DC-GRID PHYSICAL MODELING PLATFORM DESIGN AND SIMULATION*

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ABSTRACT

This work develops a 6-terminal low voltage DC grid to study DC grid under various scenarios or its interaction with AC system. In order to have the same physical characteristics as the high voltage practical project, this paper presents an equal capacity ratio principle to help the parameter design in low voltage DC grid. All the parameters are selected according to the parameters of the high voltage reference system based on equal capacity ratio principle and optimized by simulation model. Simulation models of original VSC-MTDC and 6-terminal low voltage DC grid are built in PSCAD/EMTDC to validate the equal capacity ratio principle and the simulation results prove the equivalency. Based on the voltage margin control, a coordinated master-slave control method is proposed. The performance of the 6-terminal DC grid is studied under a variety of faults, simulation results proves that the DC bus voltage of the DC grid can be controlled steadily after faults.

Keywords: DC grid, equal capacity ratio principle, voltage coordinating control, simulation model

INTRODUCTION

Features like high reliability, efficiency, electromagnetic compatibility and without phase control requirement or reactive power problems turn DC grid into an interesting and promising technological option. The DC grid has superior characteristics compared with the AC grid. Each power generator connected to the DC grid can easily be operated cooperatively because it controls only the DC bus voltage. With the rapid development of distributed generation, energy storage systems (ESS) and power electronic loads, future power systems will be certainly more and more based on direct current (DC) architectures.

Adoption of a DC grid provide more operational flexibility, such as: increased control over DC and AC side power flow; active power could be exchanged while each ac network maintains its autonomy, hence decreasing the risk of AC fault propagation from one AC network to another; low transmission losses; and could optimize the performance of nearby AC lines in terms of active and reactive power flow [1-3]. Large offshore wind farms located far from their grid connection point will require HVDC to connect to shore to reduce cable losses and decrease reactive power requirements [4-5]. Moreover, a DC grid based on multi-terminal voltage-source converter multi-terminal direct current (DC) technology (VSC-MTDC) might offer significant advantages for the interconnection of the turbines within the wind farm [6-7]. Practical projects of DC grid have been

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designed in the European countries to connect offshore wind farms to the AC grids.

Other practical efforts that develop DC grid can be seen in US, Japan, Korea and European countries through the efforts of conceptual design and demonstration projects for DC grid [8]. In order to study DC grid under various scenarios or its interaction with AC system, an acceptable solution is setting up a low voltage, small capacity DC grid in laboratory. Therefore, this paper designs a 6-terminal DC grid. The priority objective of the low voltage DC grid is having the same physical characteristics as the high voltage practical project. According to this requirement, this paper presents an equal capacity ratio principle to help the parameter design in low voltage DC grid. All the parameters are selected according to the parameters of the high voltage reference system based on equal capacity ratio principle and optimized by simulation model.

CONFIGURATION OF THE DC GRID

The low voltage DC grid in laboratory is designed at 500V with 6 terminals which is given in Figure 1.The capacity of each terminal is set at 10kW. Terminal 1, Terminal 2 and Terminal 3 are connected to the AC system. Terminal 4 is connected to energy storage system with bidirectional DC/DC as its interface. Wind power system or a PV system is integrated to the DC grid at Terminal 5. The last terminal is designed to provide electric power to AC load through VSC which using three-phase two-level topology.

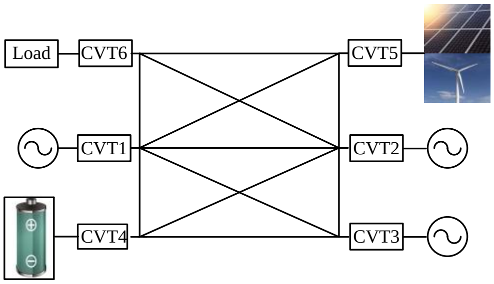


Figure 1: Configuration of the DC grid

Figure 2 shows the voltage source converter applied in DC grid. u_s is AC power system voltage and u_c is output voltage of the converter at AC side. i is the converter current and i_s is the power system current. u_{pcc1} is the voltage at PCC. u_{dc} is voltage of the converter at DC side and i_{dc} is the current inject to the DC grid by the converter. $i_{dc\ line}$ is the current flow through the DC line. P_S and Q_S is the power inject to the AC power system by the converter. P_C and Q_C is the power flow to the converter. R and L is the equivalent resistance and inductor between AC power system and the converter, therefore the transformer in figure 2 is ideal.

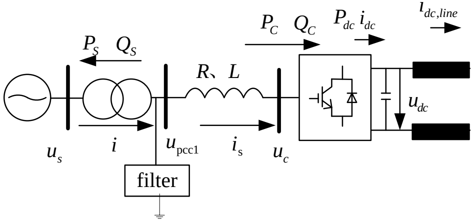


Figure 2: The voltage source converter in DC grid

EQUAL CAPACITY RATIO PRINCIPLE

Most of the parameter design method is only suitable for high voltage with large capacity VSC-MTDC system. The priority objective of the low voltage DC grid is having the same physical characteristics as the high voltage practical project. Therefore, this paper uses equal capacity ratio principle to help the parameter design in low voltage DC grid. The parameters in low voltage DC grid is selected according to the high voltage reference system at first, and then optimized by simulation model.

$$\frac{\omega_1 C_1 U_{N1}^2}{S_{N1}} = \frac{\omega_2 C_2 U_{N2}^2}{S_{N2}} \tag{1}$$

$$\frac{\omega_1 L_1 I_{N1}^2}{S_{N1}} = \frac{\omega_2 L_2 I_{N2}^2}{S_{N2}} \tag{2}$$

Where S_{N1} and S_{N2} is rated capacity of each system, U_{N1} and U_{N2} is rated voltage of each system, C_1 and C_2 is capacitor in each system, L_1 and L_2 is inductor in each system, ω_1 and ω_2 is angular frequency of each system.

DC CAPACITOR

Parameter design

The reference system is a 10kW DC grid, its DC voltage is set at 800V, and the capacitor at DC side is $1020\mu F$. By following equation (1)

$$\frac{\omega \cdot 1020 \cdot 800^2}{10k} = \frac{\omega C_2 500^2}{10k} \tag{3}$$

Equation (3) gives the DC capacitor is 2611.2μF, and its optimized value is 2400μF. As the convertor is bipolar topology, the grounded capacitor at each polar is 4800μF.

Verification

The DC Capacitor directly impacts transient characteristics of DC grid. When there is a fault in AC system, both the AC and DC system will see large scale power oscillation which may lead to overvoltage. The unbalanced fault cause secondary harmonic oscillation voltage. As the reactance of DC capacitor correspond to the second harmonic power is relevant high, it cause bigger voltage oscillation. Therefore, it is important to consider the inhibition effects when design the DC capacitor.

Reduce DC voltage oscillation

When a system is unbalance, the second order harmonic active power is

$$\Delta P_S = \sqrt{3}kU_N I_N \cos(2\omega t+\varphi_1)=kS_N\cos(2\omega t+\varphi_1) \tag{4}$$

Where k is second order harmonic active power oscillating coefficient, S_N is the rated capacity of the system, φ_1 is initial phase angle of second order harmonic power. If we only consider the DC component and second order voltage harmonic, the voltage of the converter is

$$u_d = U_{DC} + \Delta U_{DC}\sin(2\omega t+\varphi_2) \tag{5}$$

Where U_{DC} is the DC component, φ_2 is initial phase angle of second order harmonic power, $\Delta U_{DC}\sin(2\omega \mathrm{t}+\varphi_2)$ is the second order voltage harmonic. Equation (5) gives the second order harmonic power at the DC side as

$$\begin{aligned}\Delta P_d &= 2\omega C_d \Delta U_{DC} U_{DC}\cos(2\omega t+\varphi_2)\\ &+ 2\omega C_d \Delta U_{DC}^2 \sin(2\omega t+\varphi_2)\cos(2\omega t+\varphi_2)\end{aligned} \tag{6}$$

As $2\Delta U_{DC}{}^2$ in Equation (6) is relevantly small, the second part in Equation (6) can be ignored. Equation (6) is rearranged as

$$\Delta P_d = 2\omega C_d \Delta U_{DC} U_{DC}\cos(2\omega t+\varphi_2) \tag{7}$$

Neglect the switching loss and transmission line loss which gives us $\Delta P_S=\Delta P_d$. We also suggest $\varphi_1=\varphi_2$, by combination of Equation (5) and Equation (6), we get

$$C_d = \frac{kS_N}{2\omega U_{DC}\Delta U_{DC}} \tag{8}$$

Suppose the max value of voltage fluctuation value as ΔU_{DCmax}, therefore

$$C_d \geq \frac{kS_N}{2\omega U_{DC}\Delta U_{DCmax}} \tag{9}$$

Or

$$C_d \geq \frac{k}{2\omega(\frac{\Delta U_{DCmax}}{U_{DC}})}\cdot\frac{S_N}{U_{DC}{}^2}(0<\mathrm{k}\leq 1) \tag{10}$$

While k=1

$$C_d = \frac{1}{2\cdot 2\cdot\pi\cdot 50\cdot 0.05}\cdot\frac{10000}{500^2} = 1273.24\mu F$$

Store electric power

The DC capacitor storage electric power which could last for a certain time to guarantee the system operates at rated power. Assume the time constant related to DC capacitor is τ and it equals to

$$\tau = \frac{C_d U_D{}^2}{2S_N} \tag{11}$$

If τ is smaller than 5ms, the capacitor value in equation (11) can inhibit small disturbance or transient overvoltage. Normally τ is 2ms in real project, therefore

$$C_d \geq \frac{\tau\cdot 2S_N}{U_D{}^2} = \frac{2\cdot 10^{-3}\cdot 2\cdot 10\cdot 10^3}{500^2} = 160\mu F(\tau=2ms)$$

$$C_d \geq \frac{\tau\cdot 2S_N}{U_D{}^2} = \frac{5\cdot 10^{-3}\cdot 2\cdot 10\cdot 10^3}{500^2} = 400\mu F(\tau=5ms)$$

All in summary, the DC capacitor value is set at 2400μF.

FILTER PARAMETER DESIGN

Most of the filter in VSC-MTDC is high pass filter, and second order high pass filter is the most widely used. Suppose the filter cutoff frequency is 450Hz and Q_{filter} is 0.08. According to the equal capacity ratio principle, the capacity is 0.25kW (each phase). Figure 3 gives the impedance characteristic of the filter.

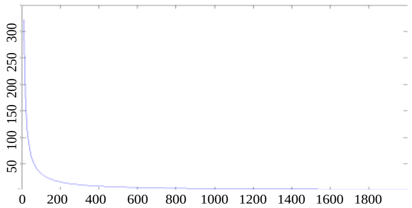


Figure 1: The impedance characteristic of the filter

DC GRID TRANSMISSION LINE

The transmission line is also chosen according to the equal capacity ratio principle and use T-type equivalent circuit. The reference system is a ±200kV high voltage system with its capacity equals to 200MW. The DC grid in laboratory is designed at ±250V, each terminal capacity is 10kW. Thus the voltage ratio is 800, power ration is 20000 and impedance ratio is 32. We get the T-type equivalent circuit and line parameter as figure 4.

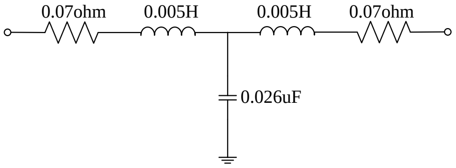


Figure 2: T-type equivalent circuit

REACTOR VALUE DESIGN

The output voltage of converter at AC side u_c is

$$U_C = U_{PCC1} + I \times X_{eq} = (1+X)U_{PCC1} \tag{12}$$

Where $X=\omega L$.

The relationship between output voltage of converter at AC side and DC side is

$$U_C = \frac{\mu M}{\sqrt{2}} U_{DC} \tag{12}$$

Where μ is utilization efficiency of DC voltage, M is the modulation ratio. U_{DC} is DC voltage. Because of the control margin and fluctuation of AC and DC voltage, M is set at 0.95. Therefore,

$$U_C = (1+X)U_{PCC1} \le \frac{0.95\mu}{\sqrt{2}} U_{DC} \tag{14}$$

The nominal voltage value at DC side is 500V and X equals to 0.25. Substituted in equation (14),

$$(1+0.25)U_{PCC1} \le \frac{0.95\frac{\sqrt{3}}{2}}{\sqrt{2}} 500 \text{, } \quad U_{PCC1} \le 232.7V \tag{15}$$

The low order harmonics increase along with the U_{pcc1} and M decrease, therefore the transformer secondary voltage (phase to phase) is 230V. Define S_{aB}=10kVA, U_{SB}=230V, thus

$$I_{SB} = \frac{10}{230\sqrt{3}} = 25.1A \tag{16}$$

Thus

$$Z_{aB} = \frac{230}{25.1\sqrt{3}} = 5.2905\Omega \tag{17}$$

Therefore the equivalent reactance is

$$L = \frac{0.25 Z_{aB}}{\omega} = 4.21mH \tag{18}$$

Take off the leakage reactance of the transformer which is about 1.4032mH, the reactor value is 2.81mH.

EQUIVALENCY VERIFICATION

All the parameters of the 6-terminal low voltage DC grid is designed based on a 500kV high voltage VSC-MTDC system which has 3 terminals. The voltage source converter uses the three-phase two-level topology. The DC voltage of VSC1 is controlled at constant which is 500kV, while the power flow through VSC2 and VSC3 is controlled constant which are 200MW and -200MW. Simulation models of original VSC-MTDC and 6-terminal low voltage DC grid are built in PSCAD/EMTDC to validate the equal capacity ratio principle. Figure 5 illustrates voltage waveform of VSC-MTDC system. The voltage waveform (Terminal 1, Terminal 2 and Terminal 3) of DC grid is shown in figure 6. The simulation results of low voltage DC grid mainly agree with the VSC-MTDC system DC voltage waveform, which proves the equivalency.

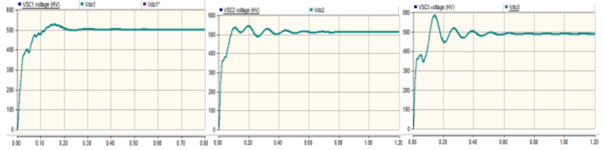


Figure 3: voltage waveform of VSC-MTDC system

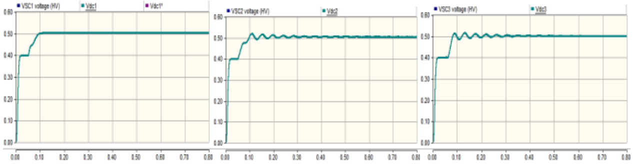


Figure 4: Voltage waveform of DC grid

CONTROL SYSTEM

Master-slave control, voltage margin method and droop control are typical control methods for DC grid. When the master-slave strategy is employed to regulate DC bus voltage in a DC grid, its voltage is determined by the constant DC voltage control converter. At this scenario, the DC voltage will be unstable when the active power is unbalance or the constant DC voltage control terminal is tripped off against faults. Therefore the DC voltage must be controlled through the coordinating control of the system supervisor layer through communication. Based on the research work above, this paper designs control strategies for DC grid which include control strategy for VSC and bidirectional DC/DC terminal, and coordinated control strategy among multiple terminals.

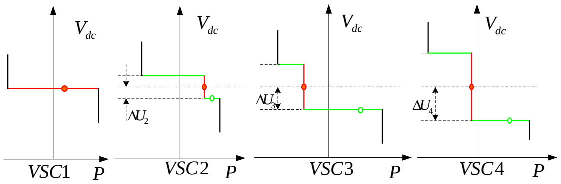


Figure 5: Operation and control characteristics of the DC grid

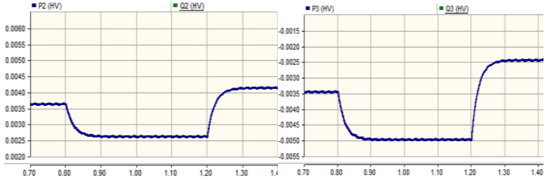
Based on the voltage margin control, a coordinated master-slave control method is proposed. Figure shows the operation and control characteristics of the DC grid. Accordance with the laboratory voltage level, the voltage margin value is calculated, where$\Delta U_2<\Delta U_3<\Delta U_4$. Under the steady state, their operational characteristics follow the red line. The DC voltage of VSC1 is controlled at constant, the rest three converters are designed to deliver or inject proper active power. If there is a fault at Terminal 1, the DC voltage at Terminal 2 is controlled at constant, which means its operational characteristics change to the green line and other terminals remain unchanged. The basic principal is the converter with smallest voltage margin will be considered to control DC voltage first. Instead of following the red line, the selected converter will adjust to the green line. The black lines give the operation limit of each converter.

SIMULATION RESULTS

The model of the 6-terminal low voltage DC grid in Fig.1 is tested in PSCAD/EMTDC.The DC voltage at Terminal 1 is controlled at 500V. Terminal 2 delivers 3.5kW active power from AC system to the DC grid, while Terminal 3 delivers 3.5kW active power from DC grid to the DC system. Terminal 2 is connected to energy storage system with bidirectional DC/DC as its interface. A PV system is integrated to the DC grid at Terminal 5. The last terminal provides electric power to AC load through VSC which using three-phase two-level topology.

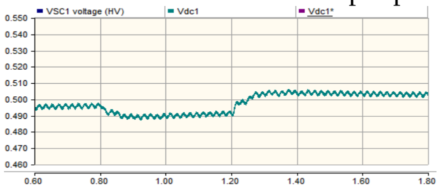
Case 1

The output power of Terminal 2 is 3.5kW, it decrease to 2.5kW at 0.8s, at 1.2s it increase to 4kW and Figure 8(a) is its simulation result. The output power of Terminal 3 is -3.5kW, it decreases to -5kW at 0.8s, at 1.2s it increases to -2.5kW. Figure 8 (b) gives the simulation result. The DC voltage waveform of Terminal 1, Terminal 2 and Terminal 3 is shown in Figure 9. Figure 10 illustrates the AC current waveform of Terminal 2 and Terminal 3 during the simulation process.

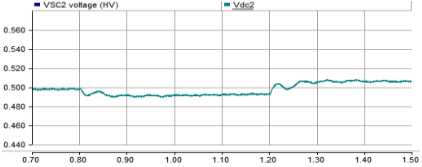


(a) (b)

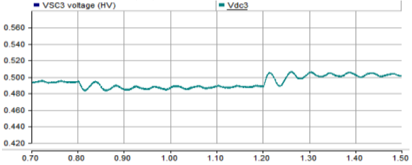
Figure 6: Simulation result of output power



(a) Terminal 1

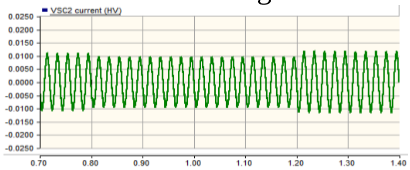


(b) Terminal 2

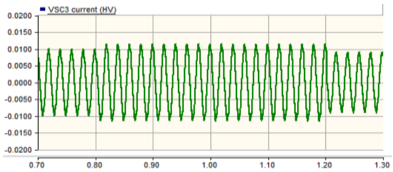


(c) Terminal 3

Figure 7: The DC voltage waveform



(a) Terminal 2

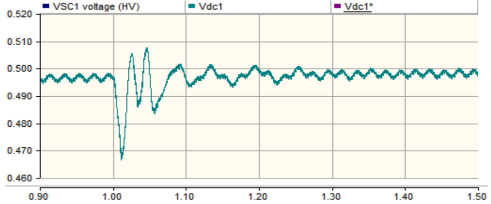


(b) Terminal 3

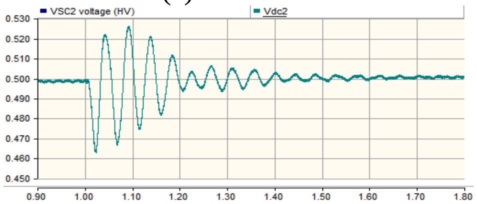
Figure 8: The AC current waveform

Case 2

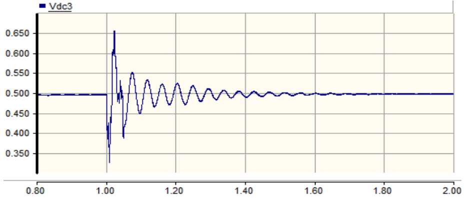
Figure 11 gives the simulation results of DC waveform at each terminal when there is a short circuit fault at the DC side of Terminal 3 at 1*s* and last for 0.05*s*. Figure 12 is the current waveform.



(a) Terminal 1

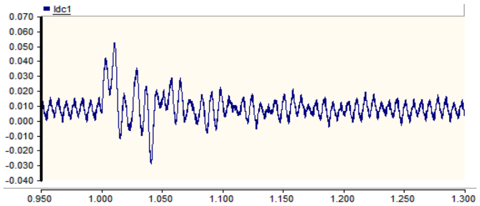


(b) Terminal 2

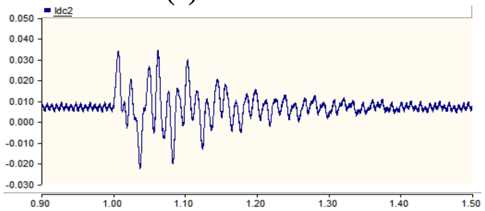


(c) Terminal 3

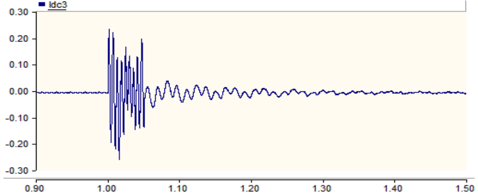
Figure 9: DC waveform at each terminal



(a) Terminal 1



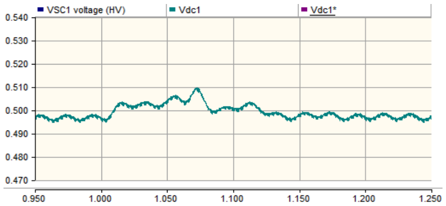
(b) Terminal 2



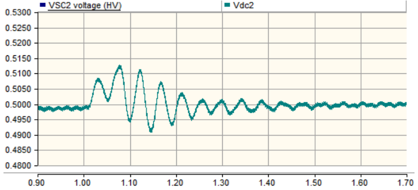
(c) Terminal 3

Figure 10: current waveform at each terminal

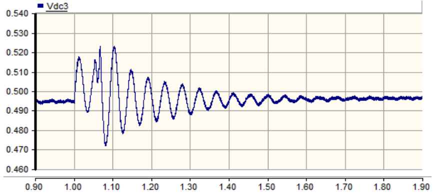
Figure 13 gives the simulation results of DC waveform at each terminal when there is a three-phase short circuit fault at the AC side of Terminal 3 at 1*s* and last for 0.05*s*. Figure 14 shows the current waveform.



(a) Terminal 1

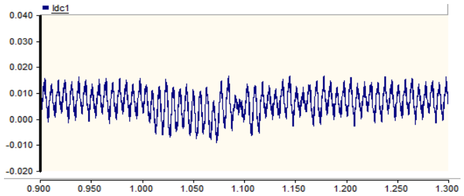


(b) Terminal 2

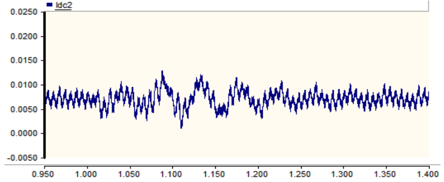


(c) Terminal 3

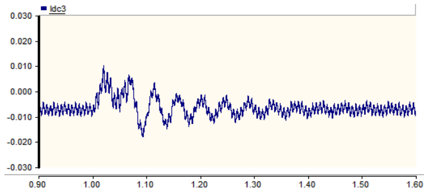
Figure 11: DC waveform at each terminal



(a) Terminal 1



(b) Terminal 2



(c) Terminal 3

Figure 12: current waveform at each terminal

The simulation results prove that the DC bus voltage of the DC grid can be controlled steadily after a variety of faults which include grounding fault at AC or DC side of the system.

CONCLUSIONS

Developing a low voltage, small capacity DC grid in laboratory to study DC grid under various scenarios or its interaction with AC system is convenient and practical. The equal capacity ratio principle helps the parameter design in low voltage DC grid. All the parameters are selected according to the parameters of the high voltage reference system based on equal capacity ratio principle and optimized by simulation model. The simulation results prove that the low voltage, small capacity DC grid has the same physical characteristics as the high voltage practical project.

Based on the voltage margin control, a coordinated master-slave control method is proposed. Accordance with the laboratory voltage level, the voltage margin value is calculated. With carefully selected margins based on the system strength and converter type, the DC bus voltage of the DC grid can be controlled steadily after a variety of faults. A digital simulation model of the 6-terminal low-voltage DC grid in laboratory is built using PSCAD/EMTDC. Simulation results validate the feasibility of the proposed coordinated control strategy. It can maintain the DC bus voltage and against active power unbalance or tripping off converters.

REFERENCES

[1] G. P. Adam, et al. *Network fault tolerant voltage-source-converters for high-voltage applications in AC and DC Power Transmission*, 2010. ACDC. 9th IET International Conference on, 2010, pp. 1-5.

[2] L. Haifeng, et al. *Coordination and optimization of small signal modulators in multi-infeed HVDC systems*, in Transmission and Distribution Conference and Exposition, 2003 IEEE PES, 2003, pp.35-40 Vol.1.

[3] J. Reeve and S. P. Lane-Smith. *Multi-infeed HVDC transient response and recovery strategies*, Power Delivery, IEEE Transactions on, vol. 8, pp. 1995-2001, 1993.

[4] C. Meyer, et al. *Control and Design of DC Grids for Offshore Wind Farms*, IEEE Transactions On Industrial Applications, 2007, vol. 43, no. 6, pp. 1475-1482.

[5] W. Lu and B.-T. Ooi, *Optimal acquisition and aggregation of offshore wind power by multi-terminal voltage-source HVDC*, *IEEE* Trans. Power Del., vol. 18, no. 1, pp. 201–206, Jan. 2003.

[6] P. Bresesti, W. Kling, R. Hendriks, and R. Vailati, *HVDC connection of offshore wind farms to the transmission system*, IEEE Trans. Energy Convers., vol. 22, no. 1, pp. 37–43, Mar. 2007.

[7] Gang. Shi, Guoxiang. Wu, Xu. Cai, Zhe. Chen. *Coordinated control of multi-terminal VSC-HVDC transmission for large offshore wind farms*, 2012 IEEE 7th International Power Electronics and Motion Control Conference- Ecce Asia, vol.2, pp. 1278-1282, (2012)

[8] Nilanjan. Ray. Chaudhuri, Rajat. Majumder. *Modeling and stability analysis of MTDC grids for offshore wind farms: A case study on the North Sea benchmark system*, Power and Energy Society General Meeting, 2011 IEEE, pp. 1-7.