A method of Modelling and Simulating the Back-to-Back Modular Multilevel Converter HVDC Transmission System

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Abstract. This paper proposes a method to simulate a back-to-back modular multilevel converter (MMC) HVDC transmission system. In this paper we utilize an equivalent networks to simulate the dynamic power system. Moreover, to account for the performance of convertor station, core components of model of the converter station gives a basic model of simulation. The proposed method is applied to an equivalent real power system.

1. Introduction
Back-to-Back HVDC is mainly used in the power system that connecting non-synchronous networks. The development of electric power system is bound to be large-scale connected. With the development of HVDC transmission technology, back-to-back HVDC transmission system has been developing rapidly since 1980s[1,2,3].

Back-to-back DC convertor station can use flexible DC units and the conventional back-to-back DC units which operated in parallel. The flexible DC unites can not only bear the fundamental role of electrical energy transmission, and can also offer reactive power to optimize the capacity of AC filters[4,5].
In addition, the flexible DC unites can improve the DC system recovery characteristics while faults take place at the AC lines[6].
There are a variety of operation modes for the back-to-back flexible DC convertor[7,8,9,10]. Different operation models can change the power flow of the entire system. It is required to carry out a research for the special requirements of the back-to-back flexible DC convertor station.

2. Computation conditions
A real system in the west of China in 2016 is used as basic data in this study. In this system, the HVDC Project is used to connect two AC systems while receive-side is a weak AC system. Meanwhile, the near-region short-circuit level of DC rectifier side and inverter side is low.
2.1 Models
In this paper, the BPA is used to build electromechanical transient simulation model and PSCAD/EMTDC is used to build electromagnetic transient simulation model.

The main components used in the model are as follows: Generator is build using an Eq/Ed model with automatic excitation regulator, governor and power system stabilizer. The damping factor is considered as 0. Two-ends DC model in BPA program (DN model) is used to build DC transmission system model. In addition, DC control system, DC over load capacity, low voltage limit (VDCOL), frequency limit control (FLC) and other major aspects of the model and parameters are the same to the actual system. Load is considered using load frequency characteristics ZIP static model, each network load model parameters are shown in Table 1.

2.2 N-1 fault
In AC Line N-1 fails analysis, we consider a three-phase short-circuit fault occurs at ends and the midpoint of the 500kV AC line respectively. The fault clearing time of near side is 0.09 seconds and away side is 0.1 seconds.

2.3 Stability Criteria
Transient stability:
After the grid suffering disturbance, internal synchronization system power angle is required swing through the first and second oscillation period without losing step. Then, the central point voltage of the system is required to be restored gradually.

Frequency stability:
At any time the frequencies is required below 51.5 Hz and higher than 47.5 Hz, and the frequency of the system after the accident can be quickly restored to 49.2 Hz ~ 50.5 Hz.

Thermal stability:
Under normal mode transmission operation model, the distribution equipment requires not exceed the normal load capacity of the device after the accident.

N-1 fault correction:
After N-1 normal AC fault correction, the DC system can be restored to normal steady-state, the DC converter does not lock. Meanwhile, voltage, current and power does not oscillate sharply.

3. Overview of simulation models

3.1 Dynamic equivalent of large power grid
In order to facilitate the study of the dynamic characteristics of asynchronous network, the dynamic equivalent of Power Grid is necessary to carry out. In order to facilitate the development of electromagnetic transient modelling and analysis, it is necessary to ensure the dynamic response

| Power Grid | Side  | Constant Impedance Load | Constant Current Load | Constant Power Load | Frequency change 1% Caused by active changes | Frequency change 1% reactive |
|------------|-------|-------------------------|-----------------------|---------------------|---------------------------------------------|-----------------------------|
| A          | Sending-side | 30%                     | 30%                   | 40%                 | 1.2                                         | -2                          |
| B          | Receive-side | 30%                     | 40%                   | 30%                 | 1.8                                         | -2                          |
| C          | Receive-side | 30%                     | 40%                   | 30%                 | 1.2                                         | -2                          |
| D          | Receive-side | 30%                     | 40%                   | 30%                 | 1.2                                         | -2                          |
| E          | Receive-side | 40%                     | 30%                   | 30%                 | 2                                           | -2                          |
characteristics of the grid and reduce the size of the grid. Grid 1 equivalent system for asynchronous networking project using 2016 network data and retaining only the nearby nodes. Detailed equivalent methods and equivalent results are described below.

3.2 Equivalent Simplification Method
The system is equating the use of BPA simplified procedures based on dynamic equivalence coherent equivalent method. The core of the method is to divide the clusters according to the principle that the generator has the same form of oscillation in the transient process. On the basis of this method, the aggregation of generators and simplification of networks are carried out. The basic procedures are as follows:

1. Identify research system and keep a detailed data of the system;
2. Determine coherent cluster;
3. Simplify generator and bus model;
4. Network Simplification;
5. Polymerize generator and control system model and determine its parameters.

3.3 Equivalent system modelling using EMTDC

1) Equivalent Networks
In the simulation model of HVDC system, a DC control model similar to that of the existing DC control system is adopted. The back-to-back DC adopts the conventional back-to-back and flexible back-to-back model. In order to facilitate the simulation settings, the conventional back-to-back DC model of the unit capacity and quantity can be adjusted, soft straight unit model can change the capacity. Back to back DC models are equipped with detailed control and protection module. In the above model, the DC and ground lines of the HVDC system are frequency-dependent transmission line models; the back-to-back DC belongs to the back-to-back DC without the DC overhead line model; the generator model uses a detailed generator model, generator set excitation regulator, the governor and PSS control; AC line using Bergeron (Bergeron) line model, the equivalent line impedance is represented; integrated load model constant impedance load, constant current and constant power to. The system contains electrical node 2050, including 16 generators, communication lines, transformers node 74.

In this paper, the BPA is used to build electromechanical transient simulation model and PSCAD/EMTDC is used to build electromagnetic transient simulation model. The main components used in the model are as follows: Generator is build using an Eq/Ed model with automatic excitation regulator, governor Model.

2) Electromagnetic Transient Model
In EMTDC electromagnetic transient model, power supplies, transformers, motors, overhead transmission lines are considered. A part of components in this model have same characteristics to the electromechanical transient model, which are the resistors, inductors, capacitors and other passive components. Therefore, electromagnetic transient model is studied to build this model.

a) Generator Model:
In PSCAD / EMTDC, the synchronous motor model is based on the synchronous motor Park equation, including the three-phase stator windings abc, field winding f, and the vertical axis rotor damper winding D, cross-axis direction of the rotor with a damper winding Q and g. The seventh-order model can be used to simulate the stealthy synchronous motor. In order to simulate the salient pole synchronous motor, no cross-axis damper winding g is considered. It is called sixth-order model. The saturation characteristic of the motor's magnetic circuit is simulated by using the generator's no-load characteristic curve. It can also be simulated by setting the generator saturation characteristic without considering the generator saturation characteristic. Generator model parameters accordance with both the equivalent circuit parameters directly input and test parameters.

In addition, the model needs the rated capacity and rated voltage to reflect the initial operation of
the generator unit, such as the terminal voltage amplitude and the phase angle. PSCAD/EMTDC the graphic generator module includes a stator abc three-phase parameters. The input signal including: a generator rotational speed control signal (ω), mechanical torque signal (Tm) and excitation control signal (Ef). The output signals include tachometer output (ω), electromagnetic torque output (Te), mechanical output torque (Tm), field current (If), the excitation voltage (Ef0), output-side voltage and current signals (Vt and It).

Figure 1: Generator Model

PSCAD/EMTDC the generator model parameters are calculated by the BPA system equivalent data, including a reference voltage generator, rotational inertia H, stator resistance Ra, direct-axis transient synchronous reactance Xd, the quadrature axis synchronous reactance Xq, direct axis transient open-circuit time constant Td0. The cross-axis transient open time constant Tq0. The stator leakage reactance Xl, saturation coefficient SG1.0 motor rated voltage, the motor saturation coefficient of 1.2 times the voltage of SG1.2, motor damping coefficient D, d-axis sub-transient reactance. If the value is default, it is necessary to convert the Ra, Xd', Xq', Xd, Xq, XL to reference system (100MVA).

b) Transformer model:
There are two transformer models in EMTDC, one is the classical transformer model, and the other is the UEMC (Unified Magnetic Equivalent Circuit) transformer model. For classic transformer model, the transformer of each phase is independent and it ignores the interaction between the phases. UMEC models consider the interaction between the phases.

In addition, the two transformer models are fundamentally different in core saturation simulations. In the classic model, transformer saturation is modelled by injecting step currents into the windings, which may cause the windings unbalanced. In UMEC model, since it simulates according to the transformer saturation curve, this will not lead the degree of saturation of each phase imbalance. In this study, a classical transformer model was used.

Load model:
The integrated load model is described as follows:

\[ P = P_0 \cdot \left( \frac{V}{V_0} \right)^{NP} \cdot (1 + K_{PF} \cdot dF) \]  \hspace{1cm} (1)

\[ Q = Q_0 \cdot \left( \frac{V}{V_0} \right)^{NQ} \cdot (1 + K_{QF} \cdot dF) \]  \hspace{1cm} (2)

Where,
P - equivalent active power load;
P0 - rated single-phase active power;
V - load voltage;
V0 - load rated phase voltage;
NP - voltage characteristics of active;
KPF - active power frequency characteristic index;
Q - the equivalent load reactive power;
Q0 - rated single-phase reactive power;
NQ - reactive power voltage characteristic index;
KQF - reactive power in the frequency characteristics of the index.

If the voltage characteristic NP, NQ is 2 in the equations, load model is the shunt admittance load, 
P0 and Q0 represent rated three-phase active and reactive power respectively. V0 represent the rated 
line voltage. The specific analysis is as follows:

\[
P = P_0 \cdot \left( \frac{V}{V_0/\sqrt{3}} \right)^2 \cdot \left( 1 + K_{PF} \cdot dF \right) \tag{3}
\]

Similarly,

\[
Q = Q_0 \cdot \left( \frac{V}{V_0/\sqrt{3}} \right)^2 \cdot \left( 1 + K_{QF} \cdot dF \right) \tag{4}
\]

The equivalent system has two types of data load models:
1: Constant active/reactive load;
2: Admittance active/reactive load.

4. Flexible DC Model

4.1 Fundamentals of Flexible DC
The flexible DC Voltage Source Converter (VSC) have two ends, which are sending end, and the 
receiving end, both ends of the converter has the same structure. Flexible DC transmission system 
consists of inverter, AC filter, commutation reactor and converter transformer and other components. 
Each arm of the converter has a plurality of fully controlled power electronic switching devices.

Since VSC is used full-controlled devices, not only can control the turn-on of the device, but also 
can control the turn-off, which has two degrees of freedom control, it is possible to control the inverter 
output voltage amplitude and phase simultaneously. Therefore, in terms of the exchange system, VSC 
can be equivalent to a generator, which can independent control of active and reactive power in four 
quarters PQ plane. High performance flexible HVDC system depends largely on the performance of 
VSC.

4.2 Main Component Model of Flexible DC Main Circuit
1) Voltage source converter
The voltage source converter is the core component of the HVDC transmission system, and it affects 
the performance and operation mode, Equipment costs and operating losses of the whole commutation 
system. Voltage source converter has a variety of topologies, such as two-level, three-level and multi-
level. Combined with the actual situation back-to-back HVDC research, this paper focus on the 
modular multi-level type (MMC) voltage source inverter, the simulation model is shown below.
2) Converter transformer

In the simulation, converter transformer not only can transfer voltages for VSC converter, but also provide a flexible linear system ground potentially.

Since the back-to-back station is accessed to 500kV high voltage system directly, grid-side converter transformer windings are star-connected. Although a triangular-connection is adopted, zero-sequence current can be isolated by the grid side and the converter valve, a separate grounding device is needed to ensure the reliability of flexible DC. If a star connection is adopted, the neutral point cannot be directly grounded, the zero sequence current cannot be isolated.

To solve the above problems, the simulation model with Yy coupling transformer is adopted, wherein the valve winding is grounded through large resistor. The convertor can meet the requirements of simulation using this model.
3) Other components
As there is no DC line in the back-to-back DC unit, the two converters are located in the same valve hall and directly connected.

MMC sub-module element simulation model can set the number of sub-modules and energy storage capacitance values and other parameters.

![Figure 5: MMC sub-module model](image)

Since the storage capacitors are mounted in the MMC on each sub-module, there is no necessary to install centralized large-capacity capacitors on the DC side.

In addition, arm reactors are connected in series on each bridge arm, which means the conventional commutated reactor connected in order to reduce short-circuit current and filter out part of the harmonic. For MMC converter, arm reactor is also used to eliminate inrush current circulation and fault conditions.

4.3 Flexible DC Control and Protection System
Flexible DC control system is mainly composed of inner loop current controller and outer loop controller. The basic control characteristics of the flexible direct transmission system are determined by the outer loop power controller. The controller at each end of the flexible DC can control a variety of physical and reactive power parameters, and each end have to select one physical parameter of the two types to control.

At the same time, DC voltage has to be controlled at least at one end in the DC transmission system. Therefore, there are a variety of combinations of control strategies in the flexible DC transmission system.

The figure 6 indicates the hierarchical structure of the back-to-back DC control system.

![Figure 6: Flexible DC model](image)

The SSC in the figure 6 is the outer loop power control module. This module is used to generate the active and reactive control signals for the inverter. Each end of the inverter contains a PCP module to control loop current.

The trigger pulse generating PWM signals and controls the active and reactive current of its output to track the change of the outer loop command value. Protection functions at each end of the inverter are provided in the DPR module.
5. Conclusion
This paper proposes a method to simulate a back-to-back MMC HVDC transmission system. In this paper, an equivalent networks are established to simulate the dynamic power system. According to the core components of model of the converter station, the performance of convertor station is calculated. The proposed method is then applied to a real power system.

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