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Dynamic Behaviour of Multi-Terminal VSC-Based HVDC after a Converter Outage: DC Control Strategy

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Abstract.

The aim of this paper is to evaluate the effect of DC-voltage control strategy on dynamic behaviour of multi-terminal Voltage-Source Converter (VSC)-Based HVDC after a converter outage. In this paper, two dc voltage control strategies are considered: (i) *standard voltage margin method* (SVMM) and (ii) *standard voltage-droop method* (SVDM). The impact is evaluated in this paper using time-domain simulations on simple test system using DIgSILENT® PowerFactory™ considering a sudden disconnection of a converter-station. Simulation results demonstrate how important is the dc-voltage control strategy and the location/number of dc-buses involved in the dc-voltage on the dynamic response of the MTDC systems. The voltage margin control is capable to survive a converter outage just if this converter is operating on constant power mode.

Key words

Dynamic response, multi-terminal HVDC, MTDC, Voltage Source Converters.

1. Introduction

European Union (EU) has imposed dramatic reduction of CO_2 emissions, for such purpose, it is required a massive reduction of emission in electricity generation sector, as consequence, it is really important to maximize the power contribution coming from offshore wind power plants distant from the shore. Dc networks look quite attractive for the network integration of this clean energy [1, 2]. *Voltage Source Converter* (VSC) *High Voltage DC* (HVDC) transmission systems empower the usage of more elaborate configurations such as the *Multi-terminal VSC-HVDC* (MVSCDC) networks. It offers higher reliability, redundant and flexible technology to enable the massive integration of offshore wind power in future power systems [3].

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 involving since the classical steady state performance [4-8], classical and security constrained optimal power flow [7, 9-11], modelling [12-14], control and protection [15-20], and simulation of dynamic behaviour [4, 21-24]. An 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. Cable and converter station outages creates a serious risk of instability in hybrid ac/dc network because to the large amount of power transmitted by MTDC system. Dc voltage control is the vital aspect that indicates the power balance and the stability of an MTDC system.

The objective of this paper is to evaluate impact of the dc voltage control strategies on the dynamic behaviour of multi-terminal VSC-based HVDC following a converter outage, two strategies are analysed in this paper: *Standard Voltage Margin Method* (SVMM) and *Standard Voltage Droop Method* (SVDM). Section 2 presents a general introduction about the main control systems in MTDC systems and presents the theoretical background of dc voltage strategies. Section 3 shows the simulations results and discussion about impact of the dc voltage control strategies on the dynamic behaviour of multi-terminal VSC-based HVDC following a converter outage. Finally, Section 4 concludes. Contribution of this paper includes: (i) demonstrates bipolar configuration can provide minimal voltage deviation from the initial nominal voltage than mono-polar network (ii) bipolar configuration (small dc voltage droops) allow the operation within the rated voltage limits.

2. Control of MTDC Systems

The control schemes have a large impact on system dynamics. It is an important task to determine the modelling requirements of the control schemes. The control system for a MTDC is composed of two different layers of controllers [25]: (i) *terminal controllers* and (ii) a *master controller* as illustrated in Fig. 1.

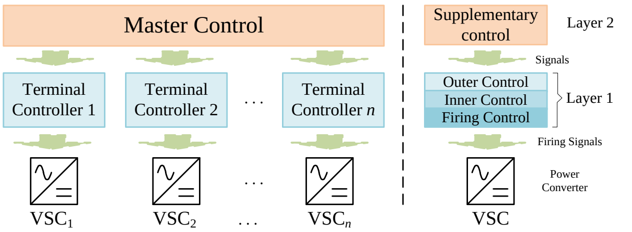
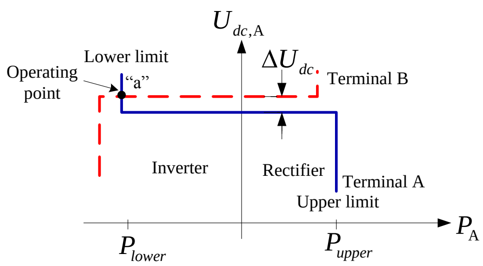


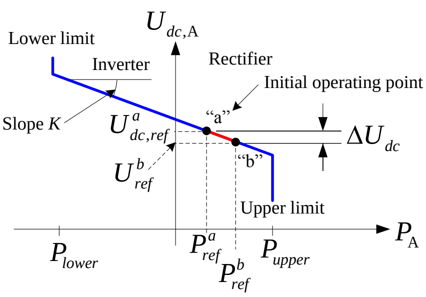
Fig. 1. Schematic representation of MTDC control system hierarchy [25].

The *master controller* is provided with minimum set of functions necessary for coordinated operation of the terminals and the terminal controllers (outer controllers) are mainly responsible for active power control, reactive power control, dc voltage regulation, and ac voltage regulation. The *current controller loop* is the inner and faster part of the cascaded control strategy. This control produces the firing signals from the current reference values (i^*_d, i^*_q) received from the outer controllers and *dq* transformed currents from transducer devices (i_d, i_q).

Dc voltage control is certainly one of the most important tasks given to the VSC-HVDC stations inside a MTDC network. A well-controlled dc voltage on a MTDC system is a guarantee of the power balance between all the interconnected nodes. Considering the operational requirements for dc voltage on MTDC, the literature provides two main control strategies which possibly can be applied in future transnational networks [26]: (i) *Standard Voltage Margin Method* (SVMM) and (ii) *Standard Voltage Droop Method* (SVDM). These methods enable sharing of load among two or more dc voltage regulating terminals operating in parallel and provide controls in MTDC.



(a) U_{dc}-P characteristic showing the operating point "a" in VMM for one terminal



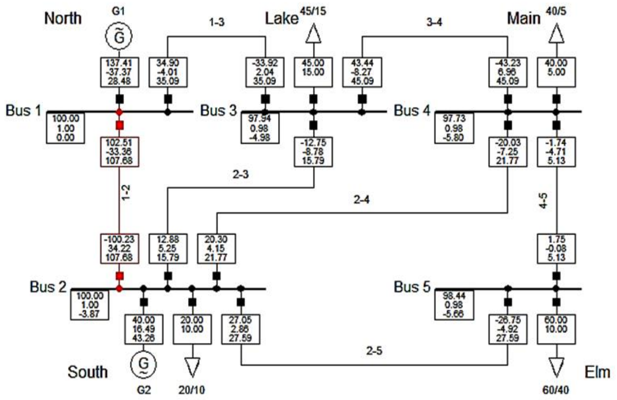
(b) U_{dc}-P characteristic showing the operating point "a" in SVDM for one terminal.

Fig. 2. General U_{dc}-P characteristic of dc voltage control strategies.

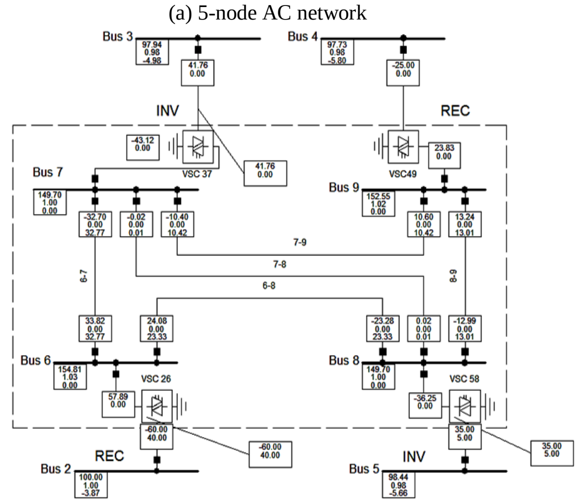
The SVMM is defined as the difference between the dc reference voltages of the two terminals [27-29]. Fig. 2(a) shows the U_{dc}-P characteristics of both terminals at Terminal A, the intersection U_{dc}-P of the characteristics of each terminal is the operating point "a". The dc voltage-droop, *K*, indicates the degree of compensation of power unbalance in the dc network at a cost of reduction in the dc bus voltage. This principle of SVDM control is shown in Fig. 2(b).

3. Simulation and Results

In this paper, the dynamic behaviour of a MTDC system after the loss of a converter station is analysed. Time-domain simulations are based on a hybrid ac/dc system. The ac networks is based on the classical 5-node test network taken from the book of Stagg and El-Abiad [30], for illustrative purposes the dc network is a 4-node VSC MTDC network. It consists of 4 VSC stations tied together by 5 dc submarine transmission cables rated at 150 kV describing a parallel multi-terminal HVDC. DIgSILENT PowerFactory^{TM} [31] is used to perform the time-domain simulations, the model of all controllers are developed using *DIgSILENT Simulation Language* (DSL).



(a) 5-node AC network



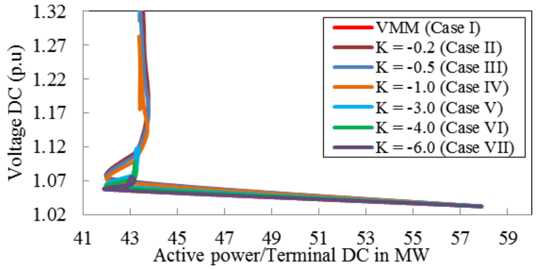
(b) 4-node MTDC network

Fig. 3. Steady state condition for the hybrid ac/dc test network.

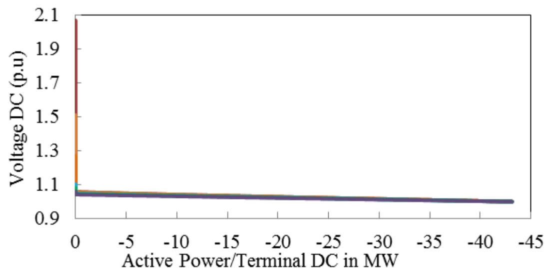
Two dc network configurations are studied in this section: (i) *mono-polar network configuration* and (ii) *bipolar network configuration*. Two dc voltage control strategies are considered in this paper: (i) *Standard Voltage Margin Method* (SVMM) and (ii) *Standard Voltage Droop Method* (SVDM). Seven cases are evaluated: *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. Converter stations VSC26, VSC58, VSC49 converter stations are directly controlling their reactive power injections (constant *P*-mode). The converter station VSC37 is also used to control the voltage at bus 3 (U_3 = 0.98 pu). *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 *K* = -1.00. *Case III:* It is similar to Case II but it consider *K* = -3.00, *Case IV: K* = -4.00, *Case V: K* = -6.00, *Case VI: K* = -0.50 and *Case VII: K* = -0.20. A single contingency is considered where outage converter station is VSC37.

A. Mono-polar Network Configuation

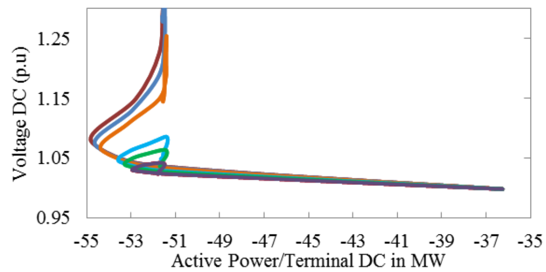
The plot of U_{dc} versus P_{dc} of the *Cases I-VII* following a sudden disconnection of VSC37 are shown in Fig. 3. Results, shows that there is some level of control coupling between the converter terminals using SVMM and SDVDM.



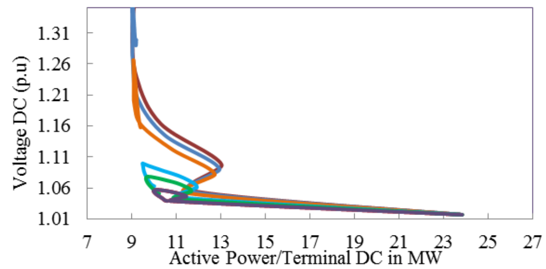
(a) VSC26



(b) VSC37



(c) VSC58



(d) VSC49

Fig. 3. Simulation results: U_{dc}-P_{dc} plot of several Cases. Mono-polar Network Configuration.

On dc bus 6, *Case II* (*K* = -0.2) attains the highest maximum instantaneous voltage value of 2.0761 pu at 0.30 sec taking a longer period of time to peak. *Case VII* where *K* = -6.00 takes shorter time of 0.15 sec to reach the maximum instantaneous voltage on the dc buses having its lowest values 1.0759 pu on bus 6. *Case I* shows the lowest variation of steady state voltage at 1.0376 pu and *Case II* have the highest variation of 1.6885 pu.

It can be concluded that the slope *K* in droop control influences the voltage response in the system such that, the smaller the slope value, the lower the peak value attained and the faster time it takes to peak having low variation from steady state voltage. There is power imbalance resulting from the converter outage however, the power produced is shared between the terminals having the same droop characteristics provided the terminals have enough capacity to compensate the power unbalance. *Case I* using VMM shows the highest variation of steady state power flow because only one converter is capable of controlling the dc voltage in the system at a time (U_{dc}-*Q* mode) with the other converters controlling active power (*P*-*Q*).

Table I shows percentage of change resulting from the converter outage on other buses. The lowest voltage change is in *Case I* and for droop controller as the *K* values gets smaller, the voltage change decreases (where *K* = -0.40 and -0.60 showed low changes in value).

Table I. Percentage of dc voltage change (%) after sudden disconnection of VSC37 for Mono-polar Network

Bus	*Case*						
	I	*II*	*III*	*IV*	*V*	*VI*	*VII*
6	3.21	68.85	31.47	17.68	8.198	5.78	5.78
7	0.21	67.73	30.03	16.07	6.46	4.03	4.03
8	0.21	67.73	28.68	14.56	4.81	2.34	2.34
9	1.68	67.58	29.86	15.89	6.31	3.92	3.92

From Table I, *Case II* (K = -0.2) has very high percentage change in dc voltage and as the slope value decreases, the percentage change also decreases. It can be deduced that a system is prone to imbalance when operating large slope constants in droop control implying that a small slope *K* value results in greater sensitivity to dc bus voltage at the expense of larger deviations of power flow from the nominal power however this will allow for a stronger dc network. *Case I* maintained the lowest voltage change, voltages on buses 7 and 8 decreased to 149.6 kV, 0.21% less than controlled nominal voltage. The dc cable power flows response of the *Cases I-VII* following a sudden disconnection of VSC37 are shown in Fig. 4.

Table II. Maximum instantaneous dc power flow transfer (P_{ij}) in dc power cables in MW

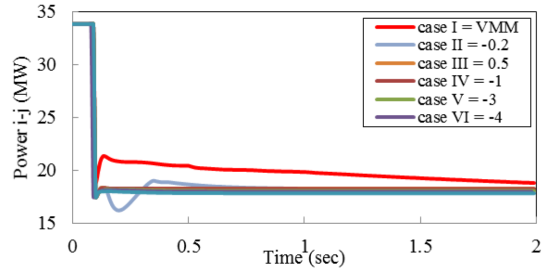
Cable	*Case*						
	I	*II*	*III*	*IV*	*V*	*VI*	*VII*
6 - 7	21.33	18.32	18.21	18.13	18.01	18.35	18.36
6 - 8	31.52	25.49	25.31	25.27	25.22	25.48	25.49
7 - 8	22.52	17.59	17.37	17.30	17.21	17.66	17.72
7- 9	-1.64	1.28	1.10	1.03	0.88	1.36	1.93
8 - 9	18.13	10.35	10.60	10.67	10.87	10.24	9.65

B. Bi-polar Network Configuration

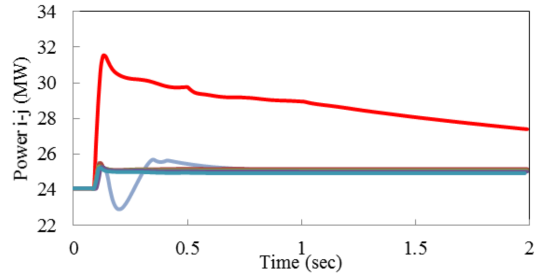
Six instances, *Case II-VII*, are evaluated for the bipolar network in this paper. This considers the use of multiple dc slack bus, where all converter stations are using controller based on SVDM. The following slope coefficient *K* for the droop control is considered *Case II-VII*: *K* = -0.20, -0.50, -1.00, -3.00, -4.00, and -6.00.

Table II. Percentage of dv voltage change after sudden disconnection of VSC37: Bi-polar Network Configuration

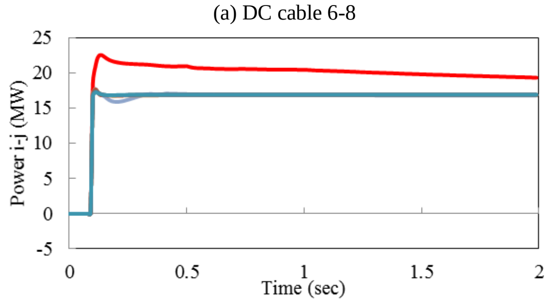
Bus	*Case*					
	II	*III*	*IV*	*V*	*VI*	*VIII*
6	3.302	15.817	23.731	29.455	30.195	30.941
7	2.674	16.229	24.186	29.946	30.691	31.441
8	2.674	16.589	24.585	30.378	31.128	31.883
9	2.914	16.293	24.256	30.028	30.765	31.514



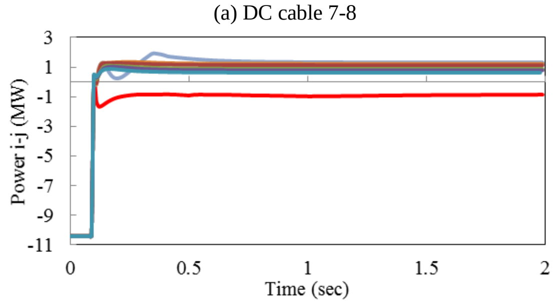
(a) DC cable 6-7



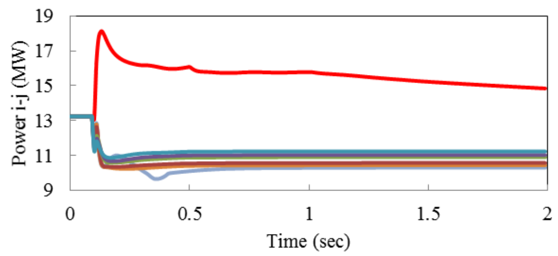
(a) DC cable 6-8



(a) DC cable 7-8



(a) DC cable 7-9



(a) DC cable 8-9

Fig. 4. Simulation results: power flows on dc submarine transmission cables for several simulation cases. Mono-polar Network Configuration.

From the Table II, *Case II* on dc bus 6 has the highest nominal voltage change of 3.30% from the rated nominal voltage. As the slope constant decreased, the voltages where seen to be within the voltage limit. This is better be understood looking at it from the maximum instantaneous voltage attained where *K*= -0.20 reaches 1.720 pu which is 63.85 away from the rated nominal voltage. *K* = -6.00 reached a max of 1.055 pu which is just 0.5% deviation from the rated voltage and is able to come back to steady state voltage of 1.035 pu quickly (recall the operation limit is max 1.050 pu). Simulation results show a level of power imbalance resulting from the converter outage however; the excess power produced was successfully shared between the terminals having the same droop characteristics provided the terminals have enough capacity to compensate for the power unbalance.

4. Conclusion

This paper evaluates the impact of the dc voltage control strategy on the dynamic behaviour of multi-terminal VSC-based HVDC following a Converter Outage, two strategies are analysed in this paper: SVMM and SVDM. Simulation results have shown that in the event of an outage of a converter station, there is power imbalance in the MTDC network which is successfully distributed among the various converter terminals. The rate and efficacy of power balancing is however based on the control strategy and network configuration implemented. This was verified by the ability of converters using a smaller droop constant *K* in SVDM to deliver a quicker response than those having a larger droop or using SVMM scheme. A comparison of mono-polar and bipolar network showed that bipolar network delivered a better power stability with minimal voltage deviation from the initial nominal voltage than mono-polar network. Bipolar using smaller droops where seen to operate within the rated voltage limit and had 3.3% overvoltage for a larger droop constant. Also, results showed that power oscillations in the ac side are transferable to the dc side if a converter exceeds the rated current limit.

Acknowledgement

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Table A. Numerical parameters of controller used at VSC stations in MTDC network.

VSC Station	*Control*	*Controller Gain [pu]*	*Time Constant [sec]*	*Min. Current on q-d axis (I_{min})[pu]*	*Max. Current on q-d axis (I_{max}) [pu]*
VSC26	*Q*	K_q = 3.00	T_q =0.2	-1.03	1.03
	P	K_p = 1.00	T_p =0.1	-1.03	1.03
VSC37	*Q*	K_q = 3.00	T_q =0.2	-1.03	1.03
	P	K_p = 1.00	T_p =0.1	-1.03	1.03
VSC49	*Q*	K_q = 1.00	T_q =0.1	-1.03	1.03
	P	K_p = 1.00	T_p =0.1	-1.03	1.03
VSC58	*Q*	K_q = 3.00	T_q =0.2	-1.03	1.03
	P	K_p = 1.00	T_p =0.1	-1.03	1.03

Table B. Converter Set points.

Converter Station	*Control Mode*	*Active Power Set point [MW]*	*Reactive Power Set point [MVAR]*	*Operation Mode*
VSC37	*U_{dc}-Q*	41.00	0.00	DC slack bus
VSC26	*P-Q*	-60.00	40.00	Rectifier
VSC58	*P-Q*	35.00	5.00	Inverter
VSC49	*P-Q*	-25.00	0.00	Rectifier

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