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Impact of HVDC line on the convergence property of AC/DC power flow calculation

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ABSTRACT

This paper explores the impact of HVDC line on the convergence property of AC/DC power flow calculation. Firstly, the model of AC/DC power flow computation is constructed, including unified method and alternate iterative method. Then, an improved Levenberg–Marquardt (LM) method with line search technique is developed to solve the nonlinear equations of AC/DC power flow. To test the convergence property of the proposed method, LM method with trust region technique and Newton method are also employed. The researches on the impact of heavy DC transmission power and multiple HVDC lines on the convergence property of AC/DC power flow calculation are made on a modified IEEE 118-bus AC/DC hybrid test system. Simulation results show that the developed method under the model of alternate iterative method is superior to other methods under different models in convergence property. For the influence of heavy DC transmission power on the convergence property, it is improved by the new parameter configuration of DC transmission line firstly and adding proper new shunt capacitor on the weak nodes secondly; for the influence of multiple DC transmission lines on the convergence property, it can also be improved by the change of control mode firstly and adding new shunt capacitor secondly, which are based on the least square solution obtained by proposed method under the model of alternate iterative method.

Introduction

With the introducing of large power electronic components into power system, especially for the high voltage direct current (HVDC) transmission line, these bring great challenges to the modern power system operation. How to improve the convergence property of AC/DC power flow calculation under the critical work conditions has also drawn great attention. Meanwhile, the sensitivity analysis, and the initial values of transient or steady state calculation in power system are relied on the power flow results. Therefore, it is of great significance to research the impact of HVDC line on the convergence property of AC/DC power flow calculation.

Currently, major approaches to improve the convergence property of AC/DC power flow calculation are based on the unified method or alternate iterative method [1–16]. In [8,9], the improved Levenberg–Marquardt method (LM) combined with trust region technique did a satisfied job to solve AC and DC equations, and explored the maximal expanding times of load withstood by AC/DC hybrid system. An improved method based on alternate iterative method for AC/DC power flow computation was presented in [10], and the convergence property could be improved by adjusting the converter transformer tap position. By introducing step size optimization multiplier to adjust the correction vector in the unified method and alternate iterative method, good convergence property could be obtained in [11–13]. An AC/DC power flow calculation model of steady-state voltage source converter multi-terminal direct current (VSC MTDC) has put forward in [14–16].

Although the improved methods in the literatures presented above improved the convergence property of AC/DC power flow under the critical work conditions or even the ill-conditioning cases, these work conditions with bad convergence property are primarily caused by heavy load or small impedance branches. Under the new situation, the operation of modern power system is becoming complicated than ever before due to introduction of HVDC transmission line or flexible AC transmission system, and the reasons for non-convergence of power flow are not the same as that in the traditional case, such as parameter configuration or control mode of DC transmission line, lack of reactive power in rectifier and inverter, and the jacobian matrix close to singularity.

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Unluckily, there are few references comprehensively analyzing the impacts of HVDC line on the convergence property of AC/DC power flow. Therefore, this appears to be some unsolved fundamental tasks. (i) Comparisons and analysis of improved approaches, based on the model of unified method and alternate iterative method respectively, to solve AC/DC power flow computation have not reported yet. (ii) Few references discussed and explored what was the maximal value of DC transmission power in HVDC line adding in the power system. (iii) Few references explored the correct parameter configuration and proper control mode of DC transmission line for improving convergence property of AC/DC power flow under the ill-conditioning case.

To tackle the identified problems above is the main job in this paper. Above all, to find a method with strong robust and good convergence property is the crucial basis for solving problems. Currently, the primary methods to solve the nonlinear equations of AC/DC power flow include Newton method, optimal multiplier method and Levenberg–Marquardt (LM) method. Newton method with quadratic convergence, was widely employed to solve nonlinear equations of power flow, whereas, the drawback of this method is sensitive to the initial values. Optimal multiplier method, fails to adjust the distribution of power flow and stagnant in the iterative process when the initial value is far from the solution, although it can always maintain the steepest descent direction. LM method, can not only change the iteration step size but also change the iteration direction in the iterative process, simultaneously. Besides, the solution of the nonlinear equations of power flow could be obtained by LM method without special operation on initial values when the initial point was far from the solution.

Luckily, the improved LM method combined with line search technique emerged [17–21], which showed that this method can bypass the approximate singular region of jacobian matrix in the iterative process by introducing damping factor μ_k. In addition, it has good convergence property for solving nonlinear equations and even performed well for ill-conditioning problems; it can also provide a least square solution when there exists no solution of the nonlinear equations of AC/DC power flow. Based on this improved LM method, the research to the impacts of HVDC line on the convergence property of AC/DC power flow calculation can be made, and the contributions of this paper are identified as follows. (1) Both unified method and alternate iterative method are employed to solve AC/DC power flow computation, which based on Newton method, LM method with line search technique and LM method with trust region technique [8,9,22–24], to solve nonlinear equations, respectively. Comparison and analysis of these methods to solve AC/DC power flow calculation are made. (2) The maximal value of DC transmission power in HVDC line adding in the power system is explored, and the corresponding limit operation state can be obtained. (3) The analysis of the impacts of heavy DC transmission power and multiple DC transmission lines on the convergence property are also made. (4) Under the ill-conditioning case, Newton method is divergent to solve AC/DC power flow computation while the proposed LM method, in some extent, can find least square solution. Based on the solution information provided by LM method, the convergence property of Newton method can be improved and the AC/DC power flow solution can also be obtained by adjusting parameter configuration or changing control mode of DC transmission line firstly, then adding new shunt capacitor on the corresponding weak node.

The following of paper is outlined as follows. Section "The mathematical model of AC/DC power flow" gives a brief introduction of the mathematical model of AC/DC power flow, including AC power flow equations and DC system equations. Section "Solution of AC/DC power flow" describes the unified method and alternate iterative method to solve AC/DC power flow calculation, respectively. The detailed procedures of LM method with line search technique to solve nonlinear AC and DC equations are presented in Section "Levenberg-Marquardt method with line search technique". A numerical example associated with a modified IEEE 118-bus AC/DC hybrid test system is shown in Section "Numerical example", followed by the relevant concluding remarks in Section "Conclusion".

The mathematical model of AC/DC power flow

AC power flow equation

For the AC node, the corresponding power flow equations can be described as follows:

$$\begin{cases} \Delta P_i = P_{Gi} - P_{Di} - U_i \sum_{j \in i} U_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) = 0 \\ \Delta Q_i = Q_{Gi} - Q_{Di} - U_i \sum_{j \in i} U_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) = 0 \\ i = 1, \ldots, N-1 \end{cases} \tag{1}$$

where P_{Gi}, Q_{Gi} are output of real power and reactive power by generator, P_{Di}, Q_{Di} are real and reactive load, U_i is the amplitude of node voltage, G_{ij}, B_{ij} are conductance and susceptance between node i and j, θ_{ij} is the difference of phase angle of voltage between node i and j, N is the number of AC node, respectively.

If a HVDC transmission line adds into power system, the corresponding DC power should be added to the AC power flow equations. For the specific DC node, (1) should be modified as (2).

$$\begin{cases} \Delta P_i = P_{Gi} - P_{Di} - U_i \sum_{j \in i} U_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) - U_{dk} I_{dk}\, sign(i) = 0 \\ \Delta Q_i = Q_{Gi} - Q_{Di} - U_i \sum_{j \in i} U_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) - U_{dk} I_{dk} \tan\varphi_k = 0 \end{cases} \tag{2}$$

where U_{dk} is the DC voltage, I_{dk} is the DC current, φ_k is the power factor angle, respectively. Both the rectifier and inverter consume reactive power. For the rectifier, it consumes real power, so $sign(i) = 1$. For the inverter, it provides real power, so $sign(i) = -1$.

DC system equation

In general, the DC system equations include converter voltage equations Δd_{1k} and Δd_{2k}, DC network equations Δd_{3k} and control equations Δd_{4k} and Δd_{5k}. The DC system equations can be written in (3) [25,26].

$$\begin{cases} \Delta d_{1k} = U_{dk} - k_{Tk} U_i \cos\theta_{dk} + X_{ck} I_{dk} \\ \Delta d_{2k} = U_{dk} - k_{\gamma} k_{Tk} U_i \cos\varphi_k \\ \Delta d_{3k} = sign(k) I_{dk} - \sum_{j=1}^{n_c} g_{dkj} U_{dj} \qquad (k = 1, 2, \ldots, n_c) \\ \Delta d_{4k} = d_{4k}(I_{dk}, U_{dk}, \cos\theta_{dk}, k_{Tk}) \\ \Delta d_{5k} = d_{5k}(I_{dk}, U_{dk}, \cos\theta_{dk}, k_{Tk}) \end{cases} \tag{3}$$

where k_{Tk} is the ratio of converter transformer; θ_{dk} is the trigger angle α_i for the rectifier; θ_{dk} is the extinction angle γ_i for the inverter; k_r is a constant, which is equal to 0.995 [25]; g_{dkj} is the elements of node conductance matrix in the DC network by eliminating the contact node; n_c is the number of converters, respectively. Two unknown variables can be eliminated due to the specific control mode Δd_{4k} and Δd_{5k}. Therefore, the number of unknown variables is identical to the number of equations. Then, AC/DC power flow calculation can be solved by unified method and alternate iterative method, respectively.