Parameter stability region analysis of nonlinear link in primary frequency regulation process based on description function method

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Abstract. For the primary frequency regulation process of power system, there are some key nonlinear links in the model. After the optimization and transformation of water turbine governor for suppressing ultra-low frequency oscillatory in southwest power grid, its ability to participate in power grid frequency regulation is weakened. And the amplitude and frequency limit of power grid frequency fluctuation are increased; the number of frequency crossing the deadband limit of primary frequency regulation is increased; and the influence of nonlinear link is prominent. The previous pure linear system analysis methods are difficult to carry out effective analysis. Based on this, the paper proposes to use the description function method to analyze the influence of nonlinear links in the system. The parameter stability regions of nonlinear links in different types of frequency regulation models are determined according to the improved Nyquist criterion. Firstly, the nonlinear transfer function models of primary frequency regulation for different types of hydropower, thermal power, and direct current FC are established. This paper summarizes the structural similarity of nonlinear links of different primary frequency regulation resources, and the steps of analyzing its nonlinear link are put forward, and the corresponding simulation verification is carried out.

1. Introduction

These guidelines, written in the style of a submission to J. Phys.: Conf. Ser., show the best layout for your paper using Microsoft Word. If you don’t wish to use the Word template provided, please use the following page setup measurements[1]. The back-to-back flexible DC project in Chongqing and Hubei Province connects the southwest power grid with the central China power grid, forming a southwest synchronous power grid covering Sichuan, Chongqing and Tibet[1-2].

In order to solve the ultra-low frequency oscillation risk of high ratio hydropower system, the speed regulation system of hydropower unit is usually optimized adaptively, such as reducing the PID parameters of governor to improve its damping performance, and giving full play to the regulating role of direct current FC[1-3]. However, reducing the PID parameters of governor not only improves its damping performance, but also reduces its ability to participate in power grid frequency regulation. The amplitude and frequency limit of power grid frequency fluctuation increase; The number of frequency crossing the deadband limit of primary frequency regulation and secondary frequency...
regulation is increased, and the influence of nonlinear links is prominent, so it is necessary to carry out targeted research.

In reference[4], based on the single machine equivalent model of the system, the influence of the deadband of three different governors on the frequency oscillation is studied by using the description function method. The law of the influence of the deadband on the frequency oscillation in the single machine system is analyzed and summarized theoretically, which provides the basis for the analysis of the influence of the deadband on the frequency oscillation in the multi-machine system. In reference[5], the frequency regulation control analysis model of photovoltaic power station before (pure conventional power supply) and after access is established. Considering the deadband and saturated nonlinear link in the model, the stability range of frequency regulation control gain before and after access is analyzed by using the nonlinear Nyquist stability criterion based on description function. In reference[6-7], a stability analysis method of primary frequency regulation process oscillations based on value set approach is proposed. Taking Yunnan Power Grid as an example, the principle of ultra-low frequency oscillations is analyzed and the improvement measures are put forward. In reference[8], an equivalent method for frequency oscillation analysis of multi-machine systems is proposed, and the system is equivalent to a single machine system, which improves the calculation efficiency of frequency oscillation mode in the primary frequency regulation process. The above literature studies the case of a single deadband link. For all governors in a multi-machine system, the deadband is the same, then it can be equivalent to a deadband, but if there are many types of nonlinear link with different parameters in the actual system, it needs to be studied[9-10].

In this paper, the stability analysis of the "deadband - PID controller-limiting" construction of primary frequency regulation is carried out, and the stability domain of its parameters is analyzed by using the description function method, and the simulation verification of this method is carried out.

2. "Deadband-PID controller-limiting" construction
For the feedback links of hydropower, thermal power, direct current FC and other primary frequency regulation processes, in order to ensure the stability of the system regulation and the limitation of the maximum frequency regulation, there are usually deadband and amplitude limiting links in the feedback loop. Through the analysis of the typical primary frequency regulation model, it is not difficult to find that the frequency difference is adjusted by PID controller through deadband and amplitude limiting and other nonlinear links. In order to study in detail the influence of the "dead time link-PID controller-limiting link" structure[11] on the stability of the system, the description function method is introduced to analyze the stability of the system in detail.

3. Description function method and stability criterion
The description function method is a classical method for studying the non-linear link, which is suitable for different orders nonlinear system and widely used in the control research of the power system[12-13]. In this paper, the stability of the nonlinear link before and after the PID controller in the primary frequency regulation process is analyzed by using the description function.

3.1. Description function analysis of nonlinear link
The system using the description function method shall satisfy the following two conditions[14]:
1)The non-linear part is singularly symmetrical, so the output does not contain the DC component;
2)The linear part is low-pass filter, so the high-frequency harmonic component in the output can be ignored.

The input function of the feedback link of primary frequency regulation can be described as sinusoidal signal \( x(t) = A \sin \omega t \), where \( A, \omega \) is a time variable. The steady-state output of the nonlinear link is expanded by Fourier series:

\[
y(t) = A_0 + \sum_{n=1}^{\infty} (A_n \cos \omega t + B_n \sin \omega t) = A_0 + \sum_{n=1}^{\infty} Y_n \sin(n \omega t + \phi_n)
\]  
(1)
In the formula, $A_i$ is the direct current component and $Y_i \sin(n \omega t + \phi_i)$ is the $n$th harmonic component. Based on the two application conditions of the description function method, if $n > 1$, $Y_i$ is very small, it can be ignored. Therefore, the fundamental wave is dominant in the output $y$, which can be used to approximate the whole output. Based on this, the effect of the nonlinear part can be described by dividing the input by the output fundamental wave. It can be represented by $M(A, \omega)$.

$$M(A, \omega) = Y_i e^{i \phi_i} / A$$

(2)

Considering the fundamental harmonic component, then nonlinear system based on description function is shown in figure 1.

Figure 1. Nonlinear system based on description function

The description function of the deadband is expressed as:

$$M_1(A) = \frac{2K}{\pi} \left[ \pi - a r \sin \frac{a}{A} - a \sqrt{1 - \left( \frac{a}{A} \right)^2} \right], A \geq a$$

(3)

The description function of the limiters is:

$$M_2(A) = \frac{2K}{\pi} \left[ a r \sin \frac{b}{A} + b \sqrt{1 - \left( \frac{b}{A} \right)^2} \right], A \geq b$$

(4)

3.2. Improved Nyquist Criterion

Based on the description function method, an improved Nyquist criterion for the primary frequency regulation system with nonlinear links can be used for stability analysis. Being different from the classical Nyquist criterion, according to the system characteristic equation (5), the nonlinear link characteristic of the represented curve replace the key point (-1,0) in the Nyquist criterion, and the specific judgment of stability method is the same as the Nyquist criterion. Figure 2 shows the stability relationship between negative inverse description function, that is, the negative reciprocal of the nonlinear part gain and the position of linear part transfer function.

$$1/N(A, a) + G(j \omega) = 0$$

(5)

Compared with the traditional Nyquist criterion, replacing the original single feature point with the curve can better reflect the influence of the internal structure of the nonlinear link on the stability of the system[13].
4. Stability region of nonlinear Link under Primary Frequency Regulation

4.1. Principle of the Determination of the Stability of the Nonlinear Link

First, a method of determining parameter domain with a single nonlinear link is presented.

1. According to the characteristic of a nonlinear link by a description function, selecting a group of suitable input sinusoidal signal amplitudes $A_i$ according to a primary frequency regulation adjustment range to obtain a corresponding $N(A_i, a)$ set;

2. According to the improved Nyquist criterion, the $N(A_i, a)$ stability boundary and the corresponding parameter stability range under a single nonlinear link can be obtained.

For a typical structure of the primary frequency regulation feedback loop, a PID control link exists in the middle of the dead zone and the limiting link, and the input $B_i$ of the limiting link is connected with the deadband link input $A_i$ through the equivalent substitution of the amplitude. Next, the parameter determination principle of "dead zone link-PID controller-limiting link" composite structure is introduced.

3. The nonlinear links in a typical structure are represented by the description function method respectively, and the combination is represented as $N(A_i) N(B_i)$, where $B_i$ and $A_i$ have a conversion relation associated with a PID controller;

4. For the determined deadband, a set of $N(A_i)$ values can be unique determined by the description function method, and the stable range of $N(B_i)$ with regard to $N(A_i)$ value and limit amplitude $a$ can be determined by using the parameter domain determination principle of a single nonlinear link in (2).

5. Finally, according to the improved Nyquist criterion, the stable range of $N(A_i) N(B_i)$ is determined, and the stable domains of the respective parameters are respectively determined.

4.2. Stable domain of nonlinear link

Taking the primary frequency regulation of hydropower as an example, the primary frequency regulation model and key parameters of the governor system of hydraulic turbine are mainly as follows: the primary frequency regulation model of $K_p=3.3$, $K_i=0.4$, $K_d=0.3$, $T_w=3$, $T_J=8$; figure 3 is a block diagram of the basic structure of primary frequency regulation model of hydraulic turbine.

![Figure 3. Primary frequency regulation model of hydraulic turbine](image)

Its open-loop transfer function can be expressed as follows:

$$G_K(s) = \frac{\left(1 + sK_p + s^2K_d + (1 + T_Ds)K_L\right)}{(s + B_pK_J)(1 + T_Ds)(1 + T_Gs)(2H_eqs + D_eq + K_L)} \times \frac{(1 - T_w s)}{(1 + 0.5T_w s)}$$

As can be seen from the Nyquist criterion, a curve of $G(s)$ and $-1/N(A)$ is plotted on the complex plane, as shown in figure 4. Where $-1/N(A)$ is referred to as a negative inverse description function. The intersection point represents the critical stable point of the system, from which the critical gain of the nonlinear part can be obtained.
Figure 4 is relationship between deadband gain and input $Ai$. The intersection point in the graph is a deadband gain corresponding to the input $Ai$ and deadband setting value $a$. Figure 4 shows that the smaller the deadband gain is, the better the stability of the system is. When the initial amplitude is greater than critical value $Ai$, the system oscillates and diverges; and when the initial amplitude is less than $Ai$, the system oscillates and attenuates. The range of the system stable input $Ai$ and that of the deadband setting value $a$ in this critical gain are known from the derivation.

Take a set of deadband input amplitude $Ai$, to $A_1$, $A_2$, ..., $A_i$. The deadband setting value corresponding to $Ai$ is variable. Similarly, the limiting link is in the same feedback channel, then the corresponding limiting link input $Bi$, is set to $B_1$, $B_2$, ..., $B_i$. The limiting setting value $b$ is corresponding to $Bi$. These parameters can approximately describe nonlinear systems as a cluster of linear systems. The characteristic equations of the primary frequency regulation with typical nonlinear structures are as follows:

\[
\begin{align*}
1 + N(A_1, a)C(j\omega)N(B_1, b)G_1(j\omega) &= 0 \\
1 + N(A_2, a)C(j\omega)N(B_2, b)G_2(j\omega) &= 0 \\
&\vdots \\
1 + N(A_i, a)C(j\omega)N(B_i, b)G_i(j\omega) &= 0
\end{align*}
\] (7)

By using the amplitude of $Ai$ to represent the input $Bi$ value, the deadband and the limiting link may be considered to pass the same input $Ai$, where $Bi$ can be expressed as:


\[ B_i = A_i N(A_i, a) \sqrt{K_p^2 + (K_d - K_i)^2} \]  

(8)

Under the condition of determining the parameters of other links of primary frequency regulation, the joint gain \( N(A_i, b) \) parameter of the corresponding deadband and limiting link can be obtained for a group of deadband setting value \( a \) with the best stability. It is shown in figure 6.

From figure 4, curves \( G(s) \) and \(-1/N(A)\) have intersections \((-0.94, j0)\) and at this point, the curve of \(-1/N(A)\) increases along the direction of \( A \) from the unstable region to the stable region, and there is periodic motion at the intersection point. According to formula:

\[ \text{Im}[G(j\omega)N(A)] = \text{Im}[G(j\omega)]N(A) = 0 \]  

(9)

\[ \text{Re}[G(j\omega)N(A)] = \text{Re}[G(j\omega)]N(A) = -0.94 \]  

(10)

Under the condition of critical stability, the amplitude \( A \leq 0.376 \) and \( b \leq 0.15 \) are obtained, that is to say, if the input signal and limit amplitude of nonlinear link to ensure the stability of the system are less than this value, the system tends to be stable.

5. Simulation verification

The model is set up in Matlab to verify the correctness of the method presented in this paper. The parameter selection is as follows:

2\(H_{eq}=8; \text{B}_{p}=0.04; \text{K}_{p}=4; \text{K}_{i}=0.4; \text{K}_{d}=0.3; \text{Tw}=3; \text{a}_{1}=0.02; \text{a}_{2}=0.015; \text{a}_{3}=0.015; \text{b}_{1}=0.1; \text{b}_{2}=0.2; \text{b}_{3}=0.1, \) where in the parameter group 1 selects the parameter in the parameter stable domain, and the parameter group 2,3 are the critical stable boundary parameter. The simulation results are shown in the figure 7.

![Figure 7. Frequency curves under different deadband and limit amplitudes](image)

According to the frequency change, it is not difficult to see that the forward direction of deadband increases and the reverse decrease of amplitude limit is conducive to the stability of the system. In other words, these changes can reduce the equivalent gain of nonlinear links in the system. The parameters group 2 and 3 are critical stability boundary parameters, and the system will eventually tend to zero damping oscillation.

6. Conclusion

In this paper, the general structure of the "Dead band link-PID controller-limiting link" in the feedback loop is studied by the analysis of the primary frequency regulation model of hydropower, thermal power and direct current FC. The stability of the nonlinear structure is analyzed by describing the function method, and the typical simulation parameters of the primary frequency regulation model are given. The parameter stability region of the deadband and the limiting link is calculated, and the simulation verification is carried out.
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