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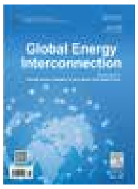

Full-length article

Evaluation of optimal UPFC allocation for improving transmission capacity

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Abstract: A unified power flow controller (UPFC) combines the advantages of various flexible alternating current transmission system (FACTS) devices into a powerful format. Using a 500 kV power grid, this study evaluates the selection and use of a UPFC to improve transmission capacity. The “UPFC unit capacity control proportionality coefficient” is introduced to quantify the control effect of the UPFC, and an optimal calculation method for the UPFC capacity is presented. Following the proposal of a UPFC site selection process, the data of an existing power grid is used to conduct simulations. The simulation results show that the UPFC has a strong ability to improve transmission capacity, and its use is greatly advantageous. Additionally, by applying the proposed selection method, the control effect and economic benefits of the UPFC can be comprehensively considered during project site selection. These findings have a guiding significance for UPFC site selection in ultra-high voltage power grids.

Keywords: Unified power flow controller, UPFC unit capacity control proportionality coefficient, UHV power grid, Transmission capability, Optimal capacity calculation, UPFC site selection.

1 Introduction

As the power load increases, the insufficiency between the demand to improve power flow distribution and the availability of construction land for power sources has become more prominent. In order to maximize the power grid supply capacity, various unified power flow controller (UPFC) projects have been built and put into operation in China [1]. UPFC is an advanced flexible alternating current transmission system (FACTS) device, which represents the commanding point of FACTS technology [2]. The operation of UPFC project plays an exemplary role in solving the problems of power grid construction [3].

There are not only very few academic studies on UPFC engineering application schemes, but also no unified standard for UPFC control effect evaluation. In previous research, the problem of UPFC location and capacity was divided into two methods: the optimal flow method [4–6] and the sensitivity analysis method [7–9]. However, the actual network topology is complex and will lead to tedious and blind calculations [10]. Therefore, this study evaluates the selection and application of a UPFC in a 500 kV power grid, mainly for the purpose of improving transmission

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capacity limitations caused by uneven power flow distribution.

The paper is structured as follows. First, the UPFC's working principle and model is introduced. Thereafter, through the analysis of the ultra-high voltage (UHV) power grid's current operating status and typical UPFC application scenarios, this paper presents the concept of the "UPFC unit capacity control proportionality coefficient," so as to realize the quantitative evaluation of UPFC application effect. Based on this coefficient, this paper studies the problem of UPFC locating and sizing, and proposes a UPFC selection process at the technical level. Finally, an existing provincial power grid is simulated an example, and the results thereof analyzed.

2 UPFC operating principle

2.1 Positioning of UPFC in FACTS technology

Almost all FACTS elements are based on the controlled switching of power electronic devices to realize power flow control, voltage regulation, enhancement of transient stability, and mitigation of low-frequency system oscillations effectively [11].

Table 1 shows the qualitative comparison results of FACTS devices such as static VAR compensators (SVC), static synchronous compensators (STATCOM), thyristor-controlled series compensations (TCSC), thyristor controlled phase shifting transformers (TCPST), and UPFCs in improving the static voltage stability, transient stability, and power transmission capacity of the system (• indicates that the effect is average, •• indicates that the effect is above average, and ••• indicates that the effect is very good) [12]. It can be seen that the UPFC has strong capabilities in all the functions. UPFC projects not only have significant safety, economic, and social benefits, but also important demonstrative significance.

Table 1 Comprehensive effects comparison of common FACTS devices

device name	static voltage stability	power transmission capacity	transient stability
SVC	•••	•	•
STATCOM	•••	•	••
TCSC	•	•••	•••
TCPST	•	••	•••
UPFC	•••	•••	•••

2.2 UPFC basic structure

A UPFC is a new power flow control device composed of a parallel STATCOM and a series (static synchronous series compensator) SSSC. Its model and the structure diagram are shown in Fig. 1 [13], where $\dot{U}_1$ and $\dot{U}_2$ are node voltages at both ends of the line where the UPFC is located, and the phase angle difference between them is θ.

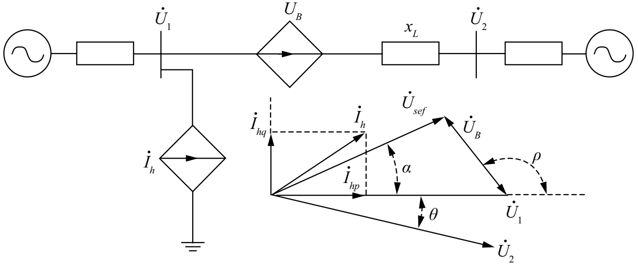


Fig. 1 UPFC model and the structure diagram (reprinted from [13])

The series part of a UPFC can be equivalent to a voltage source, which is represented by $\dot{U}_B$. The amplitude is represented by U_B, and phase angle by ρ. The controllable range of U_B is $[0, U_{B\max}]$ and that of ρ is $[0, 2\pi]$.

If U_1 is taken as the reference vector and the line's capacitance and resistance are ignored, the line power without the UPFC is

$$P_0 = \frac{U_1 U_2}{x_L}\sin\theta \tag{1}$$

$$Q_0 = \frac{U_2^{\ 2}}{x_L} - \frac{U_1 U_2}{x_L}\cos\theta \tag{2}$$

When the UPFC is installed in the line, the voltage at the sending end becomes $U_{sef}(U_{sef} = U_1 + U_B)$. At this time, the line power is

$$P' = \frac{U_{sef} U_2}{x_L}\sin(\theta + \alpha) \tag{3}$$

$$Q' = \frac{U_2^{\ 2}}{x_L} - \frac{U_{sef} U_2}{x_L}\cos(\theta + \alpha) \tag{4}$$

The model of the parallel part of the UPFC is a current source (represented by $\dot{I}_h$). With $\dot{U}_1$ as the reference vector, $\dot{I}_h$ can be decomposed into active current $\dot{I}_{hp}$ and reactive current $\dot{I}_{hq}$.

When $I_{hp} > 0$, the parallel side injects active power into the system. When $I_{hp} < 0$, the parallel side absorbs active power from the system. When $I_{hq} > 0$, the parallel side injects capacitive reactive power into the system. When $I_{hq} < 0$, the parallel side injects inductive reactive power into the system.

By controlling $\dot{I}_h$, the UPFC can realize the power exchange between the parallel side and the system, so as to adjust the bus voltage, control the reactive power compensation, and balance the active power of the DC capacitor [14].

2.3 UPFC calculation model

In this paper, the UPFC modular power injection model in the PSD-BPA power system analysis software package is adopted [15]. The series terminal is equivalent to an injection power of the node, so we can set the power flow target directly. At the same time, the reactive power control or the fixed node voltage control can be carried out at the parallel end. The control parameter matrix C is shown below:

$$C = \begin{bmatrix} P' & Q' \\ Q_{SNT} & \\ & U_{SNT} \end{bmatrix} \tag{5}$$

where the first line represents the series part control model and P' and Q' express the power flow target. Lines two and three represent the parallel part control model; Q_{SNT} expresses the reactive power control target, and U_{SNT} is the fixed node voltage.

In a scenario where the UPFC is used to solve a line overload problem and improve transmission capacity, only P' and Q' are set in the calculation, Q_{SNT} or U_{SNT} are not set. In this way, the current can be transferred to other lines in the section [16].

3 Demand analysis of 500 kV power grid

3.1 Power grid's current situation and existing problems

Until the establishment of an extra-high voltage backbone grid, 500 kV lines will still exist as part of the provincial grid skeleton and trans-provincial transmission channels, and continue to play an important role in power exchange within and between provinces.

In the operation of the main grid, the following problems are often encountered:

(1) Existence of high and low voltage electromagnetic ring network and complex ring network.

(2) Limited transmission capacity and grid instability.

(3) Control problem of reactive power balance.

China's energy resources are unevenly distributed. Energy resources and electricity demand are inversely distributed, which leads to limited transmission capacity. Owing to thermal, transient, and dynamic stability problems, approximately 1/4 of the transmission lines capacity is limited. This affects mainly cross-regional communication lines and heavy load sections in the regional grid [17].

3.2 Application of UPFC in 500 kV power grid

In some areas, the power grid structure is relatively fixed, and problems such as power flow and reactive voltage exist for a long time. UPFCs can be used to improve system performance when the conventional scheme is difficult to solve or the cost is high. Typical application scenarios include:

(1) The grid's power flow is complicated and the power flow distribution needs to be optimized.

(2) The power flow distribution of the transmission section is uneven, and the section transmission capacity needs to be improved.

(3) The long-distance large-capacity AC transmission has dynamic stability problems, so the system damping needs to be improved.

(4) There is a voltage stability problem in the power grid.

For the application scenarios where the section transmission capacity is limited by the uneven power flow distribution, attention should be paid to the effect of UPFC on power flow control [18]. For the application scenarios where the power grid's reactive power support capability should be improved, attention should be paid to the effect of the UPFC on reactive power support capacity. In practical engineering applications, it is advisable to carry out calculations of power flow, reactive voltage, system stability, and short-circuit current in order to determine the UPFC operation control mode after it is connected to the system [19].

Judging from the problems faced by UHV grids, the urgency of grid demand, and comprehensive utilization benefits, the promotion and application of UPFC should first consider scenarios where the section transmission capacity is limited. In this scenario, the UPFC can maximize its power flow control ability, and result in considerable utilization benefits.

4 Optimal UPFC allocation method for 500 kV power grid

A UPFC's power flow control ability can be used to transfer the power flow from a section's heavy-load line to the its light-load lines, so as to reduce the overloaded line's power flow. The installation location and capacity calculation of the UPFC will determine its power flow control effect.

4.1 Quantitative evaluation method of UPFC control effect

Based on the analysis results in Section 3, this section conducts a detailed study on the evaluation indexes of UPFC power flow control.

In this study, the "UPFC unit capacity control proportionality coefficient" (K_{UPFC}) is put forward to achieve quantitative evaluation of the UPFC power flow control effect. K_{UPFC} is the ratio of the lifting capacity of the section transportation to the installed UPFC capacity, as shown in (6). The larger the value of K_{UPFC}, the better the control effect of the UPFC unit capacity.

$$K_{UPFC} = \frac{\Delta P_{UPFC}}{S_{UPFC}} = \frac{P_{up} - P_0}{S_{UPFC}} \tag{6}$$

where S_{UPFC} is the capacity of the UPFC installed, ΔP_{UPFC} represents the power flow control effect of the UPFC (namely section lifting power), P_{up} is the section transport power with UPFC installed, and P_0 is the original transport power.

S_{UPFC} is directly related to economic costs. When the equipment capacity is larger, the initial costs IC and the later maintenance costs OC are higher [20], as shown in equations (7) and (8):

$$IC = C_{UPFC} \cdot S_{UPFC} \tag{7}$$

$$OC = \sum\nolimits_{k=1} \left[C_{YX}(k) S_{UPFC} + C_{JX}(k) S_{UPFC} \right] \tag{8}$$

Among them, C_{UPFC} is the unit cost of UPFC, the unit is $yuan/MVA$. C_{YX} and C_{JX} is the operating cost and maintenance cost of the unit capacity UPFC, and the value is related to the operating environment of the specific equipment, and the unit is $yuan/(MVA \cdot year)$. K stands for years of operation.

ΔP_{UPFC} is directly related to the reliability benefit. The increase of transmission power can improve the reliability of the power supply and reduce the cost of user power outages [20].

It can be seen that K_{UPFC} can be used to comprehensively evaluate the installation effect of UPFCs from the perspectives of economy and improved system stability.

4.2 Optimization method of UPFC installation position and capacity

The essence of using UPFC to improve power flow's distribution and solve the problem of line's overload is to use UPFC's power flow control ability to transfer the power flow from the heavy load line to the section's light load lines, so as to reduce the overload line's power flow. The installation location and capacity calculation of UPFC will determine UPFC's power flow control effect. In this part of study, to ensure a single variable, UPFC is installed at the head of line, that is, the power flow sending end in default.

4.2.1 UPFC site selection method

To fully develop the UPFC control performance and maximize the overall benefit of a UPFC project, this paper puts forward the following general configuration principles based on existing engineering experiences [21–26]:

(1) Prioritize trans-provincial connection sections.

(2) Prioritize transmission cross-sections in provinces.

Adding UPFCs on these kinds of cross-sections can play a role in balancing the power flow, thereby improving the power exchange capacity of the cross-section and the power dissipation capacity of the DC converter station near the area power grid.

On the basis of the above general configuration principles, it is necessary to carry out in-depth N-1 and N-2 fault checks on the lines to find out the weak links of important sections in the power grid. This analysis is useful in finding alternative locations for UPFC installations [27].

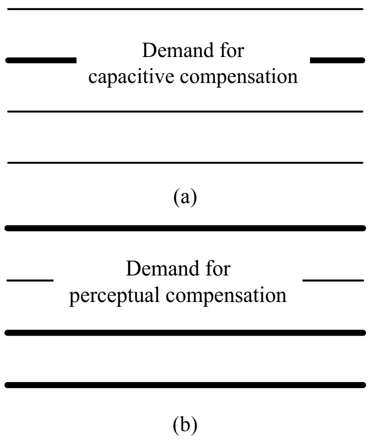
4.2.2 Determination of UPFC installation line

Following the determination of the demand point of the UPFC, the specific installation line is selected according to the section's compensation demand.

The typical setup of an inductive compensation demand system is shown in Fig. 2(a). Most of the lines in this section show light-load, and only one line is heavy-load. In this case the UPFC should be installed on the heavy-load line to transfer the load flow to the adjacent light-load lines.

The typical setup of a capacitive compensation demand system is shown in Fig. 2(b). Most of the lines in this section show heavy-load, and only one line is lightly loaded. In this case the UPFC should be installed on the light-load line to transfer the heavy-load line's load flow to this lightly loaded line.

When the number of heavy-load lines and light-load lines in the section is the same, it is usually best to compare



(a)

(b)

Fig. 2 Schematic diagram of power flow control demand with UPFC device (thick line indicates heavy power flow, thin line indicates light power flow)

the two schemes of limiting power flow in the heavy-load lines or raising power flow in the light-load lines. Thereafter it can be determined whether to install the UPFCs in the heavy-load or light-load lines.

When attempting to solve the problem of transmission line overload, priority should be given to install the UPFC directly on the overload line. The capacity requirement of installing the UPFC directly on the overload line is smaller than that of the other lines in the section [28].

4.2.3 UPFC optimal capacity calculation

When aiming to improve the cross-section transmission capacity, the UPFC's parallel side capacity (denoted by S_{UPFCp}) is usually taken as a series side capacity (denoted by S_{UPFCs}), socan be expressed as follows [29–31]:

$$S_{UPFC}= S_{UPFCp}+S_{UPFCs}=2S_{UPFCs}= 2\sqrt{3}U_B I \tag{9}$$

where I is the rated current of the UPFC's series side, which can be selected according to the rated current of the line where it is located.

The cross-section's transmission capacity is limited by the N-1 static power flow constraint, i.e., the failure of one circuit in the section causes the overload of another circuit. The faulty line is called L_{EF}, the overloaded line is called L_{EO}, and the remaining lines are denoted by L_{Ei} (the total number of branches is m_E, $i \in 1\left[m_E - 2\right]$). Since L_{EO}'s active power exceeds the limit after N-1 faults of L_{EF}, the UPFC is installed in L_{EF} to improve the section current and enhance the transmission capacity.

L_{EO}'s active power is controlled to the rated power (denoted by $P_{EO\max}$), and the UPFC's reactive power control target is set according to the line's power factor μ_{EO}, as shown in (10). On the premise that the line parameters and the initial state of the power grid are known, according to (3) and (4), the equivalent voltage value and phase angle at L_{EO}'s transmission end can be obtained, so as to obtain the equivalent voltage source model of the UPFC at this time, namely U_B and ρ.

$$\begin{Bmatrix} P' = P_{EO\max} \\ Q' = \tan(\cos^{-1}\mu_{EO}) \end{Bmatrix} \tag{10}$$

According to Fig. 1, the numerical size of U_B is determined by the D-value between P_0 and P' (that is $U_B \propto \left|P' - P_0\right|$). The larger the D-value, the larger the value of S_{UPFC}. At the same time, if the difference between P_0 and P' increases, then ΔP_{UPFC} increases, indicating that the lifting effect becomes stronger [32]. This can be expressed by the following formulas:

$$\Delta P_{UPFC} = y_1(P', P_0) \tag{11}$$

$$S_{UPFC} = y_2(P', P_0) \tag{12}$$

The UPFC device achieves control of the line power target by changing the serial voltage (U_B). From a UPFC performance viewpoint, the higher U_B, the stronger the regulation of the flow. However, excessive U_B will significantly increase S_{UPFC} and technical difficulty. Therefore, the upper limit of U_B needs to be determined according to the economy of the UPFC device. At the same time, too small a U_B cannot effectively regulate the line power flow function. Therefore, it is necessary to determine the lower limit of U_B according to the section capacity improvement demand.

According to [33], with the increase of the section's target transport capacity, ΔP_{UPFC} remains the same, and the required increase in the converter output increases, which means $\Delta P_{UPFC}/S_{UPFC}$ becomes smaller and the UPFC's efficiency decreases. In this capacity range, there is a saturation relationship between the UPFC capacity and the section boost transfer ability.

Substituting S_{UPFC} into (13) allows for comprehensive consideration of both the technical difficulty and economy of UPFC installation.

$$\max K_{UPFC} = \max F(S_{UPFC}) = \max \frac{\Delta P_{UPFC}}{S_{UPFC}} \tag{13}$$

4.3 Optimized configuration of UPFC selection process

Fig. 3 shows the UPFC site selection flowchart for a 500 kV grid. By comparing the control effect of each installation position horizontally, this method can quickly realize the optimal installation position of the UPFC.

In this process, UPFC site selection and optimal capacity calculation are divided into the following steps:

(1) Based on grid data, power grid operational analysis is carried out. Inter-provincial and intra-provincial cross-sections where the N-1 safety check failed are selected.

(2) The UPFC installation line is chosen according to the demand characteristics of the section.

(3) If there is a margin to increase the cross-sectional capacity, S_{UPFC} should be calculated when K_{UPFC} is maximized.

5 Simulation analysis of UPFC application scheme

This section uses a 500 kV grid in a province in China as the research object to analyze the effect of a UPFC installation on the power grid. This section carries out the economic analysis of the optimized UPFC scheme. The calculation uses 2020 planning data from provincial operation planning report.

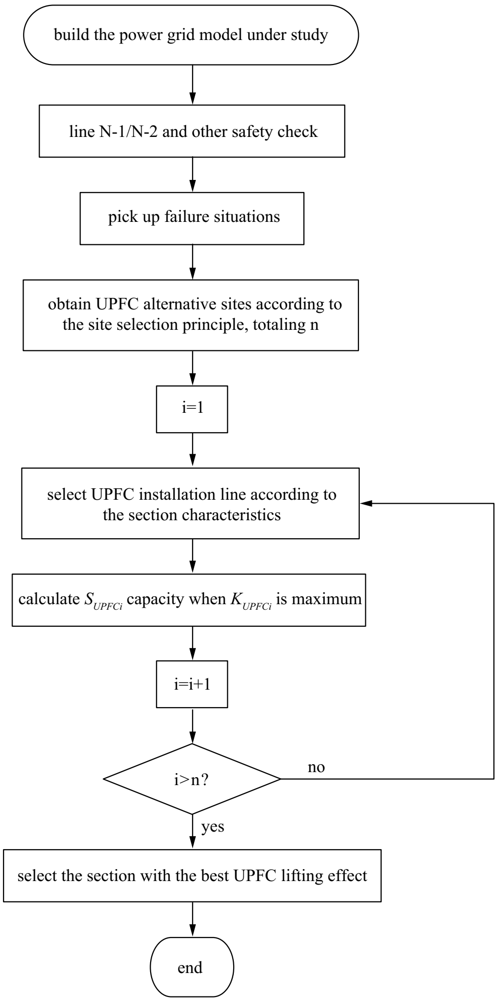


Fig. 3 Flow chart of UPFC installation site selection

5.1 UPFC installation location analysis

Based on the results of line N-1/N-2 checks and UPFC site selection principles, three UPFC demand sites were obtained in this power grid. The three sections are all important provincial sections, namely, the Northern-Central section, Central-South section, and Western delivery section.

(1) Northern-Central section

North-Central section is composed of four circuits. The section has the same number of heavy-load lines as light-load lines.

The installation line of the UPFC was chosen following determination of which option is more economical between installing on light-load or heavy-load lines.

After verification, it was found that the section transmission power could be increased by approximately 1000 MW by addition of the UPFC. Fig. 4 compares the required UPFC capacities for light-load and heavy-load lines at different section lifting powers.

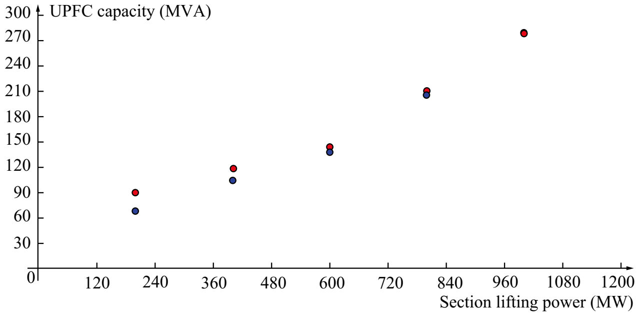


Fig. 4 Comparison of UPFC capacities required for the light-load and heavy-load lines of the Northern-Central section (the red dots represent that UPFC is installed on the light-load line side, the blue dots represent that UPFC is installed on the heavy-load side.)

With the increase of section lifting power, the differences between the line current carrying capacities decrease, and the differences between UPFC capacities also decrease. However, the economic effect of installing the UPFC in heavy-load lines is better than that of installing it in light-load lines. Therefore, the UPFC is selected for the head of heavy-load double circuit lines.

(2) Central-South section

Central-South section is composed of six circuit lines, with more light-load lines than heavy-load lines. It is a typical case of inductive compensation demand. The UPFC is selected for the head of heavy-load single circuit line.

(3) Western delivery section

This section is composed of five circuit lines, with more light-load lines than heavy-load lines. It is a typical case of inductive compensation demand. The UPFC is selected for the head of heavy-load double circuit lines.

5.2 UPFC optimal capacity calculation

Following determination of the UPFC installation line, the UPFC is distributed into the data model. This example uses 50 MW as the gradient for calculation. In each calculation, first the section power is adjusted towards the target power by adjusting generator output on both sides of the section, then the required UPFC capacity under this adjustment is calculated, after which the corresponding K_{UPFC} is found. Thereafter, by comparing all calculation results, S_{UPFC} at maximum K_{UPFC} can be obtained, which is the optimal result considering both economy and stability.

(1) Northern-Central section

It is found that the maximum section power can be increased by 1017 MW when a UPFC is installed in the Northern-Central section. Fig. 5 shows the correlation between S_{UPFC} and ΔP_{UPFC}, where it can be seen that there is a saturation relationship between the two parameters.

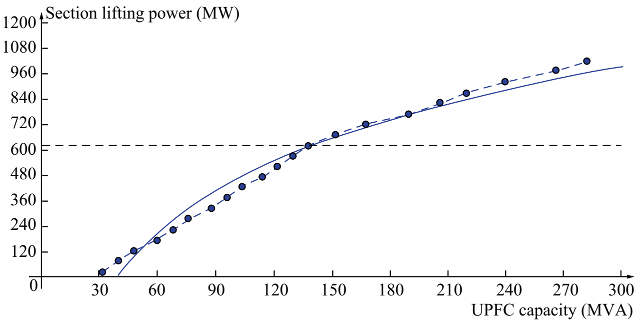


Fig. 5 Relationship between UPFC capacity and section lifting power in the Northern-Central section

The simulation results show that K_{UPFC} is largest when S_{UPFC}=138 MVA, and ΔP_{UPFC}= 623 MW. Table 2 presents a selection of data for detailed analysis.

Table 2 Calculation results of Northern-Central section

	calculation results (partial)						
	S_{UPFCs}<138			optimal	S_{UPFCs}>138		
ΔP_{UPFC} (MW)	74.9	225	473	**623**	771	870	1017
S_{UPFCs} (MVA)	40	68	114	**138**	190	220	282
K_{UPFC}	0.94	1.65	2.08	**2.26**	2.03	1.98	1.80

It can be seen that the required UPFC capacity increases with the increase of ΔP_{UPFC}. When S_{UPFCs}<138 MVA, K_{UPFC} increases with S_{UPFCs}, that is, the improving effect of unit capacity increases with the increase of UPFC capacity. For S_{UPFCs} >138 MVA, K_{UPFC} decreases with S_{UPFCs}, as the UPFC capacity increases, its improving effect decreases. Therefore, in order to ensure the optimal control effect, S_{UPFCs} should be 138 MVA in the North-Central section.

(2) Central-South section

It is found that the maximum section power can be increased by 932 MW when a UPFC is installed in the Central-South section. Fig. 6 shows the correlation between ΔP_{UPFC} and S_{UPFCs}, where it can be seen that there is a saturation relationship between the two parameters.

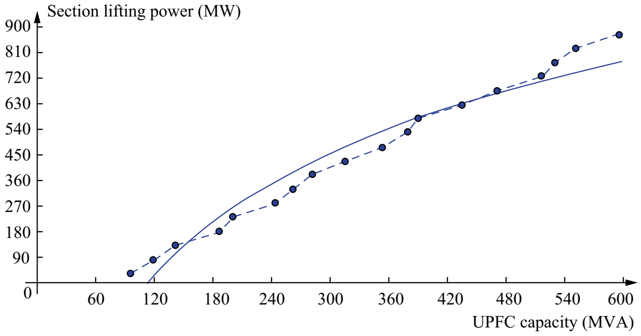


Fig. 6 Relationship between UPFC capacity and section lifting power in Central-South section

The simulation results show that K_{UPFC} is largest when S_{UPFCs}=190 MVA, and ΔP_{UPFC}=587 MW. Table 3 presents selected data for detailed analysis.

Table 3 Calculation results of Central-South section

	calculation results (partial)						
	S_{UPFCs}<190			optimal	S_{UPFCs}>190		
ΔPUPFC (MW)	181	32	478	**587**	626	725	932
S_{UPFCs} (MVA)	88	126	172	**190**	213	253	330
K_{UPFC}	1.03	1.31	1.39	**1.55**	1.47	1.43	1.41

It can be seen that the required UPFC capacity increases with the increase of ΔP_{UPFC}. When S_{UPFCs} < 190 MVA, the improving effect of unit capacity increases with the increase of UPFC capacity. For S_{UPFCs} >190 MVA, as the UPFC capacity increases, its improving effect deteriorates. Therefore, in order to ensure the optimal control effect, S_{UPFCs} should be 190 MVA in the Central-South section.

(3) Western delivery section

It is found that the maximum section power can be increased by 1044 MW when a UPFC is installed in the Western delivery section. Fig. 7 shows the correlation between ΔP_{UPFC} and S_{UPFCs}.

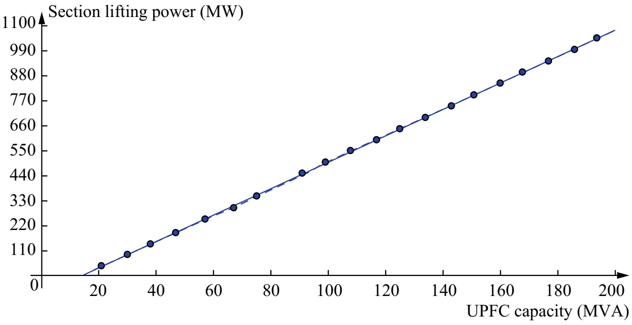


Fig. 7 Relationship between UPFC capacity and section lifting power in Western delivery section

The simulation results show that K_{UPFC} is largest when S_{UPFCs}=184 MVA, and ΔP_{UPFC}=1044 MW. Table 4 shows the detailed analysis of selected data.

It can be seen that the required UPFC capacity increases with the increase of ΔP_{UPFCs}. As the peak of K_{UPFC} is at maximum section power, the curve does not show saturation characteristics. However, if the section power can be further improved, the unit lifting capacity of UPFC will decrease.

Table 4 Calculation results of Western delivery section

	calculation results (partial)					
	S_{UPFCs}**<184**					**optimal**
ΔP_{UPFC} (MW)	92.4	252	450	649	945	**1044**
S_{UPFCs} (MVA)	20	47	81	115	167	**184**
K_{UPFC}	2.31	2.68	2.78	2.82	2.83	**2.84**

5.3 UPFC effect comparison and economic analysis

Power flow calculations were carried out before and after UPFC installation. The comparison of the optimal result of each section is presented in Table 5.

Table 5 Optimal result of individual sections

Section	S_{UPFCs} **(MVA)**	ΔP_{UPFC} **(MW)**	K_{UPFC}
Northern-Central section	276	623	2.26
Central-South section	380	578	1.52
Western delivery section	368	1044	2.84

The priority of the above three application scenarios for projects is as follows: Western delivery section > Northern-Central section > Central-South section.

The UPFC of the Western delivery section includes a 184 MVA series converter and a 184 MVA parallel converter. The project investment is approximately 450 million Yuan [34]. The Western delivery section UPFC project can solve the problem of "stuck neck" in the section's power flow transmission, and effectively improve the section transmission capacity by 1044 MW. This will lead to an improved safe operation level and avoid the costly and challenging construction of a 500 kV transmission channel.

6 Conclusions

This paper provides methods and recommendations for the site selection and application of UPFC devices in power grid planning. Following detailed evaluation, the following conclusions are reached:

(1) Being a FACTS device that has accurate power flow control ability, the UPFC has the means to effectively improve transmission capacity.

(2) The installation position and capacity of a UPFC have great influence on its control effect and economic benefit. In order to achieve the same control effect, a UPFC installed on heavy-load lines requires less capacity than one installed on light-load lines. The control effect of a UPFC is not proportional to its capacity. Before reaching the optimal value, the control effect increases with the increase of capacity. When a UPFC's capacity reaches a certain point, the control effect of the unit capacity will decrease as the capacity increases.

(3) The UPFC point selection method proposed in this article is practical, which has guiding significance for site selection and implementation of UPFC projects.

While this study achieved it objective, it did not cover other application effects of UPFC. Therefore future research will include problems related to UPFC optimal configuration under other application scenarios or multiple optimization objectives.

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