

## Technical analysis of 500kV oil-immersed series transformer for unified power flow controller

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**Abstract.** 500kV series transformer is the key equipment in Suzhou 500kV unified power flow controller(UPFC) project, which undertakes the regulation of voltage and power between the converter and the line. Due to the special connection mode and operating condition, 500kV series transformers differ from conventional ones. First, the main insulation of the line side winding is matched with the line voltage grade, and the longitudinal insulation of the end is determined by the overvoltage level, which brings complex characteristics of the insulation level of the line side windings. Secondly, the lightning full-wave impulse test and the applied AC voltage withstand test are also different from the conventional transformers. Finally, the special working condition of series transformer causes the high requirement of anti-short circuit ability and over excitation capability. In Suzhou UPFC project, a large number of technical researches, aiming at difficult problems of the complex insulation of the windings, the special test technology, the anti-short circuit ability and the high excitation ability, have been carried out for 500kV oil-immersed series transformer. In this paper, the technic analysis of 500kV series Transformer in Suzhou UPFC project is carried out from various aspects, such as operating conditions, technical characteristics and test requirements.

### Introduction

Unified Power Flow Controller (UPFC) is a kind of advanced and flexible transmission technology. It is a thyristor control device which can realize shunt compensation, series compensation, phase shift and voltage regulation. Through fast reactive stimulation, UPFC can adjust the current and improve the transmission capability of the system without changing the frame structure, so as to dynamically support the voltage of the access point and to improve the system voltage stability[1, 2]. However, up to now, there are only four UPFC devices in operation in the world, which are located in the United States Power (American Electric, AEP) Kentucky State Inez Substation, the United States New York Electric Power Bureau Marcy Substation, South Korea, south half of the Kangjin Substation and China's Jiangsu Nanjing West Ring Iron North Substation [3,4]. The Suzhou UPFC substation, which was put into use in 2017, is the first 500kV voltage grade UPFC project in the world.

500kV series transformer, undertaking the task of adjusting converter and line voltage and power transmission, is the key equipment in UPFC project. The line side winding of series transformer is connected with transmission lines, and the valve side winding is connected with the converter, which generates a voltage with controllable amplitude and phase transformed to the line side by the series transformer. The voltage can be equivalent to an amplitude and phase adjustable power supply in the line, realizing the function of UPFC [5]. Due to the special connection mode and operating conditions, series transformers differ significantly from conventional ones. The main insulation of the line side winding is matched with the line voltage grade, but the rated voltage of the line side winding is often far below the line voltage, which brings complex characteristics of the insulation level of line side windings. Therefore, the lightning full-wave impulse test and the applied AC voltage withstand test are also different from conventional transformers. In addition, the special working conditions of the series transformer put forward higher requirements in anti-short circuit and over excitation.

In this paper, the technic characteristics of 500kV oil-immersed series transformer in Suzhou Unified Power Flow Controller Project are analyzed in depth.

### Operating condition

The series transformer is used in the unified power flow controller. Its line side winding is connected with high voltage grade lines, the valve side winding is connected to the converter, and the balance winding only provides channels for third harmonic. The input and exit of the series transformer are controlled by line side circuit breakers and disconnectors, as shown in Fig. 1. Via closing the line side circuit breaker and opening two disconnectors at line side, series transformer exits operation. If the disconnectors are closed and the breaker is open, the series transformer is put into operation.

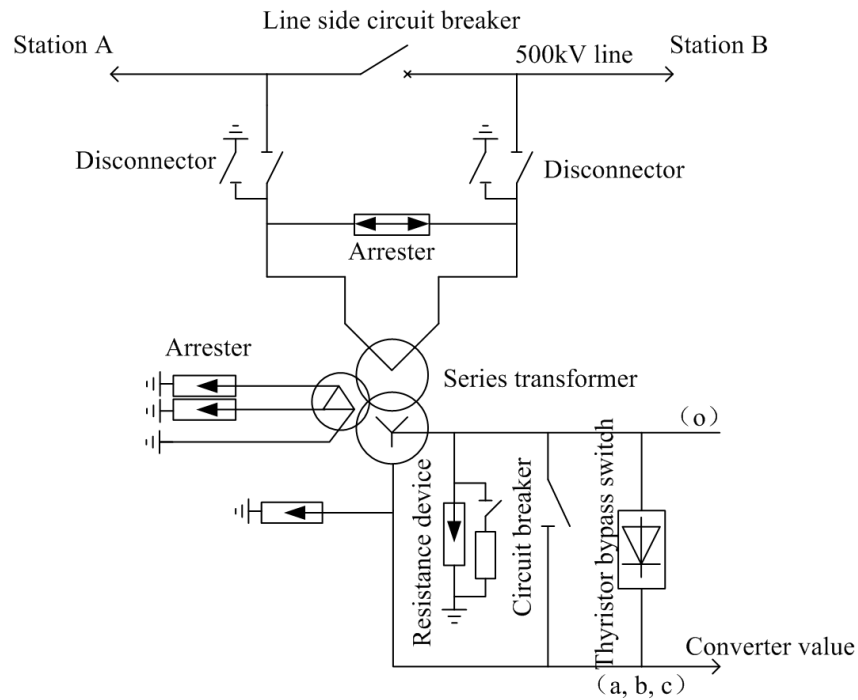


Fig. 1 Schematic diagram of the series transformer in UPFC

Because the rated voltage of series transformer line side winding is lower than system voltage, the turn number of line side winding is less than that of conventional 500kV transformer, and the insulation between the ends of the line side winding is hard to withstand the standard lightning overvoltage of 500kV system. It is necessary to limit the lightning overvoltage between two terminals of the line side winding, which can reduce the difficulty of producing the series transformer. The type of arrester bridged at the line side should match the insulation level of the line side windings. A Suzhou UPFC Project 500kV series transformer is shown in Fig. 2.



Fig. 2 500kV Series Transformer

Under normal operating conditions, the current of line side winding and the valve side winding of a series transformer is basically rated. The line side winding rated current is consistent with the line rated current, and the rated current of the valve side winding is calculated according to the transformation ratio.

In the case of valve side stuck-open fault, the impedance of the series transformer is changed from the line side, which is close to a line series reactor. Regardless of the change of external power flow, the series transformer line side winding still needs to flow through the line rated current, but the valve side winding and the balance winding current is zero.

In case of single phase grounding fault in the line side, the valve side winding will be operated to short-circuit conduction by the thyristor bypass switch in a very short time. The line side winding vision year maximum short-circuit current, according to the 500kV UPFC project short-circuit current calculation, is approximately 10 times of rated current.

## Technical features

### Basic parameters

The basic parameters of Suzhou UPFC Project 500kV series transformer are shown in table 1. The series transformer line side is relatively 500kV voltage grade, but the rated voltage of the line side winding is only  $43.5\text{ kV}/\sqrt{3}$ , far below the rated voltage of valve side. The 10kV voltage level balance winding provides third harmonic channels in delta connection. The single-phase capacity of 500kV series transformer is 100MVA, and the capacity of balance winding is 34MVA.

Tab.1 Basic parameters of series transformer

	Line Side winding	Valve side winding	Balance winding
Rated voltage (kV)	$43.5/\sqrt{3}$	$105/\sqrt{3}$	10
Rated capacity (MVA)	100	100	34

### Type of structure

The winding form of 500kV series transformer is single phase and double winding, with balance winding and without taps.

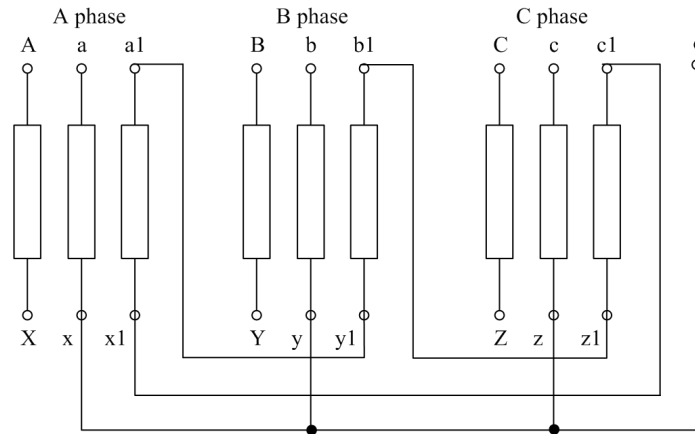
Because of the connection to line, the insulation level to ground of series transformer line side winding matches 500kV line voltage grade, so the series transformer winding adopts independent double winding structure instead of self-coupled form.

In addition, the series transformer valve side winding is connected with the converter, which can change amplitude and phase of voltage, so the series transformer does not need to adjust the voltage via on-load tap changer.

### Winding connection

The connection group symbol of 500kV series transformer has a large difference with the conventional transformer, mainly because its line side windings are connected with lines, and it does not form a star or a delta connection like conventional three-phase transformer.

The winding connection: I0 (line side winding), I0 (valve side winding) and i0 (balance winding) in single-phase, and III (line side windings), yn (valve side windings) and +d11 (balance windings) in three-phase. Two terminals of the line side winding are educed respectively, and the winding connection diagram is shown in Fig. 3.



**Fig. 3 500kV Series transformer winding connection diagram**

**Insulation level**

The line side winding is connected into 500kV system, and its insulation level should mainly refer to 500kV system.

Considering the characteristics of small turns amount and over-voltage in the line side windings, the windings are determined to be uniform insulation. The insulation level of the windings is shown in table 2.

**Tab.2 Insulation level of windings**

Rated withstand voltages for series transformer	Rated switching impulse withstand voltage phase-to-earth (peak)	Rated lightning impulse withstand voltage (peak)	Rated short-duration induced or separate source AC withstand voltage (r.m.s)
Line side winding terminal-to-terminal	750kV	950kV	200kV
Line side winding phase-to-earth	1175kV	1550kV	680kV

The particularity of series transformers determines that the number of windings in the line side is less than that in the valve side, and the line side winding is hard to withstand the lightning impulse overvoltage of the 500kV system.

In order to limit the level of lightning over-voltage between two ends of the line side winding, the lightning over-voltage between the line side windings of the series transformer is limited to around 750kV by the bridged-connection arrester. Therefore, the rated full-wave lightning impulse withstand voltage (peak value) is designed as 950kV, which can not only guarantee the insulation safety margin, but also reduce the difficulty in design and manufacture of series transformers.

Due to the existence of thermal standby state of the 500kV series transformer in operating conditions, the rated phase-to-ground full-wave lightning impulse withstand voltage (peak value) of line side winding is designed as 1550kV. The insulation design, delivery test and hand-over test are carried out under the condition of short circuit between two ends of the line side winding.

The design of rated short time induced voltage or the applied AC withstand voltage is far greater than the running overvoltage and the test transmission overvoltage, but it cannot be verified because of the special structure of the series transformer.

The insulation level of valve side winding and balance winding is designed according to the system design reference standard and the request of satisfying transmission overvoltage during insulation tests of line side windings.

**Withstand short-circuit capacity**

In case of phase-to-phase or phase-to-ground short circuit, the short-circuit current on lines, which is much greater than that of conventional transformers under this mode, will pass through the series transformer line side winding. Considering the limitation demand of the series transformer

short-circuit current and the converter capacity, the short-circuit impedance of series transformer is considered as 20%. According to the long-term short-circuit current calculation, maximum short-circuit current of 500kV bus is 53kA. Considering the influence of line branch and the series transformer short-circuit impedance, the fault current of the series transformer winding is 37kA. The impulse coefficient of short-circuit current is 2.69 [6], so the peak value of short-circuit current of series transformer can be 99.53kA. The 500kV series transformer is verified by short-circuit test to meet the requirement of short circuit capability.

**Withstand over-excitation capability**

In the normal operation of the series transformer, the valve side winding is in conduction with a low resistance, and only a few ampere currents in the line side windings are used for excitation. In the case of valve side open fault, the line side winding current is restrained by the transmission capacity, changing slowly, then the series transformer is equivalent to a series reactor. The line current will all participate in the excitation, resulting in serious excitation state in series transformer. The flux density of the series transformer cores in normal operating condition and in valve side open fault is shown in Fig. 4 and Fig. 5.

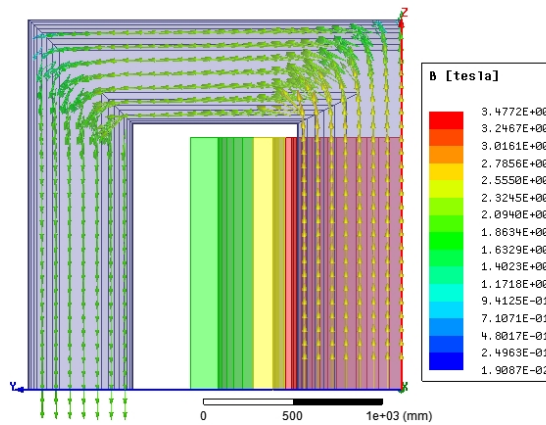


Fig. 4 The core magnetic field under valve winding open circuit

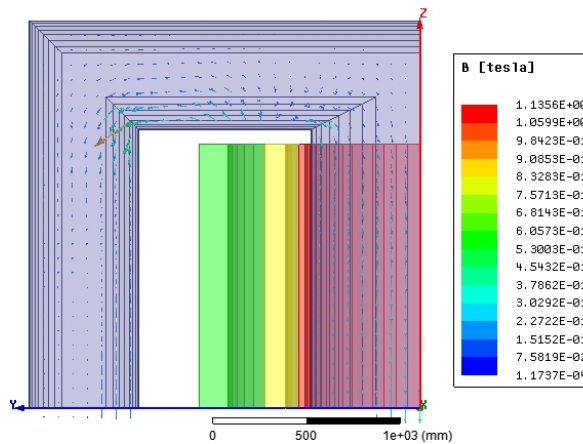


Fig. 5 The core magnetic field under normal operation

The flux density of silicon steel is usually saturated at 2T, and it can be seen that the magnetic saturation appears in the core in valve side open state.

**Test requirements**

**Lightning impulse test**

The uniform insulation design is used in series transformer line side winding, and the lightning wave can invade at both ends of the line side winding. Therefore, the lightning full-wave impulse test should be carried out at each end of both side windings. The overvoltage transfer inside the series transformer is more complex and more serious than conventional transformers, so the line side winding and balance winding can not be only grounded in the test of lightning full-wave impulse test, and the check of the side winding and balance winding is necessary. Therefore, when the test is

carried out in the line side winding, considering the transmission overvoltage, the ends of valve side winding and the balance winding should be connected with arresters, which should be consistent with project configuration.

When the lightning full-wave impulse test is carried out at the line side winding, one end of the line side winding is applied the voltage and the other end is grounded by a shunt. One end of the valve side winding is grounded directly and the other end is grounded by arresters, which is the same as the balance winding. Test wiring diagram is shown in Fig. 6.

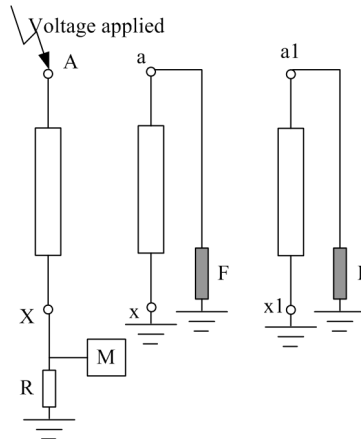


Fig. 6 Lightning Impulse test of the side windings of the series transformer

According to the actual wiring situation of the project, the lightning impulse test of the line side winding adopts both ends short connection mode. The test wiring diagram is shown in Fig. 7, the test voltage is applied to both ends of the line side winding. One end of the valve side winding is grounded by a surge arrester, and the other end is grounded by a shunt. One end of the balance winding is grounded by a lightning arrester and the other end is grounded directly.

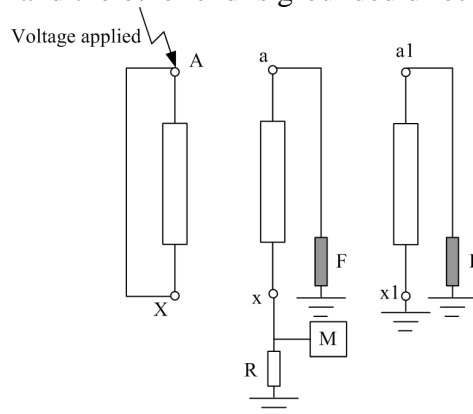


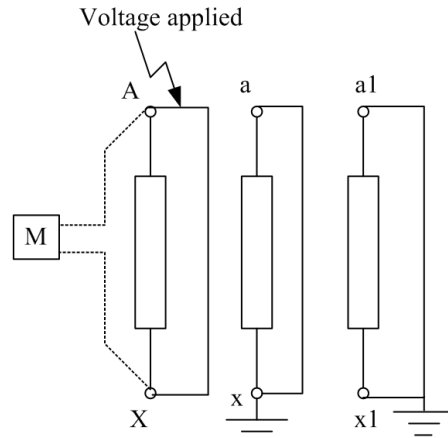
Fig. 7 Lightning Impulse test of the winding of the series Transformers to earth

Due to the existence of arresters, the tests carried out after full voltage full-wave impulse should include some reduced voltage full-wave impulse tests, and the reduced voltage values should be the same as those of the tests in rising to the full voltage impulse tests. For example: 60%, 80%, 100%, 100%, 100%, 80%, 60%. For lightning full-wave impulse tests with lightning arresters, there may be some differences in waveforms between reduced voltage tests and full voltage tests, and it is feasible to compare the waveforms of tests with same test voltages. If there are no obvious differences, it should be considered as qualified test.

#### External AC withstand voltage test

The main insulation level of the series transformer line side windings does not match the longitudinal insulation level between the terminals. The main insulation level is related to the line voltage level, and the rated short time induction or the applied AC withstand voltage is 680kV. But the longitudinal insulation level between the ends of the line side windings should be determined by considering the rated voltage, winding turns and various overvoltage levels. It is designed as 200kV, lower than main insulation level. Therefore, the maximum inductance of line side winding in

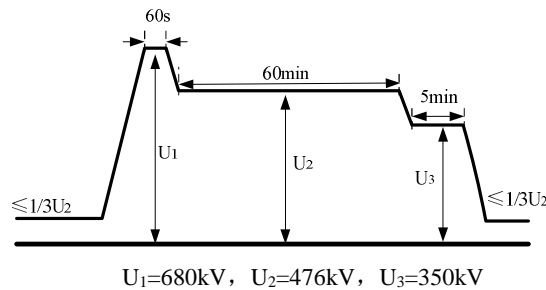
long-time AC induction voltage-withstand test is only up to 1.7 times of rated voltage (approx. 42.7kV), which is insufficient to verify the partial discharge level of line side winding main insulation, so applied AC withstand voltage test is necessary. Partial discharge measurement should be carried out with the test simultaneously, and the test wiring diagram is shown in Fig. 7.



**Fig. 8 The test of the external voltage withstand test of the series transformer line side winding**

The applied voltage should be measured in accordance with the voltage time sequence shown in Fig. 8 to verify the partial discharge performance of the transformer.

- 1) The power supply is connected when the voltage is lower than  $U_2/3$ , and  $U_2$  is 1.5 times the highest phase-to-ground voltage.
- 2) Raise the applied voltage to  $U_1$  and keep 60s.  $U_1$  is the applied test withstand voltage.
- 3) Reduce the voltage to  $U_2$  and keep 60min, measure the partial discharge.
- 4) Reduce the voltage to  $U_3$  and keep 5min.  $U_3$  is 1.1 times the highest phase-to-ground voltage. Measure the partial discharge.
- 5) When the voltage is reduced to less than the  $U_2/3$  voltage, the power can be disconnected.



**Fig. 9 Test procedure**

The partial discharge in each test period should not be greater than 100pC.

## Conclusions

In this paper, the differences and characteristics between 500kV oil-immersed series transformers and conventional transformers are fully considered. Basic parameters, structure type, connection group symbol, insulation level, short circuit capability and withstanding excitation ability of 500kV oil-immersed series transformers are analyzed in terms of technical characteristics. The unique test items of 500kV oil-immersed series transformers, such as the lightning full-wave impulse test and the specific requirements of the applied AC withstand voltage test, are specified.

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