Analysis of Single-phase Short-circuit Current Suppression Measures at Converter Stations and Their Effects on Power System Reliability

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***Abstract*—Aiming at the issue that the single-phase short-circuit current at the 500kV side of Yibin and Fulong converter stations has exceeded the breaking capacity of breaker, the reason is analyzed and the measures are put forward to reduce the single-phase short circuit, including limiting the output of thermal power near field, converter transformers neutral grounding by small reactance and 500kV lines adding series reactors. The limiting effects of single-phase short-circuit current and the impacts on power grid equipment operation and power supply reliability of different measures are compared. Feasible suggestions for reducing single-phase short-circuit current and improving power grid reliability are given.**

Keywords-converter station; neutral grounding by small reactance; single-phase short-circuit current; series reactor

I. Brief Introduction

Along with the expanding of the power grid construction and the strengthening of the AC and DC hybrid system, the short-circuit current level of the power grid is increasing year by year, and the single-phase short-circuit current of some buses is larger than the three-phase short-circuit current. Short-circuit current exceeding standard will bring difficulties to equipment selection, endanger the safety of people and equipment, which has become a main problem faced by power system planning and operation [1].

In the current Power System Analysis Software Package (PSASP), the converter transformer model is integrated in the DC system model. The DC system is treated as a load and does not provide short-circuit current when the model is used in the three-phase and single-phase short-circuit calculation. But in the actual power system, the converter transformer has a significant effect on the single-phase short-circuit current.

The capacity of converter transformers at Yibin and Fulong stations is respectively 9696MVA and 7706MVA, which is very large, and the converter stations have closely connection with neighboring 500kV power network [2]. Considering the influence of converter transformers on the zero sequence impedance and the centralized access of large capacity mating power supply such as Xiangjiaba and Xiluodu, the single-phase short-circuit current at the 500kV side of Yibin and Fulong converter stations has exceeded the three-phase short current or even exceeds the breaking capacity of breaker [3]. Measures need to be taken to limit the short-circuit current and ensure the safe operation of power grid.

The suppression measures of short-circuit current can be taken from the two aspects of grid structure and substation [4]. According to the actual situation of the power grid, reasonable measures should be taken to limit the short-circuit current on the basis of ensuring the reliability of power supply.

II. Analysis of Single-phase Short-circuit Current at Converter Station

A. Short-circuit Current Calculation

The power grid in the near area of Yibin and Fulong converter stations is given as the figure below.

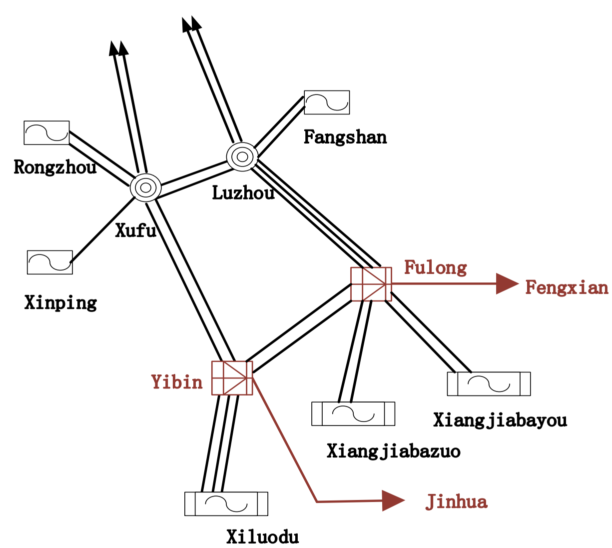

Figure 1. Power grid of Binjin and Fufeng DC nearby area.

The short-circuit current is calculated using PSASP 7.3 based on the following conditions: generators full open, the capacitance and reactance at the 500kV stations and the 220kV stations out of service, filters of converter stations and high voltage reactors of 500kV lines in service. The calculation results of the short-circuit current at the 500kV side based on Sichuan power grid of 2018 are shown in Table I.

TABLE I. RESULTS OF SINGLE-PHASE SHORT CIRCUIT CURRENT AT THE 500 KV BUS

Station	Three-phase short-circuit current (kA)	Single-phase short-circuit current (kA)
Yibin	55.15	64.03
Fulong	54.84	64.05
Xufu	55.15	56.65
Luzhou	52.42	47.41

From the calculation results we can see that the single-phase short-circuit current at the 500kV side of Yibin and Fulong converter stations is higher than 63kA.

B. Influence of Converter Transformers on Short-Circuit Current

UHVDC system is bipolar with two 12-pulse converters in series. There are four converter transformers in every converter station with two Yn/Y wiring transformers and two Yn/Δ wiring transformers [5]. The single-phase short-circuit current is deeply influenced by transformers with Yn/Δ connection.

For the transformers with Yn/Δ connection, zero sequence current loop can be formed by the transformer winding and earth due to the neutral point grounding when the zero sequence voltage is applied to the star-connection side. At the same time, the zero sequence electromotive force and zero sequence current are generated at the delta-connection side. The zero sequence current will form circulating current in delta side, so there is no connection between the zero sequence network of the transformer and the external circuit. The equivalent circuit is given as figure 2.

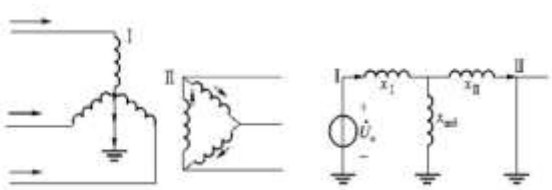

Figure 2. Zero sequence equivalent network of Yn/Δ transformer.

In the figure, X_I and X_{II} respectively represent the positive sequence reactance in transformer primary and secondary side. X_{m0} represents the leakage resistance.

The excitation reactance is usually many times larger than the leakage resistance of the winding, and the zero sequence impedance is very close to the positive sequence impedance for the transformers with Yn/Δ connection in the load center area [6]. So the zero sequence reactance of the Yn/Δ connection transformer can be simplified as follows:

$$X_{(0)} = X_I + X_{II} \qquad (1)$$

For the transformers with Yn/Y connection, there is no zero sequence current path and the zero sequence equivalent circuit is opened in the secondary side. The equivalent circuit is given as figure 3.

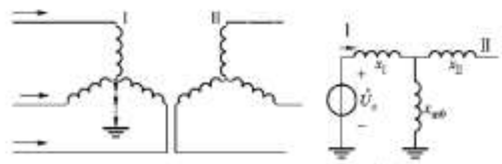

Figure 3. Zero sequence equivalent network of Yn/Y transformer.

The zero sequence reactance of the Yn/Y connection transformers can be represented as follows:

$$X_{(0)} = X_I + X_{m0} \qquad (2)$$

It is considered that the zero sequence reactance of Yn/Y wiring converter transformer is infinite because of the great excitation reactance.

Considering the influence of Yn/Δ wiring transformers, the zero sequence equivalent network at the 500kV system side of converter stations has a zero sequence branch with small impedance in parallel, which has a significant effect on the single-phase short-circuit current of the converter station. By computation, the single-phase short-circuit current at the 500kV side of Yibin and Fulong stations is increased by more than 12kA when the converter transformers are considered.

C. Influence of Step-up Transformers of DC Auxiliary Power Supply on Short-circuit Current

The installed capacity of Xiluodu (Binjin DC auxiliary power supply) and Xiangjiaba (Fufeng DC auxiliary power supply) is 9*770MW and 8*800MW. Generator-transformer connection unit is adopted for the main wiring of each power plant. For all the step-up transformers with Yn/Δ connection, the neutral point is directly grounded except for the 8 transformers of Xiangjiaba neutral grounding by small reactance of 18 ohm.

The wiring diagram of generator and transformer with unit connection is shown as below.

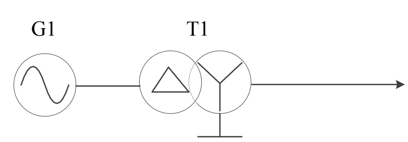

Figure 4. Wiring diagram of generator and transformer with unit connection.

The positive and zero sequence equivalent networks are shown as below.

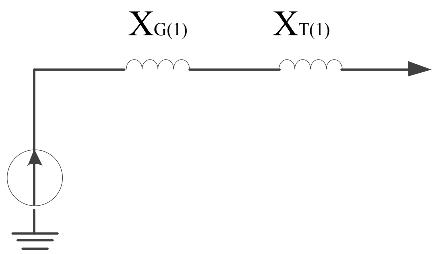

Figure 5. Positive sequence equivalent network.

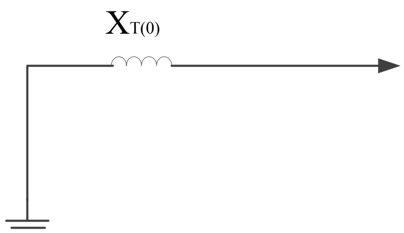

Figure 6. Zero sequence equivalent network.

In the figures above, $X_{G(1)}$ represents the positive sequence reactance of the generator, $X_{T(1)}$ represents the transformer leakage reactance, X_{T0} represents the zero sequence equivalent reactance of the transformer.

The step-up transformers with Yn/Δ connection will provide zero sequence access when there is an asymmetrical fault at the high voltage side. When the transformer is neutral grounding by small reactance X_N, the equivalent impedance of the zero sequence network can be represented as follows:

$$X_{\Sigma 0} = X_{T0} = X_{T(1)} + 3 * X_N \tag{3}$$

The positive sequence impedance can be represented as follows:

$$X_{\Sigma 1} = X_{T(1)} + X_{G(1)} \tag{4}$$

From the upper formulas and equivalent circuit diagrams it can be seen that the positive sequence reactance of the equivalent network is greater than zero sequence reactance due to the existence of positive sequence reactance of the generator, which will lead to the single-phase short-circuit current larger than the three-phase short-circuit current at the high-voltage side.

For all the step-up transformers of DC auxiliary power supply, the neutral-point is directly grounded except for the 8 transformers of Xiangjiaba， which is another reason for the single-phase short-circuit current at the 500kV side of converter stations larger than the three-phase short-circuit current. If all the step-up transformers of Xiluodu and Xiangjiaba are neutral unearthed, the single-phase short-circuit current at Yibin and Fulong converter stations can be reduced by about 5kA.

III. Analysis of Suppression Measures on Single-Phase Short-circuit Current at Yibin and Fulong Converter Stations

To limit the single-phase short-circuit current, measures can be taken from the aspects of increasing the positive or zero sequence impedance of the system.

A. Limiting the Output of Thermal Power Near Field

Limiting the output of thermal power is the most direct way to reduce the short-circuit current of the system. It can also be considered as a way to increase the positive sequence impedance of the system. To ensure the full transmission of UHV DC in summer, limiting measures of the single-phase short-circuit current of the converter stations can be taken by limiting the thermal power nearby rather than DC auxiliary power such as Xiluodu and Xiangjiaba. Taking the summer mode of 2018 as an example, the single-phase short-circuit current at the 500kV buses of Fulong and Yibin converter stations can be limited to 62.7kA and 62.3kA respectively by shutting down a thermal power unit of Rongzhou, Fangshan and Xinping respectively, which are near the converter stations.

During the period of peak load in summer, limiting the output of thermal power may lead to inadequate dynamic voltage supporting ability in the near area. In addition, with the rapid growth of power load in Yibin and Luzhou area, restricting the output of thermal power may cause the main transformers in Xufu and Luzhou substations not satisfying the N-1 check and weaken the power supply capability of the power grid. Therefore, limiting the start-up can only be used as a temporary solution to restrict short-circuit current.

B. Converter Transformer Neutral Grounding by Small Reactance

The Yn/Δ connection mode of converter transformer is the most important factor for the 500kV single-phase short circuit current of the converter station exceeding the standard. Therefore, Yn/Δ wiring transformers neutral grounding by small reactance to increase the zero sequence reactance can be used to limit the single-phase short-circuit current. With the gradually increasing small reactor value of the transformer's neutral, the limiting effect on single-phase short-circuit current reaches a saturation value [7]. Usually, the small reactance value is chosen not larger than 1/3 of the leakage reactance of transformer. Based on comprehensive consideration of the effect of reducing single-phase short-circuit current and the practical application of small reactance in Sichuan, the selected value of neutral reactor at the Yn/Δ wiring transformers of Yibin and Fulong converter stations is 14ohm in this paper. After adding small reactance, the single-phase short-circuit current at the 500kV side of Yibin and Fulong converter stations can be reduced to 60.5kA and 60.3kA respectively in 2018, which is lower than the breaking capacity of breaker.

The most important risk of adding small reactance comes from the insulation level of neutral point. The lightning over-voltage and the switching over-voltage can be limited by the installation of arrester, but the maximum value of power frequency over-voltage of the transformer's neutral point must be in the power frequency withstand voltage range [8].

The power frequency over-voltage withstanding level of the converter transformer's neutral point at Yibin and Fulong stations is 95kV. When the single-phase grounding fault occurs at the 500kV bus of the converter station, the short-circuit current can be represented as follows:

$$I_c = \frac{3U_k}{X_{\Sigma 1}+X_{\Sigma 2}+X_{\Sigma 0}//X_{T0}} \tag{5}$$

Among them, U_k represents the voltage prior to fault; $X_{\Sigma 1}$、$X_{\Sigma 2}$、$X_{\Sigma 0}$ respectively represent the positive sequence reactance, the negative sequence reactance and the zero sequence reactance of the external system of converter station.

In the process of single-phase short circuit, the value of the positive, negative and zero sequence current is equal. Therefore, the current flowing through the neutral point of converter transformers can be represented as follows:

$$I_N = \frac{3I_{C0}X_{\Sigma 0}}{X_{\Sigma 0}+X_{T0}} = \frac{I_C X_{\Sigma 0}}{X_{\Sigma 0}+X_{T0}} \tag{6}$$

Generally think the positive sequence reactance is equal to the negative sequence. The neutral point voltage can be represented as follows:

$$U_N = I_N X_N = \frac{3U_k X_N}{2X_{\Sigma 1}+X_{T0}+\frac{2X_{T0}X_{\Sigma 1}}{X_{\Sigma 0}}} \tag{7}$$

From the above it can be seen that the greater the neutral point reactance, the higher the neutral point voltage.

Taking the most serious neutral point over-voltage into consideration, which means that the external positive sequence reactance of the converter station should take the minimum value, assuming that the three-phase short-circuit current at 500kV side of the converter station is 63kA, and the zero sequence impedance of the converter station is 3 times of the positive sequence impedance. It can be calculated that the power frequency voltage of neutral point at Yibin converter station reaches 69.7kV, which still has a fairly large insulation margin. Even if three Yn/Δ wiring transformers are in overhaul, the power frequency voltage of the remaining Yn/Δ wiring converter transformer's neutral point is only 82.7kV, which still has a certain margin.

According to the above calculation, adding small reactance at the neutral point of converter transformers is a feasible scheme to limit the single-phase short circuit. However, because the converter transformer is very special, it needs careful consideration to install small reactance. In addition, influenced by the grid structure and other factors, the effect of small reactance limiting single-phase short-circuit current is limited, and it mainly restricts the single-phase short-circuit current of the station where it installs.

C. AC transmission Lines Adding Series Reactors

The series reactor can increase line impedance and achieve the purpose of limiting short-circuit current. It is a traditional measure to limit the short-circuit current.

The series reactor is simple, safe and reliable, and has the advantages of simple to maintain, mature in technology and highly feasible in engineering implementation [9]. In 2008, the series reactor of 14ohm was installed on the Sijing side of Sijing-Huangdu 500kV line, which is the first application of the series reactor in China. In addition, the installation of short-circuit current limiter (FCL) has no effect on the normal operation of the power grid and can effectively solve the problem of short-circuit current exceeding the standard, but the working current of the equipment may be lower than that of the series reactor, and the scope of application is smaller [10-11]. So it is scarcely applied at present，and the operation performance need to be further verified.

The electrical distance between the two converter stations is very short and the transmission line is only 14km. So it is practical to install series reactors at Yibin-Fulong AC double-circuit transmission lines to weaken the link between the two converter stations and increase the equivalent impedance of the system. The single-phase short-circuit current at Yibin and Fulong converter stations can be restricted to below 57kA by installing series reactors of 14ohm.

Series reactors can effectively limit the single-phase and three-phase short-circuit current. However, the cost of series reactor is relatively great and it will increase the reactive and active power loss of the system after it is connected to the system. In addition, the series reactor will change the distribution of power flow in the near area, and the stability of the system and the control limit of transmission interfaces need to check again. This scheme can be used as a long-term alternative to limit short-circuit current.

IV. CONCLUSION AND ADVICE

Considering the influence of converter transformers on short-circuit current, the single-phase short-circuit current at the 500kV side of Yibin and Fulong converter stations has exceeded the breaking capacity of breaker. For limiting the single-phase short-circuit current, following three measures can be taken:

1. Temporary measure: limiting the output of thermal power near field. The single-phase short-circuit current at Fulong and Yibin converter stations can be limited to be lower than the breaking capacity by shutting down a thermal power unit of Rongzhou, Fangshan and Xinping respectively.

2. Modification scheme 1: converter transformer neutral grounding by small reactance. It is suggested that converter

transformers with Yn/Δ connection neutral grounding by small reactance can be employed first when the following conditions are satisfied: site condition and insulation level of neutral point. The single-phase short-circuit current at the 500kV side of Yibin and Fulong converter stations can be reduced to below the breaking capacity of breaker by adding small reactor of 14ohm to the neutral point of Yn/Δ wiring converter transformers.

3. Modification scheme 2: Yibin-Fulong AC double-circuit transmission lines adding series reactors. Adding series reactors has a remarkable effect on limiting short circuit current. However, the cost of series reactor is relatively great and the installation needs power interruption. Besides, the transmission limit of the near section must be re checked. This can be used as a long-term alternative scheme.

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