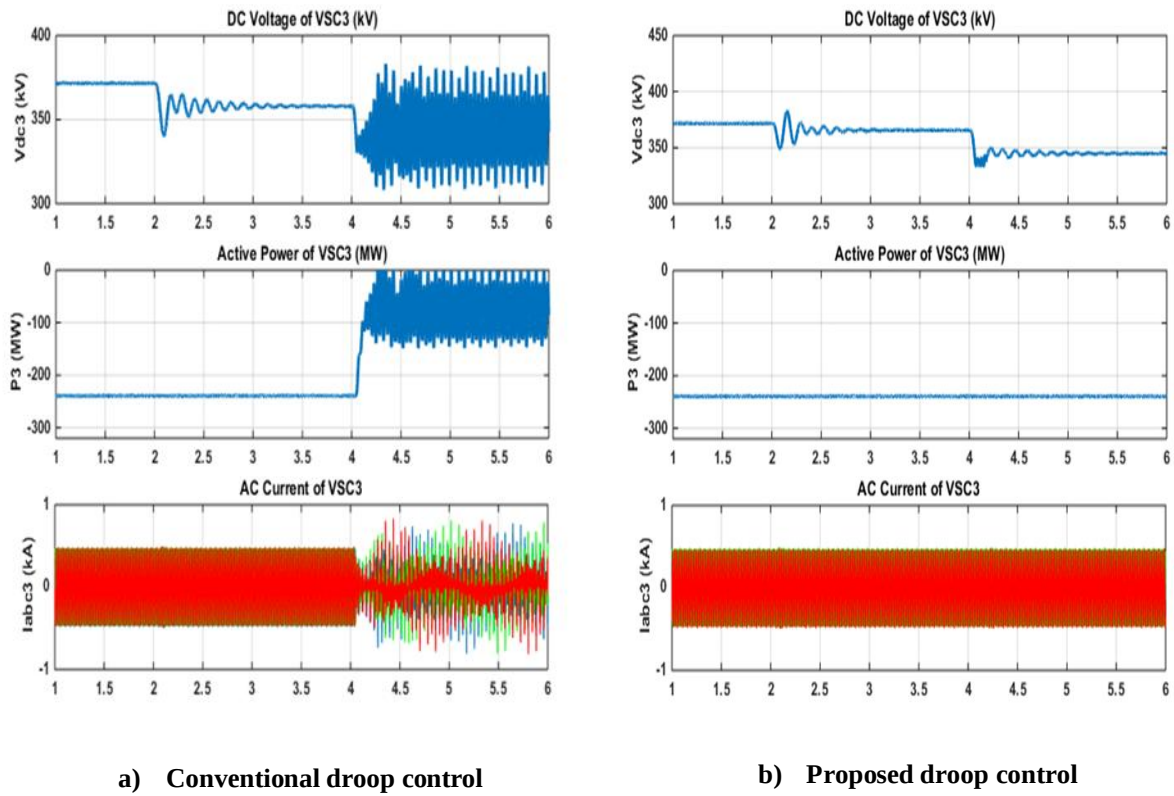


Figure 17: DC voltage, Active power and AC current of VSC3.
Source: Authors, (2026).

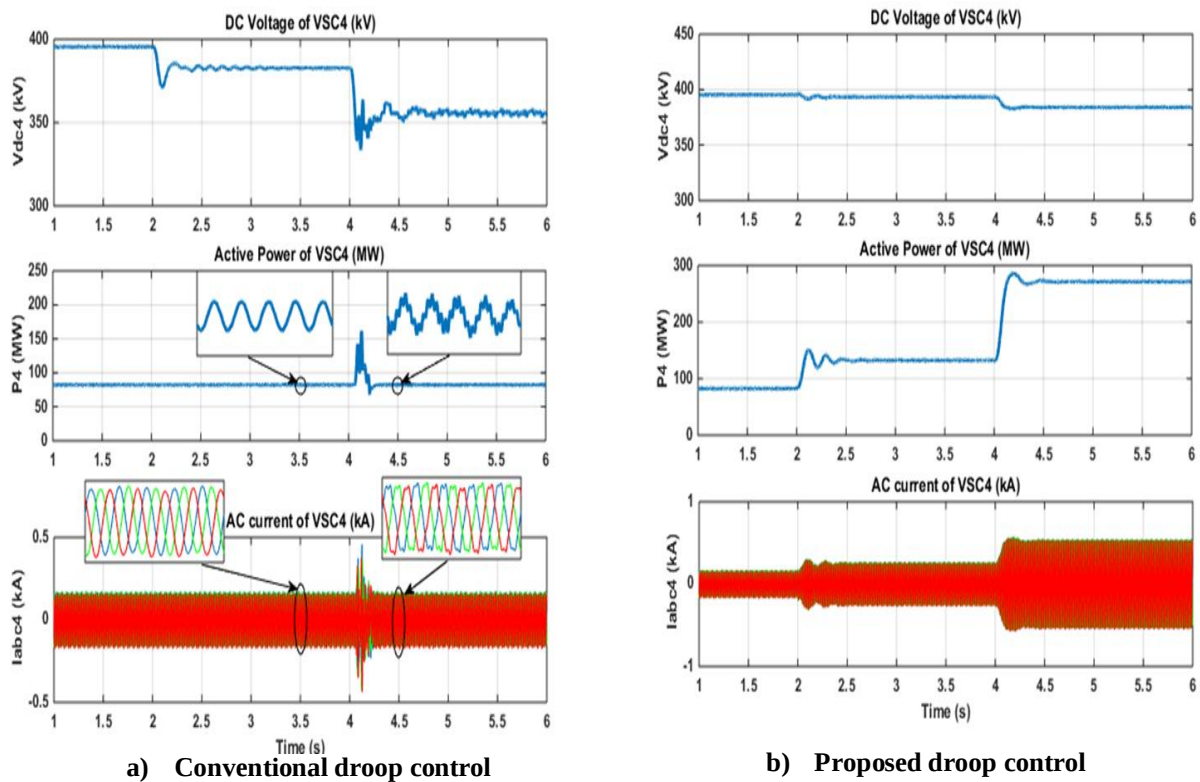


Figure 18: DC voltage, Active power and AC current of VSC4.
Source: Authors, (2026).

VI. CONCLUSIONS

In this work, an adaptive droop control strategy with a modification has been proposed to enhance dynamic performance, DC voltage stability, and fault tolerance of VSC-MTDC systems under conditions of converter outage. By adapting voltage margin theory together with instantaneous droop parameter readjustment, the method surpasses the limitations of conventional fixed-slope droop control, achieving more uniform power sharing, faster post-disturbance recovery, and improved system robustness under severe transients. Simulation from a ± 400 kV four-terminal VSC-MTDC network in PSCAD/EMTDC confirms that the proposed control reduces peak DC voltage deviations by 45–60%, active power overshoot by 40–55%, and settling times by 35–50% compared to conventional droop control. In addition, up to +65 MW of extra contribution from passive converters provides backup support against overload on other remaining terminals, while operating within limits under N–1 and N–2 contingencies. It will be preceded by hardware-in-the-loop (HIL) testing to assess the strategy in realistic operating conditions, machine learning-based optimization for autonomous control of droop parameters as a function of dynamic network states, and extension of the framework to hybrid AC/DC smartgrids with high-penetration renewable energy sources and advanced energy storage devices. These developments aim to place the developed control method as a pillar for the future generation of resilient, intelligent HVDC transmission infrastructures.

VII. AUTHOR'S CONTRIBUTION

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