Polytype Dynamic Reactive Power Equipment Planning Method for Receiving-End Power Grid

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Abstract. Due to the interaction between AC and DC systems, the multi-DC feeding receiving-end power grid is prone to have safety and stability problems. Reactive power equipment can improve the transmission capacity of power grid at the same time avoid voltage drop which is gradually applied in receiving-end power grid. In this paper, a polytype dynamic reactive power equipment coordination optimization model based on static and transient voltage stability is proposed, which can be used for dynamic reactive power planning of receiving end power grid to satisfy the safety and stability standards and the minimum investment scheme limited by installation conditions. The guiding significance of the model for dynamic reactive power planning is illustrated by an example of the reactive power planning for the south Suzhou power grid in East China.

1. Introduction

Since the period of Tenth Five-Year Plan which the West-to-East Power Transmission Project construction started [1,2], after more than ten years of construction, the world's largest receiving-end power grid has been built in the eastern load centre area with rapid economic development but relatively scarce primary resources. By the end of 2017, the East China Power Grid has fed eight outgoing DC circuits, with a maximum capacity of 39760 MW and obvious AC-DC hybrid characteristic.

Most of the voltage collapse accidents in the world are located in the receiving power grid of the load centre [3-7]. Because of the close electrical connection and high load density, the interaction between AC and DC systems and between DC and DC systems of the receiving-end power grid is very strong. Once the bus voltage of the converter station falls due to the fault of AC system, it is easy to cause the failure of DC commutation and the occurrence of cascading faults.

Lack of adequate reactive power support is the main factor causing voltage instability [8]. Reactive power planning can significantly improve the reactive power flow and distribution of the whole network by determining the optimal installation location and capacity of static/dynamic reactive power compensation equipment, enhance the static and transient voltage stability level of receiving-end power grid[9], improve the transmission capacity of power grid[10], and prevent large-scale voltage collapse accidents[11]. Static reactive power compensation equipment mainly includes shunt capacitors and reactors, which are used to compensate the reactive power loss of transformers and the reactive power deficit of power grid when the transmission capacity of lines is excessive [12]. Dynamic reactive power compensation equipment mainly includes generators, phase modulators,
STATCOM, UPFC and so on, which can quickly dispatch reactive power during the process of accident disturbance, which is very important to prevent power grid collapse accidents.

The existing methods of dynamic reactive power planning only consider static or transient voltage stability are more mature, while the research of dynamic reactive power planning considering both static and transient voltage stability is less[13]. Literature [14] proposes a reactive power planning method aiming at reducing the voltage interaction between DC systems. Literature [15-18] chooses the location of dynamic reactive power planning based on trajectory sensitivity analysis. Literature [19] proposes a dynamic reactive power optimal allocation algorithm based on the index of fault limit clearance time. Literature [20, 21] solved the optimization of reactive compensation by taking different economic indicators as objective functions. On the other hand, with the development of high-power power electronic switch equipment in China in recent years, new FACTS equipment such as STATCOM and UPFC have become more and more mature, and have been applied in power grid. For example, the recently put-into-operation 500 kV UPFC project in Southern Suzhou Power Grid will coordinate with the ongoing synchronous compensator project to ensure the safety and stability of power grid. However, there are few studies on reactive power equipment planning methods considering multi-type dynamic reactive power equipment coordination and optimization, and neither the existing reactive power equipment allocation principles nor the reactive power planning model[22, 23] has a comprehensive analysis of the new FACTS device.

Therefore, based on considering both static and transient voltage stability, this paper proposes a multi-type dynamic reactive power equipment coordination optimization method, which takes the capacity of various types of static and dynamic reactive power equipment at each transformer station as a variable.

In order to meet the minimum investment of safety and stability criteria, this model proposes a multi-type reactive power planning method for receiving-end power grid considering actual site conditions, and the application of the model in DC receiving-end power grid is empirically studied by taking Southern Suzhou Power Grid in East China as an example.

2. Principle and Characteristics of Several Dynamic Reactive Power Equipment

2.1 Synchronous Compensator

Synchronous compensator can absorb or output reactive power from power grid by changing the magnitude of excitation current. In over-excitation operation, the synchronous compensator supplies the inductive reactive power to the system, playing the role of reactive power supply; in under-excitation operation, it absorbs the inductive reactive power from the system and plays the role of reactive load. When DC commutation failure occurs in the system, a large amount of instantaneous reactive power can be provided to support the grid voltage and restrain commutation failure.

2.2 Static Var compensator (SVC)

SVC is a hybrid device using thyristor switching capacitor and thyristor controlled reactor (TSC + TCR). Its schematic diagram is shown in Figure 1.

The reactive power from SVC is shown as equation (1):

\[ Q = \left( \omega C - \frac{2\beta - \sin 2\beta}{\pi\omega L} \right) U^2 \]  \hspace{1cm} (1)

Adjusting the conduction angle \( \beta \) of thyristor can absorb the superfluous capacitive reactive power from SVC, and if inductive reactive power compensation is needed, all TSC can be removed.
2.3 **Static Synchronous Compensator (STATCOM)**

STATCOM, also known as static var generator, is one of the core equipment and technologies of flexible AC transmission system (FACTS), which is mainly composed of high-power power electronic equipment and shunt DC capacitors.

The basic principle of STATCOM is to connect the self-commutating bridge circuit directly in parallel with the network through resistors and reactors. According to the instructions of reactive power and active power of the input system, adjusting the amplitude and phase of the output voltage on the AC side of the bridge circuit or directly controlling the AC side current of the bridge circuit to absorb or output the reactive current that meets the requirements of the system, so as to achieve the purpose of dynamic reactive power compensation. The schematic diagram is shown in Figure 2.

The reactive power from STATCOM is shown in equation (2):

$$Q = \frac{U_1 - U_2}{\omega L} U_2$$  \hspace{1cm} (2)

2.4 **Unified power flow controller (UPFC)**

UPFC can accurately adjust the directional transmission of power flow and improve the controllability of AC transmission lines. At the same time, it can also improve the transient stability of power system and the control ability of power grid voltage by adjusting the voltage in stable operation and recovery voltage after fault through appropriate reactive power.

The UPFC structure for single-circuit line control is shown in Figure 3. It consists of two back-to-back voltage source converters. Two back-to-back converters share DC buses. Both of them are connected to the system through converter transformers. The converter transformers corresponding to
converter 1 are connected in parallel, and the converter transformers corresponding to converter 2 are connected in series. Two-way flow between two converters, each converter’s AC output terminal can independently output or absorb reactive power.

**Figure 3.** Diagrammatic sketch of UPFC

The principle of node voltage control is that the shunt converter injects reactive power into the system node through the converter, such as equation (3) and equation (4).

\[
\dot{I}_{sw} = -j \frac{\dot{U}_s - \dot{U}_{sh}}{X_T} \\
Q_{sh} = \text{Im}\left( U_s \ast I_{sh} \right)
\]

**Figure 4.** Dynamic compensation equipment applied to power grid

In order to observe the response characteristics of different types of dynamic reactive power compensation equipment, this study makes fault response to the same simulation system (Figure 4). The fault is selected as three-phase short-circuit fault in 1.5 seconds, and the fault is removed in 1.6 seconds.

In Figure 5, the output of each equipment in the post-fault transient process can be observed. The output of each equipment is very small before the system failure, only the output of the synchronous compensator is larger than that of the power electronic equipment. After system failure, UPFC, STATCOM, SVC and other power and electronic equipment are affected by control delay and system voltage, and their reactive power output cannot reach peak value. However, under the strong excitation, the synchronous compensator can reach its peak quickly in this time window, so it is generally better than UPFC, STATCOM and SVC in this time window. After fault removal, UPFC, STATCOM, SVC and other power and electronic equipment reach their peak reactive power output and remain stable with the recovery of system voltage. However, the output of the synchronous compensator cannot be guaranteed in this time window. Therefore, UPFC, STATCOM and SVC are generally better than the synchronous compensator in this time window, and the response time and maximum output of SVC are far behind other equipment. After the system returns to stability, the
output of all the equipment decreases gradually, and there are different steady-state output according to the different control strategies set by the equipment.

![Figure 5. Response curve of dynamic compensation equipment](image)

3. Coordination and optimization model of multi-type dynamic reactive power equipment

\[
\begin{align*}
\min & \sum_{i=1}^{N} P_i (Q_{st}, Q_{dt}) \\
\text{s.t.} & \quad P_i = P_s \cdot Q_{st} + P_f \cdot Q_{dn} \\
& \sum_{i=1}^{N} Q_{st} \geq Q_{D} + \sum Q_{TC} \\
& Q_{C} \geq Q_{F} + 0.5 \times (Q_{TN} - Q_{TC}) \\
& Q_{sn} \leq Q_{sn \text{ max}} \\
& Q_{dn} \leq Q_{dn \text{ max}} \\
& I_{sn} (Q_{sn}, Q_{dn}) \leq I_{sn \text{ max}} \\
& V_{mn} (\Omega) \leq V_{mn \text{ max}} \\
& \theta_{mn} (\Omega) \leq \theta_{mn \text{ max}} \\
& S_{fi} (\Omega) \leq S_{fi \text{ max}} \\
& S_{fi} (\Omega) \leq S_{fi \text{ max}} \\
& \text{for } n = 1,2,...,N \\
& \text{for } m = 1,2,...,M \\
& \text{for } i = 1,2,...,k \\
& \text{for } j = 1,2,...,l
\end{align*}
\]

In the above formulas:

- \( N, M, k \) and \( l \) are the number of transformer stations, power plants, branches and transformers in the region.
- \( Q_{sn} \) and \( Q_{dn} \) are the capacity of static and dynamic reactive power compensation equipment for transformer stations in the region.
- \( Q_{sn} = [Q_{ls}, Q_{Cn}]^T \), \( Q_{ls} \) is the reactance, \( Q_{Cn} \) is the capacitance.
- \( Q_D \) is the capacitive reactive power fed into the system in small DC mode.
- \( Q_{TC} \) is the reactive power loss when the line adjacent to the nth transformer station is overloaded.
- \( Q_{TN} \) is the charging power of the line adjacent to the nth transformer station when it meets the basic reactive power balance and static reactive power compensation principle. That is to say, the inductive reactive compensation should satisfy the charging power of the line and the reactive power...
fed into the system in a low load DC mode near the area. Capacitive reactive power compensation satisfies the main transformer loss and reactive power gap under heavy load (which can be approximately compensated according to the main transformer loss).

$$Q_{dn} = [Q_{1x}, Q_{2x}, ..., Q_{nx}]^T$$, $x$ is the number of types of dynamic reactive power compensation equipment. Generally, the same transformer station does not use a variety of dynamic reactive power equipment mixed configuration, that is, if $Q_{bx} > 0$, then $Q_{dn} = 0, \lambda \neq Y$.

$P_n$ is the total investment to install $Q_{xn}$ and $Q_{dn}$ in the transformer station.

$P = [P_1, P_2, ..., P_x]$ is the unit investment of static inductive and capacitive reactive power equipment.

$Q_{dx}$ is the total investment to install all kinds of dynamic reactive power equipment, $P_d = [P_1, P_2, ..., P_x]$.

$Q_{dn}$ is constrained by the maximum capacity $Q_{dn \max}$ of static reactive power equipment in the station.

$Q_{dn}$ is constrained by the site constrained capacity of various types of dynamic reactive power equipment.

$I_{scn}$ is the short-circuit current of the nth transformer station, which is constrained by the short-circuit interruption capability $I_{scn \max}$ of the station.

$V_n(\Omega)$, $\theta_n(\Omega)$, $S_{bn}(\Omega)$ and $S_{jn}(\Omega)$ are transformer station voltage, generator power angle, branch power flow and transformer power flow under fault set $\Omega$. These safety and stability parameters are constrained by voltage stability $[V_{min}, V_{max}]$, power angle stability $[\theta_{min}, \theta_{max}]$, line thermal stability $S_{jn \max}$ and transformer overload capacity $S_{jn \max}$.

In order to formulate the plan $Q_{dn}$ efficiently, the sensitivity analysis method can be used to find the weak buses in the system and determine the location of reactive compensation, which can provide guidance for the location of reactive power compensation equipment and load shedding measures. For the research area of the receiving-end power grid, in the sensitivity test of a transformer station, if the reactive power change $\Delta Q_n$ is applied, the voltage change of each station can be obtained $\Delta U_1, ..., \Delta U_n$, then the sensitivity of the transformer station is shown in equation (16):

$$K_n = \frac{\sum \Delta U_n}{\Delta Q_n}$$

According to the order of sensitivity, an appropriate design scheme can be obtained.

4. Case Study on Coordination Planning of Dynamic Reactive Power Equipment in Receiving-End Power Grid

The southern power grid of Suzhou has a large load, which requires a large amount of power support from the external power grid to meet the balance of power supply and consumption. This situation leads to the large power flow of the external power exchange channel in the southern area of Suzhou. Once a fault occurs, it is easy to cause large-scale power flow transfer and continuous commutation failure of Jinsu DC. In order to improve voltage stability and reduce DC commutation failures in southern Suzhou power grid, additional equipment such as synchronous compensator, STATCOM and UPFC are considered in southern Suzhou power grid. How to scientifically plan the installation location and capacity of several types of dynamic reactive power equipment is particularly critical.

The southern power grid of Suzhou consists of Mudu, Chefang, Yushan, Wujiang transformer station and Tongli converter station. It receives electricity through Jinsu DC and four external AC lines, as shown in Figure 6. In this paper, 2025 is selected as an example to study the coordinated planning of multi-type dynamic reactive power equipment.
Figure 6. Topological graph of south Suzhou 500kV power grid

$$Q_{de} = [Q_{1n}, Q_{2n}, Q_{3n}, Q_{4n}, Q_{5n}]^T, \quad n=1,2,3,4,5,$$

representing Mudu, Chefang, Wujiang, Yushan and Tongli respectively. The dynamic reactive power schemes for each station are SVC capacity $Q_{1n}$, STATCOM capacity $Q_{2n}$, UPFC capacity $Q_{3n}$ and synchronous compensator capacity $Q_{4n}$, as shown in Table 1. $P_s = [45,51]$ (Yuan/kVA), $P_d = [196,1250,620,610]$ (Yuan/kVA).

The fault sets $\Omega$ are all N-1 and N-2 faults and DC unipolar and bipolar blocking accidents in the network. $[V_{min}, V_{max}]$ and $[\theta_{min}, \theta_{max}]$ are selected according to the requirements of power system stability guidelines. The thermal stability capacity of the line and the overload capacity of the transformer are selected according to the actual equipment. Safety and stability constraints are obtained by BPA simulation tool of China Electric Power Research Institute.

Table 1. Installation restrictions for static compensator (MVA)

| Station | Current capacity of Static Reactive Power Equipment [Reactor, Capacitor] | $Q_{on-max}$ [Reactor, Capacitor] |
|---------|---------------------------------------------------------------|----------------------------------|
| Mudu    | [240,360] [240,660]                                           |                                  |
| Chefang | [180,320] [180,360]                                           |                                  |
| Wujiang | [300,900] [360,1200]                                          |                                  |
| Yushan  | [60,660] [120,840]                                            |                                  |
| Tongli  | [0,3520(filter)] [0,3520(filter)]                             |                                  |

Based on the coordinated optimization model of multi-type dynamic reactive power equipment, the predicted scale of various reactive power equipment in Southern Suzhou Power Grid can be obtained, as shown in Table 2. The results show that it is not necessary to add new inductive reactive power equipment in the southern power grid of Suzhou without adding new receiving channels.

Table 2. Voltage sensitivity for south Suzhou power grid (MVA)

| Station | Voltage sensitivity $K_v$ (kV, Mvar) |
|---------|-------------------------------------|
| Yushan  | 0.0140                              |
| Mudu    | 0.0151                              |
| Huiquan | 0.0158                              |
| Chefang | 0.0131                              |
However, with the increase of load and the operation of main transformers at Wujiang and Mudu stations, 640MVA static capacitors are needed in the southern Suzhou power grid. In order to ensure the safe and stable operation of the power grid, the Mudu station 3×250MVA UPFC, Wujiang station 300MVA STATCOM and Tongli station 2×300MVA synchronous compensator can be optimized and put into operation, as shown in table 3.

Table 3. Result of dynamic compensation planning (MVA)

|       | Mudu | Chefang | Wujiang | Yushan | Tongli |
|-------|------|---------|---------|--------|--------|
| $Q_1$ | 240  | 180     | 300     | 60     | 3520   |
| $Q_2$ | 660  | 360     | 1080    | 780    |        |
| $Q_3$ |      |         |         |        | 300    |
| $Q_4$ |      |         | 3×250   |        | 2×300  |

5. Conclusion
In this paper, under the constraints of transformer station installation conditions and power system stability capacity, a multi-type dynamic reactive power equipment coordination optimization model is proposed for the receiving-end power grid with the objective of minimizing investment scheme.

The model can be used for dynamic reactive power planning of receiving-end power grid, which avoids the waste of land resources and social resources caused by the redundancy of reactive power capacity of power grid, but also install appropriate static and dynamic reactive power compensation equipment by matching equipment characteristics with system requirements. It is of great significance for dynamic reactive power planning of receiving-end power grid.

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