Reactive Power Demand Estimation and Dynamic Reactive Power Optimal Allocation for HVDC Receiving Network

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Abstract. The transient voltage stability of the receiver system is severely challenged by the AC-DC interaction and the short electrical distance between individual DC drop points of the receiver network. Firstly, the dynamic reactive power of DC receiver system is analyzed in this paper. The analysis of the dynamic reactive power in the DC receiver system is presented in this paper. In addition, the evaluation method for the reactive power necessary to sustain the voltage of the converter bus AC system is proposed, taking into consideration the voltage drop mechanism when a DC block occurs. Finally, a mechanism for the reactive power dynamic optimization of the AC-DC receiving power network is proposed based on the sensitivity of the transient voltage track index. The optimal access node is determined by quantitatively evaluating the bus transient voltage increase of the inverter station when each node is connected to the dynamic compensation device of reactive power, and the simulation calculation is carried out by the actual power network to validate the performance of the methodology.

Keywords: DC receiving power network; transient voltage stability; reactive power evaluation; dynamic reactive power optimization.

1. Introduction

The adoption of UHV DC transmission technology has significantly impacted the structure of China's power grid. However, a mismatch in the development of AC and DC networks has resulted in a grid that displays the feature of "strong direct and weak alternating current" [1-2]. With the increasing penetration of DC power in the regional network, the local hydro and thermal units at the receiver end of the network are limited, and the reactive power and active power backup of the network is insufficient, making it easy to experience voltage and frequency stability problems. With the increase in high voltage DC transmission project construction and operation, more and more multiple DC feed into the same receiving end network, the same transmission end network by different DC lines performance, DC and DC, DC and AC coupling between the greater complexity, making the receiving end network single fault is easier to chain fault development [3], a single regional fault is easier to develop the global fault, which poses more serious challenges to the safe and stable operation of the network. This means that keeping the system running safely and stably is becoming more challenging.

During typical operation of the UHV DC transmission project, a significant quantity of reactive power must be absorbed by the reactive power compensating equipment of the CS (CS), which lacks reactive power control capability [4]. When the AC grid at the receiver side is disturbed, the AC grid voltage fluctuates, and the voltage change affects the operating state of the DC transmission system and changes the reactive power demand, as well as the capability of the CS filters to output reactive power. The combination of the two results in the DC transmission system's reactive power impact on the receiver end of the AC system, and if the receiver end of the AC system is not strong enough to withstand the impact, voltage instability will occur [5]. During the operation of UHVDC, the AC network must provide phase change current. If the electrical strength of the receiver end of the AC system decreases, the risk of phase change failure during DC operation will increase [6]. Continuous failure in phase change can cause DC blocking, resulting in the transfer of current to other DC transmission systems or inter-provincial contact lines. The heavier trend of the contact line increases the reactive power leakage, the voltage level of the contact line drop point decreases, the receiver terminal of the AC system voltage stability has a negative effect. Adverse effect on AC system voltage stability [7].

This study initially examines the dynamic reactive power of the DC system and suggests a technique for evaluating the system's reactive power dynamic requirements following DC blocking caused by the AC system. Additionally, we explore a reactive power dynamic optimized assignment method based on voltage trajectory sensitivity, which helps to enhance the voltage support capacity of the weak AC system at the receiver side.

2. Dynamic reactive power analysis of DC systems

When the system is running stably before the fault, the AC/DC reactive power exchange is almost zero. When the AC fault leads to the transient process of commutator bus voltage reduction (millisecond level), V_d, I_d and λ are rapidly changed by adjusting the commutator trigger angle, thus affecting the commutator reactive power consumption. The AC filter and shunt capacitor have not yet acted (mechanical casting, second level), and cannot track the converter reactive power change in real time, leading to the destruction of the inverter station's reactive power balance and non-zero exchange of that.

If the voltage drop on the converter bus is minimal and will not cause a DC phase loss, the converter will engage its undervoltage current limiting control characteristic, VDCOL, to reduce the DC current. The change in reactive power compensating power is proportional to the square of the voltage, and the change in reactive power of CS is approximately proportional to the voltage, i.e., $Q_a>0$, which needs to be absorbed from the AC side of the reactive power. The DC voltage and power will drop to zero as the current increases when a significant drop is triggered by the loss of the DC phase transition, that is, $Q_a<0$, the performance of the characteristics of reactive power supply, general faults occur after the protection of the ability to act quickly, the duration of this phase is shorter, the impact on the system is small.

The process of system recovery after relay protection action can be divided into the following two phases: 1) VDCOL is not released from current limitation; 2) VDCOL is released from current limitation.

After the fault disappears, the converter bus voltage increases rapidly while DC and power are still recovering (VDCOL delay), and the inverter station continues to supply reactive power $Q_a < 0$ to the network, behaving as a short-duration reactive power supply characteristic.

When the voltage exceeds the set value of VDCOL, the DC power increases significantly due to the increase in DC current, resulting from the voltage yet to recover. The inverter maintains a fixed angle control to prevent another phase-change failure accident. As a result, the power factor is low, leading to a higher consumption of reactive power, i.e., $\Delta Q_d>0$. While the reactive power of the shunt capacitor is at a minimum and ΔQ_c is negative. That is to say, in the course of the recovery of the DC power, the inverter station reconverges the bus voltage. Before restoring to normal level, the AC system requires a continuous absorption of reactive power (about several hundred milliseconds), which is manifested as reactive load characteristic and has a cross large effect on voltage.

3. Assessment of System Reactive Power Demand after DC Blocking

When the AC side of the DC transmission line experiences an out-of-phase condition, the DC side of the line is blocked and no active power is generated and no reactive power is absorbed. For the sudden power shortage caused by DC blocking, the AC system will undergo power transfer and the current will be redistributed. The line loss will be increased and the overall system voltage level will be reduced, and all the reactive power generated from the bus of the transformer station is fed back into the AC grid, thus providing some backup power to the grid. This paper evaluates the reactive power required to increase the voltage level within a specified range in response to an AC system fault that causes a DC block, resulting in an abrupt decrease in the AC system voltage level.

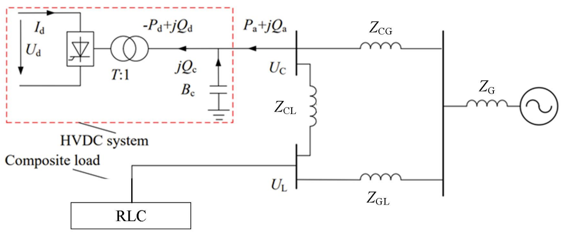

Fig. 1 HVDC equivalent receiving network

Taking the equivalent receiver-end network displayed in Fig. 1 as the study item, the AC measurement power is equivalent to voltage source and equivalent internal resistance, and the load is comprehensive load, which is analyzed by constant impedance model. The relationship equation between the bus voltage and the reactive power of the CS can be written according to the balance between the reactive power supplied by the CS and the reactive power consumed by the AC system.

Let the transient voltage at the CS bus be UC, the generator node voltage be U_G, and the load node voltage be UL after DC blocking. According to the reactive power balance can be obtained:

$$\begin{aligned} Q_C = &\frac{X_{CG}}{X_{CG}^2+R_{CG}^2}\left|U_C-U_G\right|^2+\frac{X_{LG}}{X_{LG}^2+R_{LG}^2}\left|U_L-U_G\right|^2 \\ &+\frac{X_{LC}}{X_{LC}^2+R_{LC}^2}\left|U_L-U_C\right|^2+\frac{1}{X_G}\left|U_G-E_G\right|^2+\frac{X_L}{X_L^2+R_L^2}\left|U_L\right|^2 \end{aligned} \tag{1}$$

where, X_{CG}, X_{LG}, X_{LG} are the line reactance between the CS bus to the power-side bus, the load node to the power-side bus and the CS bus to the load node, RCG, RLG, RLG are the line resistance between the CS bus to the power-side bus, the load node to the power-side bus and the CS bus to the load node, X_G is the equivalent power supply internal resistance in the AC side, X_L is the size of the load reactance, and E_G is the equivalent power supply potential.

Equation (1) contains three unknowns, i.e., U_C, U_L, and U_G, which can be obtained by applying the KCL law to the power-side bus and load node:

$$\begin{cases} \dfrac{E_G-U_G}{Z_G}=\dfrac{U_G-U_C}{Z_{CG}}+\dfrac{U_G-U_L}{Z_{GL}} \\ \dfrac{U_L}{Z_L}=\dfrac{U_G-U_L}{Z_{GL}}+\dfrac{U_C-U_L}{Z_{CL}} \end{cases} \tag{3}$$

Associative equations (1) and (2) can be collapsed into expressions for U_L and U_G with respect to the CS bus voltage U_C to obtain the relationship equation for the CS bus voltage with respect to the reactive power capacity Q_C:

$$U_C=f(Q_C) \tag{4}$$

According to the limited range of UHV DC near bus voltage, it can be put into equation (3) to get the size of reactive power compensating capability to meet the requirement of transient voltage of DC near region. The above is the assessment method of reactive power capacity required to keep the AC side voltage from exceeding the limit range when DC blocking occurs at the receiver terminal of the network.

When capacitors are used to provide reactive power for the DC system, the voltage and reactive power curves calculated according to the proposed relevant parameters are shown in Fig. 2, and the coordinates are per unit value.

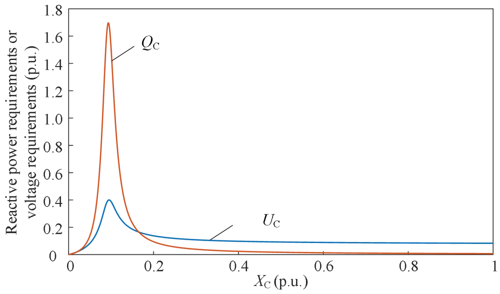

Fig. 2 Voltage and reactive power curves

4. Dynamic reactive power optimal allocation method based on voltage trajectory sensitivity

The power system's voltage is dependent on the strength of the reactive power. The loss in line voltage during system operation can be represented by $\Delta V=(PR+QX)/V$. Through dynamic reactive power compensation, the reactive power of the DC CS under disturbance can be locally balanced as far as possible, the transfer amount ΔQ is reduced, and the corresponding voltage increase amount is $\Delta V=\Delta QX/V$, and The voltage levels at both the converter and load buses on the DC converter side are raised with the aim of enhancing the robustness of the DC power grid, the motor load operation and the transient voltage stability of the power grid.

It is crucial to identify the ideal access point for reactive power compensation to enhance the voltage reliability of the multi-DC-fed receiving network. In this study, the bus that is being considered for reactive power balance is first decided on the basis of electrical distance. Select relatively serious AC faults, compare the track sensitivity index of the bus transient voltage rise before and after each candidate bus is connected to the reactive power dynamic compensator with the identical volume, and decide the appropriate position for the reactive power dynamic compensating device.

4.1 Candidate bus set identification

For the transient voltage issue arising from the nearby AC fault of the DC CS, it is crucial to ensure adequate reactive power dynamic back-up of the AC power grid. The dynamic compensating device for reactive power must be reasonably configured to supply a significant quantity of reactive power immediately post-fault to support the inverter bus voltage and maintain the voltage stability of the DC system.

Overall, faults occur randomly and the electrical distance remains fixed. The compensation effect is better when the electrical distance between the compensating point and the inverter station is shorter (or the sensitivity is higher). By effectively increasing the bus voltage of every DC near region to enhance the restoration properties of the DC supply, the weighted sum of the rated DC power is considered as the evaluation index to define the voltage stability support index:

$$S_i=\sum_{j=1}^{n}K_j(ADVCF_{ji}\Delta V_i)P_{Nj} \tag{5}$$

where, P_{Nj} denotes the *j*th DC nominal power; the AC-DC system voltage coupling action factor $ADVCF_{ji}$ depends mainly on the electrical distance of the grid structure; The voltage increase at the reactive power compensating point following the input of reactive power is denoted as ΔV_i , and Kj represents the weighting factor. These values are assumed to remain constant during initial determination.

4.2 Reactive Voltage Trajectory Sensitivity Indicator

After installing the reactive power dynamic compensating device on node *j*, the optimal placement is decided based on the trajectory sensitiveness of the node voltage V_i with respect to the injected reactive power Q_j, and the trajectory sensitiveness index of the reactive power voltage may be determined as shown below:

$$I_{TSj} = \sum_{i=1}^{n} W_{bi} [\sum_{k=1}^{N_k} \partial V_i / \partial Q_j |_{t=t_k}] \tag{6}$$

where, n denotes the total nodes in the network, W_{bi} denotes the weight of node i, N_k and t_k are the all sampling points and sampling time respectively; V_i and Q_j are denote voltages at node i and the reactive power compensation capacity of node j respectively; $\partial V_i / \partial Q_j |_{t=t_k}$ represent the track sensibilities of V_i about Q_j at t_k time.

Considering that the reactive power of SVG injection system with fixed capacity (SN) is constantly changing with the change of bus voltage, rather than constant reactive power injection, and the following trajectory sensitivity index is constructed:

$$\begin{aligned} I_{GTSj} &= I_{TSj} S_N \Delta t \\ &= \sum_{i=1}^{n} W_{bi} \sum_{k=1}^{N_k} [V_i(t_k, Q_{j0} + \Delta Q_j) - V_i(t_k, Q_{j0})] \Delta t \end{aligned} \tag{7}$$

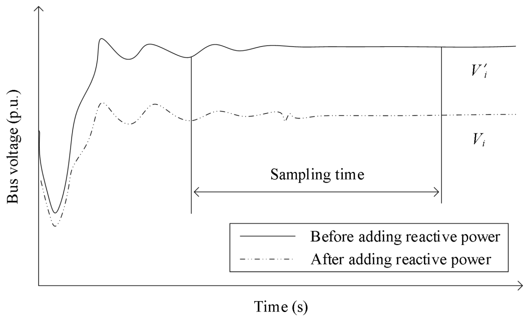

Fig. 3 Physical significance of improving track sensitivity index

The right part in this formula reflects the increase in sampling time or simulation time of the voltage responding curve for every node in the system before and after installing the SVG with the capacity of node j, as shown in Fig. 3.

After the addition of SVG, the node voltage sag degree decreases. The change of the voltage transient stability margin index of the converter bus node before and after the addition of SVG is calculated, and the difference value is regarded as the sensitivity indicator of the voltage improvement track of the rear node, which more precisely indicates the extent of bus transient voltage enhancement:

$$I'_{GTSj} = \sum_{i=1}^{n} W_{bi} (\eta_{V_i'} - \eta_{V_i}) \tag{8}$$

The larger I'_{GTSj} is, the better the voltage sustaining capability of the converter bus connected to the SVG node, and less influence of disturbances on the DC side and the active power deficit of the system at the receiver side. The balance of reactive power is ensured in the CS. The reactive power flow transfer and the influence on the AC grid voltage are decreased, achieving the goal of enhancing the transient voltage stabilization.

5. Case Studies

5.1 Determine the candidate busbar set

Considering the asynchronous interconnection of Yunnan power grid and Chuhui, Niu from the IMIESCR is small, from the West CS and Suidong CS, Huizhou CS electrical distance is fairly close, faults in the AC system are likely to cause the failure of repeated DC commutation at the same time will be detrimental to the secure operating of the receiver terminal of the power system. Hence, from the west CS, Suidong CS, Puqiao CS were assigned 1.5, 1.5, 1.3, Guangzhou CS weight coefficient of 1.2, other CS weight assigned 1.

By calculating the VSS indices of each bus, the set of suitable buses possessing the highest reactive power support ability to each converter bus of the CS at the 500kV site of Guangdong Power Grid can be classified into the following three categories:

Reactive power support for Congxi CS (Niuzhong DC), Suidong CS (Chuhui DC) and Qiaoxiang CS (Puqiao DC). At present, the Guangdong power grid has been configured with reactive power compensation stations: MUMIAN, BEIJIAO, SHUIXIA and DONGGUAN, which shows the correctness of the preliminary analysis.

5.2 Dynamic reactive power optimization

The main purpose of installing a reactive power dynamic compensating device aims to solve the problem of transient voltage stabilization, which needs to be further calibrated by time domain simulation to decide the optimum compensating position.

By analyzing the set of faults with large impact on the system as described before, the 500kVZC-BJ line and DG-PC line N-2 faults are mainly considered, and since the faults occur randomly and will result in simultaneous commutating failures of several DCs, the weights are all taken as 1; the capacity of SVG (using the actual SVG model) is added as 200Mvar to the various candidate nodes (1 The weights are all set to 1. For the verification of the fault simulation, SVGs with a capacity of 200 Mvar (using the actual SVG model) are placed on each of the candidate nodes (Nos. 1-15); W_{bi} is considered as the nominal transmitting power of each DC. The calculation results are normalized and the results are shown in Fig. 4 below.

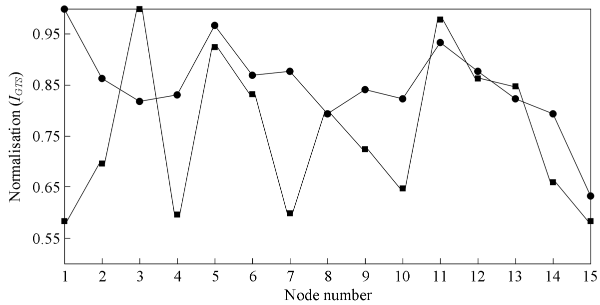

Fig. 4 Normalized nodal voltage reactive power improvement trajectory sensitivity metrics

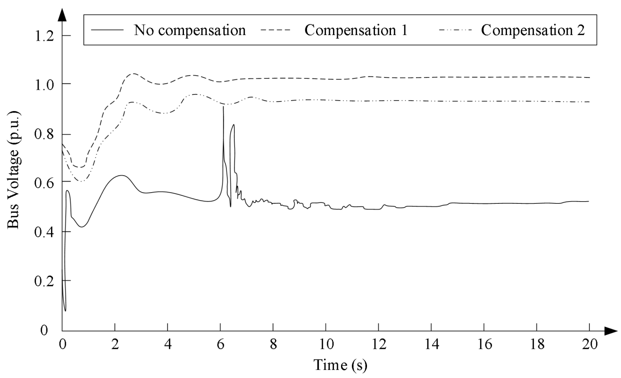

Fig. 5 Voltage changing curves at different compensation positions

Fig. 4 displays that node 1, node 5, and node 11 are the suitable sites for allocation in each region with normalized results of the sensitivity of the node voltage reactive trajectory acquired from the metrics introduced in part 3. Literature [8] also designates node 3, node 11, and node 5 as the best allocation locations.

Under the identical fault situation (N-2 fault on BL-HL line), SVGs of equal output are placed at Node 1 (Compensating pattern 1) and Node 3 (Compensating pattern 2), respectively, and the output is presented in Figure 5.

The node transient voltage stability margin corresponding to compensation mode 1 and compensation mode 2 is 0.637 and 0.456, respectively, and the voltage increase of dynamic reactive power compensation device installed on node 1 is obviously better than that of node 3. Compared to the trajectory sensitivity index calculated with ten equal weights considering voltage drop, the enhanced trajectory sensitivity index, which considers different voltage drop degrees with varying weights, is more appropriate.

6. Conclusions

AC faults result in subsequent DC commutation failure and chain faults are the primary causes of instability at the receiving end voltage. To address this, this study proposes an evaluation method for the reactive power required by the receiver grid after DC lock. Based on this, a dynamic reactive power optimal allocation scheme of the AC-DC receiving network is proposed, which combines the reactive power trajectory sensitivity and the transient voltage robustness threshold index. The candidate busbar set was determined by electrical distance and the AC fault set, which had a major influence on voltage robustness, was identified by fault search. The trajectory sensitivity indices before and after the dynamic reactive power compensating device were compared to find the optimum connection node. The transient voltage robustness of the Guangdong power system under a variety of disturbances is analyzed by means of simulation. DC lock fault and AC channel fault have little influence on the transient voltage, and the voltage robustness can be effectively improved by DC modulation. Focusing on the serious AC faults in the vicinity of the inverter station, the improved trajectory sensitivity index is employed to quantitatively assess the improvement of the transient voltage robustness of the system by connecting the reactive power dynamic compensating device to each node, and the effectiveness of the scheme is verified.

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