A new approach to reduce AC grid for coupled HVDC systems

Fei Dou¹, Weiyuan Wang¹, Yiqing Xu², Lijun Wang², Xuan Yu²,³ and Jiliang Xue²

¹ State Grid Jiangsu Electric Power Co., Ltd., Nanjing 210000, China; ² East China Electric Power Design Institute Co., Ltd., Shanghai 200063, China; ³ Email: 2324@ecepdi.com

Abstract. When the dynamic performance study of the HVDC system are carried out or the over voltage characteristics is analysed, electromagnetic transient simulation is needed. The reduction of the AC system is inevitable since the computation burden is huge taking the whole ac grid as well as detailed HVDC models into account. Because the task is to maintain the dynamic response of AC system in a short term and focuses inside the HVDC transmission system, reasonable reduction of the ac grid can be done to simplify this problem without effecting the analysis conclusion. However, the existing approaches to reduce large ac grid aims to analyse the transient stability under asymmetric faults. In these methods, the remaining ac grid is still too large considering full HVDC models which is usually represented by simplified ones. In order to solve the specific aforementioned problem, multi-port Thevenin equivalent is adopted to simplify the original large power grid. By the transient stability simulation and short-circuit calculation, the node impedance matrix can be obtained. According to the admittance matrix obtained by the impedance matrix, the structure of the equivalent system as well as the impedance of the source are determined. The power flow of the equivalent system approximates that of the original system based on the quadratic programming. A UHVDC hierarchically connecting to grids of two voltage levels i.e. 500 kV and 1000 kV is taken as an example, which verifies the validity of the proposed method. Given the relatively small scale of the reduced system, further study on the full HVDC system can be done under computational constraints.

1. Introduction

When studying the dynamic performance of the HVDC transmission system or the over-voltage characteristic after a while design, the electromagnetic transient simulation is needed [1-2]. This simulation contains the full HVDC models i.e. the thyristors represented by switchable resistances, the complex and actual digital control systems, as well as the transformers, smooth reactance, filters and so on in order to simulate the dynamic performance of the HVDC systems as accurate as possible. Under the computational constraints, the reduction problem of the ac system is encountered. A very small-scale yet reasonable reduced system is needed to save the computation resources. This problem is essentially different from the transient stability problem when asymmetric (under the symmetric condition, it is easy to analyse using transient stability program) fault occurred [3-4]. General speaking, the stability of the power system depends on the structure of higher voltage levels. Multiple HVDC systems are interacted through the main grid, so does the interaction of ac/dc systems [5]. In this problem, the HVDC models are represented as simplified ones just in accordance with the external...
behaviour and the scale of ac grid still remains big because reduction of areas of the grid results inaccuracy or even invalidation of the stability conclusion [6-7]. However, the design of the HVDC transmission controller or the calculation of the over voltage characteristics focuses on the details inside the HVDC system and the interested period only lasts 2 seconds or shorter after a fault occurs [1-2]. So, much reduction can be done to the ac grid to handle this situation.

Given an actual modern power system, it is saved as formatted data structures specified by some transient stability program such as BPA or PSS/E [8]. It is a trouble to get the corresponding admittance matrix using these programs, though they support electrical calculations very well. This situation increases the difficulty of the reduction. So, it is urgent to develop a systematic approach to reduce the power system which is not only adequately accurate but also making full use of these off-the-shelf programs.

In the system consisted of a single HVDC system, the short circuit ratio (SCR) is crucial and is a basic index to evaluate the contribution of the ac system and almost decides the dynamic performance of the HVDC system to some extent [9]. So, when reducing the system consisted only a single HVDC systems or multiple HVDC systems far away, a feasible approach is to solve the Thevenin equivalence, which keeps the SRC the same [10]. However, the modern power system consisted many tightly coupled HVDC systems whose interactions cannot be neglectable. In Jiangsu Province, a special HDVC transmission system is connected to the grid on two different voltage levels within a substation. The higher end connects to the 500kV grid while the lower end connects to the 1000kV grid under the consideration of insulation. Under these circumstances, these closely coupled HVDC systems are to be remained even when the focused problem is inside the HVDC system because they interact closely. As an extension of single port Thevenin equivalence, multiple port Thevenin equivalence can be used [11]. In multi-infeed AC/DC systems, the interaction is often described by the multi-infeed Interaction Factor (MIIF) proposed by CIGRE working group [12]. To solve the MIIF, the method based on the transient stability simulation is most accurate because it uses the whole system without reduction yet very simple. As a result, it is a benchmark to evaluate other methods [13-14]. This factor is determined by the structure of the ac grid and can be obtained by transient stability programs. So, this paper uses it to reduce the ac grid with coupled HVDC systems.

In this paper, a novel approach which adopts short circuit calculation and transient stability simulation to reduce the power system with closely coupled HVDC systems is proposed. The contribution of this paper is summarized as follows: (1) a systematic approach to reduce the large ac grid is proposed taking full use of off-the-shelf transient stability programs without explicitly solve the admittance of the whole system. (2) this approach reduces the huge ac grid into a very small-scale one that saves lots of computational resources for the full and complex HVDC model, while this small system still approximates the dynamic behaviour of the original one. (3) A case study is performed focused on aforementioned special HVDC transmission system in Jiangsu province. This case study validates the similarity between the reduced and the original system. The remainder of this paper is organized as follows: Section 2 briefly describes the equivalent structure of the reduced system and the parameters of equivalent structure is solved in section 3 in detail. Section 4 carries out an actual case study followed by a detailed discussion. Conclusions are drawn in section 5.

2. Equivalent structure

In order to study the interaction of multiple HVDC systems in multi-infeed system as well as to reduce the ac system as much as possible, the buses can be categorized into different layers, i.e., they are classified into groups which is 1 layer, 2 layer and n layers away from the ac bus in the converter station. The equivalent structure is determined by n, the buses with n layers are remained and buses on the n layer makes up of the boundary connecting the equivalent sources and connecting to other boundaries with virtual branches. Yet in general, Figure 1 illustrates both the original system and proposed system forming a two infeed HVDC system remaining 1 layer of ac buses. The dotted line in Figure 1(a) presents indirect electrical connection and the system in the circle is outside the boundary.
Only 1 layer of buses and HVDC systems are remained in the reduced system illustrated in Figure 1(b). The buses on the boundary are connected to each other and equivalent sources. The short circuit calculation is performed with respect to the remaining buses in the original system in order to obtain the diagonal elements of the impedance matrix as a base for further use.

![Diagram](image)

**Figure 1.** (a) hierarchically connected AC/DC system, (b) simplified system structure corresponding to (a).

### 3. Determination of parameters of the equivalent system

#### 3.1. Definition of MIIF

According to [12], the MIIF is defined as a ratio \( \delta V_j / \delta V_i \), where \( \delta V_i \) is a voltage drop (approximately 1%) in the converter station indexed by \( i \) resulting from some amount of reactive load, \( \delta V_j \) is a voltage drop of another converter station indexed by \( j \). This concept can be expanded to any buses in a power grid. According to the nodal equation of the network,

\[
\mathbf{V} = \mathbf{ZI}
\]

where \( \mathbf{V} \) represents the voltage phasor of nodal voltages of the network, \( \mathbf{I} \) represents injected current into the nodes, \( \mathbf{Z} \) represents the system impedance matrix. When a proper amount reactor is put in use leading to a voltage drop of approximately 1% on node \( i \), the difference in current injected is \( \Delta I_i \) within a short period, while others keep the same. So, the corresponding nodal equation changed to:

\[
(\mathbf{V} - \Delta \mathbf{V}) = \mathbf{Z} \left( \begin{bmatrix} 1 & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & 1 \end{bmatrix} \right) \begin{bmatrix} 1 \\ \ldots \end{bmatrix} \Delta I_j = \mathbf{Z}_{ii} \Delta I_j
\]

where \( \mathbf{Z}_{ii} \) is the \( i \)th column of \( \mathbf{Z} \), the subscripts represent the dimension of variables. Thus, the MIIF between node \( i \) and \( j \) is

\[
M_{ij} = \frac{Z_{ji}}{Z_{ii}}
\]

where \( Z_{ii} \) is on the row \( x \) and column \( y \) in \( \mathbf{Z} \). Because MIIF is easy to get by the simulation program, the ratios of off-diagonal elements with the diagonal ones in the impedance matrix are obtained, which further leads to the whole system impedance matrix and the admittance matrix by matrix inversion operation. It is worth noting that the impedance matrix is obtained column by column and the final matrix is not necessarily symmetric. So, a post process is performed to force the impedance matrix to be symmetric.

\[
\mathbf{Z} = 0.5(\mathbf{Z}^T + \mathbf{Z})
\]

Further the admittance matrix is obtained by:

\[
\mathbf{Y} = \mathbf{Z}^{-1}
\]

#### 3.2. Parameters of equivalent branches and sources

The parameters of equivalent branches between buses on the boundary can be solved by \( \mathbf{Y} \), i.e. the admittance of the branch between buses \( r \) and \( s \) is \(-1/Y_{rs}\), the transient reactance of the equivalent source is the sum of the corresponding row in \( \mathbf{Y} \). Necessary modifications are needed to perform in
order to be consistent with the branches inside the original system, which leads to a final admittance matrix $Y_s$.

3.3. Power flow of equivalent sources

Given $Y_s$, the injected current on each node has been determined if steady voltages keep the same on all remaining buses according to the nodal equation (1). It will lead to contradiction between the reduced and original system. Thus, necessary modifications on voltages of buses on the boundary are needed in order to keep the similarity of power flow as much as possible.

Let $\Delta V = V - V_s$, where $V_s$ presents voltage phasors after modification, while $V_s$ presents the original ones. Thus,

$$Y_s \Delta V_s = I - Y_s V_s$$  

where $I$ presents injected current phasor on each node. It is a definite value if it is inside the reduced system, while it has to be optimized when it is on the boundary. In order to keep the steady operation as much as possible, a quadratic programming problem is to be solved [15].

$$\min \| \Delta V \|^2,$$

s.t. $Y_s \Delta V_s = I - Y_s V_s$

$$\Delta V_i = 0, i \in \Omega$$

where the superscript $i$ represents row $i$ of a vector or a matrix, $\Omega$ represents nodes inside the reduced system. After solving the above problem, the voltages of buses on the boundary can be obtained.

$$\hat{V}_b = \Delta V_b + V_b$$

which further leads to determination of active and reactive power of equivalent sources.

$$S = V_{be} \otimes \left( Y_s V_{be} \right)^*$$

where superscript * represents conjugation, and $\otimes$ represents Schur-Hadamard product. The power flow of equivalent machines is determined by (9) and their transient reactance parameters are determined according Section 3.2. Other parameters include open-circuit time constant, synchronous reactance as well as parameters of excitation regulators follow the typical values of nearby actual ones.

4. Case study

4.1. Introduction of the tested UHVDC transmission system

The tested UHVDC transmission system is the first UHVDC with capacity of 10000 MW in the world. It connects to the ac grid hierarchically to 500 kV and 1000 kV [16]. When to reduce the ac grid, this paper takes $n$ in section 2 to be 1 as an example. The corresponding diagram is illustrated in Figure 2. After reduction as proposed by this paper, some virtual branches and machines are added to the system in Figure 2. It is worth noting that there are more 10,000 buses in the original ac grid and thousands of generators, branches and transformers which is impossible to carry out detailed simulation of the HVDC system under the hug computational burden.

![Figure 2. Diagram of the test UHVDC systems.](image)
4.2. Power flow of the reduction system

The comparison of node voltages of the reduced system and those of original system is listed in Table 1. The comparison of power flow (only a single circuit is shown when there are multiple) through remaining branches between reduced and original systems is listed in Table 2.

Table 1. Comparison of voltage phasor in the original and the reduced system

| Bus name | Original system (magnitude/p.u. phase/deg) | Reduced system (magnitude/p.u. phase/deg) | Branch name | Original system/100MVA | Reduced system/100MVA |
|----------|------------------------------------------|------------------------------------------|-------------|------------------------|-----------------------|
| H        | 1.03 (-18.2) 1.03 (-17.4)               | H→A_H 58.7+9.2j 59.4-1.7j               |
| L        | 1.04 (-19.5) 1.04 (-15.0)               | A_H→B_H 93.8+2.1j 90.5-5.6j            |
| A_H      | 1.03 (-18.4) 1.03 (-17.6)               | A_H→C_H -41.1+17.0j -39.5+17.8j        |
| B_H      | 1.02 (-27.5) 1.04 (-26.3)               | L→A_L 12.7+3.5j 11.5+3.9j              |
| C_H      | 1.02 (-9.8) 1.02 (-9.8)                 | L→C_L 10.7+4.0j 12.3-7.7j              |
| A_L      | 1.03 (-21.0) 1.03 (-16.3)               | L→B_L 35.2+4.6j 35.7+4.6j              |
| B_L      | 1.03 (-22.1) 1.04 (-17.8)               |                                          |
| C_L      | 1.03 (-20.9) 1.03 (-16.2)               |                                          |

As can been seen in Table 1, the power flow of reduced system is similar to that of the original system and the voltage differs not larger than 0.02 p.u. and phase not greater than 5 degrees.

4.3. Short circuit current of the reduced system

Short circuit scanning is performed using the reduced and original system and results are compared in Table 3.

Table 3. Comparison of short circuit in the original and the reduced system

| Bus name | Original system/kA | Reduced system/kA | Relative error/% |
|----------|--------------------|-------------------|------------------|
| H        | 23.86              | 26.03             | 9.1              |
| L        | 38.77              | 34.87             | 10.0             |
| A_H      | 26.32              | 26.84             | 2.0              |
| B_H      | 35.67              | 37.38             | 4.8              |
| C_CH     | 23.86              | 23.37             | 2.0              |
| A_L      | 38.09              | 35.80             | 6.0              |
| B_L      | 38.41              | 35.94             | 6.4              |
| C_L      | 37.54              | 35.80             | 4.6              |

As can been seen in Table 3, the relative error of short circuit current is less than 10%, thus, the effectiveness of the proposed method on the static aspects are verified by Section 4.2 and 4.3.

4.4. Dynamic performance of the reduced system

In order to verify the proposed method on the dynamic aspect, a three phase to ground fault is carried out in the simulation. Given the fact that the dynamic performance of HVDC systems is determined by the voltage of buses, only voltages are shown in the following figures. Figure 3 illustrates the comparison of the dynamic performance of voltages when a fault occurred between L and C_L at 1s and the faulted branch is cut off at 1.1s. Figure 4 illustrates the comparison of dynamic performance of voltages when a fault occurred between H and C_H at 1s and the faulted branch is cut off at 1.1s.
As can be seen in Figure 3, 4, the buses in the same voltage level as the faulted bus show consistent dynamic performance in reduced and original systems. They affect each other significantly since they couple more tightly and the impedance between them is small. Once a fault occurs, the voltage fluctuated in a wide range. On the other hand, buses in the other voltage level only fluctuating in a narrow range during the fault due to the large impedance. They show some similarity during the fault and the same steady value afterwards. But they differ in some extent right after the fault. General speaking, these verify the effectiveness of the proposed method.

5. Conclusions
The conclusions can be made as follows:
(1) The method proposed in this paper can make the reduced equivalent system has a very similar static performance, e.g. the power flow and short-circuit current, as that of the original system.
(2) The proposed method explicitly models the interaction between multiple HVDC systems. Thus, the dynamic performance is more accurate especially when multiple HVDC systems are coupled closely, just can been seen in figure 3, 4. The buses in different voltage levels share similar dynamic performance during fault and after settled down.

(3) The method proposed by this paper is very easy to implement in the off-the-shelf transient stability programs.

References
[1] Chang H and Fan J 2006 System Design and its Localization of UHVDC Transmission Project Power System Technology 30(16) 1-5 (in Chinese)
[2] Zhu Y, Jiang W and Wu Y 2008 Influence of UHVDC Control and Protection Characteristics on Inner Overvoltage Power System Technology 32(8) 6-9 (in Chinese)
[3] Kang Y, Lu S and Cheng L 2017 A Reduction Method of Large Power Systems for Electromagnetic Transient Simulation and Its Application in China Southern Grid Electric Power Construction 38(1) 31-38 (in Chinese)
[4] Weng H, Xu Z and Wang X 2012 A Reduction Method for AC/DC System of China Southern Power Grid Power System Technology 3(3) 108-12 (in Chinese)
[5] Dong H, Weng H, An F, et al. 2014 Reduction and modelling method of large-scale alternating current/direct current power systems for electromagnetic transient simulation Iet Generation Transmission & Distribution 8(10) 1667-1676
[6] Weng H, Xu Z 2012 Dynamic reduction of large-scale AC/DC power systems via retaining the trunk network International Journal of Electrical Power & Energy Systems 43(1) 1332-1339
[7] Sun J, Guo X and Zhang J 2009 Dynamic Characteristics of Receiving-End of Multi-Infeed HVDC Power Transmission System Power System Technology 33(4) 57-60 (in Chinese)
[8] Li Z, Han W and Huang L 2010 Construction and Analysis of the RTDS Testing Platform for Islanding Operation of Yunnan-Guangdong UHVDC System Southern Power System Technology 4(2) 47-51 (in Chinese)
[9] Xu Z 2004 Analysis of hybrid AC/DC power systems the China Machine Press (in Chinese)
[10] Guo X, Guo J and Wang C 2015 Practical Calculation Method for Multi-infeed Short Circuit Ratio Influenced by Characteristics of External Characteristics of DC System Proceedings of the CSEE 35(9) 2143-51 (in Chinese)
[11] Zhang B, Chen S and Yan Z 2007 Advanced power system analysis (2nd edition) the Tsinghua University Press (in Chinese)
[12] CIGRE Working Group B4.41.Systems with multiple DC infeed. Paris: CIGRE, 2008
[13] Aik D and Andersson G 2013 Analysis of Voltage and Power Interactions in Multi-Infeed HVDC Systems IEEE Trans. on Power Delivery 28(2) 816-24
[14] Shao Y, Tang Y 2013 Analysis of Influencing Factors of Multi-Infeed HVDC System Interaction Factor Power System Technology 37(3) 794-799 (in Chinese)
[15] Gao L 2014 Numerical optimization method The Peking University Press (in Chinese)
[16] Yang W, Jia Y and Lei X 2018 Analysis of Simulation Calculation and On-site System Test Results for Xitai UHVDC Project with Hierarchical Connection to 500 kV/1000 kV AC Grid Power system Technology 42(7) 2255-61 (in Chinese)