Research on application scheme of UPFC in UHV power grid based on multi-objective evaluation

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Abstract. UPFC can distribute the line transmission power rationally and improve the stability of power grid operation, which is not only the focus of the current attention of the engineering community, but also the hot spot in the academic field. Aiming at the application of UPFC in UHV power grid, this paper first introduces UPFC’s principle and function. Based on the analysis of the problems in UHV power grid planning, this paper proposes the UPFC application scenarios in UPFC power grid. Then using BPA simulation platform, this paper calculates and analyzes the feasibility of each UPFC alternative location in different scenarios. Finally, based on the fuzzy evaluation, the comprehensive evaluation of each scheme in technical level is carried out. The results show that UPFC has strong capability in improving the transmission capability and improving the system voltage, which can solve the problems that UHV Power Grid will face effectively.

1. Introduction

UHV power grid is faced with some partial problems such as short-circuit current exceeding the standard, uneven current trend in transmission section, thermal stability exceeding the limit, etc. in planning. Traditional solutions like breaking up the electromagnetic loop network will lead to the weakening of the main grid. In addition, according to the EHV development plan, partial UHV power grid will present a pattern of multiple EHV DC feeds at the same time. If the electrical distance between two EHV DCs is relatively short, there will be a risk of simultaneous commutation failure [1]. It is urgent to adopt new ideas and new devices to solve the above contradictions.

As the most powerful FACTS device, UPFC can control the line impedance, voltage and power angle, and also can regulate active and reactive power flow of the transmission line simultaneously or independently. It provides a new technical means to solve the problems of uneven power flow distribution in the current power grid. At the same time, it also provides a new regulation mode for the improvement of power supply capacity, reactive voltage level and reliability of the power grid [2].

At present, the theoretical research on the UPFC site selection and volume problem is mainly divided into sensitivity method and optimal power flow method [3, 4]. However, the actual grid topology is complex with many considerations. The above methods may cause complicated calculations and incomplete considerations [5]. Aiming at the current situation and future planning of UHV power grid, this paper proposes a multi-objective optimal configuration method of UPFC. Through combing the problems faced by UHV power grid, this paper summarizes UPFC’s application scenarios in the power grid. Through calculation, the paper judges the application feasibility of UPFC in different scenarios, and then makes a comprehensive evaluation to get the ranking of each
distribution point at the technical level. In the case simulation part, this paper puts forward the recommended scheme of UPFC application in UHV power grid through the simulation calculation.

2. UHV Power Grid Development Planning and Problems

In 2020, a number of EHV DCs will be completed and put into operation [6, 7]. After the completion, UHV power grid’s exchange capacity has been continuously enhanced, and the weak link between two regional power grids has become a bottleneck of security and stability. The existing 500kV main grid load capacity tends to be saturated, far beyond the original function positioning, and it is difficult to meet the development requirements of the power grid. The problems of thermal stability, transient stability, dynamic stability, voltage stability, and short-circuit current exceeding the standard are prominent, leading to the increase of safety control measures such as cutting machine and load. UHV power grid will face the following problems [8, 9]:

- The cross-section’s power transmission and transmission limit of UHV power grid is mostly limited by the overheated stability limit, caused by the unbalanced power flow of the lines between provinces. If the power flow on the line can be balanced, the section between provinces still has increased margin.
- Under the hedging mode of the power grid, it will cause a large disturbance and will stimulate weak damping.
- With more EHV DC project put into operation, there is a risk of multiple DC commutation failures in the grid. DC power disturbance poses a new challenge to the safe and stable operation of UHV power grid.
- With the load growth of UHV power grid, the problem of short-circuit current exceeding the standard at some stations is highlighted.

3. Application of UPFC in UHV Power Grid

3.1. Basic structure and principle of UPFC

As shown in Figure 1, UPFC is a new power flow control device composed of parallel STATCOM and series compensation SSSC. The series and parallel sections of the UPFC are each equivalent to an ideal power supply.
The UPFC series connection can be equivalent to a voltage source, denoted by $\hat{U}_{pq}$, and the amplitude and phase angle of $\hat{U}_{pq}$ can be continuously adjusted. The amplitude adjustment is limited based on the size of the UPFC capacity, but the angle adjustment is not limited.

Figure 2 shows the various control functions of UPFC, among them, $\hat{U}_s$ is the sending terminal voltage and $\hat{j}$ is the line current. Figure 2 (a) shows the voltage regulation function, this is, the UPFC series injection voltage is the same or opposite to the direction of the terminal voltage. At this time, UPFC only adjusts the amplitude of the voltage, and does not change the phase of the voltage. Figure 2 (b) shows the series compensation function, the compensation voltage is perpendicular to the phase of the line current. Figure 2 (c) shows the phase angle adjustment function. For details, the voltage' amplitude is not changed, and the phase angle is changed. At this time, the compensation voltage generated by the UPFC is on the arc shown in the figure, which is equivalent to the phase shifter. Figure 2 (d) shows the automatic power flow control function, in which case UPFC is a combination of the first three functions [10].

The model of UPFC parallel part is a current source, denoted by $I_h$. With the voltage of the node where the UPFC parallel terminal is located as the reference vector, $I_h$ is decomposed into the active current $I_{hp}$ and the reactive current $I_{hq}$. The phasor diagram is shown in Figure 2. When $I_{hp} > 0$, the parallel lateral system injects active power. When $I_{hp} < 0$, the parallel side absorbs active power from the system. When $I_{hq} > 0$, the parallel lateral system injects capacitive reactive power. When $I_{hq} < 0$, the parallel lateral system injects inductive reactive power. By controlling $I_h$, the power exchange between the parallel side and the system can be realized, thereby achieving the functions of adjusting the bus voltage, controlling the reactive power compensation and balancing the active power of the DC capacitor [11].

3.2. Analysis of UPFC’s application scenes in UHV power grid

According to the application scenario of the power grid, UPFC can select one or more functions as its control objective, improve the power grid operation, and solve the problems faced. UPFC plays an important role in improving the section’s transmission capacity, increasing the voltage stability and suppressing the simultaneous commutation of DC in the Power Grid. It is an effective way to solve the existing problems of UHV Power Grid.

3.2.1. Improve power grid transmission capacity based on power flow control technology. The transmission limits of some 500kV sections are limited by the problem of some individual lines’ thermal stability exceeding the limit, which be caused by the unbalanced section flow. Therefore, if the power flow on the section line can be balanced, the 500kV section still has an increased margin [12]. Under the existing technical means, the measures of trend-optimized control are very limited. The method of adjusting generator output and line breaking has the characteristics of discrete range and poor flexibility power flow control, and has the risk of reducing the safety and reliability of power grid operation. In contrast, UPFC provides a new solution for trend-optimized control.
From Figure 3, it can be seen that, after UPFC is installed in the transmission section, the power flow control function can be used to adjust the line and section flow dynamically, avoiding the situation of heavy load and light load coexisting. Thereby, the cross-sectional delivery power is balanced and the transmission limit is greatly increased.

![Diagram showing the effect of UPFC installation on power flow]

**3.2.2. Improve voltage stability based on Dynamic Reactive Power Compensation Technology.**

UPFC’s parallel side can provide reactive power support of different capacities for the power grid through the regulation of power electronic components. It adjusts the system voltage with lower harmonics, higher efficiency, and faster dynamic response. Thereby, the effect of compensating for frequent fluctuations of reactive power in the power grid, improving the power grid’s power factor, improving the voltage quality and use efficiency, and reducing network loss are achieved [13].

When the grid is in normal operation, the UPFC operates as a normal capacitor or reactor, but compared to the group switching of capacitors or reactors, UPFC can provide reactive support of any capacity within the capacity range, with better linearity. In the transient mode of power grid, UPFC can provide dynamic reactive power support, compensating the reactive power of AC bus in a very short time (tens of milliseconds), so as to provide good voltage support for the receiving system, which is conducive to improving the system’s voltage stability and the power grid’s voltage quality.

**3.2.3. Suppressing DC simultaneous commutation failure based on voltage regulation technology.**

Commutation failure is a common fault on the inverter side of DC system using thyristor as the commutation valve element. Both the disturbance of AC system and the fault of DC system itself will lead to commutation failure [14].

Because UPFC can restrain the voltage oscillation of bus to some extent and improve the voltage stability of power system bus, connecting UPFC to HVDC system can provide dynamic reactive power support for the system, stabilize the AC side voltage of HVDC system and restrain the occurrence of commutation failure to some extent [15].

**4. Feasibility study and evaluation method of UPFC distribution**

In view of the UPFC scheme in UHV power grid, it is necessary to carry out feasibility studies on improving transmission capacity, suppressing commutation failure and improving voltage stability. Then, the technical evaluation of each UPFC layout is carried out to obtain the technical level prioritization. The method uses the multi-objective fuzzy evaluation method in mathematics [16].

First determine the factor set \( X \), as shown in equation (1):
Among them, \( x_1 \) represents the feasibility of UPFC to improve power grid transmission capacity. \( x_2 \) represents the feasibility of improving voltage stability and \( x_3 \) represents the feasibility of UPFC to suppress commutation failure.

The membership function adopts 0-1 evaluation, and 0 indicates that the UPFC application scenario cannot solve the problem of the grid.

The feasibility of UPFC to improve the grid’s transmission capacity is judged by UPFC unit capacity control proportional coefficient \( K_{UPFC} \), as shown in equation (2):

\[
K_{UPFC} = \frac{\Delta P}{S_{UPFC}}
\]

\( \Delta P \) indicates the transmission improvement amount, the unit is MW. \( S_{UPFC} \) is the UPFC capacity, and the unit is MVA. When \( K_{UPFC} \), is bigger than 1, it indicates that the UPFC scheme is feasible in this application scenario [17], so \( x_1 \) takes the value 1, otherwise \( x_1 = 0 \).

The feasibility of UPFC to improve the voltage stability is judged by the bus recovery voltage value after the fault. If the bus recovery voltage is increased after the UPFC is installed, \( x_2 = 1 \).

In the case of DC simultaneous commutation failure, if the area of DC simultaneous commutation failure due to line failure is reduced after UPFC installed, \( x_3 = 1 \).

Final determination of the weight of each indicator, as shown in equation (3):

\[
A = (a_1, a_2, a_3)
\]

The priority index has a large weight, while ensuring \( \sum_{i=1}^{3} a_i = 1 \).

Improving the transmission capacity is the primary application scenario of UPFC in UHV power grid, and suppressing DC simultaneous commutation failure is an auxiliary function. Therefore, the value of \( A \) is \((0.6, 0.3, 0.1)\).

According to equation (4), the fuzzy evaluation results of each UPFC distribution point are obtained:

\[
B = A \odot Y
\]

5. Simulation analysis of UPFC application scheme in UHV power grid

This section uses the BPA simulation platform for power flow analysis and stability calculation. UPFC uses a modular equivalent power injection model [18]. According to the planning grid, the feasibility and application effect of UPFC are analyzed. This paper takes an actual large-area power grid as an example. According to the application scenario analysis, three UPFC layout sections are selected, which are represented by numbers ①, ② and ③.

In this section, Section ③ is selected for specific calculation and simulation analysis, and the rest of the installation sites adopt the same analysis method.

5.1. Feasibility analysis of UPFC to improve the transmission capacity of cross section

Section ③ is composed of six circuits. The power receiving limit is subject to the thermal stability limit. After the N-1 fault of the 500kV double line, the power of the other circuit is 2203MW, which exceeds the thermal stability limit (2200MW). The limit of section ③ is 6748MW. At this time, the current distribution is very uneven. There are many light-duty lines in section ③, which is typical of inductive compensation demand.

The capacity of UPFC installed in the 500kV double circuit line is 390MVA (series 2×190MVA, parallel 10MVA), which can balance the two channels and improve transmission capacity.

Considering the thermal stability of the line after the failure, after adding UPFC, the transmission capacity of the section can be increased by 578 MW. In section ③, \( K_{UPFC} = 1.5, x_1 = 1 \).
5.2. Feasibility analysis of UPFC to improving voltage stability

There is an important 500kV double circuit line in section ③, of which the total power under normal mode is 2563.9MW. In case of N-1 fault on the line, the system transient response with or without UPFC is shown in Figure 4. It can be seen that the system can keep maintain stability after the failure, UPFC can not only reduce the fluctuation of node voltage value, but also improve the recovery voltage of 500kV bus in cross-section connected stations.

![Figure 4. Comparison curve of 500kV station voltage variation with or without UPFC (N-1 fault)](image)

Another 500kV double-circuit transmission active power is 2129MW. After N-2 fault occurs in the line, the system transient response is shown in Figure 5. It can be seen that the system can maintain stable operate, UPFC can effectively reduce the voltage shake and increase the recovery voltage.

![Figure 5. Comparison curve of 500kV station voltage variation with or without UPFC (N-2 fault)](image)

In section ③, $x_2=1$ in summary.

5.3. Feasibility analysis of UPFC to suppress DC simultaneous commutation failure

The power grid with section ③ has two EHVDC fed in centralized. The two EHVDC receiving end bus bars are geographically close and have a short electrical distance. Through the N-2 fault scan of the 500kV line, it is found that:

- some line faults will cause the commutation failure of EHVDC I;
• some line faults will cause the commutation failure of EHVDC II;
• some line faults will cause the two EHVDCs to fail to commutate at the same time.

Through statistical calculation, it can be concluded that after UPFC installed, the area where 500kV line N-2 fault in the province leads to DC simultaneous commutation failure becomes smaller. In section 3, \( x_3 = 1 \).

5.4. General comparison

Through the feasibility analysis and calculation of the same three scenarios for the other two UPFC locations, the following results can be obtained:

\[
\begin{align*}
x_1 \rightarrow (0,1,1) \\
x_2 \rightarrow (1,0,1) \\
x_3 \rightarrow (0,0,1)
\end{align*}
\]

The fuzzy evaluation results of each UPFC distribution point are as follows:

\[
B = A \circ Y = (0.6, 0.3, 0.1) \circ \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix} = (0.3, 0.6, 1)
\]

To sum up, it is recommended to install UPFC device in section 3, which can not only improve the transmission limit, but also improve the power supply stability of the grid.

6. Conclusion

In this paper, a method of selecting UPFC points based on fuzzy evaluation is proposed. Each UPFC point is evaluated by feasibility analysis in different application scenarios, at the same time, this method can be used to arrange the UPFC points at the technical level. The examples show that UPFC has a good effect in improving transmission power and grid voltage, and can effectively solve the planning problem of UHV power grid.

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