An Improved Coordinated Control strategy of VSC-MTDC Distribution Network

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Abstract— **In this paper, an improved coordinated control strategy of voltage-source-converters multi-terminals dc systems (VSC-MTDC) in the distribution network is proposed by combining the properties of droop control, modified double stage voltage margin and an undead-band voltage droop control. This approach has three benefits: First, the main converter with droop control characteristics associated with constant active power control can set the reference voltage for the dc system and it is convenient for the regulation of dc voltage and for restraining power variations. Second, several converters simultaneously shared the duty of dc voltage reference control with equal priority. Third, the combination of droop, modified double stage voltage margin and undead-band droop control minimize overvoltage and under voltage during the transient response, allows a smooth and better transition to a new operating point when the system is subjected to small and severe disturbances. Finally, simulations under normal and abnormal conditions and comparison to voltage margin and voltage droop control strategy verify the effectiveness of the proposed approach.**

Keywords— ***MTDC distribution network, VSC, DC voltage margin, DC voltage droop control, coordination control.***

I. INTRODUCTION

The fast expansion of high voltage direct current (HVDC) and the growing amount of distributed renewable energy sources are stimulating engineers and researchers to think towards the future of DC grids. Unfortunately, the integration of renewable energy source raised stability concerns amongst others issues [1]. Currently DC technology based on VSC has been acknowledged as a major technology to build the future DC power grid[2],[3]. Comparable to frequency control in the AC system, DC voltage control is certainly one of the most significant aspects to guarantee operation and stability of a VSC MTDC grid. Numerous research papers discussed control issues related to MTDC system. Proposed control strategies present their own advantages and disadvantages. In a master-slave control only a single converter station known as master or main converter is configured to function as constant DC voltage mode, while the others called slaves terminals are set to work in constant power mode. The implementation of the master control strategy is quite simple but an outage of the master converter results in over-voltage or under voltage and subsequently total collapse of the entire MTDC network[4],[5],[6]. Another technique called voltage margin control can be documented as an improved constant dc voltage control because it holds more than a single station in voltage control mode. Once the main dc control VSC terminal is offline or exceeds its limits, another VSC converter will take over the responsibility of dc voltage regulation at a new value[7], [8] [9]. Unfortunately, this approach still has some insufficiencies, predominantly in a large system, because only one converter possesses the duty of controlling dc voltage at a time. Voltage droop control is more consistent because it allows distinctive converter stations to cooperatively sustain power balance and regulate the dc voltage at the same time; which avoids the growth of voltage oscillations associated with the voltage margin method caused by the transition of voltage regulation duty [10], [11], [12]. In [13] an adaptive droop control is proposed based on the dc system operating conditions. In [14] a hybrid control strategy presenting the features of both droop and voltage margin control is proposed, where the main converter is set as constant dc voltage control, and two others are configured as voltage droop and voltage margin control respectively.

So far, VSC based DC technology used in the transmission network has been applied a lot worldwide both theoretically and practically[15], [16]. Nevertheless, research on MTDC distribution network is far from sufficient all around the world. Structures of medium voltage network are far more complex than that of the transmission network, which creates a great challenge to the practice of MTDC distribution network[17]. Recent trends reveal that DC distribution network plays an essential role in increasing the reliability, quality, and efficiency of the power system in upcoming smart grids and accelerating the integration of distributed energy sources into the grid [18], [19]. The VSC-MTDC distribution system has small inertia, large power disturbance, and many controllable terminals; it is necessary to design a coordinated control strategy with high reliability[20], [21].

In this paper, an improved coordinated control strategy of voltage-source-converters multi-terminals dc systems (VSC-MTDC) in the distribution network is proposed by combining the properties of droop control, modified double stage voltage margin and undead-band voltage droop control strategies. This approach is convenient to restrain large power and voltage variations and guarantee the stability of the DC system. Finally, the effectiveness of the approach is verified by comparing the system performance with voltage

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margin and droop controlled system, and also abnormal and normal conditions been tested. To the best of the author's knowledge, this type of improved coordinated control has never been implemented previously in a VSC-MTDC distribution network.

II. MODELING AND CONTROL OF VSC-MTDC GRIDS

The concept of VSC-MTDC grids is described by the linking of over two VSC systems. In order to gain control of a MTDC grids, DC voltage, active power, reactive power and AC voltage are key variables to be regulated.

Vector control method been used in the majority of VSC stations control strategies [1], [22], [23]. The independent control of key variables such as: active power, reactive power, AC and DC voltages can be achieved by employing vector control strategy and modulation technique. By the same way, the AC currents and voltages of the VSC station (at the PCC) can be expressed in the rotating direct-quadrature (d-q) reference frame and synchronized with the AC grid voltage via a phase-locked loop (PLL). Fig. 1 illustrates the general architecture of the vector control strategy at a VSC-HVDC station.

A. Inner Current Controller

A group of well tuned proportional –integral (PI) controllers which monitors the reference currents gives by the outer controllers, and outputs the voltage reference for the VSC (U_{dref} and U_{qref}). constitutes the inner current controller. To understand the structure of the ICC, the relation between converter-side voltage (u_c), and the voltage at PCC (e_s) can be expressed by,

$$e_s - u_c = R_T i_c + L_T \frac{di_c}{dt} \tag{1}$$

Where, i_c is the moving from the AC grid to the VSC station, and R_T and L_T symbolize the total resistance and inductance between the VSC and PCC. With the help of Park transformation method, (1) can be reformulated in d-q reference frame by,

$$e_d - u_d = R_T i_d + L_T \frac{di_d}{dt} - \omega L_T i_q \tag{2}$$

$$e_q - u_q = R_T i_q + L_T \frac{di_q}{dt} - \omega L_T i_d \tag{3}$$

Where ω represents the angular frequency of the AC voltage at the PCC. The functioning of the ICC is derived from (2)-(3) and its structure is shown in Fig. 2. Switching signals for VSC are then produced after the reference voltages (U_{dref} and U_{qref}) been transformed back into the *abc* reference frame.

B. Outer Controller

The main responsibility of the outer controllers is to generate the reference currents for the inner current controller (i_{dref} and i_{qref}) As shown in Fig. 1, their structure is composed of active and reactive channels. The active power or DC voltage control is managed under the active channel while the reactive channel is responsible for the reactive power or amplitude of AC voltage at the PCC.

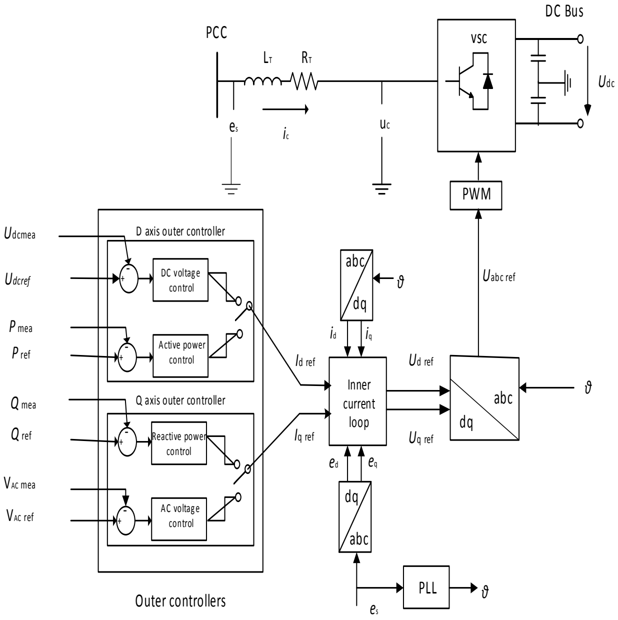


Fig.1. Architecture of vector control at a VSC station

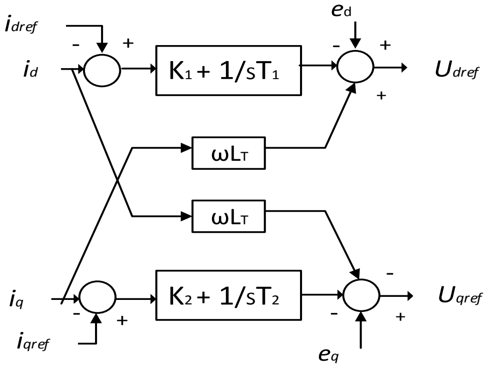


Fig.2. Structure of the Inner Current Controller

The following power equations in d-q reference frame can be used,

$$P = u_d i_d \tag{4}$$

$$Q = -u_d i_q \tag{5}$$

The proper regulation of active power flowing in and out from the AC grid is a main driver to maintain the DC voltage at its reference value. Therefore, the variation of the d-axis current (i_d) enables the DC voltage control within the admissible range.

III. IMPROVED DC VOLTAGE COORDINATED CONTROL

An improved dc voltage coordinated control is proposed here. This strategy has three benefits: First, the main converter with droop control characteristics associated with constant active power control can set the reference voltage for the dc system and it is helpful for the regulation of dc voltage and for restraining power variations. Second, several converters simultaneously shared the duty of dc voltage reference control with equal priority. Third, the combination of droop, modified double stage voltage margin and undead-band droop control minimize overvoltage during the transient response, and allows a smooth and better transition to a new operating point when the system is subjected to small and severe disturbances.

A. Droop control with power limits

To ensure the power balance of the VSC-MTDC distribution system, a droop control with power limits strategy is implemented in the main converter. Fig. 3 shows the outer loop controller's structure and DC voltage-power characteristic curve of the droop control with power limits.

In Fig.3, P_{max}(P_{min}) is the maximum (minimum) limits of converter's real power. P_{ref} (U_{dcref}) is the steady-state reference value of active power (DC voltage), and P_{mea} (U_{dcmea}) is the measured value. K_i and T_i are gain and integral time constant of PI controllers. K refers to droop constant. Two main control modes are adopted in this strategy:

1) Droop control mode: when the operating point of the VSC station is within the voltage dead-band (U_{dchref} and U_{dclref}), droop control mode, based on a fixed droop coefficient, is adapted to regulate the system DC voltage.

2) Constant active power control mode: when the operating point of the VSC station exceeds the voltage dead-band, the converter switch to constant active power control mode (P_{max} and P_{min}).

The operating modes of this control strategy are reversely similar to the dead band droop control approach where the VSC station adopts constant active power control when its operating point is within the voltage dead-band, otherwise, the droop-control using a unique droop ratio, is actuated.

B. Modified two stage voltage margin control

If a large disturbance appears in the system, the power balance would not be preserved and DC voltage might be out of control. In order to secure the voltage control under an abnormal operating condition, a modified two-stage voltage margin control converter is designed as a backup station dc overvoltage and under voltage backup station but also participate in dc voltage regulation to its reference value. The two-stage controller is more robust and versatile hence preferable for MTDC control as the requirements for communication between the converter terminals is more reduced. Fig. 4 shows the outer loop controller's structure and dc voltage-power characteristic curve of the modified two- stage voltage margin controlled converter station.

In Fig.4, P_{mea} (U_{dcmea}), is the measured value of active power (DC voltage), U_{dchref} (U_{dclref}) is the higher (lower) value of DC voltage margin control. K_i and T_i are gain and integral time constant of PI controllers. K refers to droop constant. Two main control modes are adopted in this strategy:

1) Dc voltage Droop control mode: in normal operating condition within the DC voltage range of [U_{dchref}, U_{dclref}], droop control mode is adopted.

2) Constant DC voltage control mode: when a fault occurs in the system such that the DC voltage rise (fall) to the voltage upper (lower) limit, the converter switch to constant DC voltage control and try to stabilize the DC voltage at the reference value.

C. Undead-band droop control

"Undead-band" droop control was recommended in[24] . The control is entirely based on voltage droop control, but differentiates between normal and disturbed conditions by using different droop constants for these two conditions mode. It improves the reliability of the system by allowing others converters to simultaneously share the dc voltage regulation duty.

1) In normal operating condition: Droop control mode is adopted and tries to keep the system DC voltage close to its reference value.

2) In disturbed operating condition: when a fault occurs in the system such that the DC voltage rise or fall from its reference value, the converter switch to a lower droop constant value in order to limit voltage deviation and keep the new operating point close to the reference operating point. Fig. 5 shows the outer loop controller's structure and dc voltage-power characteristic curve of the undead-band droop controlled converter station. In Fig.5, P_{mea} (U_{dcmea}), is the measured value of active power (DC voltage), U_{dchref} (U_{dclref}) is the higher (lower) value of DC voltage margin control.) $U_{dch1ref}$ ($U_{dcl1ref}$) is the higher (lower) reference value of DC voltage droop control when there is a disturbance. K_i and T_i are gain and integral time constant of PI controllers. Ki refers to droop constant. In this paper, the optimization of K is not discussed

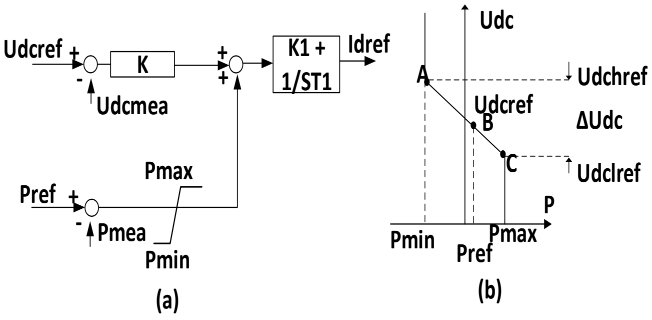


Fig. 3. Droop control with power limits : (a) Outer loop controllers structure, and (b) DC voltage-power characteristic curve.

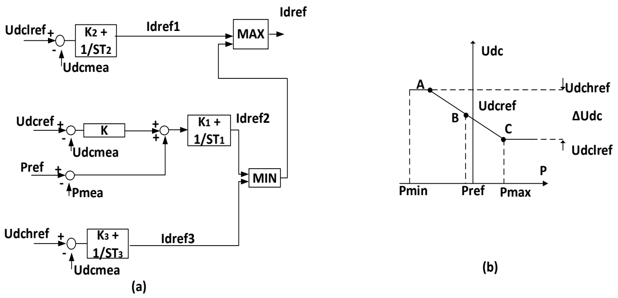


Fig. 4. Modified two stage voltage margin control: (a) Outer loop controllers structure, and (b) DC voltage-power characteristic curve.

IV. SIMULATION STUDIES

A. A four-terminal VSC-MTDC distribution system

A four-terminal VSC-MTDC distribution system is built in PSCAD simulation software. And the structure of the system is shown in Fig.7. Droop control with power limits and constant reactive power control are implemented in the converter station VSC_1. The modified two stage voltage margin control and constant reactive power controls are adopted for converter station VSC_2. Undead-band droop control and constant reactive power control are implemented in converter station VSC_3. VSC_4 is set as constant AC voltage control and the PV system adopted a MPPT control strategy. The light intensity is fluctuating randomly and the PV output power changes with time. The test system is composed of three AC grids with terminal voltage of 5kV, the frequency is 50Hz, the rated voltage of the MTDC grid is 10kV, and the DC line resistance been neglected. The control characteristics of $VSC_{1,2,3}$ stations are shown in Fig.7, of which, U_{dcref} = 10kV, $Pmin$ = -4.5MW, $Pmax$ = 6.5MW, P_{2ref} = -2.5MW, P_{3ref} = -2MW, U_{dclref} = 9.5kV, U_{dchref} = 10.5kV, $U_{dcl1ref}$ = 9.95kV, $U_{dch1ref}$ = 10.4kV, K=20, K_1&K2=15

B. The Results of Simulation

In order to verify the effectiveness of the improved coordinated approach, 2 scenarios been studied:

- Scenario 1: The converter VSC_1 is removed from service at *t*=2s

The Fig. 7 shows the system dynamic response while VSC_1 is removed from service at *t*=2s. Before *t*=2s, VSC_1 , VSC_2 and VSC_3 have the same priority in controlling DC voltage. The PV output power is constantly fluctuating around 3 MW, which also causes the constant fluctuation of P_1 and P_3. When *t*= 2s, VSC_1 is out of service, the DC system is lacking active power and VSC_2, VSC_3 quickly respond by injecting power into the dc grid in order to stabilize the DC voltage. The system DC voltage is stable, and the control effect is good.

- Scenario 2: A three-phase short-circuit, located VSC_2 AC-side is applied at *t*=2s,and cleared at t=2.3s

The Fig. 8 shows the system dynamic response while a three-phase short-circuit, located at VSC_2 AC-side is applied at *t*=2s,and cleared at *t*=2.3s. At *t*=2s, the fault will reduce VSC_2 absorption power close to zero and cause the increase of DC voltage. VSC_1 reduced its output power and VSC_3 absorbs more power in order to stabilize the DC voltage. The voltage fluctuates but does not collapse. At the time t=2.3s, the AC fault was cleared, DC voltage increased rapidly, the power of each converters is restored and DC voltage value move back to 10KV.

C. Comparison of control strategies

In this section the same previous 2 scenarios been investigated, and the system DC voltage response of different control strategies been analyzed and compared.

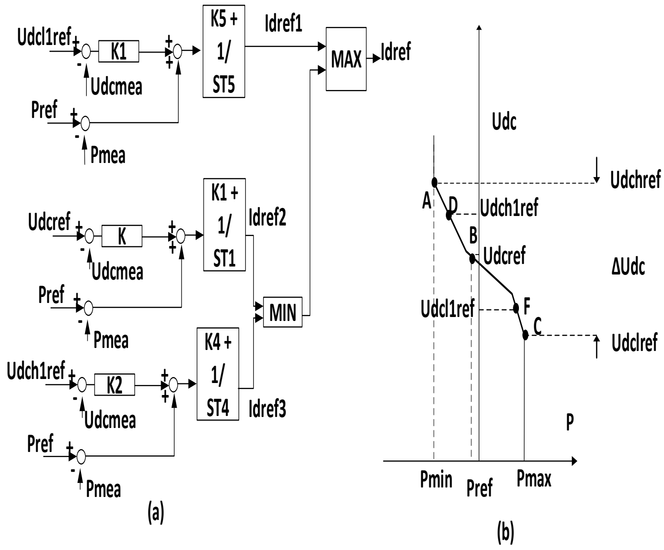


Fig. 5. Undead-band droop control: (a) Outer loop controllers structure, and (b) DC voltage-power characteristic curve.

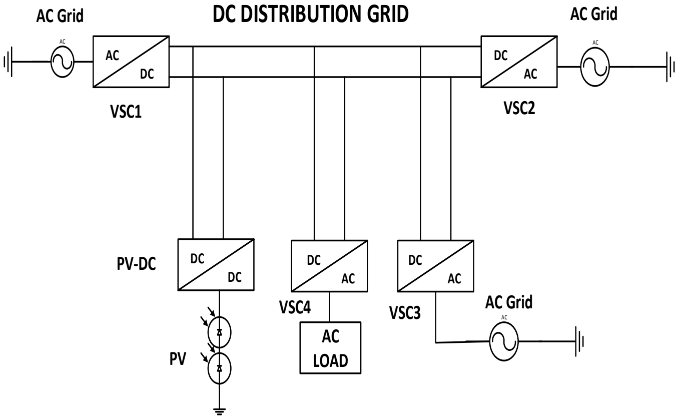
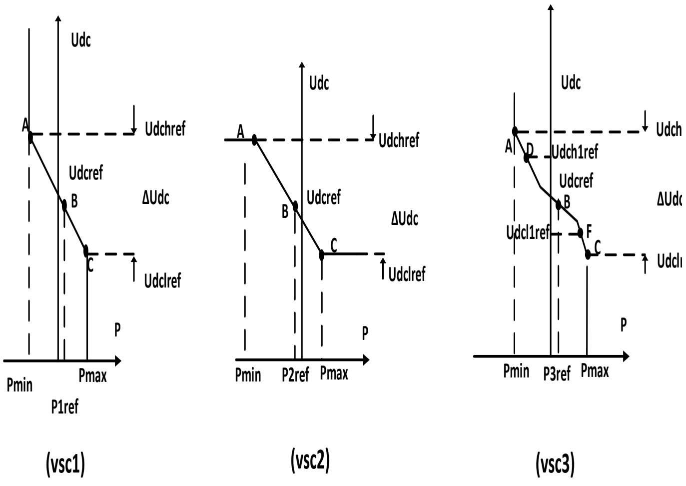


Fig.6. Structure of four terminals VSC-MTDC distribution network.



(vsc1) (vsc2) (vsc3)

Fig.7. $VSC_{1,2,3}$ DC voltage-power characteristic curves.

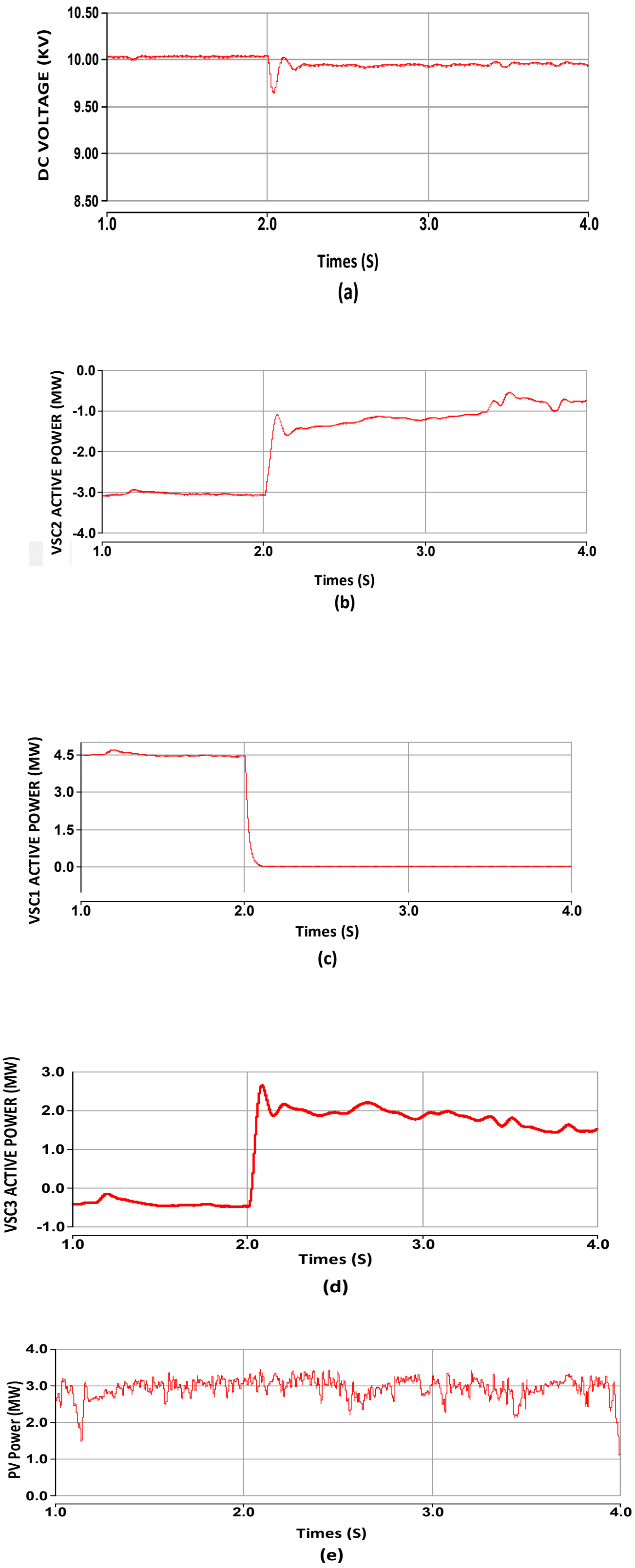


Fig.7. DC system dynamic response while VSC$_1$ is removed from service at t=2s: (a) DC voltage, (b) VSC$_2$ Active power, (c) VSC$_1$ Active power, (d) VSC$_3$ Active power, (e) PV power.

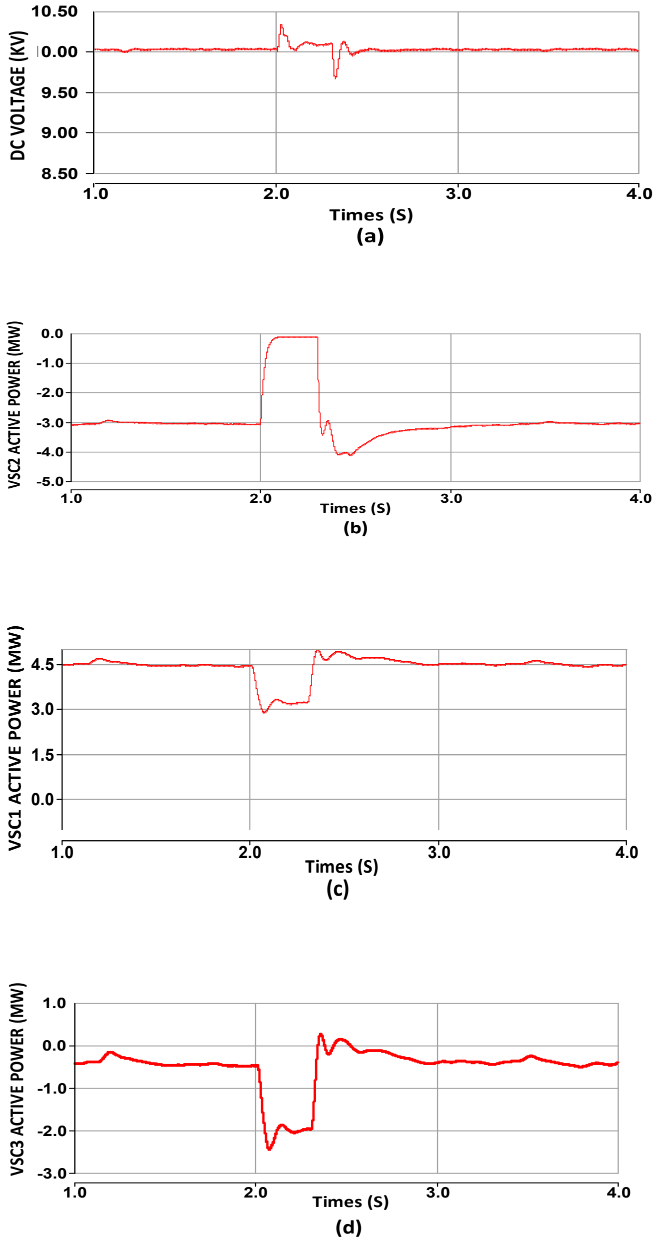


Fig.8. DC system dynamic responses while a three-phase short-circuit, located VSC$_2$ AC-side is applied at t=2s, and cleared at t=2.3s:(a) DC voltage, (b) VSC$_2$ Active power, (c) VSC$_2$ Active power, (d) VSC$_3$ Active power.

TABLE I Different control strategies characteristics

Control strategy	G-VSC1	G-VSC2	G-VSC3	PV	AC load
Voltage Margin control	Voltage margin	Voltage margin	Constant active power	MPPT	Constant AC voltage
Droop control	Droop	Droop	Constant active power	MPPT	Constant AC voltage
Improved control	Droop control with power limits	Modified two-stage Voltage margin	Undead-band Droop	MPPT	Constant AC voltage

Table I gives the characteristics of each control strategies. Fig.9 illustrates the system DC voltage responses with different control strategies under scenario 1 and 2, and Table II shows the DC voltage overshoot values obtained from the different control strategies under scenario 1 and 2. The combination of both voltage droop and voltage margin control strategies shows the superiority of the proposed approach, with a smoother transition, faster response and lower undershoot value. Fig.9 (a) shows that the proposed approach allows the system to reach a new operating point closer to the original reference DC voltage. The more coordinated converters are involved in the DC voltage, the better the DC voltage will be in steady state.

TABLE II Performance Comparison

Performance criteria	VM	Droop	Improved control
Undershoot (Scenario 1)	0.15	0.06	0.02
Undershoot (Scenario 2)	0.06	0.06	0.05

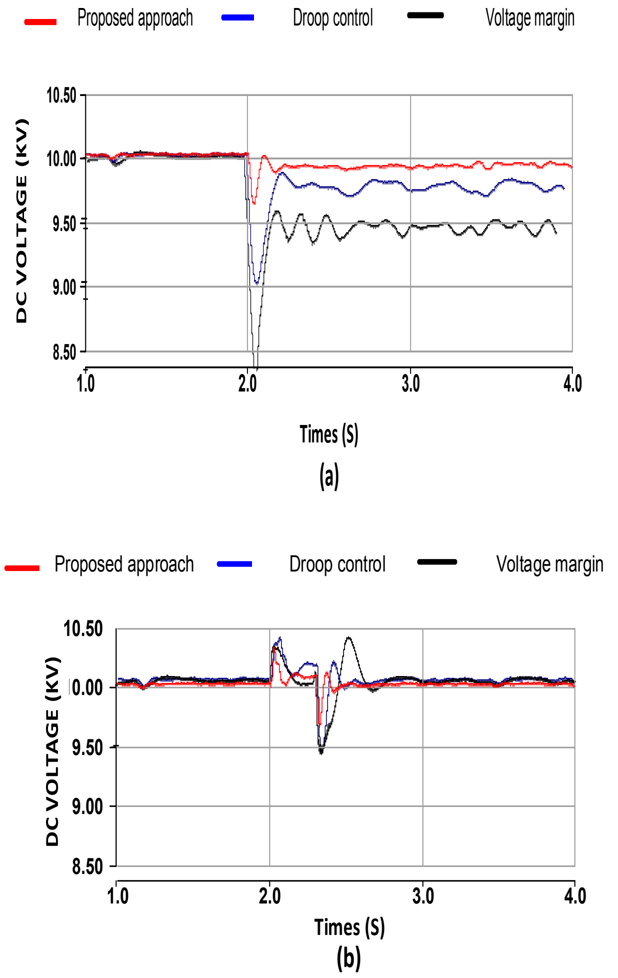


Fig.9 illustrates the system DC voltage responses with different control strategies under scenario 1 and 2.

V. CONCLUSION

An improved coordinated control strategy for VSC-MTDC distribution network has been proposed in this paper. Droop control with power limits and constant reactive power control are applied in the main converter station, modified two stage voltage margin control and constant reactive power controls are applied for the backup converter station, and another undead-band droop controlled converter station simultaneously participate in DC voltage regulation at equal priority as the main converter station. This strategy has three benefits: First, the main converter with droop control characteristics associated with constant active power control can set the reference voltage for the dc system and it is helpful for the regulation of dc voltage and for restraining power variations. Second, several converters simultaneously shared the duty of dc voltage reference control with equal priority. Third, the combination of droop, modified double stage voltage margin and undead-band droop control minimize overvoltage during the transient response, and allows a smooth and better transition to a new operating point when the system is subjected to small and severe disturbances. The simulation and comparisons under normal and abnormal conditions verify the effectiveness of the proposed strategy.

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