Impact of DC Control Strategies on Dynamic Behaviour of Multi-Terminal Voltage-Source Converter-Based HVDC after Sudden Disconnection of a Converter Station

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***Abstract*—Multi-terminal HVDC (MTDC) transmission system using Voltage Source Converter (VSC) provides an increased transmission network capacity and generally enhanced system reliability, security and controllability. The aim of this paper is to evaluate the impact of dc-voltage control strategies on dynamic behaviour of MTDC VSC-Based HVDC after the sudden disconnection of a converter station. Two dc voltage control methods are considered in this paper: (i) voltage margin method and (ii) standard voltage-droop method. The impact is evaluated using time-domain simulations on simple test system using. The sudden disconnection of a converter-station is used as disturbance. Simulation results demonstrate there is a "collaborative scheme" for the dc voltage support when two converters on the MTDC operate with dc voltage droop characteristic.**

***Index Terms*—Control system, high voltage direct current, multi-terminal HVDC, voltage source converter.**

I. Introduction

The *Multi-terminal HVDC* (MTDC) systems are being studied as flexible solution for the future massive integration of offshore wind power, including potential benefits to provide additional support connecting non-synchronous power systems [1], [2]. The most appropriate technology in MTDC is HVDC system based on *Voltage Source Converter* (VSC) as it provides an increased transmission network capacity and generally enhanced system reliability, security and controllability.

Outstanding efforts on the research on MTDC have been developed in several areas in recent times. A quite a number of publications are devoted to several subject of MTDC: steady state performance [2], [3], [4], [5], until modelling and simulation of dynamic behaviour [6], [7]. However, there is one important aspect that requires evaluation, the traditional reliability and availability related to outages as to transient reliability related to performance during and recovery after temporary faults and disturbances. It is an important aspect due to the large amount of power transmitted by MTDC system.

The aims of this paper is to evaluate impact of the dc voltage control strategy on the dynamic behaviour of multi-terminal VSC-based HVDC following a sudden disconnection of a converter station, two strategies are analyzed in this paper: *Voltage Margin Method* (VMM) and *Standard Voltage Droop Method* (SVDM).

II. Control Schemes for a MTDC System

The control system for a MTDC system can be divided into two types: (a) *central master controller* which is a global area controller and (b) *local terminal controllers* used locally at each converter station [7]. The general picture of the control scheme is depicted in Fig. 1.

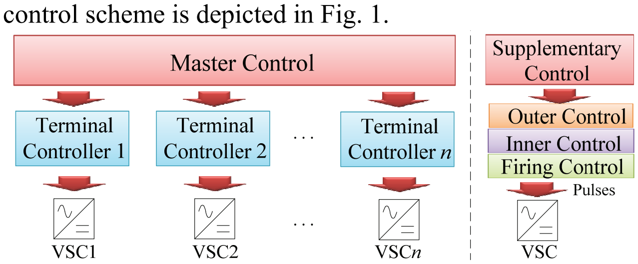

Fig. 1. Schematic representation of MTDC control system hierarchy [7].

The *terminal controllers* control the specific converters by calculating the PWM pulses for the converter bridges. *Firing control* is the lowest level on it and it acts very fast. *Inner control*, *outer control* and *supplementary control* are used for increasingly higher level functions, and have increasingly higher cycle times. The inner control or current control loop is designed to be much faster than the outer controllers. The outer controllers are the ones responsible for providing the current references signals for the inner current controller.

The terminal controllers determine the behavior of the converter at the system bus. They are designed for the main functions for controlling: active power, reactive power, AC and the dc voltage.

The *master control* optimizes the overall performance of the MTDC by regulating the dc side voltage. It is provided with the minimum set of functions necessary for coordinated operation of the terminals in the dc circuit, i.e. start and stop, minimization of losses, oscillation damping and power flow reversal, black start, ac frequency and ac voltage support.

A general overview about the terminal controllers is depicted on Fig. 2.

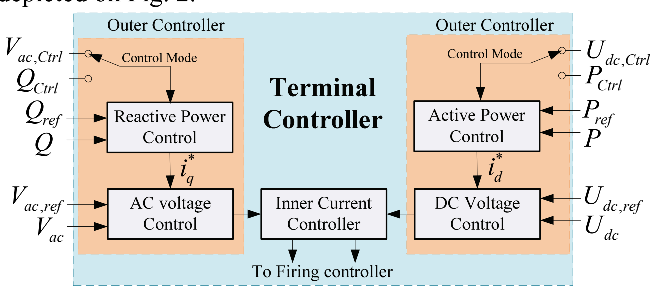

Fig. 2. Representative block diagram of a Terminal Controller in a MTDC system [7].

A. Current Controller

The current controller loop is the inner part of the cascaded control strategy. It needs to be very fast as compared to the outer controllers so as to achieve control system stability. It is supplied current reference values from the outer controllers and *dq* transformed currents from transducers. The objectives of the inner controller are to track the current reference values given by the outer controllers and to generate voltage reference values i.e. u_d^* and u_q^* fed to the controlled voltage source (see Fig. 3).

B. Power Controller

The active power controller is designed to regulate the active power (P) exchanged at the common bus to match the given reference value (P_{ref}) by modifying i_d^*. The output of the active power controller (i_d^*) is the reference input to the *d*-axis current controller of the inner current loop. In order to limit the magnitude of current in the VSC-HVDC to a maximum limit, the output of the active power controller is followed by a limiter function of $\pm i_{max}$ limits, where: $i_{max} = i_{rated}$ (see Fig. 4).

C. Reactive Power Controller

The objective of this controller is to govern the reactive power (Q) exchanged at the common bus to match the given reference value (Q_{ref}) by modifying i_q^* (see Fig. 5).

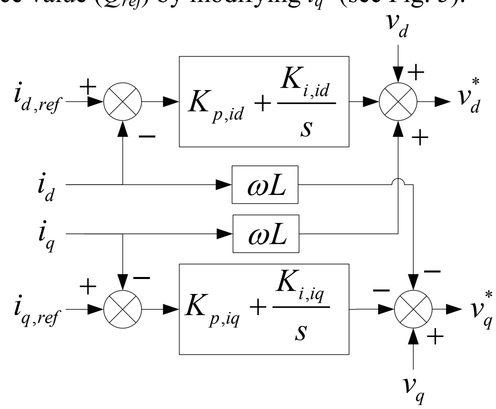

Fig. 3. Basic scheme for inner-Current Controller.

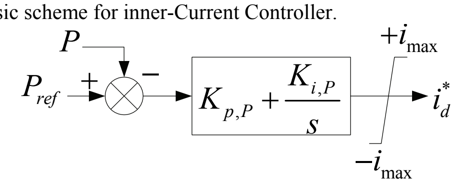

Fig. 4. Basic scheme for active power controller.

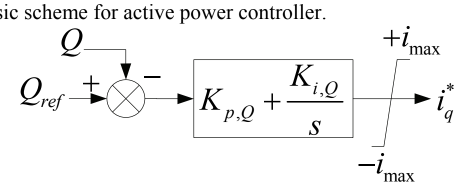

Fig. 5. Basic scheme for reactive power controller.

The output of the reactive power controller (i_q^*) is the reference input for the reactive current controller of the inner current loop. i_q^* is limited to $\pm I_{q\text{-}max}$ in such a way that the total converter current should not exceed the rated current ($I_{max}=I_{rated}$). This takes the assumption that that priority is given to transfer of active power. Hence:

$$i_{q-\max} = \sqrt{I_{\max}^2 - \left(i_d^*\right)^2} \tag{1}$$

D. AC voltage controller

This controller is designed to regulate the amplitude of the ac voltage (V_{ac}) at the common bus to be equal to the given reference value by modifying i_q*. This implies that the controller governs the converter to generate an amount of reactive power so that the voltage at the common bus matches the given reference value ($V_{ac,ref}$) (see Fig. 6).

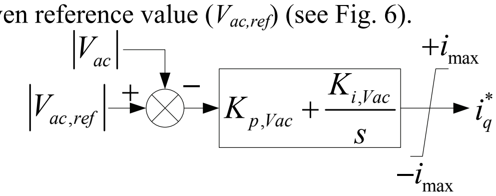

Fig. 6. Basic scheme for AC voltage controller.

III. DC VOLTAGE CONTROLLER

Considering the operational requirements for dc voltage on MTDC, the literature provides two control strategies which possibly can be applied in future transnational networks [7]: (i) the *standard voltage droop method* (SVDM) and the (ii) *voltage-margin method (VMM)*. These control methods are explained on the general scheme for HVDC system considering only two converter substations (see Fig. 7).

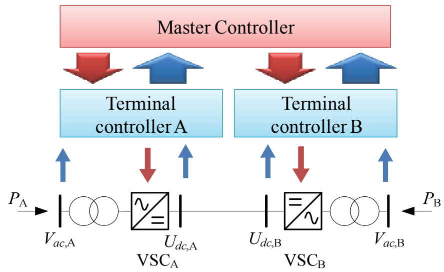

Fig. 7. General scheme for two converter stations HVDC system. VSC_i operates as inverter (P_i<0) or rectifier (P_i>0) depending in power direction.

A. Standard Voltage Droop Method (SVDM)

The *voltage margin* is defined as the difference between the dc reference voltages of the two terminals [8]. Fig. 8 shows the U_{dc}-P characteristics of both terminals at Terminal A, the intersection U_{dc}-P of the characteristics of each terminal is the operating point "a".

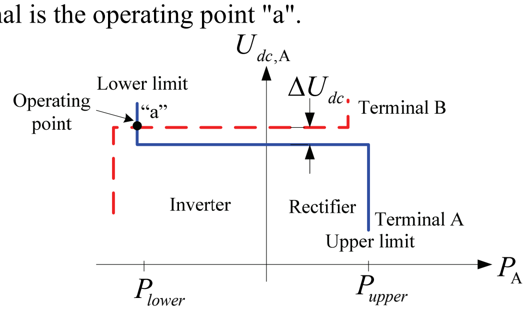

Fig. 8. U_{dc}-P characteristic showing the operating point "a" in VMM for one terminal.

When the active power is to be transmitted from Terminal B to Terminal A (P_A<0, P_B>0), the voltage margin (ΔU_{dc}) is subtracted from the dc reference voltage for Terminal A. Terminal B (rectifier) determines the dc system voltage and Terminal A (inverter) controls the active power (P_A) determined by the lower limit of the dc voltage regulator. The dc voltage controller tries to keep the dc voltage to the reference value $U_{dc,ref}$ by adjusting P_A, until P_A reaches the upper limit or the lower limit [7] (see Fig. 9).

The voltage margin method gives reliable way of controlling MTDC without the need for communication between terminals and is capable of keeping the steady state voltage with in preset limits even after load switching and disconnection of some converter terminals. But on the other hand, this method implies allocation of only one terminal at a time for the regulation of dc voltage and the other terminals do not experience significant change during changes in power flow of the dc network [7].

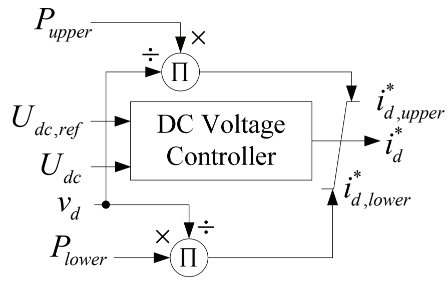

Fig. 9. Basic scheme for VMM controller with adjustable limits.

Frequency droop control is a well established method and the basis for stable operation in all ac grids. The systems frequency is used as a global measure for the instantaneous balance between power generation and demand [9]. The *dc voltage-droop method* is a coordinated control to maintain a power balance and a desired power exchange in the MTDC. This control is a modification of the *VMM* control where the horizontal line sections (P_{lower}<P_A<P_{upper}) of the U_{dc}-P characteristic curves is replaced by a line with small slope (ρ_c) [10]. The dc voltage-droop, ρ_c, indicates the degree of compensation of power unbalance in the dc grid at a cost of reduction in the dc bus voltage. This principle of *VMM* control is shown in Fig. 10.

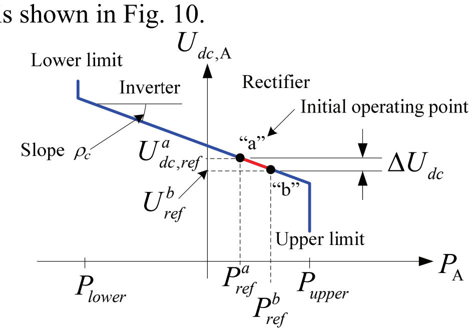

Fig. 10. U_{dc}-P characteristic showing the operating point "a" in VMM for one terminal.

When $U_{dc,A}$ drops (e.g. due to large withdrawal of power someplace else in the dc network, operation point moves from "a" to "b") the slack converter station (VSC_A) will increase the active power injection in the dc grid P_A until a new equilibrium point ($U^b_{dc,ref}$, $P^b_{A,ref}$), at a lower dc voltage, is reached ($U^b_{dc,ref} = U^a_{dc,ref} - \Delta U_{dc}$).

The use of a proportional dc voltage-controller allows multiple converters to regulate the voltage at the same time and the concept of distributed slack bus is possible.

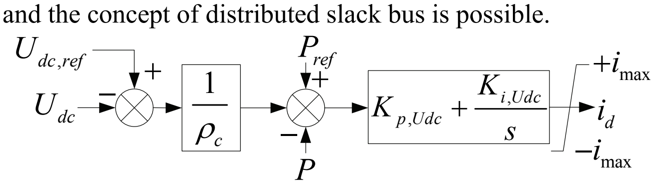

Fig. 11. Basic scheme for SVDM controller.

Fig. 11 shows how is implemented the droop characteristic based on the power active controller. When voltage droop control is used in the absence of a PI controller, the voltage controller's active power P will change when the value of the dc bus voltage changes

IV. Simulation and Results

Time domain-simulations are used to evaluate dynamic behaviour of dc voltages and power flow in a test MTDC network. The ac network is based on classical 5-node test network from the book of Stagg and El-Abiad [11] and 4-node VSC MTDC network is included. Details of the steady state undisturbed conditions are shown in Fig. 12.

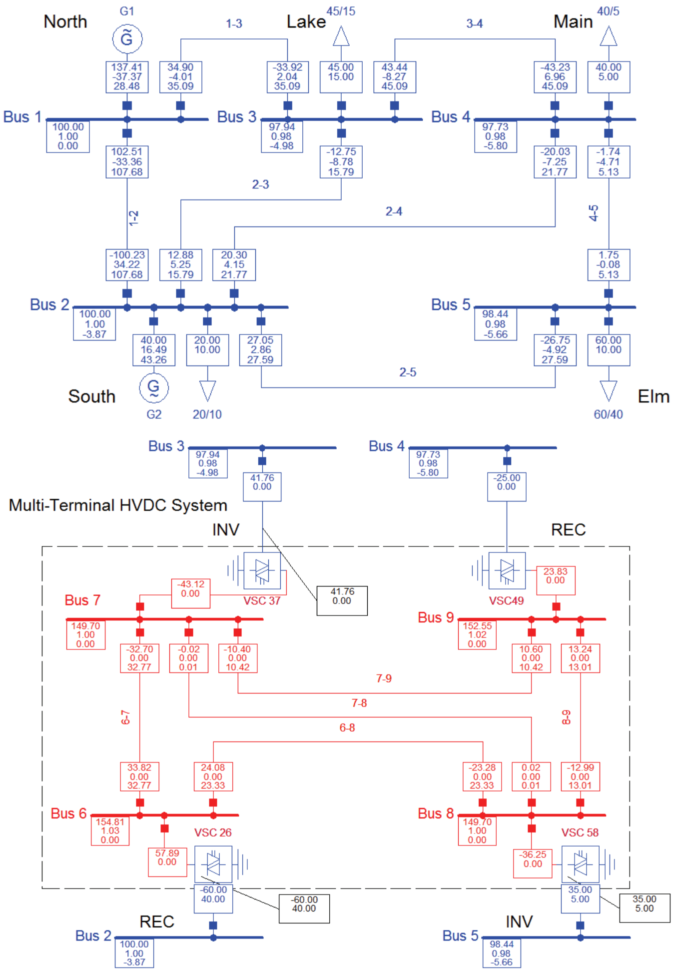

Fig. 12. 5-node test ac network and 4-node VSC MTDC system between nodes 2, 3, 4, and 5.

DIgSILENT PowerFactory™ is used as simulation tool, the model of all controllers are developed using *DIgSilent Simulation Language* (DSL). All simulations are performed using a personal computer based on Intel®, Core™ i7 CPU 2.0GHz, 8 GB RAM with Windows 7 Home Edition 64-bit operating system.

Three cases are evaluated in this paper

- *Case I*: The converter station VSC37 is chosen as dc slack-bus when the VMM is used, thereby controlling the voltage on the dc network. The other converter stations (VSC26, VSC58, VSC49) are directly controlling their reactive power injections (constant Q-mode). The converter station VSC37 is also used to control the voltage at bus 3 (0.998 p.u).
- *Case II*: This case considers the use of multiple dc slack bus, in this case, all converter stations are using controller based on SDVDM considering $\rho_c = -2.00$.
- *Case III*: It is similar to *Case II* but it consider $\rho_c = -5.00$.

Two simple contingencies are simulated in this paper.

A. Scenario A: Sudden Disconnection of VSC37

Fig. 13 shows the time-domain response of dc voltages and power flows after the sudden disconnection of one converter station VSC37 (*Scenario A*).

Considering the maximum instantaneous values on dc voltage, the *Case II* provides the lowest values (min: 1.051 p.u. at bus 6) and *Case III* provides the highest (max: 1.16 p.u at bus 6).

The voltage droop characteristic U_{dc}-P and its slope ρ_c have strong influence during the transient. A low ρ_c -value produces a low peak on the maximum instantaneous value on the dc voltage profile compared with it produced by a high ρ_c value. This contingency produces a power imbalance on the dc system (ΔP_{VSC35} = 43.2MW), and it must be re-distributed between the remaining converter stations. The *Case I* produces the lowest changes on the steady-state dc voltage and the highest changes on the power flows following the contingency (see Fig. 14).

B. Scenario B: Sudden Disconnection of VSC58

The sudden disconnection of converter station VSC58 produces an infeed loss of ΔP_{VSC58} = 55 MW, as consequence, there are dynamic changes on dc voltages and power flows in order to reach the new operational conditions. This dynamic is depicted on Fig 15.

The maximum instantaneous dc voltage on *Case II* are the lowest values (min: 1.075 p.u. at bus 6) and *Case III* provides the highest values (max: 1.139 p.u at bus 6). It is consequence of the slope ρ_c used on the characteristic U_{dc}-P.

The final steady-state dc voltage is highly modified from the initial state. These changes are detailed per case on Fig. 16.

The VSC37 kept constant the voltage at bus 3 (0.998 p.u) during the *Case I* but the system is not capable to recover the initial power flows (see Fig. 16) because the converter VSC26 and VSC49 are operating constant Q-mode (Q_{VSC49} = 0, Q_{VSC26} = 40 Mvar).

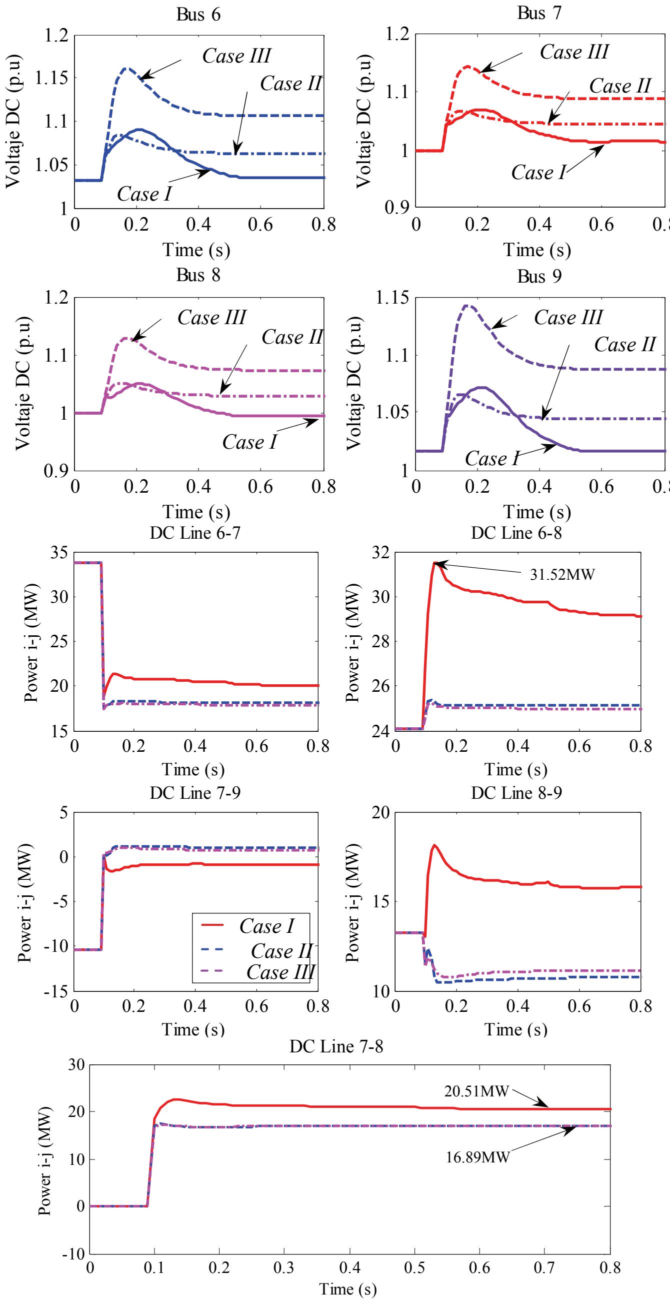

Fig. 13. Time-domain response of dc Voltages and dc Power Flows: *Scenario A*.

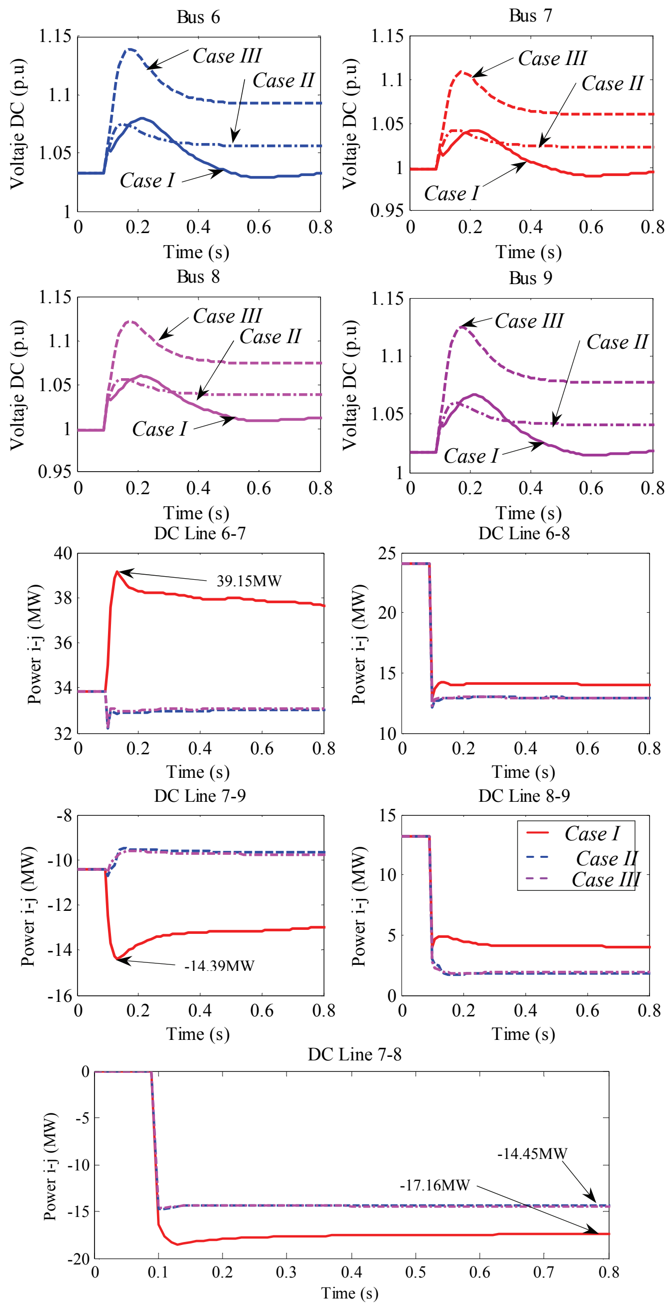

Fig. 15. Time-domain response of dc Voltages and dc Power Flows: *Scenario B*.

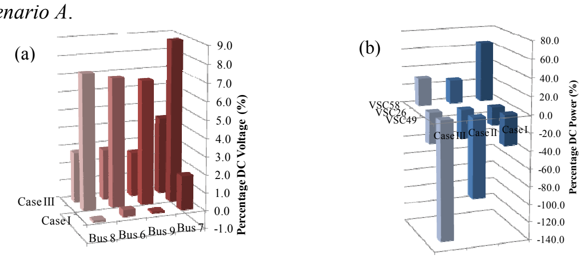

Fig. 14. (a) Changes (%) on dc steady-state voltage and (b) Converter station loading (%) conditions: *Scenario A*.

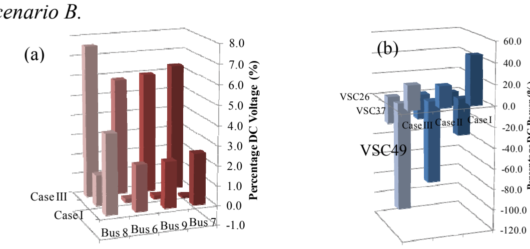

Fig. 16. (a) Changes (%) on dc steady-state voltage and (b) Converter station loading (%) conditions: *Scenario B*.

Case II and *Case III* test two different values of voltage-droop slope (ρ_c= -2.0, -5.0) and the dynamic response on the power flow transfers inside the MTDC shows how the power imbalance is shared between the active converter stations based in the droop slope. There is a collaborative scheme in this share process. The power transfer on the undersea cable 7-8 helps to establish this power distribution between converters. SDVDM provides dc voltage changes based on the changes on active power; it allows the MTDC survive a converter outage.

V. CONCLUSIONS

Simulation results show the effect of dc Voltage control strategy on the dynamic behavior of bust voltages and power flows in a MTDC system following a converter-station outage. Two different dc voltage control method are simulated in this paper: voltage margin method and voltage-droop method. Time-domain simulations on simple test system using DigSILENT® PowerFactory™ are used to evaluate the response of ac/dc bus voltage considering simple contingencies based on sudden converter-station disconnection. Three cases considering locations and type of dc voltage controllers have been considered. Two values of voltage droop slope have been tested showing that the transient response is clearly influenced by the voltage droop characteristic.

When two converters on the MTDC operate with dc voltage droop characteristic, it appears a "collaborative scheme" for the dc voltage support, sharing the task of controlling the dc voltage. Simulation results demonstrate the voltage margin control is capable to survive a converter outage just if this converter is operating on constant power mode.

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