DC-GRID PHYSICAL MODELING PLATFORM DESIGN AND SIMULATION*

Minxiao Han¹, Xiaoling Su*²¹, Xiao Chen¹, Wenli Yan¹, Zhengkui Zhao²
¹State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University
Beijing, China
²State Grid Qinghai Electric Power Maintenance Company,
Qinghai, China

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

---

*This work is supported by National Natural Science Foundation of China (51177044), Sino-Danish Strategic Research Cooperation within Sustainable and Renewable Energy, 2014DFG72620

**Corresponding author: E-mail: elevensu@163.com
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 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.

\[
\begin{align*}
\mu_{pcc1} & \text{ is the voltage at PCC. } u_{dc} \text{ is voltage of the converter at DC side and } i_{dc} \text{ is the current inject to the DC grid by the converter. } i_{dc \text{ line}} \text{ is the current flow through the DC line. } P_5 \text{ and } Q_5 \text{ is the power inject to the AC power system by the converter. } P_C \text{ and } Q_C \text{ is the power flow to the converter. } R \text{ and } L \text{ is the equivalent resistance and inductor between AC power system and the converter, therefore the transformer in figure 2 is ideal.}
\end{align*}
\]

![Diagram of the DC grid](image)

Figure 1: Configuration of the DC grid

![Diagram of the voltage source converter](image)

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.

\[
\begin{align*}
\frac{S_{N1}}{S_{N2}} &= \frac{C_1U_{N1}^2}{C_2U_{N2}^2} \quad (1) \\
\frac{S_{N1}}{S_{N2}} &= \frac{L_1I_{N1}^2}{L_2I_{N2}^2} \quad (2)
\end{align*}
\]

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, \( \omega_1 \) and \( \omega_2 \) 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)

\[
\frac{\alpha \cdot 1020 \cdot 800^2}{10k} = \frac{\alpha \cdot 500^2}{10k}
\]
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

\[ \Delta P_2 = \sqrt{3} k U_n I_n \cos(2\alpha t + \phi_1) = k S_N \cos(2\alpha t + \phi_1) \]  

(4)

Where \( k \) is second order harmonic active power oscillating coefficient, \( S_N \) is the rated capacity of the system, \( \phi_1 \) 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

\[ u_d = U_{dc} + \Delta U_{dc} \sin(2\omega t + \phi_2) \]  

(5)

Where \( U_{dc} \) is the DC component, \( \phi_2 \) is initial phase angle of second order harmonic power, \( \Delta U_{dc} \sin(2\omega t + \phi_2) \) is the second order voltage harmonic. Equation (5) gives the second order harmonic power at the DC side as

\[ \Delta P_d = 2\omega C_d \Delta U_{dc} U_{dc} \cos(2\omega t + \phi_2) \]  

(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

\[ C_d = \frac{k S_N}{2\omega U_{dc} \Delta U_{dc}} \]  

(8)

Suppose the max value of voltage fluctuation value as \( \Delta U_{DCmax} \), therefore

\[ C_d \geq \frac{k S_N}{2\omega U_{dc} \Delta U_{DCmax}} \]  

Or

\[ C_d \geq \frac{k}{2\omega} \left( \frac{\Delta U_{DCmax}}{U_{dc}} \right) ^2 S_N \quad (0 < k \leq 1) \]  

(10)

While \( k = 1 \)

\[ C_d = \frac{1}{2 \cdot 2 \cdot \pi \cdot 50 \cdot 0.05} \cdot \frac{10000}{500^2} = 127324 \mu F \]

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 \( \tau \) and it equals to

\[ \tau = \frac{C_d U_{dc}^2}{2 S_N} \]  

(11)

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

\[ C_d \geq \frac{\tau \cdot 2 S_N}{U_{dc}^2} = \frac{2 \cdot 10^{-3} \cdot 2 \cdot 10^{-10} \cdot 400 \mu F}{500^2} = 160 \mu F \]

(\( \tau = 2ms \))

\[ C_d \geq \frac{\tau \cdot 2 S_N}{U_{dc}^2} = \frac{5 \cdot 10^{-3} \cdot 2 \cdot 10^{-10} \cdot 400 \mu F}{500^2} = 400 \mu F \]  

(\( \tau = 5ms \))

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

\[
U_c = U_{PCC1} + I \times X_m = (1 + X) U_{PCC1}
\]

(12)

Where \( X = \omega L \).

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

\[
U_c = \frac{\mu M}{\sqrt{2}} U_{DC}
\]

(12)

Where \( \mu \) 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,

\[
U_c = (1 + X) U_{PCC1} \leq \frac{0.95 \mu}{\sqrt{2}} U_{DC}
\]

(14)

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

\[
(1 + 0.25) U_{PCC1} \leq \frac{0.95 \sqrt{3}}{\sqrt{2}} U_{DC}
\]

(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 \( S_{ab}=10 \text{kVA} \), \( U_{SV}=230 \text{V} \), thus

\[
I_{ab} = \frac{10}{230 \sqrt{3}} = 25.1 \text{A}
\]

(16)

Thus

\[
Z_{wb} = \frac{230}{25.1 \sqrt{3}} = 5.2905 \Omega
\]

Therefore the equivalent reactance is

\[
L = \frac{0.25 Z_{wb}}{\omega} = 4.21 \text{mH}
\]

(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.

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.
Figure 8: The AC current waveform

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 1s and last for 0.05s. Figure 12 is the current waveform.

Figure 9: DC waveform at each terminal

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 1s and last for 0.05s. Figure 14 shows the current waveform.

Figure 11: DC waveform at each terminal

Proceedings from The 55th Conference on Simulation and Modelling (SIMS 55), 21-22 October, 2014. Aalborg, Denmark
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


