Journal of Power and Energy Engineering, 2015, 3, 41-48
Published Online April 2015 in SciRes. http://www.scirp.org/journal/jpee
http://dx.doi.org/10.4236/jpee.2015.34007

Research on the Voltage Interaction of Multi-Infeed HVDC System and Interaction Factor

Shengjun Zhou[1], Guangyao Qiao[1], Chuan He[2*], Wenhui Wang[2], Tianqi Liu[2]

[1]State Grid Corporation, State Grid Smart Gird Research Institute, Beijing 102200, China
[2]School of Electrical Engineering and Information, Sichuan University, Chengdu 610065, China
Email: [*]jokerscu@gmail.com

Received December 2014

Abstract

In multi-infeed HVDC system, the interactions and influences between DC systems AC systems are complex as the electrical distances among DC converter stations which are relatively short. Multi-infeed interaction factor (MIIF) can effectively reflect the interaction among DC systems. The paper theoretically analyzes the impact factors of MIIF like the electrical distances between two DC converter stations and the equivalent impedance of the receiving end AC system. By applying the Kirchhoff's current law on the inverter AC bus, the paper deduces the analytical expressions for MIIF. From the expression, it is clear how the equivalent impedance of AC system and coupling impedance can affect MIIF. PSCAD simulations validate the effectiveness and the correctness of the proposed expression and some useful conclusions are drawn.

Keywords

Multi-Infeed HVDC, Inverter Bus Voltage, Voltage Interaction, Interaction Factor, Equivalent Impedance, Coupling Impedance

1. Introduction

With the increase of HVDC transmission lines, AC-DC parallel systems and the structure of multi-infeed DC systems will inevitably occur. A multi-infeed HVDC system is formed while inverter stations of a multi-terminal HVDC are connected to the same AC system [1]-[3]. For these types of systems, interactions among AC systems and DC systems can influence the characteristics of each other. The voltage interaction among inverter buses is a subject worthy of further study in a multi-infeed HVDC system. The characteristics of interactions in the multi-infeed HVDC system have great influence on the safe and stable operation of the whole power system [4] [5]. In-depth analysis of the relationship between the voltages of inverter station buses helps us to understand related problems.

Multi-infeed interaction factor (MIIF) proposed by CIGRE working group WG B4-41 based on the definition

[*]Corresponding author.

How to cite this paper: Zhou, S.J., Qiao, G.Y., He, C., Wang, W.H. and Liu, T.Q. (2015) Research on the Voltage Interaction of Multi-Infeed HVDC System and Interaction Factor. *Journal of Power and Energy Engineering*, **3**, 41-48.
http://dx.doi.org/10.4236/jpee.2015.34007

of voltage interaction among converter stations is a very important indicator in multi-infeed HVDC systems [6] [7]. However, present methods of calculating the interaction factors are through simulations [8] [9]. The physical meaning is unclear, and could not explain the internal reasons of interaction among subsystems. This makes the interaction factors lack of foresight [10], and unable to reflect the changes in the system structure and other influencing factors. Therefore, further studies on interactions among converter bus voltages and the analytical expressions of MIIF along with its influence to multi-infeed HVDC system have important meanings.

Reference [11] conducts a deep and detailed study on multi-terminal HVDC based on the multi-infeed short-circuit ratio defined by MIIF. Reference [12] gives the formula to calculate MIIF based on reduced Jacobian matrix of power flow, and also studies the effects of different DC system control methods on MIIF. In [13], the analytical expression of MIIF is derived by impedance matrix of system buses, and considers its influence on commutation failure. In [14], the relationship between MIIF and commutation failure is given through theoretical analysis and proved by simulations. Furthermore, methods and criteria to quickly determine commutation failure are presented. However, for a large system, inverting the admittance matrix may require large number of computations.

To overcome the drawbacks mentioned above, the paper analyzes the influences on MIIF like electrical distances between two DC converter stations and the equivalent impedance of the receiving end AC system. And the analytical expression based on system admittance to calculate MIIF is deduced using Kirchhoff's current law on the inverter AC bus. Theoretical analysis and PSCAD simulations of the analytical expression are given in an extended CIGRE standard HVDC system.

2. Multi-Infeed Interaction Factor

Multi-infeed interaction factor (MIIF) was proposed by CIGRE WG B4 Working Group in 2008 as the working guide to measure the interactions among multi-infeed HVDC converter stations [6]. In the indicator, the voltage of inverter bus is chosen as a parameter because it mostly reflects the interaction. The definition of MIIF is: induce an approximate 1% step voltage ΔU_i at bus i through the artificial switched connection of a shunt reactive element. Then observe the voltage change at bus j ΔU_j which is shown in **Figure 1**. Equation (1) defines that the ratio of these two voltages is MIIF.

$$\mathrm{MIIF}_{ji} = \frac{\Delta U_j}{\Delta U_i} \tag{1}$$

2.1. Range of MIIF

As it can be seen from the definition of MIIF, if two buses are infinitely far apart, then MIIF is 0. If two buses are connected to the same AC bus, MIIF equals 1. The range of MIIF is shown in **Figure 2**.

2.2. The Unsymmetrical Feature of MIIF

Generally speaking, $\mathrm{MIIF}_{ji} \neq \mathrm{MIIF}_{ij}$, and this will be proven in the next chapter. Large numbers of simulations indicate that the MIIF of a strong AC system to a weak AC system is high and the MIIF of weak AC system to a strong AC system is low. This is so because a 1% voltage drop in converter bus connected to a strong AC system can cause the voltage of nearby converter buses connected to weak AC systems to drop dramatically, hence

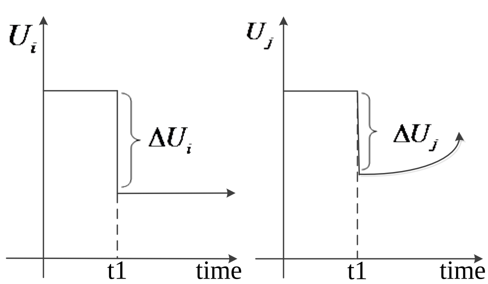

Figure 1. Determining the MIIF between two buses.

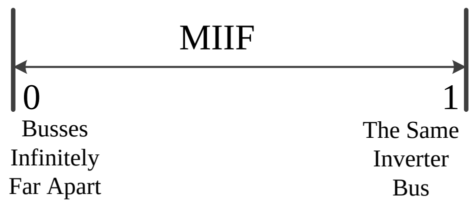

Figure 2. Range of MIIF.

$\text{MIIF}_{\text{weak system,strong system}}$ is high. On the contrary, a 1% voltage drop in converter bus connected to a weak AC system will not influence the voltage of nearby converter buses connected to strong AC systems, hence $\text{MIIF}_{\text{strong system,weak system}}$ is low.

3. Analytical Expressions of MIIF

In order to analyze MIIF of a multi-infeed HVDC system, the paper uses the simplified standard model, as shown in **Figure 3**.

In **Figure 3**, E_n denotes the effective value of AC power line voltage; X_{Nn} denotes the equivalent reactance of AC systems; U_n denotes the voltage of converter bus; n_n denotes the ratio of converter transformer; X_{cn} denotes commutation reactance; I_{Ln} denotes the line current flow to node N in converter unit; X_{fn} denotes the capacitive reactance of reactive power compensation device at inverter buses.

Define node N as the reference node, and apply Kirchhoff's current law on the inverter bus *N*, we obtain:

$$I_{1n} + I_{2n} + \cdots + I_{(n-1)n} + I_{Ln} + I_{fn} = I_{Nn} \tag{2}$$

where

$$\begin{cases} I_{Nn} = \dfrac{U_n - E_n}{X_{Nn}} \\ I_{(n-1)n} = \dfrac{U_{n-1} - U_n}{X_{(n-1)n}} \\ I_{Ln} = \dfrac{\sqrt{6}}{\pi} I_n \\ I_{fn} = -\dfrac{U_n}{X_{fn}} \end{cases} \tag{3}$$

Take Equation (3) into Equation (2), we get:

$$\frac{U_1 - U_n}{X_{1n}} + \frac{U_2 - U_n}{X_{2n}} + \cdots + \frac{U_{n-1} - U_n}{X_{(n-1)n}} + \frac{\sqrt{6}}{\pi} I_n - \frac{U_n}{X_{fn}} = \frac{U_n - E_n}{X_{Nn}} \tag{4}$$

Solve Equation (4),

$$U_n = \left(\frac{E_n}{X_{Nn}} + \frac{U_1}{X_{1n}} + \frac{U_2}{X_{2n}} + \cdots + \frac{U_{n-1}}{X_{(n-1)n}} + \frac{\sqrt{6}}{\pi} I_n \right) \left(\frac{1}{X_{Nn}} + \frac{1}{X_{1n}} + \frac{1}{X_{2n}} + \cdots + \frac{1}{X_{(n-1)n}} + \frac{1}{X_{fn}} \right)^{-1} \tag{5}$$

Define $Y_{nn} = \dfrac{1}{X_{Nn}} + \dfrac{1}{X_{1n}} + \dfrac{1}{X_{2n}} + \cdots + \dfrac{1}{X_{(n-1)n}} + \dfrac{1}{X_{fn}}$ as the self-admittance of bus *N*, then Equation (5) can be simplified as:

$$U_n = \left(\frac{E_n}{X_{Nn}} + \frac{U_1}{X_{1n}} + \frac{U_2}{X_{2n}} + \cdots + \frac{U_{n-1}}{X_{(n-1)n}} + \frac{\sqrt{6}}{\pi} I_n \right) \times \left(Y_{nn} \right)^{-1} \tag{6}$$

From Equation (6), it can be inferred that the voltage of bus *j* is:

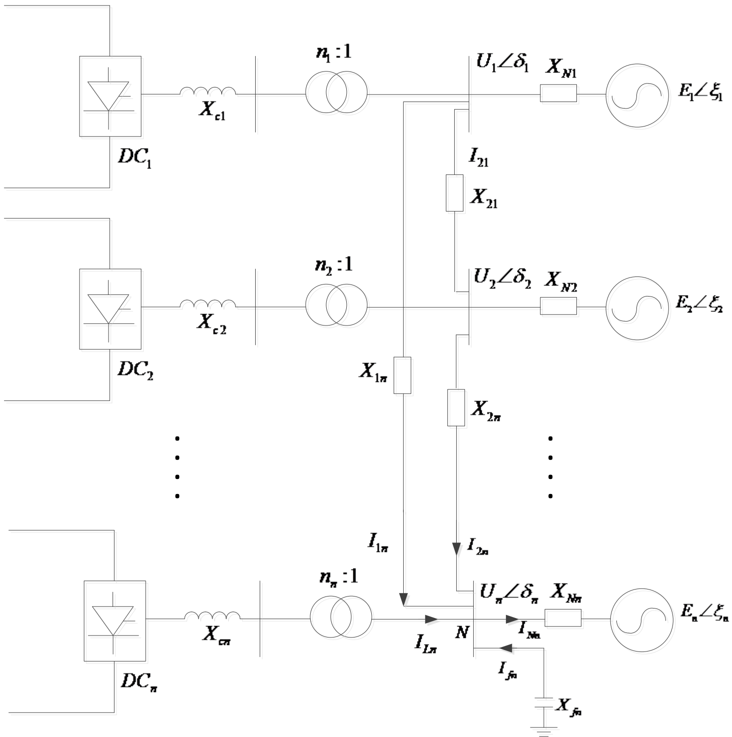

Figure 3. A multi-infeed HVDC system.

$$U_j=\left(\frac{E_j}{X_{Nj}}+\frac{U_1}{X_{1j}}+\frac{U_2}{X_{2j}}+\cdots+\frac{U_i}{X_{ij}}+\cdots+\frac{U_{j-1}}{X_{(j-1)j}}+\frac{U_{j+1}}{X_{(j+1)j}}+\cdots+\frac{U_n}{X_{nj}}+\frac{\sqrt{6}}{\pi}I_j\right)\times\left(Y_{jj}\right)^{-1} \tag{7}$$

Here we assume a voltage drop at bus *i*, and within a short time, the voltage of other buses do not change. Therefore, we obtain the voltage change at bus *j*:

$$U_j+\Delta U_j=\left(\frac{E_j}{X_{Nj}}+\frac{U_1}{X_{1j}}+\cdots\frac{U_i+\Delta U_i}{X_{ij}}+\cdots+\frac{U_n}{X_{nj}}+\frac{\sqrt{6}}{\pi}I_j\right)\times\left(Y_{jj}\right)^{-1} \tag{8}$$

Subtract Equation (7) from Equation (8), we have,

$$\Delta U_j=\left(\frac{\Delta U_i}{X_{ij}}\right)\times\left(Y_{jj}\right)^{-1} \tag{9}$$

Rearrange Equation (9), we get,

$$\frac{\Delta U_j}{\Delta U_i}=\frac{Y_{ij}}{Y_{jj}} \tag{10}$$

where Y_{ij} is the admittance between bus *i* and bus *j*, Y_{jj} denotes the self-admittance of bus *j*.

So the analytical expression of MIIF is as follows:

$$\mathrm{MIIF}_{ji}=\frac{\Delta U_j}{\Delta U_i}=\frac{\left|Y_{ij}\right|}{\left|Y_{jj}\right|} \tag{11}$$

4. Theoretical Analysis

Take a dual-infeed HVDC system as example. In real systems, it is known that $X_{f1}\gg X_{N1}$ and $X_{f2}\gg X_{N2}$. So the MIIF of bus 1 and bus 2 are simplified as Equations (12) and (13).

$$\mathrm{MIIF}_{21}=\frac{|Y_{12}|}{|Y_{22}|}=\frac{X_{N2}}{X_{N2}+X_{12}} \tag{12}$$

$$\mathrm{MIIF}_{12}=\frac{|Y_{12}|}{|Y_{11}|}=\frac{X_{N1}}{X_{N1}+X_{12}} \tag{13}$$

From Equations (12) and (13), it can be seen that MIIF_{21} is basically not affected by X_{N1}. However MIIF_{12} is greatly affected by X_{N1} where MIIF_{12} increases as X_{N1} increases. MIIF_{12} is not influenced by X_{N2} while MIIF_{21} is affected by X_{N2} where MIIF_{21} increases as X_2 increases. Both MIIF_{21} and MIIF_{12} are influenced by X_{12} where they both decrease as X_{12} increases.

We then extend the conclusion to multi-infeed HVDC system. MIIF_{ji} increases as the equivalent impedance of AC system corresponding to the *j*th converter station $X_{\mathrm{N}j}$ increases. And that means if the equivalent impedance of its corresponding AC system is great, then the inverter bus voltage of this particular converter station can be greatly influenced by other converter stations. Moreover, the influence to this particular converter station by other converter stations increases as their electrical distance decreases.

5. Simulations

Based on the CIGRE standard system, we in built a dual-infeed HVDC system. DC inverters are connected to each other through coupling impedance on the inverter buses while rectifiers are independent from each other as shown in **Figure 1** The rectifiers use constant current control and inverters use constant extinction angle control. We adopt the initializing parameters of the system from [15] where the equivalent impedance of AC system is $z_1 = z_2 = 5.4984 + j20.466\ \Omega$ and the coupling impedance is $z_{12} = 0.5 + j6.2832\ \Omega$. At 2.5 seconds, a three-phase shunt reactor is artificially switched in to cause the voltage of bus 1 to drop about 1%. In order to reduce the influence of ripple wave, we add a FFT module before bus voltages and use the DC output as the effective value of bus voltages. This is case 1 and simulation results are shown in **Figure 4**.

From **Figure 4**, it can be seen that the voltage of bus 1 drops from 0.9852 p.u. to 0.9755 p.u. while the voltage of bus 2 drops from 0.9851 p.u. to 0.9767 p.u..The MIIF_{21} is calculated from Equation (1) to be 0.8660.

Here we change the equivalent impedance of AC system connected to bus 2 to be $z_2 = 5 + j18\ \Omega$, and calculate MIIF_{21}. This is case 2. Then we introduce a three-phase shunt reactor at bus 2 to analyze the asymmetrical feature of MIIF. This is case 3. Simulation results of case 2 and case 3 are shown in **Figure 5** and **Figure 6** respectively.

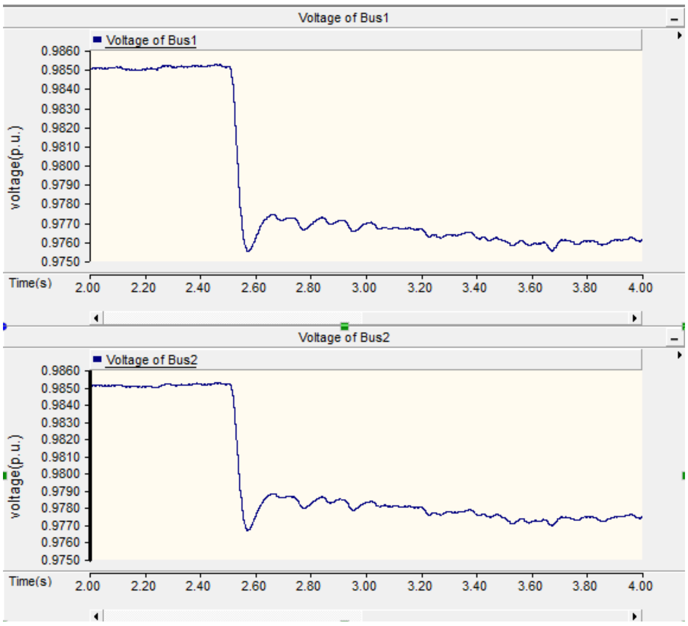

Figure 4. Voltage drops in bus 1 and bus 2 of case 1.

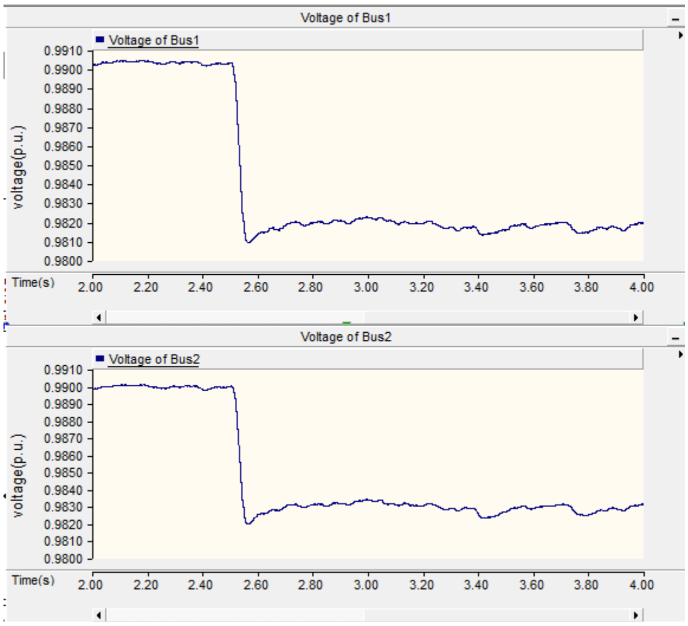

Figure 5. Voltage drops in bus 1 and bus 2 of case 2.

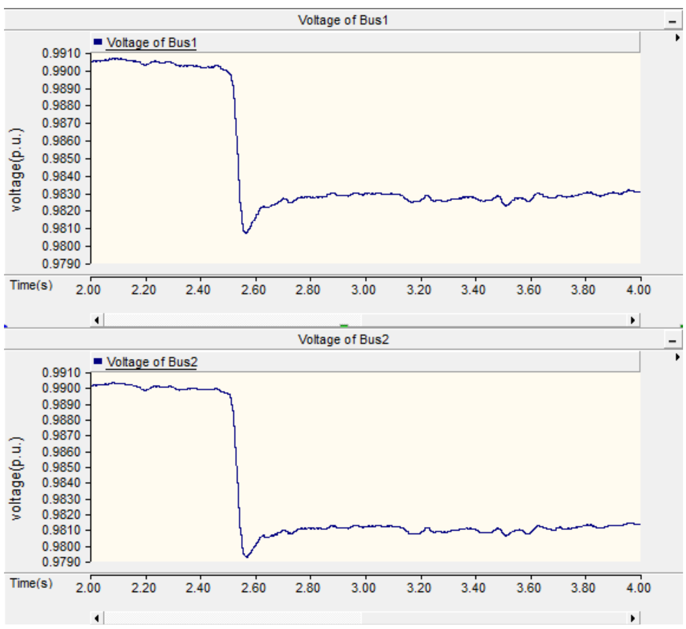

Figure 6. Voltage drops in bus 1 and bus 2 of case 3.

Then based on the original state, we change the coupling impedance to be $z_{12} = 0.75 + j9.4248\ \Omega$ to analyze the variation of $MIIF_{21}$. This is case 4 and result is shown in **Figure 7**.

The simulation results and analytical results of $MIIF_{21}$ with different AC system equivalent impedance z_1, z_2 and coupling impedance z_{12} are shown in **Table 1**. The simulation results and analytical results of $MIIF_{12}$ are shown in **Table 2**.

As it is shown in **Table 1**, **Table 2** and **Figures 4-7**, the results of simulation and theoretical calculation are basically the same. $MIIF_{21}$ increases as the coupling impedance decreases and decreases as the equivalent impedance of connected AC system decreases. Similarly, $MIIF_{12}$ shows the same characteristic. The proposed method to calculate MIIF has approximately 10% error compared to simulation result which can be concluded that it is a fast way to get a relatively accurate value of MIIF and has some worthiness to the study of multi-infeed

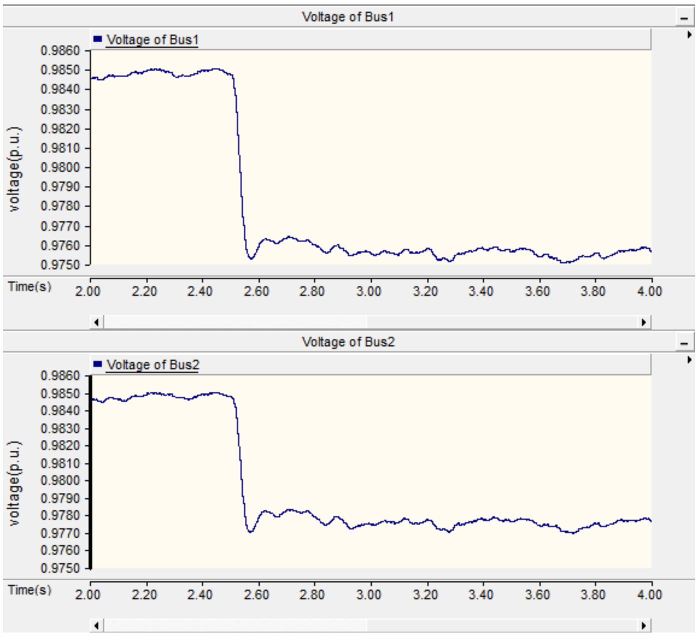

Figure 7. Voltage drops in bus 1 and bus 2 of case 4.

Table 1. Value of $MIIF_{21}$ with different z_1, z_2 and z_{12}.

$z_1(\Omega)$	$z_2(\Omega)$	$Z_{12}(\Omega)$	Simulation results	analytical results
5.4984 + j20.466	5.4984 + j20.466	0.5 + j6.2832	0.8660	0.7730
5.4984 + j20.466	5 + j18	0.5 + j6.2832	0.8468	0.7503
5.4984 + j20.466	5.4984 + j20.466	0.75 + j9.4248	0.7780	0.6940

Table 2. Value of $MIIF_{12}$ with different z_1, z_2 and z_{12}.

$z_1(\Omega)$	$z_2(\Omega)$	$Z_{12}(\Omega)$	Simulation results	analytical results
5.4984 + j20.466	5.4984 + j20.466	0.5 + j6.2832	0.8650	0.7730
5.4984 + j20.466	5 + j18	0.5 + j6.2832	0.8642	0.7730
5.4984 + j20.466	5.4984 + j20.466	0.75 + j9.4248	0.7405	0.6940

HVDC system. It should be noted that simulation results prove the symmetrical feature of MIIF which is $\mathrm{MIIF}_{21} \neq \mathrm{MIIF}_{12}$ when $z_1 \neq z_2$.

6. Conclusions

The paper analyzes the voltage interactions among inverter buses in a multi-infeed HVDC system. By applying the Kirchhoff's current law on the inverter AC bus, the paper deduces the analytical expression of the Multi-infeed interaction factor. And some useful conclusions are drawn. MIIF_{ji} and MIIF_{ij} decrease as the coupling impedance z_{ij} increases, *i.e.* if converter station *i* and converter station *j* are electrically closeed, the interaction is strong. MIIF_{ji} decreases as the equivalent impedance of the connected AC system corresponding to converter station *j* decreases, *i.e.* if one converter station has great equivalent impedance of the connected AC system, it is likely to be greatly affected by other converter stations.

Simulation results validate the accuracy and effectiveness of the proposed analytical expression of MIIF along with its theoretical analysis. It gives guidance and principle to improve the structure of power network and how to choose a good location of the receiving end of a new HVDC line.

Acknowledgements

This work is supported by Science and Technology Projects of State Grid Corporation (SGRIDL7114006).

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