AC/DC Power Flow Algorithm Considering Various Controls Transformation

Bin Yang, Lei Chuang, Lin Zhu, Cheng Guo, Zhiyi Gu, Zilong Wang
Benxi Electric Power Supply Company
State Grid Liaoning Electric Power Co., Ltd
Benxi, China
9392957@qq.com

***Abstract*—in the power flow solution of AC/DC systems, the problem of how to describe the transformation of HVDC system control method effectively must be considered for operation and analysis of actual power system. In this paper, the conversion conditions of control modes of HVDC system are presented, especially the mutual conversion of control variables of rectifier side and inverter side, and the program for power flow are presented, which based on the method of equivalent power and principle of alternant decouple solving in AC/DC system. The control effect and mutual conversion of the main control modes in HVDC system are considered in this program. The DC circuit in the EPRI-36 was modified as an example for detailed calculation and analysis through the function of user program interface (UPI) of power system analysis software package (PSASP). The AC bus voltage of rectifier side and inverter side are regulated, and calculating the power flow for the corresponding operation state. The result shows that this algorithm can deal with transformation of operating mode caused by the change of operating conditions and are favorable to power flow calculation and simulation of large scale power systems.**

Keywords—HVDC; control method transformation; AC/DC power flow calculation; PSASP; UPI

I. INTRODUCTION

With Direct-current transmission technology become ripe in electrical power system, HVDC system has been extensively used in long distance large capacity transmission and regional power grids are interconnected [1]. Therefore research on operation and control of AC/DC power network become more urgent.

There are flexible control mode in HVDC system. The main control mode include constant power control(CP); constant current control(CC); constant trigger angle control (CIA) and constant arc extinguishing angle control(CEA); constant voltage control, etc. The control mode can change on the basis of changes in operating conditions [2]. Meanwhile HVDC system are equipped transformer tap controller slow speed control equipment. In practice fast control and slow control are combined organically, ensure the system is in optimal operation state.

Because of HVDC system steady state operation and control mode is intricacy. Scholars research much investigations on control strategies transform and AC/DC power flow algorithm. In literature[3], aim at CIA and CEA control mode change when rectifier voltage rise or inverter voltage down. In literature[4], research on constant power control; constant current control; minimum trigger angle control and extinguishing angle control, but transformer tap adjustment integrate with converter control mode conversion needs to be improved. In literature[5], research on HVDC system power flow matrix irreversible condition in certain control mode and direct at these condition improvement alternate solution algorithm, but how to get combining the multiple control modes are interchangeable with AC/DC flow algorithm will need improvement.

The power flow algorithm of AC/DC system to be divided two classes, uniform iteration and alternate iteration. Coupling between AC and DC variables are considered for uniform iteration and presented good convergence with calculation of network and operation conditions. But its order of jacobian matrix is bigger than AC matrix, so the uniform iteration high requirements for programming; memory intensive; long computation time. Alternate iteration, AC/DC system flow equation is solved separately, therefore entire program constitute any of the existing AC flow program and DC system flow module. Furthermore alternate iteration is also easier to consider the constraint condition of dc variable and the reasonable adjustment of operation mode in calculation. However, the convergence of alternate iterative is not as good as the uniform iterative [6].

The algorithm is proposed in this paper consider for the main control mode effect and mutual conversion process of HVDC systems.

II. TRANSFORMING OF STATIC CONTROL MODE IN HVDC SYSTEM

The DC current flowing from the rectifier to inverter is follows [7]:

$$I_d = \frac{U_{d0r}\cos\alpha - U_{d0i}\cos\gamma}{\frac{3X_{Tr}}{\pi} + R_d - \frac{3X_{Ti}}{\pi}} \tag{1}$$

In (1), r is the rectifier side, i is the inverter side; I_{d} is the DC current; U_{d0} is the converter transformer no-load DC voltage; X_{T} is leaky reactance of converter transformer at converter valve side; α is trigger lag angle; γ is the inverter arc extinction angle; R_{d} is DC line resistance.

By (1), DC voltage and current depending on four variables: α, γ, U_{d0r} and U_{d0i}. They are control variable of DC system. In normal operation, basic mode of operation is follows:

Rectifier constant current control(CC):

$$I_d = I_{di}^{SP} \tag{2}$$

Rectifier constant trigger angle control(CIA):

$$I_d = \frac{\sqrt{2}E_{ac}T}{X_c}\cos\alpha_{di}^{SP} - \frac{\pi}{3X_c}U_d \tag{3}$$

Inverter constant arc extinguishing angle control (CEA):

$$I_d = \frac{\sqrt{2}E_{ac}T}{X_c}\cos\gamma_{di}^{SP} - \frac{\pi}{3X_c}U_d \tag{4}$$

Inverter constant voltage control(CV):

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$$U_d = U_{di}^{SP} \tag{5}$$

SP indicates setting value. All other control ways are changed by system condition change and some of the variables overshooting, they mainly include voltage changing of rectifier side and contravariant side.

Voltage (U_{tr}) change of rectifier side:

1) U_{tr} reduction, rectifier transformer ratio (T_r) reductive with keeping the α. When the T_r to the minimum ratio (T_r^{min}), the tap adjustment loses effect. It need reductive α for voltage reduction and keeping I_d constant.

2) When the U_{tr} reductive continually, the α to minimum, inverter side is not kept I_d constant. So the current control is transferred to the inverter side. There are current mutation in the control mode conversion because of current margin between rectifier and inverter.

3) U_{tr} continue to decrease, $U_{dr,}$ U_{di} decrease too, result in γ gain to a degree, γ_{min} oversize with the conversion failed, DC system stop running.

4) When the U_{tr} rise, the T_r increase, to the T_r^{max}, that will increase the α. If α_{max} over the mark, DC system stop running.

Voltage (U_{ti}) change of inverter side:

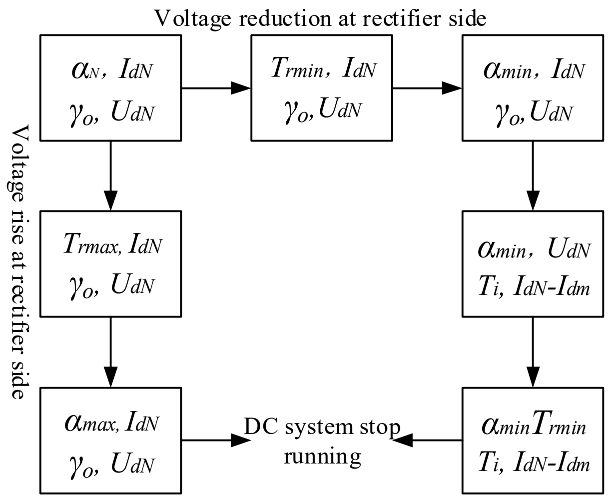
1) U_{ti} decline, inverter side transformer ratio T_i decline, when the T_i to T_i^{min}, the transformer tap is lost regulating effect. The γ will been declined for maintained DC voltage. If the γ less than γ_{min}, the inverter commutation failure and DC system stop running.

2) When the U_{ti} rise, inverter side transformer ratio (T_i) increase with keeping the DC voltage, to T_i^{max}, the transformer ratio loses effect.

3) U_{ti} continually rise, rectifier side transformer ratio (T_r) increase to the T_r^{max}, the rectifier side transformer ratio loses effect.

4) U_{ti} continually rise, increasing the α. If to α_{max} that will increase γ angle, U_{ti} continually rise, γ oversize result in the conversion failed and DC system stop running.

The above process can be expressed as fig.1.



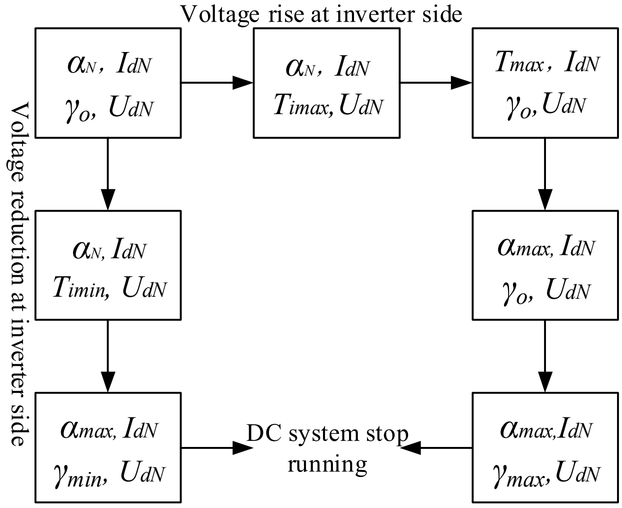


Fig.1 Control model conversion of HVDC system

If the T_r, T_i ,α, γ indicated as constant, DC system is lost regulating effect. Rectifying side DC voltage following AC system voltage changing. Power flow calculation results as shown in the fig.2.

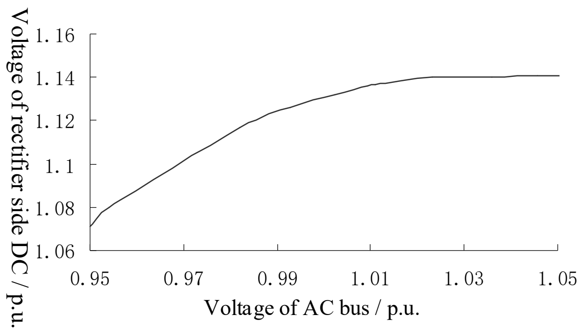


Fig.2 Power flow calculation results without DC regulation

From fig.2, without regulating effect in DC system, the voltage change of DC system is very obvious and can not maintain the stability of DC system transmission power. It also does not echo the actual operation of DC transmission system. Therefore in AC/DC system power flow calculation, the mode of control and its role of rotation must be considered.

III. Algorithm Research

A. Mathematical Model of Convertor

AC-DC system interface as shown in the fig.3.

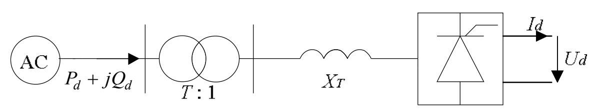


Fig. 3 Interface of AC/DC system

In Fig. 3, T is converter transformer ratio; U_d is dc line voltage; P_d, Q_d is active and reactive power is injected for AC system.

The Mathematical Model of HVDC system as follows:

$$\begin{cases} U_{d0} = \dfrac{3\sqrt{2}\dot{U}_t}{\pi T} \\ d_x = 3X_T / \pi \\ U_d = U_{d0}\cos\theta - d_x I_d \\ \mu = \beta - \arccos\left(\dfrac{\sqrt{2}I_d X_T T}{E_{ac}} + \cos\beta\right) \\ \theta = \beta - \mu \\ P_d = U_d I_d \\ Q_d = \dfrac{\mu - \sin\mu\cos(2\theta+\mu)}{\sin\mu\sin(2\theta+\mu)} P_d \end{cases} \tag{6}$$

In (6), $\dot{U}_t$ is effective value of AC bus voltage of converter transformer; β is advance angle of trigger; μ is commutation angle; θ is trigger lag angle or inverter arc extinction angle.

B. Correction of Power Flow Equations for AC Systems

Consider the influence of DC system on AC power injection, AC system traditional flow party program changed:

$$\begin{cases} \boldsymbol{\Delta P} = \boldsymbol{P}_s - \boldsymbol{P}_{ac}(\boldsymbol{\delta},\boldsymbol{V}) - \boldsymbol{P}_d(\dot{\boldsymbol{U}}_{tr},\dot{\boldsymbol{U}}_{ti}) \\ \boldsymbol{\Delta Q} = \boldsymbol{Q}_s - \boldsymbol{Q}_{ac}(\boldsymbol{\delta},\boldsymbol{V}) - \boldsymbol{Q}_d(\dot{\boldsymbol{U}}_{tr},\dot{\boldsymbol{U}}_{ti}) \end{cases} \tag{7}$$

In (7), P_s, Q_s is power injection of filter, reactive power compensation device or load; P_{ac}, Q_{ac} is power injection of AC system; P_d, Q_d is power injection of DC system. On the basis of (6), the P_d and Q_d are acquired, so in (7) without DC variate. The equation (7) can solve of Newton method or PQ method.

Its iterative computation process as follows:

$$\begin{cases} P_d = f(U_{tr}, U_{ti}) \\ Q_d = g(U_{tr}, U_{ti}) \end{cases} \tag{8}$$

$$\Delta \boldsymbol{P} / \boldsymbol{U} = \boldsymbol{B}' \Delta \boldsymbol{\delta} \tag{9}$$

$$\Delta \boldsymbol{Q} / \boldsymbol{U} = \boldsymbol{B}'' \Delta \boldsymbol{U} \tag{10}$$

1) On the basis of (6) and the controlled conversion process in Fig.1, solve an equation (8), because of the DC injection power is nothing with phase angle of node voltage, introduction of DC system with P-θ iterative matrix B' have no effect. According to new DC system variables to correct Q-U iterative matrix B'' .

2) Computing $\Delta P/U$ to solve (9) and update δ.

3) Computing $\Delta Q/U$ to solve (10) and update U.

4) Back to step *1)*, and until iterative convergence.

IV. ANALYSIS OF EXAMPLES

In (6), P_d and Q_d is power injection are joined in AC system. The reactive power of equation (6) are calculated more accurately than mathematic model of PSASP. With the reactive power of inverter side is computed to include γ, that can more accurately be estimated condition of commutation failure, for transient stability calculation are provided accurately by the power flow calculation results[9].

User program interface (UPI) of PSASP provide function and environment that make the PSASP and UPI module jointly completing a computational task. In Windows OS, the dynamic link libraries (.DLL) file can be used, that make PSASP call the DLL files and provide good user support[10]. With VC++6.0, the empty project of "Win32 Dynamic-Link Library" are set up, then it joins the empty project that the UPI files had been edited. The DLL file is to complete set up.

In EPRI-36 example system, AC/DC system power p.u. basic value S_B=100MVA; voltage p.u. basic value U_B=220kV; current, impedance basic value can be acquired by calculation; α rated value 20°, variation range 5°~40°; γ rated value 15°, variation range 5°~40°; current margin 15%; DC rated transmission power 300MW; rated current 0.6kA, DC resistance R_d=13.2Ω; bipolar operation. For clearly make out the control mode conversion of DC system, in calculation program, the adjustment range of transformer ratio is properly decreased. Detailed parameters as follow:

TABLE I. OTHER PARAMETERS OF HVDC SYSTEM

Converter type	***AC bus***	***Maximum ratio T_{max}***	***Minimum ratio T_{min}***	***Converter transformer leakage reactance /p.u.***	***Monopole compensating capacity / p.u.***
rectifier	bus 33	2.2	2.1	0.0182	0.5
inverter	bus 34	2.3	2.05	0.0152	0.5

A. Voltage Change on Rectifier Side

In rectifier AC bus33, increasing the load and setting as PQ node. The active and reactive power of the load are adjusted, that make the rectifier AC bus voltage variation in the range of 0.87~1.07p.u.; the relationship between power and voltage as follows:

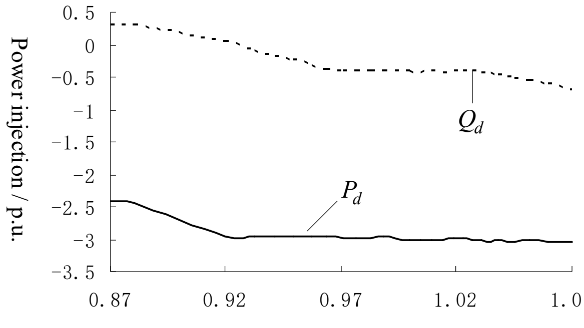


Fig. 4 Relationship between injection power and voltage

When the rectifier AC bus voltage changes, because of the regulating function of various control modes, Converter transformer ratio, the trigger angle and break angle of the converter changing situation as Fig. 5 and Fig. 6.

The Fig. 4, Fig. 5, Fig. 6 show, when the rectifier side AC bus voltage rises, for constant DC voltage and current constant, rectifier side transformer ratio T_r is risen. When the T_r to upper limit 2.2, the α is risen, in the wake of α increase, the reactive power absorbed of DC system from AC system increas obviously. When the AC bus voltage decline, first of all, reduce the T_r to lower limit 2.1, reduce trigger angle α . in the wake of α decrease, the reactive power absorbed of DC system from AC system reduce obviously. In case of α low, due to the action of compensation capacitance, DC system provide some reactive power to AC system. When the voltage drop to 0.93p.u., α drop to the $\alpha_{\min}$, the inverter side ratio T_{i} unchanged, DC current is controlled by the inverter side and reduce a current margin, the reduction of DC current reduces the active power of DC system. Ac bus voltage drop further, it make the inverter γ increasing. When it greater than $\gamma_{\max}$, DC system stop running.

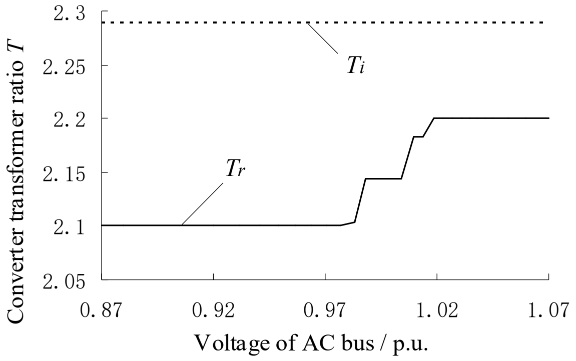


Fig. 5 Changes of rectifier transformer ratio

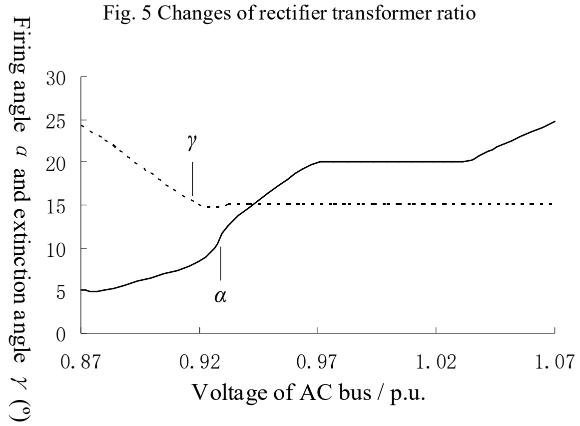


Fig. 6 Changes of α and γ

B. Voltage Change on Inverter Side

In inverter AC bus34, increasing the load and setting as PQ node. The active and reactive power of the load are adjusted, that make the inverter AC bus voltage variation in the range of 0.87~1.07p.u., the relationship between power and voltage as follows:

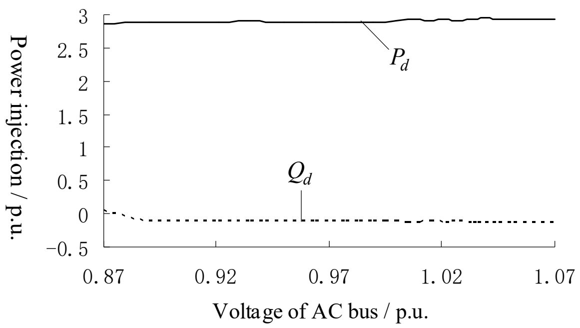


Fig. 7 Relationship between injection power and voltage

When the AC bus voltage change of inverter bus, because a variety of control mode adjustment function, the converter transformer ratio, the change of trigger angle and extinction angle of converter as Fig. 8, Fig. 9:

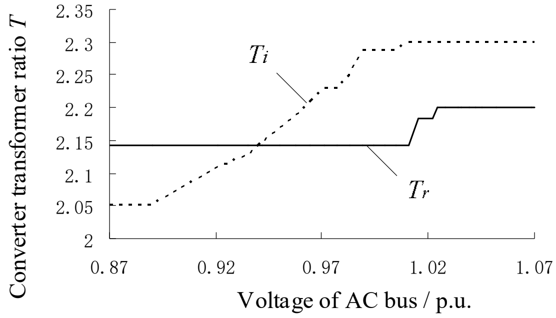


Fig. 8 Changes of transformer ratio

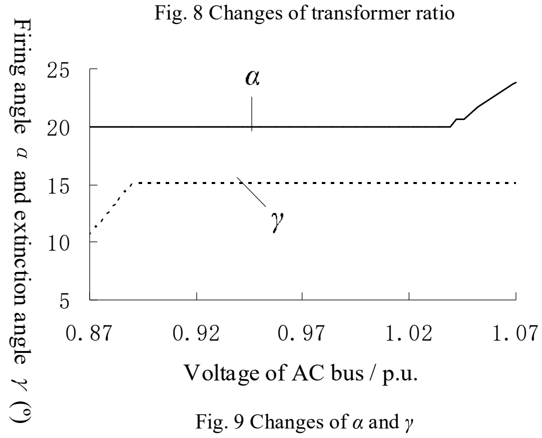


Fig. 9 Changes of α and γ

The Fig. 7, Fig. 8, Fig. 9 show, when the inverter side AC bus voltage reduce, for constant DC voltage and current constant, inverter side transformer ratio T_{i} is decreased. When the T_{i} to lower limit 2.05, the γ is decreased, in the wake of γ decrease, the reactive power absorbed of DC system from AC system reduce obviously. Due to the action of compensation capacitance, make the injection reactive power of the inverter is negative value. When the inverter side AC bus voltage rises, for constant DC voltage and current constant, inverter side transformer ratio T_{i} is risen. When the T_{i} to upper limit 2.3, the rectifier side transformer ratio T_{r} is risen, when the T_{r} to upper limit 2.2, the α is risen, when the α to upper limit, the γ is risen. Due to the small range of steady state voltage variation, when the voltage to 1.07 p.u. , the α does not reach the upper limit, so it does not have to adjust the γ.

As can be seen from the above: the algorithm can effectively deal with various control modes of DC system and the conversion process between them. If these cases are approximated, there will be large error.

V. Conclusion

This paper is based on the principle of power equivalence and alternating decoupling of AC/DC, The power flow calculation procedure of HVDC system is established, details are as follows:

1) In the user program interface (UPI) of power system analysis software package (PSASP), The HVDC system model use relatively accurate computational expressions. The calculation of reactive power is more detailed.

2) The program takes into that, when changes of running conditions, conversion of steady state operation mode of HVDC transmission, the variety of control functions are integrated and coordinated, it has practical engineering value.

REFERENCES

[1] Mao Xiao-ming, Zhang Yao, Zhang Yan. Survey on HVDC system modeling[J]. Electric Power Automation Equipment, 2007, 27(12): 14-17.

[2] Thukaram D, Jenkins L, Visakha K. Optimum allocation of reactive power for voltage stability improvement in AC-DC power systems[J]. IEE Proceedings-Generation, Transmission and Distribution, 2006, 153(2): 237-246.

[3] Zhou Shuangxi, Lu Jiali, Zhang Yuanpeng. Influence of HVDC on voltage stability[J]. Journal of Tsinghua University (Science and Technology), 1999, 39(3): 4 -7.

[4] Liu Chongru1, Zhang Boming. Transformation strategy for operation mode of converter in power flow calculation of AC/DC power systems[J]. Power System Technology, 2007, 31(9): 17-21.

[5] Liu Chongru, Zhang Boming, Sun Hongbin, et al. Advanced AC-DC Power Flow Algorithm Considering Various Controls[J]. Automation of Electric Power Systems, 2005, 39(21): 25-31.

[6] Wang Xi-fan, Fang Wan-liang, Du Zheng-chun. Modern power system analysis. Beijing: SciencePress, 2003.

[7] Xu Zheng. Dynamic analysis of AC/DC power system. Beijing: Machine IndustryPress, 2004.

[8] Shao Zhenxia，LI Xingyuan．Method of implementating digital simulation for HVDC controller[J]．Journal of sichuan university (Engineering Science Edition)，2002，34(2)：80-83

[9] Xu Decao, Han Minxiao, Ding Hui, et al. Modeling of HVDC Based on the User defined Model of PSASP[J], Automation of Electric Power Systems, 2007, 31(6): 71-76.

[10] PSASP manual. China Electric Power Research Institute. 2001