Research on Analysis and Application of Power System Stabilizer for Safe Operation of Large Nuclear Power Units

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Abstract: As more and more large-scale nuclear power units (NPU) are put into operation, power system stabilizers (PSS) are important control means for units and power grids, which play an important role in the safe operation of NPU. In this paper, by analyzing the mechanism of accelerating PSS and the power regulation characteristics of NPU, the paper proposes a type selection of PSS for NPU. By analyzing the key technical requirements of the frequency link of the accelerating PSS, it proposes some test verification measures. Combined with the nuclear power plant reactor technical specification requirements, it studies the influence of the PSS on the nuclear island during the tuning test, and then proposes the technical conditions for the PSS setting test in NPU. In view of the large-scale use of semi-speed generators in NPU, it analyzes the effects between the torsional vibration frequency and PSS of semi-speed generators, and proposes new parameter settings and logic designs for PSS to solve similar problems.

1. Introduction

In order to ensure the safety of the power grid, the excitation regulators of the main power plants in the power grid have been put into the PSS in a large scale [1].

In addition to suppressing the low-frequency oscillation of the machine, the PSS also effectively suppress the regional low-frequency oscillation. The input of the PSS is a main measure to ensure the safety of the units and the power grid. Considering the problem of reversal of the prime mover [2], most of the PSS use the accelerating PSS in the units, called PSS2A/2B.

The safety of reactor power operation is the primary consideration for the safe operation of NPU. At the same time, NPU have the characteristics of large unit capacity and low steam parameters. At present, most NPU use semi-speed generator, so the use of nuclear PSS is special. In the design of the PSS and the on-site setting test of the NPU, in order to ensure the safe operation of the NPU, it is necessary to consider the particularity of the nuclear power unit.

This paper starts with the principle of accelerating PSS, then researches on the selection problem related to accelerating PSS and NPU operation characteristics, the key technologies for PSS frequency links related to safe operation of NPU, the nuclear reactor power limitation during PSS test, the relationship between torsional vibration and PSS setting of semi-speed generator, and finally proposes the corresponding solutions to ensure the safety of NPU.
2. Principle of the Accelerating PSS
The PSS2A model is mainly based on the evolution of the generator rotor dynamic equation. According to the mechanics law of the rotating object, the following relationship can be written for the rotor of the synchronous motor:

$$ M \frac{d\omega}{dt} = T_m - T_e \tag{1} $$

Where: M is the moment of inertia of the unit rotor; Tm is the mechanical input torque; Te is the electromagnetic torque of the generator.

It is expressed by the per unit value and when the speed does not change much, the power is used to instead of the torque, then the above formula is changed to:

$$ M \frac{d\omega}{dt} = P_m - P_e \tag{2} $$

After transposition of terms and given the deviation form, $\frac{d\omega}{dt}$ is changed by S:

$$ \Delta P_m = MS \frac{\Delta \omega}{\omega_0} + \Delta P_e \tag{3} $$

Because $\Delta \omega$ contains kinds of noise, both ends of the formula are multiplied by G(S) to filter the noise. The formula is expressed as:

$$ \Delta P_m G(S) = (MS \frac{\Delta \omega}{\omega_0} + \Delta P_e)G(S) $$

The accelerating power is:

$$ \Delta P_a = (M \frac{\Delta \omega}{\omega_0} + \Delta P_e)G(S) - \Delta P_e \tag{3} $$

According to the formula (3), the transfer function of PSS2A is as follows:

![Figure 1. Accelerating PSS (PSS2A)](image_url)

$\Delta P_a$ is the input of PSS, if the mechanical input power changed, the input signal of the PSS is the accelerating power $\Delta P_a$. If the mechanical input power never changed, then there would be such relation: $\Delta P_m=0$, $\Delta P_a=\Delta P_e$, it can be seen as the electric power input PSS.

3. PSS Selection of NPU
Using the accelerating PSS, when the mechanical power changes, the accelerating power output is approximately 0, so the PSS has no output, which eliminates the reverse modulation caused by mechanical power variation. When the small disturbance cause power oscillation in the system, the output of the prime mover remains unchanged, the input signal $P_m$ of the ramp function is 0, and the output signal should also be 0. Only the electric power single signal input works in PSS2A. At this time, the PSS2A and the single electric power signal PSS is consistent, and the PSS parameter compensation is consistent too.

Through good phase compensation, it can suppress low frequency oscillations in the range of 0.2~2Hz.

Through the PSS2A model analysis, using the accelerating PSS can eliminate the reverse adjustment that occurs during the mechanical power adjustment process. At present, the second generation PWR nuclear power unit in China generally does not have the peak regulation. The possible maximum mechanical power change condition during operation is...
the RGL04 test or a circulating pump tripping, the load would be adjusted at a rate of 50 MW/min. Through the field test of the PSS2A and PSS1A models, the reverse adjustment of PSS1A is not obvious from the waveform of the RGL04 test. The comparison between the two type PSS are shown in Figure 2.

Figure 2. (a) Reverse test waveform of PSS2A    (b) Reverse test waveform of PSS1

In Figure 2 (b), the unit is quickly reduced from 1000MW to 950MW at 50MW/min, the reactive power is changed from 27MVar to 18MVar; The unit is quickly recovered from 950MW to 1000MW at 50MW/min, and the reactive power is changed from 18MVar to 25MVar. During the whole test, the excitation voltage has no change, and the reactive power variation is less than 10MVar. There is no reverse adjustment in PSS during the normal operation of the unit.

From the above analysis, it is known that it is feasible to use the PSS2A model or the PSS1A model in NPU.

4.  Analysis of Safe Operation of PSS in NPU

4.1. Frequency Link Analysis of the PSS2A

In order to eliminate the effects of mechanical power variations, a speed or frequency signal is introduced into the PSS2A model. In some excitation system supplied by an international supplier to some domestic NPU, the frequency link in the PSS2A model is not processed well[3]. If there was a large interference, the phase of frequency link and the power link in PSS2A would not be matched well, which would cause negative damping and power oscillation.

The current microcomputer excitation system generally uses the generator line voltage and current to calculate the frequency of the internal potential of the generator. The principle is shown as follow:

$$E_g = U + jIX_g$$

From the engineering point of view, the change of the generator shaft speed is the same as the change of the internal potential frequency. By measuring the generator voltage $U$ and the stator current $I$, the internal potential $E_g$ of the generator can be obtained, and the generator shaft speed can be obtained by finding the frequency of the internal potential of the generator.

There are currently two methods to calculate the internal potential frequency of the generator[4], one is to calculate the frequency by means of the zero-crossing of the internal potential waveform and. The other is the angle of the internal potential, which requires the calculated phase current and line voltage to be 90 degrees. The defect of the second method is that the angle of the current and voltage would be disturbed by inrush current when the main transformer is charging. The above-mentioned abnormal PSS2A product uses this kind of frequency calculation method.

In the system oscillation, the mechanical power may have a very small magnitude change. Because of the large dynamic range, it must be handled correctly. If the excitation device was not handled well, frequency phase in PSS2A cannot well involved in model
calculation, and an abnormality may occur. A lot of poor performance PSS is caused by insufficient hardware design or improper control parameter selection. Normally, it needs a CPU with rapid operation and high precision when designing PSS2A and it is better to use float algorithm when processing with algorithm. So, it is better to perform large external interference verification, and important small signals have sufficient accuracy verification in the field tests.

In addition, in order to verify the correctness of the frequency link, the two input signals and the output signal should have the following relationship in the field test: the integral phase of the frequency and the electric power is basically inverted, and the PSS output signal and the electromagnetic power signal are basically opposite (Figure 3) [5], these should be verified in the field test.

![Figure 3. The phase relationship between the PSS output signal and power signal](image)

4.2. The Impact on Nuclear Island During Step Test or Power Oscillation

In the normal operation of the generator, the output of the generator is coordinated with the output of the steam turbine. In the conventional thermal power plant, the output of the boiler is coordinated with the output of the turbine; In the NPU, the nuclear island is converted from the first stage pressure of the turbine to the thermal power constant to adjust the average temperature, the balance between the power of the nuclear reactor and the turbine output is regulated by the balance of the thermal power.

In the coordinated operation of the generator and the steam turbine, the electric power signal is sent to the steam turbine regulating system through the power transmitter to realize the coordinated operation between turbine power and electric power. According to the standard requirements of the power transmitter, the response time of the power transmitter is no more than 400ms. The response time of the latest microcomputer power transmitter for unit control is generally set as 50ms~90ms. When the generator excitation system performs a step test, the electric power fluctuation is within the response time of the power transmitter. In this process, the turbine power is not responding, which will not affect the nuclear reactor power. When the system experiences an increase amplitude or step test exceeded the response time of the power transmitter, the turbine power will respond. During the PSS step test, the generator power fluctuation peak time will cause a sudden change in the turbine power. Since the nuclear reactor power changes following the turbine output, when the following time was faster, it may cause nuclear island power changed. Therefore, the impact on nuclear reactor safety should be fully analyzed during the test.

Nuclear reactor technical specification requires: the nuclear reactor's rising power rate cannot exceed 3% PN/h in the first start after the nuclear power plant is assembled, when the full power stable operation time of the unit do not exceed 72 hours. When the PSS performs a 1%~4% step test under load, the fluctuation of electric power may exceed 3% PN/h. Therefore, it is necessary to avoid the time limit of the nuclear reactor's power rate limitation when conducting nuclear PSS tests.

4.3. Shaft Torsional Vibration and PSS Suppression Analysis of Semi-speed Generator
NPU’s steam parameters are lower than conventional thermal power units. At home and abroad, some NPU use semi-speed generators, which use four pole-pairs. The inherent torsional vibration frequency of these mi-speed unit is generally lower than the full-speed unit. In the current operating nuclear power unit, some units have been found to have a torsional vibration frequency as low as 6 Hz, and some units have a torsional vibration frequency as low as 8 Hz. According to the IEEE 421 standard, it is necessary to consider that the inherent torsional vibration frequency of the unit may be as low as 4~5 Hz\(^6\).

The PSS adjusts the excitation voltage and changes the output reactive power of the generator by controlling the excitation regulator. In some cases, the PSS parameters cause the natural frequency of the shaft torsional vibration to be consistent or similar oscillating signal to be input to the rotor winding by the PSS, which may cause mutual excitation between the PSS and the shaft torsional vibration, resulting in sub-synchronous oscillation. PSS2A/2B is monotonically increasing in amplitude-frequency characteristics, with up-warping characteristics, which would cause the gain margin of the entire PSS link to be small and affects the gain value at the final steady-state operation. At the same time, in the high frequency or close to the natural frequency of the shaft torsional vibration, it has a boosting effect on the shaft torsional vibration. Therefore, considering the influence of the PSS on the shaft torsional vibration of the semi-speed unit, it would generally lower the high frequency gain value. There are two methods can be used: one is to filter out the signal above 3 Hz in the second order low pass link of the PSS output, and needs to add extra links in the PSS software, and should also consider the influence of this link on the angle in low frequency; Another way is to use the PSS lead and lag compensation link, phase compensation should consider the whole frequency including the shaft torsional vibration frequency, and the phase of the low-frequency oscillation range and the shaft torsional vibration frequency should be compensated too.

For the lead and lag link \(\frac{1+T_{5}s}{1+T_{6}s}\), when it is set as \(T_6>T_5\), its phase-frequency characteristic is hysteresis and the amplitude-frequency characteristic is attenuated. According to this characteristic, for example \([7]\), a compensation link with a corner frequency of about 3 Hz and a hysteresis angle of 15° is set, the frequency characteristics are as shown in Figure 4, the gain is slowly attenuated to 76.7% of the original value at 3 Hz, and after 3 Hz the gain is rapidly attenuated, which can reduce the maximum gain to about 65% of the original value. \([8]\) \([9]\)

![Figure 4. The bode diagram of first-order lag link](image)

Considering the factors of the mechanical parameters which are affected by the shaft torsional vibration, the slope function in the PSS2A/2B model is used to reduce the PSS output deviation caused by the rapid change of mechanical power. At the same time, the ramp function also has the effect of attenuating the high frequency component of the input signal on the PSS output\([10]\) Usually the high frequency component is above 7 Hz, and the torsional vibration frequency of the full-speed generator is above 10 Hz. After the ramp function is applied, the torsional vibration frequency of the full-speed generator is also filtered out. Since the steam parameters of NPU are lower than conventional thermal power unit, many nuclear power plants have adopted semi-speed generators at home and abroad. This semi-speed generator uses a 4-pole generator, and its torsional vibration frequency is
as low as 4~5Hz. Therefore, when selecting T8 and T9 of the ramp functions, it should be noted that amplitude characteristic verification should be set according to the domestic typical value: T8=0.6s, T9=0.12s, M=5, N=1 (Figure 5).

From Figure 5, it can be seen that in 4~5Hz, the amplitude of the ramp function is less than 0.1, correspondingly attenuating the signal of the mechanical combined power. Therefore, setting the ramp function according to typical values is also safe for nuclear power semi-speed generator.

![Figure 5. Ramp function amplitude frequency characteristics (x-axis as the frequency, y-axis as the ramp function gain)](image)

5. Conclusion
This paper bases on the technical requirements of nuclear power plant reactors, nuclear generator characteristics and the use of PSS, and proposes the safety technical requirements for the use and test of PSS in NPU, then obtains the following conclusions:
1) there is no strict requirement in nuclear power units to use PSS2A model and PSS1A model;
2) In the PSS2A software and hardware design, it is necessary to verify the frequency link;
3) When carrying out the PSS step test, it is necessary to fully consider the technical requirements of the nuclear reactor technical specifications;
4) Power system stabilizer setting test needs to consider the natural frequency of torsional vibration of nuclear power half-speed unit, and take into account the influence of mechanical parameter operation on shaft torsional vibration. Through the supplemental or filtering of the ramp function parameters and the torsional frequency, the mutual excitation between the low torsional natural frequency of the half speed generator and power system stabilizer can be effectively reduced.

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