Research on Subsynchronous Oscillation in 750 kV Qinghai Grid of China

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Abstract. The series compensation project is under construction for Riyueshan-Haixi-Chaidamu 750kV lines in Qinghai grid. Chaidamu station is the sending end of Qinghai-Tibet HVDC project, which has been put into operation. According to planning, there will be a large-scale coal-fired plant near Chaidamu station. The transmission system includes AC series compensators and HVDC, and subsynchronous oscillation may take place. In this paper, the subsynchronous oscillation risk was analyzed using frequency scanning, unit interaction factor and time domain simulation. Research results indicate that subsynchronous oscillation may take place under conditions when several AC lines quit and under HVDC island condition.

Introduction

In order to increase capacity of transmission lines in Qinghai 750kV grid, and ensure delivery for clean energy such as wind, photovoltaic power, etc, a series compensation project is building in Riyueshan-Haixi-Chaidamu transmission lines in Qinghai grid [1-2]. On the other hand, Chaidamu converter station is the sending end of Qinghai-Tibet HVDC transmission project, which has been put into operation.

According to planning, there will be a new large-scale coal-fired plant near Chaidamu converter station. Theory and operating experience shows that, series compensation and HVDC may cause subsynchronous oscillation in nearby coal-fired turbines [3-4]. Subsynchronous oscillation is a type of resonance between electrical and mechanical parts, which will reduce mechanical life of the turbine shaft, and even cause shaft damage shortly in severe cases.

In this paper, researches will be carried out on subsynchronous oscillation risk of the coal-fired plant near Chaidamu converter station. The series compensation in Riyueshan-Haixi-Chaidamu transmission lines and Qinghai-Tibet HVDC lines will all be considered.

Introduction of Subsynchronous Resonance

Introduction

Subsynchronous resonance (SSR) and subsynchronous oscillation (SSO) may take place when series compensation and HVDC applied in transmission lines of coal-fired plants. SSR and SSO are a type of resonance between electrical and mechanical parts of a turbine shaft, which will reduce mechanical life of the turbine shaft, or even cause shaft damage. SSR caused by series compensation first appeared in Mohave plant, USA, whose turbine shaft was damaged twice in 1970 and 1971 [5]. Then, a specialized work group was organized by IEEE, and related researches were carried out [6-10]. In 1977, subsynchronous current was produced in HVDC system during experiment, and caused torsional vibration in nearby turbines in Square Butte, USA [11].
Generally, the torsional vibration caused by series compensation is called as subsynchronous resonance, and that by HVDC and other FACTS devices is called as subsynchronous oscillation. They can also be collectively known as subsynchronous oscillation.

Research Methods

Currently, there are many research methods for SSO caused by series compensation and HVDC [12], such as frequency scanning, unit interaction factor analysis, time domain simulation, complex torque coefficient method, eigenvalue analysis, etc. In this paper, the former three methods are used for SSO analysis.

Frequency Scanning. Frequency scanning is a method to preliminary assess SSR risk by calculating the impedance-frequency characteristics of the transmission system of a plant.

According to Thevenin equivalent method, remove all sources in the equivalent network, and add a unit current source at the connecting point of the coal-fired plant. Change the frequency of the current source, measure the voltage of the connecting point, and the impedance-frequency characteristics of the transmission system can be obtained by calculation. For a single turbine connected to the system by series compensated lines, there will be a series resonance frequency where the reactance varies from negative to positive in the impedance-frequency characteristics waveform. For a multi-turbine system or other transmission lines in parallel, there will be reactance dip in the impedance-frequency characteristics waveform. If reactance dip rate is large enough, SSR may also occur. Here, reactance dip rate is defined as \[ \frac{X_{\text{max}} - X_{\text{min}}}{X_{\text{max}}} \times 100\% \].

Frequency scanning is an effective method for forecasting SSR. If frequency scanning results show that there are SSR risk, the results should be verified by time domain simulation.

Unit Interaction Factor (UIF). Unit interaction factor (UIF) method is a simple way to assess SSO risk of a generator caused by HVDC system, which is recommended by EPRI. The UIF of all coal-fired turbines near a rectifier station should be calculated, turbines with SSO risk will be selected by UIF analysis, and more researches need to be done. According to a research report by EPRI [13], UIF of a turbine affected by the HVDC control system could be calculated by the following equation.

\[
UIF_g = \frac{MW_{\text{HVDC}}}{MVA_g} \left(1 - \frac{SC_g}{SC_{\text{Tot}}}\right)^2
\]

where:

- \( UIF_g \) - the UIF for generator \( g \)
- \( MW_{\text{HVDC}} \) - transmission power of the HVDC system
- \( MVA_g \) - rated capacity of generator \( g \)
- \( SC_{\text{Tot}} \) - short current capacity at converter bus (exclude AC filters, generator \( g \) takes in operation)
- \( SC_g \) - short current capacity at converter bus (exclude AC filters, generator \( g \) quits)

UIF is a practical indicator to assess the coupling of HVDC and generators. If the UIF of a coal-fired turbine is much less than 0.1, SSO will not occur due to HVDC converter. While the UIF is close to or larger than 0.1, further researches should be done by other methods. It is worth noting that, if several turbines of the same type are connected at the same bus, they should be replaced by an equivalent turbine with a capacity of the combined value.

Time Domain Simulation. Time domain simulation is carried out by electromagnetic simulation program. The model should be established first, including series compensator, transmission lines, HVDC, network, stator and rotor of a generator, and turbine shaft. Simulate a fault by time simulation, and the torque can be calculated between adjacent mass blocks of a generator shaft. The SSR/SSO risk will be judged by variation of the torque. Time domain simulation is a precise method for SSR/SSO assessment.
Simulation Modeling

System Modeling

According to the construction scheme of Northwest grid, fixed series compensators will be built in Riyueshan-Haixi-Chaidamu 750kV transmission lines. The series compensators are arranged at both sides of the lines, and the series compensation degree is 20% for each side. The total series compensation degree is 40% for each line. The simplification diagram of the transmission system is illustrated in Figure. 1.

![Diagram of 750kV Qinghai grid.](image)

Generator Modeling

A generator consists of electrical and shaft parts. The shaft could be considered as several lumped masses, which contain high, intermediate and low pressure cylinders, generator, etc. Adjacent masses are connected by a massless spring. The main parameters of the multiple mass model include the moment of inertia of each mass, and elastic coefficient between adjacent masses. As the coal-fired plant is still in planning, the shaft parameters are made refer to typical turbines domestic and overseas. The natural frequencies are 17.0, 27.3 and 32.9Hz.

Moreover, mechanical damping should be considered with different outputs of the generators. Generally, the mechanical damping is smaller when the output of the generator is lower, and SSR risk is higher. In this paper, the mechanical damping of generators is ignored.

SSR Risk by Series Compensator

Frequency Scanning

To filter out conditions with SSR risk, researches by frequency scanning should be carried out first for the transmission system of the plant, and all possible conditions in operation should be considers. In this case, the following lines and series compensators in Figure. 1 are considered to be put into operation or quit.

- Chaidamu-Yuqia 750kV lines
- Haixi-Riyueshan 750kV series compensated lines
- Chaidamu-Haixi 750kV series compensated lines
- Yuqia-Delingha 750kV lines
- Delingha-Haixi 750kV lines
- Shazhou-Yuqia 750kV lines
- Haixi-Tala 750kV lines

Frequency scanning for different conditions is carried out according to II.B.1. Typical results are shown in Table I.
Table 1. Typical frequencies of series resonance and reactance dip of the transmission system for a coal-fired plant.

| Conditions                                           | Starting frequency (Hz) | Ending frequency (Hz) | Reactance dip rate (%) |
|------------------------------------------------------|-------------------------|-----------------------|------------------------|
| Full operation                                       | 5.7                     | 5.8                   | 17                     |
|                                                       | 24.1                    | 25.8                  | 12                     |
| Yuqia-Delingha-Haixi lines quit                      | 5.7                     | 5.9                   | 13                     |
|                                                       | 19                      | 20.8                  | 8.8                    |
| One of series compensators of Haixi-Riyueshan quits  | 5.7                     | 5.9                   | 14                     |
|                                                       | 22.6                    | 24.4                  | 12                     |
| Both series compensators of Haixi-Riyueshan quit     | 5.7                     | 5.9                   | 14                     |
|                                                       | 22.7                    | 24.5                  | 14                     |
| One of Haixi-Riyueshan lines quits                   | 5.7                     | 5.9                   | 13                     |
|                                                       | 22.6                    | 24.3                  | 11                     |
| Both Haixi-Riyueshan lines quit                      | 5.7                     | 5.9                   | 12                     |
|                                                       | 22.6                    | 24.4                  | 13                     |
| Both Chaidamu-Yuqia lines quit                       | 5.2                     | 5.7                   | 50                     |
|                                                       | 15.1                    | 18                    | 49                     |
| One of series compensators of Chaidamu-Haixi quits   | 5.8                     | 6                     | 6                      |
|                                                       | 25.4                    | 26.5                  | 1                      |
| Both series compensators of Chaidamu-Haixi quit      | 25.4                    | 26.1                  | 0.56                   |
| One of Chaidamu-Haixi lines quits                    | 5.8                     | 6                     | 7.4                    |
|                                                       | 25                      | 26.5                  | 8                      |
| Both Chaidamu-Haixi lines quit                       | 25.3                    | 26.1                  | 0.71                   |

Results in Table I shows that:

1. Operation of Chaidamu-Yuqia lines takes great effect on the impedance-frequency characteristics of the transmission system. If both of these lines quit, a reactance dip up to 20%-50% will appear in the characteristics waveform. If the frequency that the reactance drops is nearly complementary with one of the natural frequencies, which means the summary of the frequencies close to 50Hz, there will be high SSR risk.

2. Operation of series compensators of Chaidamu-Haixi is an important factor for SSR risk of this plant. If one or both series compensators are in operation, the turbines are all with some risk. Otherwise, if both series compensators of Chaidamu-Haixi quit, the reactance dip rate of the transmission system is very small.

Waveform for a typical condition is shown in Figure 2.

Figure 2. Typical frequency characteristics of equivalent impedance of the transmission system for a coal-fired plant.

**Time Domain Simulation**

SSR risk exists in the system if there are frequencies of series resonance or reactance dip that nearly complementary with one of the natural frequencies. In this chapter, further researches are carried out by time domain simulation.

The conditions are the same with Table I. A single phase fault is set in one of the Chaidamu-Haixi 750kV lines. The simulation results are illustrated in Table II.
Table 2. Time-domain simulation results of SSR analysis.

| Conditions                                      | SSR risk |
|-------------------------------------------------|----------|
| Full operation                                  | Stable   |
| Yuqia-Delingha-Haiyi lines quit                 | Stable   |
| One of series compensators of Haixi-Riyueshan quit | Stable   |
| Both series compensators of Haixi-Riyueshan quit | Stable   |
| One of Haixi-Riyueshan lines quits              | Stable   |
| Both Haixi-Riyueshan lines quit                 | Stable   |
| Both Chaidamu-Yuqia lines quit                  | Stable   |
| One of series compensators of Chaidamu-Haiyi quit | Stable   |
| Both Chaidamu-Haiyi lines quit                  | Stable   |

As shown in Table II, SSR will take place when both Chaidamu-Yuqia lines quit, and Figure. 3 illustrate the waveform. In Figure. 3, the mode 2 of the shaft diverges after the fault appears. According to results by frequency scanning, there is a large reactance dip under this condition. For other conditions with low reactance dip rate, there are no SSR risk according to simulation results. The results of both analysis methods are consistent.

![Waveform](image)

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SSO Risk by HVDC

Qinghai-Tibet HVDC project consist of Chaidamu and Lhasa converter stations and HVDC transmission lines, as shown in Figure. 1. In this chapter, the SSO risk will be analyzed for the coal-fired plant near Chaidamu station.

UIF Analysis

First the coupling between the plant and HVDC system is analyzed by UIF. The UIF results of different conditions are shown in Table III.

Table 3. UIF results under different conditions.

| Number of turbines in operation | Conditions of AC grid               | UIF    |
|---------------------------------|------------------------------------|--------|
| 2                               | Full operation                     | 0.0023 |
| 750kV lines connected to Chaidamu all quit |                     | 0.089  |
| 1                               | Full operation                     | 0.0007 |
| 750kV lines connected to Chaidamu all quit |                     | 0.044  |

As shown in Table III, UIFs of the plant are all much lower than 0.1 when the AC grid is full operation, which indicates that the coupling of generators and Qinghai-Tibet HVDC is untight under this condition. When the 750kV lines connected to Chaidamu station all quit and the 330kV lines are in operation, the UIF is still lower than critical value. It is because the transmission power
of Qinghai-Tibet HVDC is small, and the AC grid near Chaidamu station is strong. Therefore, SSO may not take place at the plant due to HVDC controllers.

**Time Domain Simulation**

The simulation model is established including Qinghai 750kV and 330kV AC grid, Qinghai-Tibet HVDC system and its controllers, generators and their shafts. A fault is set in one of Chaidamu-Haixi lines. Simulation is carried out, and the rotate speed of each mass could be obtained. The results are shown in Table IV.

| Conditions                                      | SSR risk |
|-------------------------------------------------|----------|
| Full operation of AC grid                      | Stable   |
| 750kV lines quit, and 330kV lines are in operation | Stable   |
| HVDC island                                     | Unstable |

As results in Table IV, the following conclusions can be reached.

1. When the AC grid is connected to Chaidamu station, there are no SSO risk for the coal-fired plant.

2. If all 750kV and 330kV lines quit, and the plant is connected to the network only by Qinghai-Tibet HVDC lines, SSO will take place. Figure 4 illustrated the simulation waveform.

**Conclusions**

In this paper, the SSR and RRO risk caused by series compensation in Qinghai 750kV grid and Qinghai-Tibet HVDC system is analyzed by frequency scanning, unit interaction factor and time domain simulation. Conclusions are as follows.

**SSR Risk by Series Compensation**

Analysis is carried out by frequency scanning and time domain simulation. The operation of generators, nearby 750kV lines and series compensators are all considered.

1. Under full operation and typical N-2 conditions, there is reactance dip in impedance-frequency characteristics. If the resonance frequencies are nearly complementary with one of the natural frequencies, there may be SSR risk.

2. Operation of nearby 750kV lines and series compensators takes great effect on the impedance-frequency characteristics. If one or both series compensators are in operation, the turbines are all with some risk.

3. Time domain simulation results with typical shaft parameters show that, SSR will take place when both Chaidamu-Yuqia lines quit.

As there are no actual parameters of the generator shaft, it is suggested that SSR should be reviewed using actual parameters.

**SSO Risk by HVDC**

Analysis is carried out by unit interaction factor and time domain simulation. The SSO risk of a coal-fired plant caused by Qinghai-Tibet HVDC system is analyzed.
(1) UIF analysis shows that, the UIF is 0.0023 when the AC grid of Chaidamu station is in full operation, which is much lower than 0.1. There will no SSO under this condition.

(2) Time domain simulation results show that, when the AC grid is connected to Chaidamu station, there will be no SSO risk for the coal-fired plant. While under HVDC island condition, there will be SSO. It is suggested that HVDC island condition should be avoided in practice.

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