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Application of UPFC in Fujian 500 kV power grid

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Abstract: In order to release the capability restriction of the North–South transmission channels in the 500 kV power grid of Fujian Province, this article studies the application of unified power flow controller (UPFC) to improve the transmission capability under steady-state security restriction with *N*−1 principle. On the basis of analysis of principle and structure of UPFC, a simplified equivalent model of UPFC is constructed and used in BPA simulation software. The optimal installation scheme and the minimal capacity required of UPFC are determined by comparing the results of power flow calculation in various schemes. The research result shows that the application of UPFC can effectively reduce the *N*−1 overload problem of the North–South transmission channels, and has a great economic advantage over the traditional solution. Finally, based on the technical and economic analysis, this study puts forward suggestions on the construction of UPFC in the Fujian 500 kV power grid.

1 Introduction

Many kinds of flexible AC transmission system (FACTS) devices such as Switching Virtual Circuit, Thyristor Control Series Compensation, and static synchronous compensator (STATCOM) have found increasingly wide utilisation to improve the flexibility, controllability, and stability of power system in recent years. As the latest generation of FACTS devices, unified power flow controller (UPFC) is regarded as the most innovative and powerful FACTS electronic component [1]. UPFC is structurally composed of a STATCOM and a static synchronous series compensator (SSSC), combining the advantages of both components. UPFC can realise precise power flow control and improve the transmission capability restriction and has great influence on dynamic stability and voltage stability of power grid. Since the parallel section of UPFC can provide active power for the series section, the series section of UPFC can send out and absorb both the reactive and active power. Therefore, the power flow regulating the ability of UPFC is stronger than SSSC [2, 3].

At present, the 500 kV power grid of Fujian Province has formed a large circular network with two coastal channels. In pace with the increase in load in the next few years, Fujian Province 500 kV power grid will face the following problems. First, the requirement of North–South transmission capability will be greatly increased and it is estimated that the requirement will reach 950 and 1200 MW by 2020 and 2025, respectively. Therefore, it is difficult to satisfy the growing demand of transmission capability. Second, the transmission capability is restricted drastically due to the imbalance of each transmission line capacity in North–South channel. It is imperative for Fujian power grid to solve the above-mentioned problems in the next few years. Relevant departments are studying a variety of measures such as transformation of transmission line to expanse capacity, constructing new transmission channel and strengthening the southern power source.

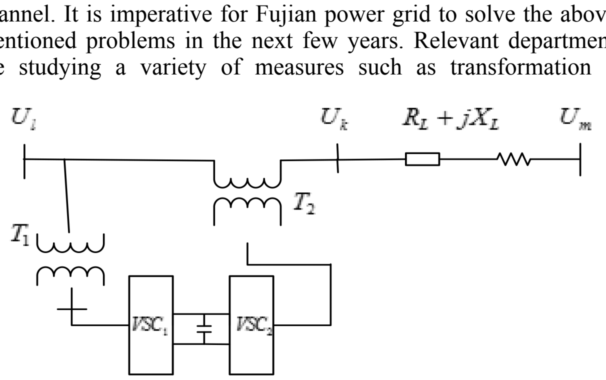

Fig. 1 *Schematic diagram of the UPFC structure*

Since the concept of UPFC has been proposed, a large volume of literature has studied the application of UPFC to optimisation of power flow and voltage regulation. On the basis of these research results, this paper analyses the effect of UPFC in Fujian Province power grid. Some suggestions on UPFC capacity and other parameters are put forward with the calculation of power flow under normal and fault conditions.

2 Simplified calculation model of UPFC

UPFC is a FACTS device, consisting of a series section and a parallel section, as Fig. 1 shows. VSC_1 and VSC_2,which are two voltage-source converters connected by a shared DC capacitor, can make active power flow bidirectionally. The parallel converter VSC_1 can provide reactive power to a grid system to regulate the node voltage; series converter VSC_2 is used to control the power flow.

The power injection model is generally used in power flow calculations with FACTS devices, which means the contribution of the line's adjustable variable to the system is transplanted to the nodes on both sides of the corresponding line. With a given control target of UPFC, this model is complicated to calculate and difficult to converge. Therefore, this paper adopts a UPFC model of power flow calculation with an additional node, which is simpler and more practical. As shown in Fig. 2, the node l is the input port of UPFC, and the node k is the output port of UPFC. UPFC can control active power, reactive power, and voltage of parallel-side node. For predigesting analysis and calculation, the node l is set as a PV node and the node k is set as a PQ node. Set $P_k + jQ_k = P_c + jQ_c$ and $U_l = U_c$, and ignore the active loss of UPFC, thus the active load and voltage of the node l are P_c and U_c, and the active and reactive load of the node k are P_c and Q_c. This simplified UPFC model with node-equivalent method simplifies power flow calculation and ensures the compatibility of the simulation software with UPFC [4–6].

3 Application of UPFC in Fujian 500 kV power grid

3.1 General situation of the Fujian 500 kV power grid

At present, there have been three transmission channels which connect the northern grid and the southern grid in Fujian Province,

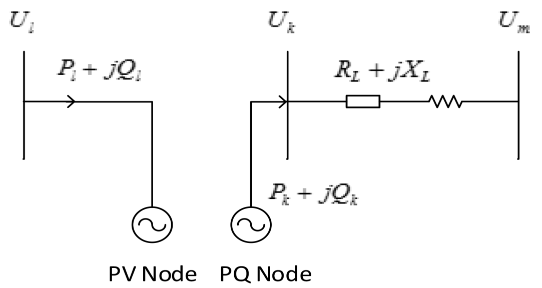

Fig. 2 *UPFC model of power flow calculation*

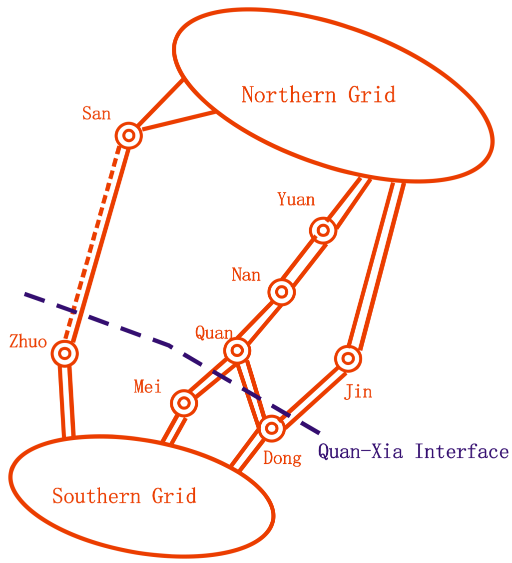

Fig. 3 *Schematic diagram of Fujian 500 kV power grid*

Table 1 Transmission capability comparison

No.	Installation scheme of UPFC	Transmission capability of the Quan–Xia interface, MW
1	install in the Yuan–Nan line	8350
2	install in the Zhuo–San line	9200
3	without UPFC	8000

while the Quan–Xia interface represents transmission capability of three North–South channels, as Fig. 3 shows. Owing to the unbalanced distribution of power flow and the small conductor cross-section of some old lines in the North–South transmission channels, the transmission capability of the Quan–Xia interface is limited to ∼7650 MW. If the second Zhuo–San 500 kV line is built in 2020, the transmission capability of the Quan–Xia interface can be increased to ∼8000 MW.

Based on the result of load forecasting and the arrangement of power source construction during the 13th Five-Year Plan period, the maximum load increment in the southern Fujian area will account for 60% of the province's total. While 80% of the province's newly installed large power capacity is located in the northern region, including ∼70% of the newly installed capacity of wind power. During the 13th Five-Year Plan period, the demanded capacity of the 500 kV North–South transmission channel will increase continually and the related lines (such as Nan–Yuan line) will exceed the limit of transmission capability. Therefore, it is urgently necessary to take measures to improve the transmission capability of North–South transmission channel in the Fujian 500 kV power grid.

3.2 UPFC schemes and effects

In the case of a circular network with multi-parallel transmission channels, the following two categories are used to taken into consideration for the installation site of UPFC. First, install UPFC on the overloaded line to restrict power flow on the overloaded line until satisfying *N*−1 principle. Second, install UPFC on the underloaded line to increase the power flow on the underloaded line, balance the power flow of each line, and improve the transmission capability in this way.

According to the principle above, there are a variety of options of UPFC installation locations to choose from. Considering the required capacity of UPFC and the actual effect, this paper focuses on the following two schemes of installation site: (i) install on the Yuan–Nan double-circuit line and (ii) install on the Zhuo–San double-circuit line.

In the first scheme, when one line of the Yuan–Nan double-circuit line malfunctions, the UPFC rapidly controls the power flow on the other line below the transmission limit after the faulty line trips and UPFC on the faulty line stops running at the same time.

In the second scheme, UPFC keeps running during the normal time, which can control the power flow on the Zhuo–San double-circuit line and balance the distribution of North–South channels' power flow. In this way, the power flow is limited to the allowable range and the transmission capability of North–South channels is improved.

In Table 1, the calculation for the power flow of the two schemes in summer peak mode and the transmission capability of the Quan–Xia interface are shown.

Table 1 shows that (i) scheme 1 can increase the transmission capability of the Quan–Xia interface by ∼350 MW. (ii) Scheme 2 can increase the power flow on the Zhuo–San double line and reduce the pressure of other North–South transmission channels. This will effectively increase the transmission capability of the Quan–Xia interface to ∼1200 MW. (iii) Both schemes can improve the transmission capability of the North–South channels, and furthermore, the effect of scheme 2 is more adaptive to the load increase than scheme 1. Therefore, scheme 2 is superior to scheme 1.

3.3 Analysis on reactive power requirements

Providing dynamic reactive power support for the grid is one of UPFC's main functions. The Yuan–Nan line is located in the Quanzhou area which is not only the maximum load area in Fujian Province, but also the access node of UHVDC in the future. Therefore, it is undoubtedly necessary to strengthen the dynamic reactive power support in this region. Moreover, Sanming and Longyan, where the Zhuo–San line is located, are the main receiving-end grids in the west Fujian Province, and lack the supply of a large-scale power source. With the development of load and the increase in the power flow from the East region to the West region, it is also necessary to strengthen the reactive power support. The construction of UPFC will not only solve the problem of power flow, but also provide the ability of dynamic reactive power support to some extent for the above-mentioned relevant regions, thus improving the security and stability of the Fujian power grid.

4 Calculation of UPFC capacity

The selection of UPFC capacity is an important step of the device selection and procurement process. The previous research has shown that UPFC capacity determines the ability of changing active power flow distribution [6, 7]. The capacity selection principle of UPFC converter in series side is according to (1), in condition of satisfying the demand for power flow control

$$S_{NV} = \sqrt{3} I_N U_{VL} \tag{1}$$

where I_N is the rated current and U_{VL} the injection voltage of UPFC's series transformer on line side converted from the valve side.

The selection of UPFC capacity needs to not only meet the recent security demands, but also consider the load growth and the change of the boundary conditions in the future. By means of *N*−1 power flow analysis based on BPA simulation software with UPFC calculation model, the power flow of Quan–Xia interface is calculated, and the UPFC converter's capacity required is calculated.

Boundary conditions of calculation: According to the load forecast published by grid planning department, the peak load of Fujian will be 44,200 MW in 2020, 47,050 MW in 2021, 50,000 MW in 2022, and 52,650 MW in 2023. In addition, the power source supply, which is planned and constructed in the south area of Fujian power grid in 14th Five-Year Plan, has a great impact on the transmission capability required of the North–South channels. Therefore, it is essential to consider the uncertainty of Quanhui Power Plant and Xiamen Pumped-storage Power Station's construction time (see Table 2).

The calculation result shows that if Xiamen Pumped-storage Power Station is not put into operation, the power flow of the Quan–Xia transmission interface will reach 8700 MW during the peak load mode in 2023. The transmission capability can satisfy the demand when UPFC capacity is 500 MVA with a certain margin. Owing to the gradual construction of Zhangzhou Nuclear Power from 2024 to 2025, the capacity of UPFC will decrease in spite of load growth. Therefore, the UPFC device with 500 MVA capacity can meet the requirement of the Fujian North–South channels' transmission capability from 2020 to 2025.

5 Economic analysis of UPFC scheme

Two options are taken into account in the economic comparison. First, the scheme of UPFC. In this scheme, the construction of the new North–South channel can be postponed. Two load levels are considered: (i) in expected boundary conditions, the UPFC device may meet the transmission needs of the Fujian North–South power transmission program from 2021 to 2025. The scheme under this condition is marked as ①. (ii) The UPFC device cannot meet the transmission demand of the Fujian North–South channel in 2023 due to the rapid increase in load or the delay of southern power supply. The scheme under this condition is marked as ②. Second, the scheme without UPFC (hereinafter referred to as the new channel program), which is marked as ③. In this scheme, a new North–South transmission channel needs to be built during 13th Five-Year Plan. The details are as follows.

The UPFC scheme: In 2020, the Zhuo–San second-circuit line will be put into operation and the UPFC will be installed on the Zhuo–San double-circuit line. With the growth of North–South transmission requirement in the future, it is planned to add a new 500 kV North–South channel and form a Fu–Xia UHV (ultra-high voltage) double-circuit line in time. Thus, the speed of load development and the capacity of the southern power source will affect the construction timing of the new channel dramatically.

The new channel scheme: In 2020, the new 500 kV North–South channel from Fu to Mei will be constructed. In 2026, when the UHV substation in Xiamen is constructed, parts of Fu–Mei 500 kV line will be transformed from 500 kV to ultra-high voltage, forming the Fu–Xia UHV line. In 2030, the Zhuo–San second-circuit line will be built to strengthen the structure of the western Fujian 500 kV power grid.

The final construction scales of these two schemes are almost the same by 2030, forming the new UHV North–South channel and the Zhuo–San double-circuit line. Nevertheless, the two schemes are different in the chronological order of construction.

According to the preliminary calculation results of the UPFC converter capacity and the reference of the UPFC project precedent and the key parameters, it is estimated that the investment of UPFC on the Zhuo–San line is ∼1 billion yuan. The construction investment of the new channel is determined according to the related feasibility research report.

Table 3 lists the annual investment estimation of the two schemes, which are converted into present value (2020) for comparative analysis.

It can be seen from Table 3 that the application of UPFC can postpone the construction of the third channel until 2026 in the case of a slow-growing load or an abundant supply of southern power source. Thus, for scheme ①, the current investment is less and the total investment (present value) is ∼5.36 billion yuan. However, the scheme of UPFC is lack of economic advantages in the case of a rapid-growing load.

Table 2 UPFC capacity required under different conditions

Year	Load of Fujian, MW	If Quan–Hui is built	If Xiamen pumped-storage is built	UPFC capacity required, MVA
2020	44,200	×	×	0
2021	47,050	×	×	38
2022	50,000	×	√	0
		√	×	267
		×	×	331
2023	52,650	√	√	67
		√	×	494

Note: Quanhui Power Plant outputs 80% of the installed capacity. Xiamen Pumped-storage Power Station outputs 100% of the installed capacity.

6 Conclusions

Targeting the problem of limited transmission capability of North–South channels owing to imbalanced distribution in the Fujian 500 kV power grid, this paper presents the solution by application of UPFC device. Through the calculation of power flow with BPA, the effect of UPFC in Fujian 500 kV power grid is analysed and the economic comparison is presented. The conclusion is as follows:

i. The application of UPFC device can counterpoise distribution of power flow on the North–South transmission channels, thus improving the transmission capability effectively. Different installation schemes of UPFC have significant differences in effect on transmission capability. Through analysis and comparison, this paper recommends installing UPFC on the Zhuo–San double-circuit line.

Table 3 Comparison of investment estimation

No.	Project	Investment (a hundred million yuan)				
		2020	2023	2026	2030	Total
①	the UPFC project	10.0				53.6
	the second Zhuo–San line	4.6				
	the Fu–Mei line			38.5		
	the Fu–Xia UHV line				32.2	
②	the UPFC project	10.0				60.1
	the second Zhuo–San line	4.6				
	the Fu–Mei line		38.5			
	the Fu–Xia UHV line				32.2	
③	the Fu–Mei line	38.5				60.7
	the Fu–Xia UHV line			32.2		
	the second Zhuo–San line				4.6	

Note: Total investment is the present value, the base year is 2020. The discount rate is 8%.

ii. Based on the operational requirements for safety and stability in the Fujian power grid, preliminary recommendation on UPFC capacity is put forward in the expected boundary condition.
iii. Compared with the scheme of constructing the new North–South channel, the scheme with UPFC has an economic advantage in the condition of load growing slowly in the next few years.

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