Implementation of DC voltage controllers on enhancing the stability of multi-terminal DC grids

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Article Info	ABSTRACT
	Because of the increasing penetration of intermittent green energy resources like offshore wind farms, solar photovoltaic, the multi-terminal DC grid using VSC technology is considered a promising solution for interconnecting these future energies. To improve the stability of the multi-terminal direct current (MTDC) network, DC voltage control strategies based on voltage margin and voltage droop technique have been developed and investigated in this article. These two control strategies are implemented in the proposed model, a ±400 kV meshed multi-terminal MTDC network based on VSC technology with four terminals during the outage converter. The simulation results include the comparison and analysis of both techniques under the outage converter equipped with constant DC voltage control, then the outage converter equipped with constant active power control. The simulation results confirm that the DC voltage droop technique has a better dynamic performance of power sharing and DC voltage regulation.

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1. INTRODUCTION

Nowadays, with the fast increase in demand for electricity in the world, the electrical network needs to be improved to facilitate exchanges and connect renewable energies such as offshore wind farms, solar photovoltaic. High voltage DC (HVDC) technology is an important technology in the interconnection of renewable energies because it has several advantages compared with a high voltage AC (HVAC) technology, (1) Bulk transmission of power over long distances, (2) Interconnection of asynchronous networks, (3) It is the only possibility to transport electricity in underground or submarine cables over distances of more than about 100 km [1-3].

Most of the HVDC links in operation today are point-to-point (PTP) with two points of connection with the AC networks, which use either LCC or VSC technology for the converters [4-6]. However, it is envisaged that a DC network consists of more than two converters station called multi-terminal direct current (MTDC) networks. The classical technology LCC-HVDC is challenging to build the MTDC network because it needs reversing the line's polarity to change the power flow. Hence, another technology called VSC-HVDC is preferred to build MTDC network because it doesn't reverse their polarity but only their current, seem to be more suitable and easier to control [7]. However, the MTDC network can adopt LCC technology. In the literature [8, 9], a multi-terminal MTDC network based on the LCC converter was presented and developed.

VSC-MTDC control based on decoupled vector control is composed of outer controllers and inner current controller [6]. To achieve the MTDC grid's flexibility, different DC voltage control strategies were developed, the master-slave technique, voltage margin technique, and voltage droop technique. For the master-slave technique, as a natural extension of the control of PTP VSC-HVDC, only one converter as known (slack bus or master) within the MTDC network could regulate the DC voltage while the rest converters would control the active power transfer and once the master converter fails due to a fault, the MTDC network will be unstable in consequence of having no converter to control DC voltage [10, 11]. For the voltage margin technique, the VSCs converters can be changed control mode between DC voltage and active power, only one slack bus at each time [12]. For the voltage droop technique, more than one converter participates in DC voltage regulation of the MTDC network simultaneously [13-15].

To solve the problem of the master-slave technique when the outage of the slack bus converter, DC voltage control strategies based on voltage margin and voltage droop techniques have been developed in this article. These two techniques are implemented in the proposed model, a ±400 kV meshed multi-terminal MTDC network based on VSC technology with four terminals [16, 17]. The voltage margin technique is automatically implemented to improve communication between the converters [12, 18]. The droop technique or decentralized technique developed in this article is a technique that allows the power sharing between different converters without communications [19]. To verify the performance of the two techniques, an outage of a VSC converter equipped with constant DC voltage control, then an outage of a VSC converter equipped with constant active power control are investigated.

The remainder of this paper is structured as: The characteristics of VSC station for interconnecting of MTDC network with different power electrical are shown in section 2. Section 3 presents different DC voltage techniques especially, master-slave, voltage margin and voltage droop techniques. Then, the developed VSC-MTDC model with four terminals using PSCAD/EMTDC is described in section 4. Section 5 reports the simulation results and compares the performance of both techniques from different scenarios. And finally, section 6 draws the conclusions of this paper.

2.   CHARACTERISTICS OF VSC-MTDC NETWORK
2.1. VSC station in MTDC network
The VSC-MTDC network is composed of VSC converters and high voltage DC transmission (cables or lines). The main diagram of a single VSC station is shown in Figure 1. This station consists of the principal component called VSC converter, which connected to the phase reactor. The phase reactor is connected to the AC network at the so-called point of the common coupling (PCC) through the transformer [6].
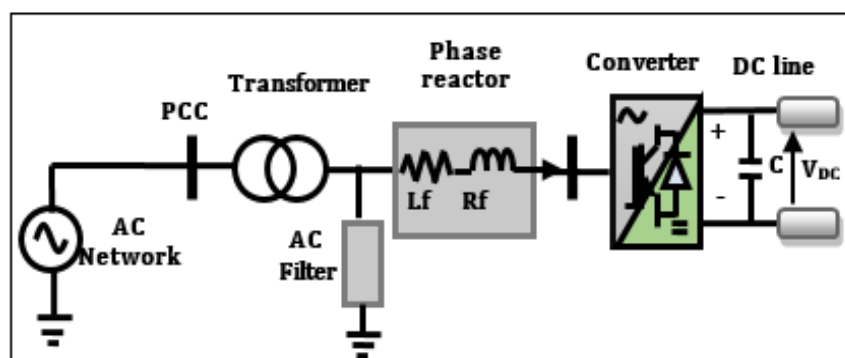

Figure 1. Main diagram of a single VSC station

2.2. MTDC network for interconnecting with power electrical
As shown in Figure 2, the MTDC network based on VSC converter is usually used to interconnect with different conventional power networks such as offshore wind farms and photovoltaic power stations [20]. In [21], a wind generation system type 4 was integrated into the AC grid through the VSC-HVDC link. The VSC converter is required for the construction of the MTDC network because it can offer several advantages [6]:
-    It has the capability of independent control of both active and reactive powers.
-    The DC link can be connected to a weak or passive AC network providing frequency control.
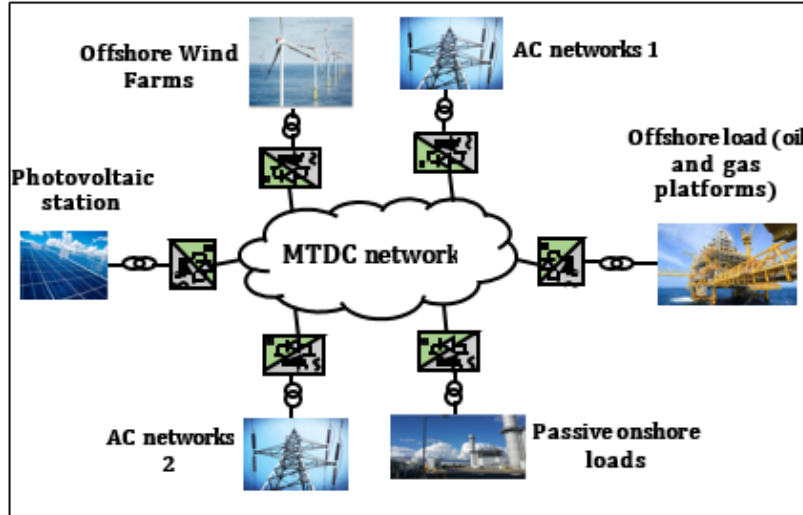-   High reduction of the harmonic content and elimination.

Figure 2. MTDC network interconnected with several electrical powers

3. DC VOLTAGE CONTROL STRATEGIES OF VSC-MTDC NETWORK

Considering in MTDC network each two-level VSC converter connected to the AC grid, the main control of the MTDC network is categorized into two different layers of controllers the VSC terminal controller and master controllers. The control strategy used at each converter is based on the vector control method in the terminal controller. Figure 3 shows the general structure of the VSC converter using the d-q vector control technique. In this technique, the AC voltages and currents measured at PCC are transformed into q-d reference axis using Clarke/Park transformations [22]. The synchronization of the VSC converter with the AC grid is performed by a phase-locked loop (PLL), which produces frequency and phase angle (θ) [23]. The designed control of this technique is divided into an inner current controller and outer controllers. The inner current controller is composed of two controllers, respectively, for d and q axis current control. The reference values of direct current (I^*_{s-d}) and reactive current (I^*_{s-q}) are garnered from the outer controllers, where DC voltage control or active power control are designed to derive I^*_{s-d} and AC voltage control, or reactive power control are designed to derive I^*_{s-q}. The instantaneous active and reactive currents (I_{s-d} and I_{s-q}) are controlled by generating the reference voltages V^*_{s-d} and V^*_{s-q}, which are re-transformed to the three phases (abc) frame and served into input signal to the PWM of the VSC converter.
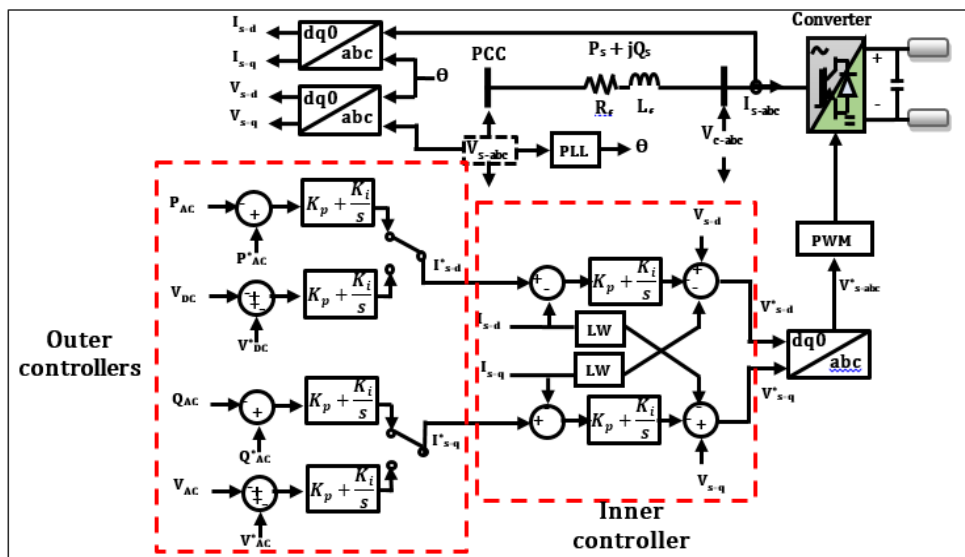

Figure 3. General structure of VSC converter using d-q vector control

The dynamics of the VSC terminal in Figure 3 can be expressed in the q-d reference axis as,

$$\frac{dI_{s-d}}{dt} = -\frac{R_f}{L_f}I_{s-d} - \frac{1}{L_f}(V_{s-d} - V_{c-d}) + j\omega I_{s-q} \tag{1}$$

$$\frac{dI_{s-q}}{dt} = -\frac{R_f}{L_f}I_{s-q} - \frac{1}{L_f}(V_{s-q} - V_{c-q}) - j\omega I_{s-d} \tag{2}$$

In the master controllers, three control strategies based on DC voltage control: master-slave, voltage margin, and voltage droop techniques are developed in a multi-terminal DC network.

3.1. Master-slave technique

Generally, the master-slave technique (coordinated control) is used for point-to-point and multi-terminal HVDC (MTDC) [24]. In this technique, one converter called (master) is designed in constant DC voltage control mode, while the remaining converters called (slaves) are described in constant active power control mode. The function of the master terminal is to maintain the DC voltage at the reference value. This converter will operate like a battery, which means that it will deliver or consume the active power to ensure the power balance of the MTDC network [25]. Figure 4(a) shows the P-V characteristics of a PTP-HVDC system, one converter (master) in orange, and another converter (slave) in blue. The master maintains a constant DC voltage, regardless of its power, while the slave injects constant power, regardless of its voltage. The difference between DC voltage measured (V_{DC}) and DC voltage of reference (V^*_{DC}) is processed through a PI regulator to produce the desired direct current reference I^*_{s-d}, the active power controller works with a similar principle as presented in Figure 4(b). The existing MTDC network using the master-slave technique in China was built in 2014 as a known Zhoushan project with five converter terminals [26]. The disadvantage of this technique is the instability of the MTDC network when a master converter fails [11]. To solve the problem of the disconnection of the master converter, two techniques called voltage margin, and voltage droop technique are developed and compared in this article.
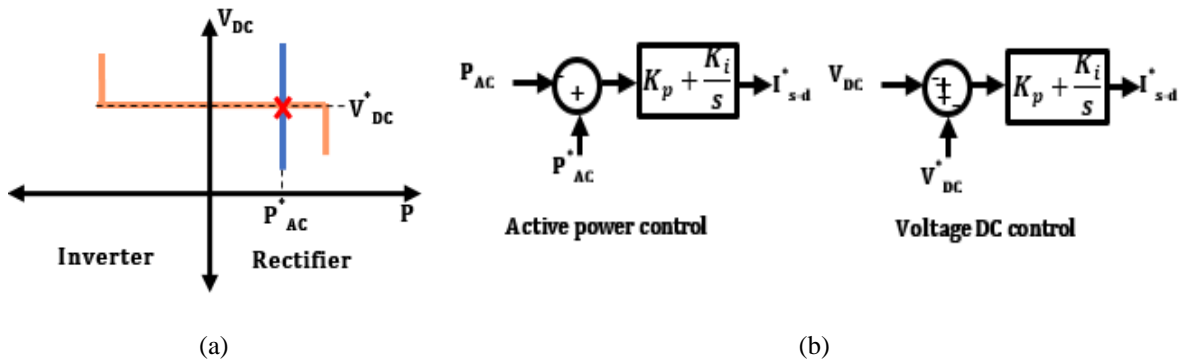

(a)   (b)

Figure 4. Master-slave technique applied to PTP-HVDC system, (a) DC voltage versus active power characteristics, (b) basic scheme of the method

3.2. Voltage margin technique

The voltage margin technique was first proposed for the VSC-HVDC network in [27]. This technique is a modification of the master-slave technique in which DC voltage and power control modes are combined, at each time, only one slack bus [12, 18]. As shown in Figure 5(a), the P-V characteristics of a PTP-HVDC system, the first converter in orange, and the second converter in blue. The first converter adopts DC voltage control mode with its reference value V^*_{DC1}, while this converter works with its limits of active power. When the limits of converter 1 are reached, the control mode of this converter will be switched to constant power control. Under this event, the control mode of converter 2 will be switched from constant power to DC voltage control mode and operate at the new set value V^*_{DC2}. The difference between V^*_{DC1} and V^*_{DC2} is called voltage margin. Generally, the voltage margin technique may be implemented in more than one VSC converter in MTDC networks. Figure 5(b) shows the implementation diagram of the technique in the VSC converter used in this paper.
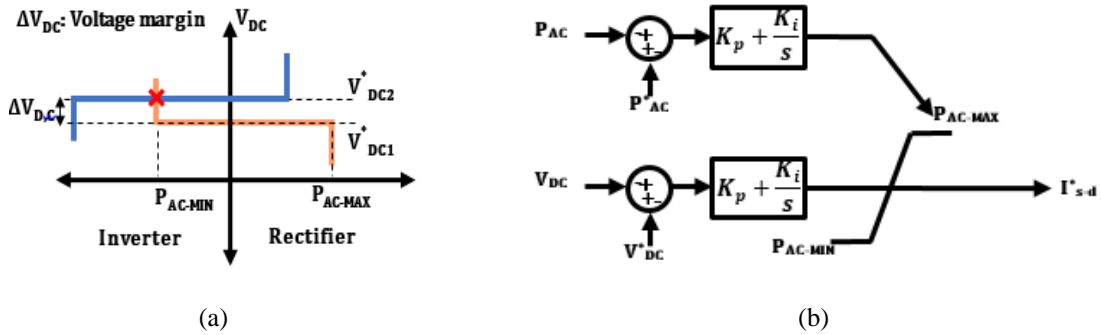
Figure 5. Voltage margin technique applied to PTP-HVDC system, (a) DC voltage versus active power characteristics, (b) Basic scheme of the technique

3.3. Voltage droop technique

The stability of the MTDC network can be improved by acting more than one converter for DC voltage regulation. The voltage droop technique works similarly to the one implemented in the AC network, where the consumption dependent frequency variation. In the DC network, the droop technique employs the droop mechanism to control the DC voltage by adjusting the converter power injections [14]. In the PTP VSC-HVDC network, only one converter is responsible for the regulation of DC voltage. However, in the MTDC network, more converter will be needed to control DC voltage. Thus, the droop technique has a better performance and flexibility between all converters for controlling the DC voltage [15, 28]. The DC voltage versus power characteristics of the droop technique is shown in Figure 6(a). This technique can be seen as a proportional control in which the droop coefficient $\rho_{V_{DC}}$ is equal to the inverse of the characteristic curve slope. The difference between the reference value of active power P_{AC}^* and the actual power P_{AC} produces corrective droop signaled by the droop coefficient $\rho_{V_{DC}}$. Equation (3) expresses the relation between the DC voltage deviation and the power sharing of the VSC converter equipped with a droop technique. Figure 6(b) shows the implementation diagram of the technique in the VSC converter used in this paper.

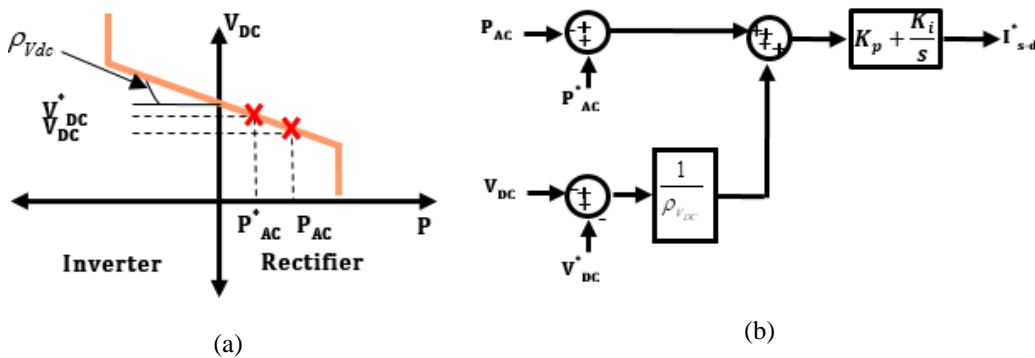$$P_{AC} = P_{AC}^* - \frac{1}{\rho_{V_{DC}}}(V_{DC}^* - V_{DC}) \tag{3}$$

Figure 6. Voltage droop technique applied to PTP-HVDC system, (a) DC voltage versus active power characteristics, (b) basic scheme of the technique

4.   MTDC SYSTEM MODEL

A four-terminal meshed MTDC network tested in this paper is presented in Figure 7. It consists of four converters based on VSC technology, which are connected with four active AC networks. The main objective of this paper is to verify the reliability of both voltage margin and voltage droop techniques under lost any converter station. The simulation results are verified by PSCAD/EMTDC software. The different scenarios studied and control strategies used in this paper are shown in Table 1. The parameters and rating values of the MTDC network are presented in Table 2.
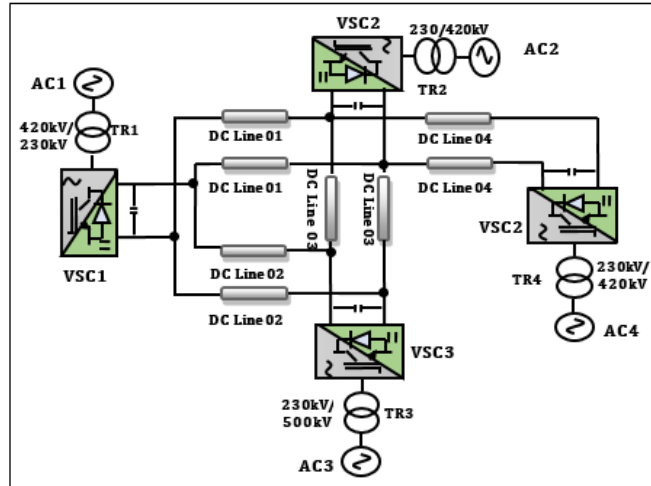
Figure 7. VSC-MTDC model with four terminals

Table 1. Different scenarios studied and control strategies

Scenarios	Control Mode			
	VSC1	VSC2	VSC3	VSC4
I-VSC1 outage	DC voltage margin	DC voltage margin	Constant power	Constant power
II-VSC1 outage	DC voltage droop	DC voltage droop	Constant power	Constant power
III-VSC4 outage	DC voltage margin	DC voltage margin	Constant power	Constant power
IV-VSC4 outage	DC voltage droop	DC voltage droop	Constant power	Constant power

Table 2. MTDC grid parameters and droop coefficients

Symbol	Parameter system	Value
S_{VSC}	VSC rated power	1500 MVA
S_b	AC network rated power	100 MVA
V_{DC}	VSC nominal DC voltage	400 kV
V_{s-c}	VSC nominal AC voltage	230 kV
Z_{AC}	AC networks impedance	26.45 Ω
Ω_{AC}	AC networks impedance phase angle	80°
S_{CR}	Short Circuit Ratio	2.5
f_{AC1}	AC frequency (VSC1)	60 Hz
f_{AC2}	AC frequency (VSC2, VSC3, VSC4)	50 Hz
f_{SW}	Switching frequency	1980 Hz
C	DC capacitor	300 μF
R_l	DC line resistance	7 Ω
L_l	DC line inductance	0.5968 H
C_l	DC line capacitance	26 μF
ρ_{VDC}	Droop coefficient	0.02 kv/MW
K_{p-DC}	Proportional gain of outer control loop (DC voltage)	0.05
T_{i-DC}	Time constant of outer control loop (DC voltage)	3
K_{p-AC}	Proportional gain of outer control loop (AC voltage)	10
T_{i-AC}	Time constant of outer control loop (AC voltage)	0.0012
K_p	Proportional gain of inner control loop	65
T_i	Time constant of inner control loop	0.00001

5. SIMULATION RESULTS

5.1. Scenario studied 1: VSC1 outage under voltage margin technique

In this case, the DC voltage margin technique is implemented, VSC1 converter (master) operates in a DC voltage control mode at 400 kV while VSC2, VSC3, and VSC4 (slaves) operate in a constant power control mode. After the outage of the VSC1 converter, the second converter VSC2 change mode control from constant power control to DC voltage control mode at a new set value 410 kV while the remaining converters operate in a constant power control mode. The outage of the VSC1 converter is considered at 2 s. The Table 3 shows a set value of the MTDC network under voltage margin technique.

Looking at Figure 8(a), it is apparent that when VSC1 equipped with DC voltage control (first master converter) is lost, the active and reactive powers of VSC1 decrease to 0. Therefore, the VSC2 is transformed into the master station and changed from constant power control to DC voltage control.

Following the outage, it can be seen that the instability of the active power of VSC2 (second master converter) when the control mode is changed then increases to 217 MW to compensate for the unbalanced power caused by the outage of VSC1 converter. The outage converter does not affect the power transit through the VSC4 converter. We can also observe after the outage, instability of the active power of VSC3 then returns to its normal state.

Figure 8(b) shows the DC voltage response of the converters following the outage of the VSC1 converter. During the change in their control mode between VSC1 and VSC2, the DC voltage of VSC2 becomes unstable and then increases to a new set value of 410 kV. Hence, the DC voltage of VSC3 and VSC4 become unstable when the control mode is changed between VSC1 and VSC2.

Table 3. Different set values of MTDC network under voltage margin technique

	Converter	VSC1	VSC2	VSC3	VSC4
Before VSC1 outage	V^*_{DC}	400 kV	-	-	-
	P^*_{AC}	-	100 MW	-300 MW	100 MW
After VSC1 outage	V^*_{DC}	-	410 kV	-	-
	P^*_{AC}	-	-	-300 MW	100 MW

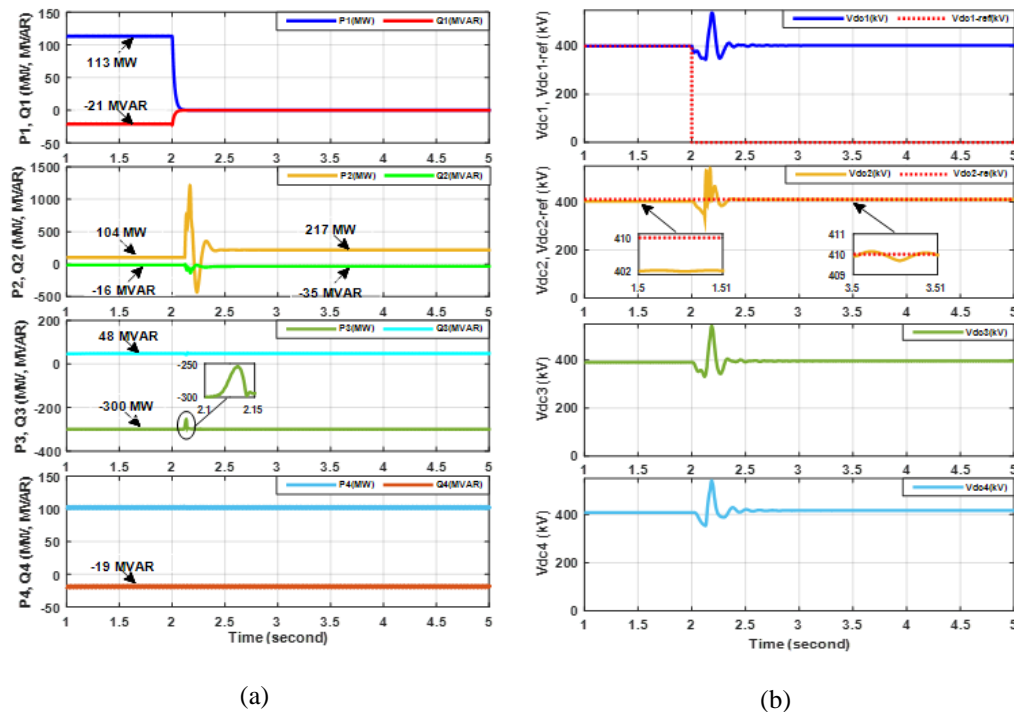(a)   (b)

Figure 8. Dynamic response of MTDC network with voltage margin technique under the outage of VSC1, (a) power transfer, (b) DC voltage

5.2. Scenario studied 2: VSC1 outage under voltage droop technique

DC voltage droop control is implemented in this case, VSC1 and VSC2 adopt voltage droop technique while VSC3 and VSC4 adopt constant power control. The outage of the VSC1 converter is considered at 2 s. The Table 4 shows the set values of the MTDC network under voltage droop technique.

Figure 9(a) shows the converters' response of the active and reactive powers following the outage of the VSC1 converter under voltage droop technique. In the steady state both VSC1 and VSC2 converters equipped with droop control act as rectifiers importing about 120 MW and 100 MW, respectively, into the MTDC network, while those VSC3 and VSC4 operate at constant power control, VSC3 works as inverter carrying around -300 MW and VSC4 act as rectifier importing about 100 MW. After the outage, it can be seen that the VSC2 converter increases its active power to 218 MW to compensate for the unbalanced power caused by the outage of the VSC1 converter. We also observe that the outage converter does not affect the power transit through both VSC3 and VSC4 converters. Therefore, the voltage droop method has better performance under the outage converter compared with the voltage margin method. It can be seen from

Figure 9(b) that the change of active power of VSC2 causes DC voltage deviation, which is reduced from 396 to 388 kV. We also observe that the DC voltage of VSC3 is reduced from 384 kV to 372 kV, and VSC4 is reduced from 402 kV to 395 kV.

Table 4. Different set values of MTDC network under voltage droop technique

Converter	VSC1	VSC2	VSC3	VSC4
V*$_{DC}$	400 kV	400 kV	100 MW	100 MW
P*$_{AC}$	-	100 MW	-300 MW	100 MW
ρ$_{VDC}$	0.02 kV/MW	0.02 kV/MW	-	-

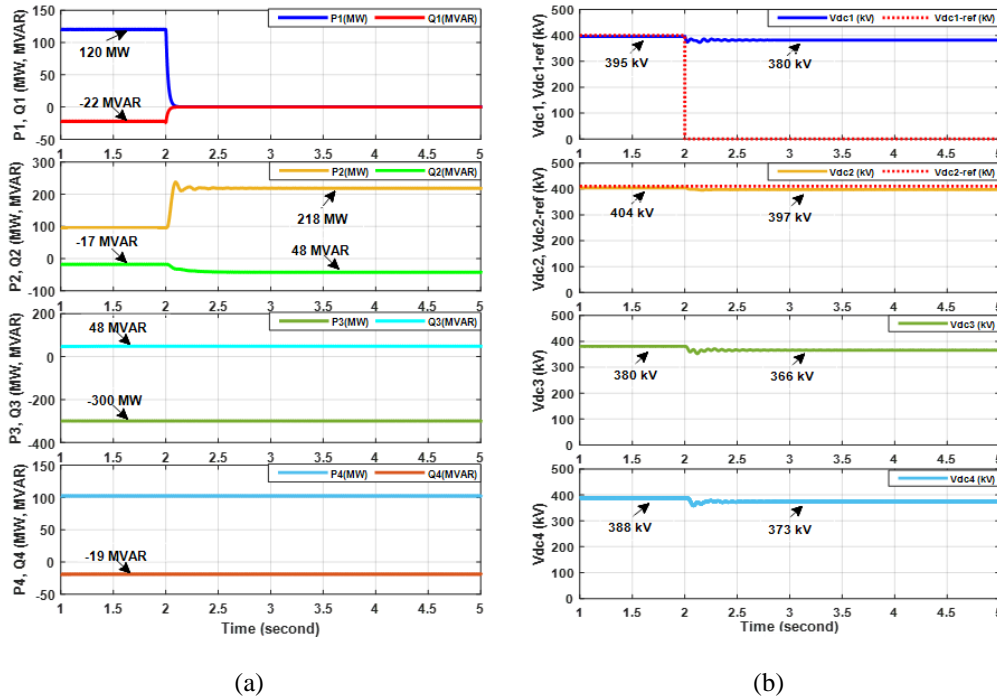(a)   (b)

Figure 9. Dynamic response of MTDC network with voltage droop technique under the outage of VSC1,
(a) power transfer; (b) DC voltage

5.3. Scenario studied 3: VSC4 outage under voltage margin technique

Scenario 3 is set up to verify the control performance of the voltage margin technique when the outage of the VSC4 converter adopts constant power control. In this case, VSC1 adopts DC voltage control with the reference value 400 kV while VSC2, VSC3, and VSC4 adopt constant power control with the reference values 100 MW, -300 MW and 100 MW respectively. The outage of the VSC4 converter considered at 2 s.

In this scenario, an outage converter equipped with constant power control (VSC4), which injects 100 MW, is considered at 2 s. As shown in Figure 10(a), the active power response of the MTDC network is presented. After the outage, the VSC1 converter (slack bus) increases its active power to 212 MW to compensate for the unbalanced power caused by the outage of the VSC4 converter. We also observe that the active and reactive powers of VSC2 and VSC3 are unchanged during the outage. The evolution of the DC voltage at the MTDC grid is illustrated in Figure 10(b). We can see, the outage of VSC4 gives some transients in the DC voltage of the three converters (VSC2, VSC3, and VSC4) then decreases to the new values. The DC voltage of the master converter (VSC1) remains at the previous level with slight fluctuation.

5.4. Scenario studied 4: VSC4 outage under voltage droop technique

DC voltage droop technique is implemented in scenario 4 during the outage of the VSC4 converter, which adopts constant power control. The outage of the VSC4 converter considered at 2 s. From Figure 11(a) above, we can see that after the outage converter, both VSC1 and VSC2 converters implemented on droop control mode participate in sharing the unbalanced power caused by the outage of VSC4 converter. The active power of VSC1 from 120 MW increased to 157 MW, and the active power of VSC2 from 100 MW

increased to 157 MW. We also observe that the active and reactive powers of VSC3 are unchanged during the outage. It can be seen in Figure 11(b). The outage converter causes a DC voltage deviation of VSC1 and VSC2 converters. The DC voltage of VSC1 is reduced from 394 kV to 392 kV, and VSC2 is reduced from 396 kV to 392 kV.
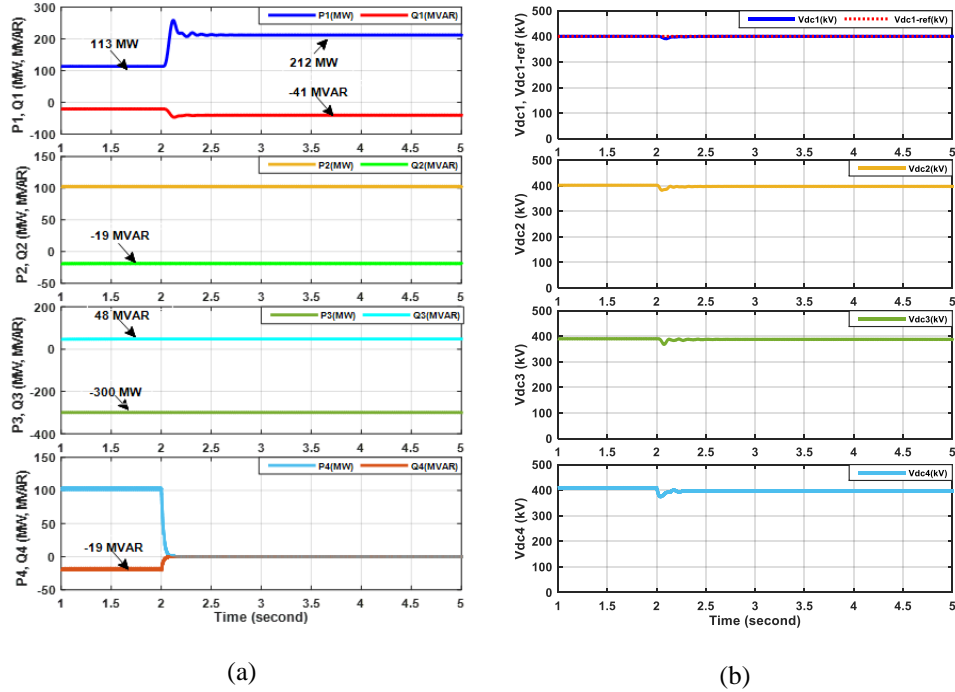

(a)   (b)

Figure 10. Dynamic response of MTDC network with voltage margin technique under the outage of VSC4;
(a) power transfer; (b) DC voltage
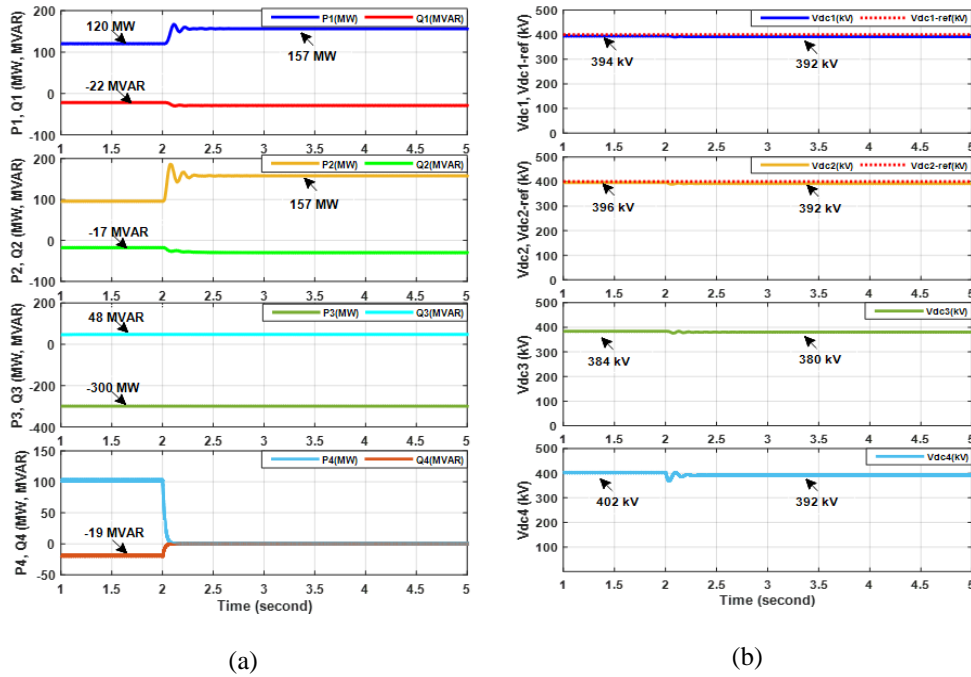

(a)   (b)

Figure 11. Dynamic response of MTDC network with voltage droop technique under the outage of VSC4,
(a) power transfer; (b) DC voltage

6. CONCLUSION

In this article, a multi-terminal based on the VSC-HVDC network with four terminals was investigated and its performance during the outage converter. Two DC voltage techniques are known as voltage margin and voltage droop were developed and studied using PSCAD/EMTDC program. The outage converter equipped with DC voltage and constant power control is considered in this work. The main conclusion of the simulation results is as: i) When the outage of the VSC converter equipped with DC voltage control, using the voltage margin technique, the MTDC network may be unstable after the outage. During the change of their role between both converters, the DC voltage of the DC grid becomes unstable. On the other hand, In the droop technique, the MTDC network has a better dynamic response and best DC voltage control and active power-sharing; ii) When the outage of the VSC converter equipped with active power control, the MTDC network responds quickly with voltage margin technique and only the slack bus converter, which can compensate for the lack of active power caused by the outage converter. In the droop technique, more than one converter participates in the DC voltage regulation and power sharing of the MTDC network. However, the main problem of this technique includes a DC voltage deviation.

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