Fault Diagnosis Analysis of Wind Turbine Gear Based on Transfer Function Model

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***Abstract*— In this paper, wind turbine fault state and normal working conditions, using the classical transfer function model in Control theory, are characterized by the external fault of the whole system. Considering the internal impact with each other in the whole wind turbine power system, main idea of the paper tries to explore whether the final impact of the fault signal on the system can be quantified.**

Keywords—Fault Diagnosis, Transfer Function, Gear, Wind Turbine

I. INTRODUCTION

Wind turbine faults are usually predicted by using sensors to measure non-electrical parameters such as temperature, mechanics or kinematics[1], and then using signal processing methods to analyze their time domain signal characteristics or frequency domain signal characteristics[2]. The operating parameters of the wind turbine and the operating parameters in the current state[3,4] are determined by manual analysis to determine the state of the wind power system. Obviously, this approach relies heavily on artificial knowledge and is highly consistent with the ideas of expert systems. Based on this idea, using system model[5] for analysis and comparison to achieve judgment is a more superior method. Here, a predictive way of thinking is proposed. The wind turbine consists of basic units or components. If any one component or several components generate certain anomalies, it will inevitably affect other components, or it is a fault that has a certain transferability.

II. BASIC DESCRIPTION OF THE TRANSFER FUNCTION MODEL

Assume that the differential equation of a linear stationary system[6,7] is

$$\begin{aligned} & a_0 \frac{d^n c(t)}{dt^n} + a_1 \frac{d^{n-1} c(t)}{dt^{n-1}} + \cdots + a_{n-1} \frac{dc(t)}{dt} + a_n c(t) \\ & = b_1 \frac{d^{m-1} r(t)}{dt^{m-1}} + \cdots + b_{m-1} \frac{dr(t)}{dt} + b_m r(t), n \ge m \end{aligned} \tag{1}$$

In the above (1), r(t) is the input of the system; c(t) is the output of the system. After the Laplace transform of (1)under the zero initial state condition, (2) is obtained.

$$\begin{aligned} & \left(a_0 s^n + a_1 s^{n-1} + \cdots + a_{n-1} s + a_n\right) C(s) \\ & = \left(b_0 s^m + b_1 s^{m-1} + \cdots + b_{m-1} s + b_m\right) R(s) \end{aligned} \tag{2}$$

Define

$$\frac{C(s)}{R(s)} = G(s) = \frac{b_0 s^m + b_1 s^{m-1} + \cdots + b_{m-1} s + b_m}{a_0 s^n + a_1 s^{n-1} + \cdots + a_{n-1} s + a_n} \tag{3}$$

Therefore,

$$C(s) = G(s) R(s) \tag{4}$$

where (4) is C(s)=□[C(t)];R(s)=□[R(t)].G(s) is defined as the transfer function of the system. Fig.1 is a calculation diagram of the transfer function, which is a graphical representation of (4). In the process of system design, the graphical way is more concise and clear in expression.

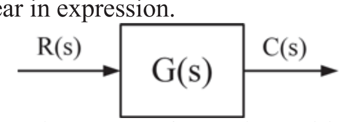

Figure 1. Transfer Function Model

Using the transfer function of the system to describe the relationship between the input and output of the system is a very effective means. The parameters of the transfer function are determined by the characteristics of the system itself, and are often composed of some of the material's main parameters such as mass, temperature, and so on. The final certainty or performance of the transfer function model is usually related to the specific environment of the application. If very precise control of the system is required, it is obvious that the more complex the mathematical model, the higher the order of the equations established can meet the control requirements to be achieved. However, complex mathematical models are difficult

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to establish, so the choice of a suitable mathematical model is also very important. In addition to the usual input and output, the system is usually accompanied by certain disturbances or errors. Most of the operating conditions have less impact on the operation of the system, but under abnormal conditions, it often becomes non-negligible and even becomes faulty. main reason. Generalized faults can be simulated with external disturbances, so this component can also be taken into account. As shown in Fig.2, the transfer function model is accompanied by a certain disturbance δ(s) in addition to the input and output. Of course, this perturbation component is also a Laplace transform of the perturbation function with time as a variable in this case.

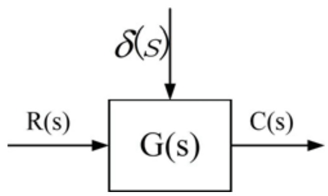

Figure 2. Perturbation Transfer Function Model

According to Fig.2, (5) is obtained.

$$\left(R(s)+\delta(s)\right)\times G(s)=C(s) \tag{5}$$

That is,

$$R(s)G(s)+\delta(s)G(s)=C(s) \tag{6}$$

So the actual output consists of two parts, the active component of the input and the active component of the disturbance. The component of the disturbance is the component of the fault when the system fails. When the system malfunctions and is in abnormal conditions, by detecting and monitoring the response of the disturbance amount, the state of the system can be judged to a certain extent, and qualitative or even quantitative fault identification becomes a possibility.

III. WIND TURBINE SIMPLE SYSTEM TRANSFER FUNCTION MODEL

A. Mechanical power and speed obtained by the wind turbine

The energy acquisition of the wind turbine is mainly derived from the kinetic energy generated by the flow of air. According to the principle of kinetic energy, the kinetic energy of the flowing gas can be obtained as follows (7).

$$\mathrm{E}=\frac{1}{2}mv^2 \tag{7}$$

where m - the mass of the flowing gas; v - the velocity of the flowing gas

Assuming that the cross-sectional area of air flow per unit time is A, then for a wind turbine, the cross-sectional area is a round surface with the following area (8).

$$A=\pi R_t^{\,2} \tag{8}$$

At the same time, the volume V of the gas flowing per unit time is obtained.

$$\mathrm{V}=\mathrm{A}v \tag{9}$$

The mass of this gas is m.

$$\mathrm{m}=\rho\mathrm{V}=\rho\mathrm{A}v \tag{10}$$

where ρ – gas density. It is also possible to obtain the kinetic energy of the gas passing through the wind turbine per unit time, and the power generated by the wind (11).

$$P_w=\frac{1}{2}\rho\mathrm{V}v^2=\frac{1}{2}\rho\mathrm{A}v^3 \tag{11}$$

Considering that the energy obtained by the wind turbine from the air flow cannot be completely lost, the wind energy utilization coefficient C_P is introduced to obtain the actual output mechanical power of the wind turbine (12).

$$P_m=C_pP_w=\frac{1}{2}\rho\mathrm{A}v^3C_p \tag{12}$$

Another important thing is that in the wind turbine system, the physical quantity is also the rotational speed ω_t of the blade rotation. Looking at the relevant design parameters of the wind turbine, we found a definition of the associated wind speed and the rotational speed of the blade - the tip speed ratio. The tip speed ratio, as a material parameter, can be seen as a known constant in the wind turbine model constructed this time. It is defined by (13).

$$\lambda=\frac{R_t\omega_t}{v} \tag{13}$$

Therefore, it can be obtained that the expression of the rotational speed ω_t of the blade rotation is as follows (14).

$$\omega_t=\frac{\lambda v}{R_t} \tag{14}$$

The (7) to (14) are expressed using a transfer function mathematical model to obtain a calculation model diagram Fig.3.

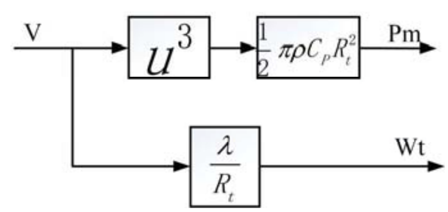

Figure 3. Wind Turbine Acquisition Power Model

Wind speed is used as input, while the wind turbine's mechanical power and wind turbine blade speed are used as outputs. In this system, the blade speed of the wind turbine and the low speed gear speed in the speed increasing gearbox in the system are considered to be identical.

B. Simple equivalent model of wind turbine shafting

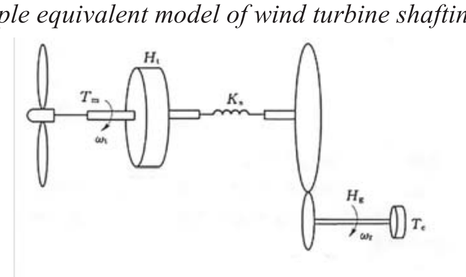

Figure.4 Shaft System Simplified Structure

The drive system constructed this time chose a relatively simple model. Fig.4 shows a schematic diagram of the shaft system[8]. The relevant physical quantities have been identified in the figure. The energy generated by the rotation of the wind turbine impeller causes the low speed shaft to rotate, and the performance at low speed is represented by the mechanical torque T_m on one side and the rotational speed ω_t on the low speed shaft. The generator side connected to the high speed shaft is subjected to electromagnetic torque T_e generated from the electromagnetic field of the generator. The main mechanical parameters of the shaft system include the stiffness K_s of the shaft, the moment of inertia J_g of the generator rotor, and the moment of inertia J_t of the rotor. The stiffness of the shaft system is usually determined by the stiffness of the high-speed shaft and the low-speed shaft and is a numerical constant. The usual moments of inertia of the generator rotor and the rotor are not directly expressed in the electromechanical system. Generally, the moment of inertia is converted into the inertia time constants H_g and H_t in seconds. Their expressions are as follows (15) (16).

$$H_t = \frac{\frac{1}{2}J_t\omega_t^2}{P_N} \tag{15}$$

$$H_g = \frac{\frac{1}{2}J_g\varpi_r^2}{P_N} \tag{16}$$

The moment of inertia J_t of the wind wheel can be roughly calculated according to the mass m_t of the wind wheel and the radius R_t of the wind wheel, and the wind wheel can be regarded as a disk of equal density distribution.

$$J_t = \frac{1}{2}m_t R_t^2$$

The two-mass model described by the state equation is represented by (17).

$$\begin{cases} 2H_t\dfrac{d\omega_t}{dt} = T_m - K_s\theta_s - D_t\omega_t \\ 2H_g\dfrac{d\omega_r}{dt} = K_s\theta_s - D_g\omega_r - T_e \\ \dfrac{d\theta_s}{dt} = \dfrac{2\pi f_e}{P_n}(\omega_t - \omega_r) \end{cases} \tag{17}$$

Most of the parameters have been indicated in the previous section, and several parameters that have not yet explained their physical meaning are now given:

ω_r—the high speed shaft speed of the shaft connection; θ_s—relative angular displacement between the two mass models (the physical parameters are not actually used in the subsequent transfer function model);f_e—the rated frequency of the grid, Determined by the parameters of the access system, it is a fixed constant D_t、D_g represent the damping coefficient of the wind turbine and generator rotor respectively; P_n—the pole number of the motor.

Perform a Laplace transform on (17) to obtain (18).

$$\begin{cases} 2H_t s\omega_t(s) = T_m - K_s\theta_s(s) - D_t\omega_t(s) \\ 2H_g s\omega_r(s) = K_s\theta_s(s) - D_g\omega_r(s) - T_e \\ s\theta_s(s) = \dfrac{2\pi f_e}{P_n}(\omega_t(s) - \omega_r(s)) \end{cases} \tag{18}$$

Eliminate $\theta_s(s)$ to get (19),

$$\begin{cases} (2H_t s + D_t)\omega_t(s) = T_m - K_s\dfrac{2\pi f_e}{sP_n}(\omega_t(s) - \omega_r(s)) \\ (2H_g s + D_g)\omega_r(s) = K_s\dfrac{2\pi f_e}{sP_n}(\omega_t(s) - \omega_r(s)) - T_e \end{cases} \tag{19}$$

The (19) expression using the transfer function model is shown in Fig. 5. The calculation model shown in Fig. 8 relates to the actual power of the wind turbine, the low speed shaft speed of the shaft system and the high speed shaft speed. An asynchronous generator provides electromagnetic torque to the drive train. This section builds the transfer function association of the drive shaft system. The mechanism of action of converting the low speed of the wind turbine into a high-speed increasing speed gearbox is not taken into account. In the next section, the simple speed-increasing gearbox model consisting of large gears and pinions is taken into account in the entire transmission system, and the entire transmission system is more complete.

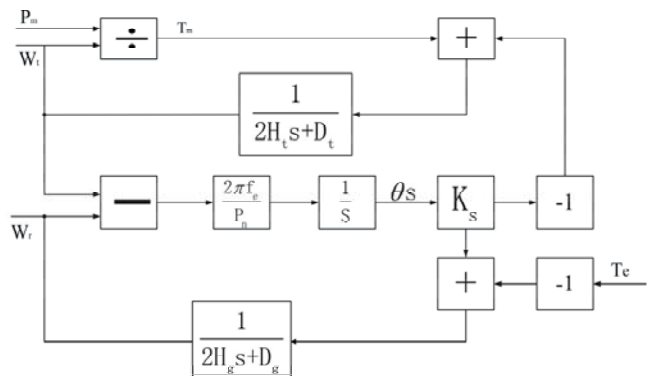

Figure 5. Shafting Model

C. *Equivalent gear pair model of speed increasing gearbox*

In order to facilitate the analysis of the impact of the gearbox failure on the entire driveline, consider the simplest gearbox [9] model. The speed-increasing gearbox is most simplified as a pair of gear pairs. The large gear is connected to the low speed shaft, and the small gear is connected with the high speed shaft. When the high speed shaft reaches a reasonable speed, it cooperates with the electromagnetic torque of the asynchronous motor to complete the conversion of mechanical energy to electric energy and input energy into the power grid. Therefore, the role of the speed-increasing gearbox in it is self-evident. Once the component fails or is damaged, it will cause extremely severe damage to the entire transmission system. Since the connection of the entire drive train is tightly coupled, the fault may also extend to the rotor of the shaft, fan impeller and generator. The fault is likely to cause severe vibration of the high and low speed shafts, blockage and tremor of the fan impeller, and breakage of the rotor of the generator. The gear pair of Fig. 6 can be used as a simple mechanical mode[10]l to analyze the impact of broken teeth on the drive train. Taking spur gear as an example, its dynamic differential equation (20) is as follows.

$$M_r\ddot{x} + C\dot{x} + k(t)x = k(t)E_c + k(t)E(t) \tag{20}$$

where x is the relative displacement of the gear along the line of action; M_r is the mass of the system consisting of two gears, ignoring the effect of motion on the inertial mass, which can be considered as a constant; C is the damping coefficient of the gear mesh; k(t) It is the stiffness coefficient of the gear meshing; E_c is the static elastic deformation. The assumed stiffness coefficient of the gear in this system is large enough, so the static elastic deformation can be neglected; E(t) is the relative displacement of the two gears, and the fault phenomenon occurs when the gear is broken. In fact, this parameter appears periodically with the frequency of the gears.

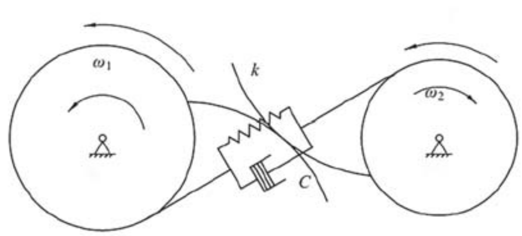

Figure 6. Gear Pair Equivalent Model

The meshing frequency of the gear is equal to the frequency of the gear multiplied by its number of teeth. From the quantitative relationship, the meshing frequency ω can be approximated as a frequency multiplication of the frequency. Taking the low speed shaft rotation speed ω_t as an example, (21) is obtained, where k is a positive integer.

$$\omega = k\omega_t \tag{21}$$

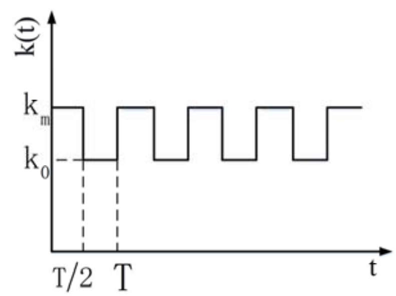

Figure 7. Meshing Stiffness Curve

The meshing stiffness curve Fig.7 is approximated as a square wave function, and the period T=2π/ω, the meshing frequency of the gear set and the change frequency of the stiffness curve are the same. Therefore, the expression of the meshing stiffness curve is (22).

$$k(t) = \begin{cases} k_{m,} & 0 < t \le \dfrac{T}{2} \\ k_0, & \dfrac{T}{2} < t \le T \end{cases} \tag{22}$$

Performing Fourier decomposition on k(t) to obtain (23),

$$k(t) = \frac{k_m + k_0}{2} + \frac{2(k_m - k_0)}{\pi}\left(sin\omega t + \frac{1}{3}sin3\omega t + \cdots\right) \tag{23}$$

If only the fundamental frequency component and the third harmonic component are included, then

$$k(t) = \frac{k_m + k_0}{2} + \frac{2(k_m - k_0)}{\pi}\left(sin\omega t + \frac{1}{3}sin3\omega t\right) \tag{24}$$

Equation (24) is obtained by Laplace transform to get (25),

$$k(s) = \frac{k_m + k_0}{2s} + \frac{2(k_m - k_0)}{\pi}\frac{\omega}{s^2 + \omega^2}\frac{2(k_m - k_0)}{\pi}\frac{3\omega}{s^2 + 9\omega^2} \tag{25}$$

The dynamic differential equation of the entire gear pair is obtained by Laplace transform (26) under the condition of ignoring the static elastic deformation.

$$M_r s^2 x(s) + Csx(s) + k(s)x(s) = k(s)E(s) \tag{26}$$

Make a suitable deformation and get (27).

$$x(s) = \frac{k(s)E(s)}{M_r s^2 + Cs + k(s)} \tag{27}$$

At this point, the displacement expression along the gear is obtained, so the output speed is also the output speed of the speed increasing gear ω(s) (28).

$$\omega(s) = sx(s) = \frac{sk(s)E(s)}{M_r s^2 + Cs + k(s)} \tag{28}$$

It can be clearly seen from (28) that the output speed of the gear pair is related to the meshing stiffness transfer function and the type of fault. And the corresponding quantitative relationship can be calculated simply by (28).

D. Asynchronous generator parameters and models

The model of the asynchronous generator [11,12] is composed of four major equations according to the theory of AC motor, which are voltage equation, flux linkage equation, electromagnetic torque equation and motion equation. Since the focus of this paper is to discuss the fault propagation problem of the transmission system, only the influence of the motion equation (29) on the relevant parameters in the transmission system is considered in the four equations. The parameters of the other three equations are electrical parameters and are internal parameters of the generator.

$$T_L = T_e + J\frac{d\omega_r}{P_n dt} \tag{29}$$

Among them, T_L—load torque; T_e—electromagnetic torque; J—the moment of inertia of the asynchronous motor; P_n—the pole pair of the motor; the drag speed of the ω_r motor, which is considered in the model considered in this paper the speed of the high-speed shaft. Perform a Laplace transform on (29) to get (30).

$$T_L = T_e + J\frac{s\omega_r(s)}{P_n} \tag{30}$$

IV. INFLUENCE OF GEAR FAILURE ON PARAMETERS OF WIND TURBINE DRIVE SYSTEM

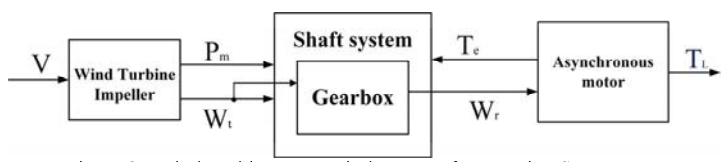

Figure 8. Wind Turbine Transmission Transfer Function System

The model diagram of the entire transmission system is shown in Fig.8.The representation of the model and transfer function expressions established in Section □ now mainly includes the following equations:

Wind turbine wind wheel:

$$P_m(s) = \frac{1}{2}\rho\pi R_t^2 v(s)^3 C_p \tag{31}$$

$$\varpi_t(s) = \frac{\lambda v(s)}{R_t} \tag{32}$$

Shaft system:

$$(2H_t s + D_t)\omega_t(s) = T_m - K_s\frac{2\pi f_e}{sP_n}(\omega_t(s) - \omega_r(s)) \tag{33}$$

$$(2H_g s + D_g)\omega_r(s) = K_s\frac{2\pi f_e}{sP_n}(\omega_t(s) - \omega_r(s)) - T_e \tag{34}$$

Speed increase gearbox:

$$\omega(s)=\frac{sk(s)E(s)}{M_r s^2+Cs+k(s)} \tag{35}$$

Asynchronous generator:

$$T_L=T_e+J\frac{s\omega_r(s)}{P_n} \tag{36}$$

The large gear in the speed-increasing gearbox, that is, the gear connected to the low-speed shaft, was used as the fault comparison of this study. From (35) (21), the (21) meshing frequency is proportional to the large gear (also low gear), and (21) is substituted into (25) to obtain (37).

$$k(s)=\frac{k_m+k_0}{2s}+\frac{2(k_m-k_0)}{\pi}\frac{k\omega_t}{s^2+k^2\omega_t^2}+\frac{2(k_m-k_0)}{\pi}\frac{3k\omega_t}{s^2+9k^2\omega_t^2} \tag{37}$$

Substituting (37) into (35) as follows,

$$\omega_t(s)=\frac{sE(s)\left(\frac{k_m+k_0}{2s}+\frac{2(k_m-k_0)}{\pi}\frac{k\omega_t}{s^2+k^2\omega_t^2}+\frac{2(k_m-k_0)}{\pi}\frac{3k\omega_t}{s^2+9k^2\omega_t^2}\right)}{M_r s^2+Cs+\left(\frac{k_m+k_0}{2s}+\frac{2(k_m-k_0)}{\pi}\frac{k\omega_t}{s^2+k^2\omega_t^2}+\frac{2(k_m-k_0)}{\pi}\frac{3k\omega_t}{s^2+9k^2\omega_t^2}\right)} \tag{38}$$

Equation (38) shows the transfer function of the low speed shaft in the frequency domain model under different operating conditions. E(s) characterizes the normal operation of the gear and the different equivalent external excitation sources in the fault state. When the gear is running normally E(t)=1,E(s)=1/s; when the broken tooth phenomenon occurs E(t)=sinω_t(t), E(s)= ω_t / (s^2+ω_t^2).By substituting different E(s) into (38), the transfer function of the low-speed axis in different states can be obtained. It is assumed that the speed is measured by a speed measuring device or other measuring instruments, and then the time domain waveform map and the amplitude spectrum and phase spectrum of the frequency domain are obtained by signal analysis, and in theory, the operating state of the system can be determined, thereby The fault analysis of wind power transmission systems has a more intuitive understanding.

The actual torque of the wind turbine can be obtained from (31) (32) to get wind turbine rotor (39).

$$T_m=\frac{P_m(s)}{\varpi_t(s)}=\frac{\frac{1}{2}C_P\rho\pi R_t^3 v(s)^2}{\lambda} \tag{39}$$

Substitute (35) and (39) into (33),

$$\omega_r(s)=\frac{\left(\left(2H_t p_n s^2+D_t p_n s+2\pi f_e K_s\right)sk(s)E(s)\right)-\frac{\frac{1}{2}C_P\rho\pi R_t^3}{\lambda}M_r s^2+Cs+k(s)v(s)^2}{2\pi f_e K_s} \tag{40}$$

Finally, substituting (40) into (36) gives the dynamic transfer equation of the entire transmission system. In the case of constant load, the transfer function order of the fault ω_r (s) is lower than that of the normal operation. According to the transmission system model analyzed in this study, the speed will decrease and the electromagnetic torque of asynchronous generator will become larger, in order to maintain the energy relationship of the system. Therefore, monitoring the rotor speed of a high-speed shaft or generator set is very necessary and a good way to predict the fault. In fact, if the electromagnetic torque can be directly detected, the effect may be better. However, because of the complex mechanical-electromagnetic energy conversion process inside the generator, it may not be realized for a long time.

V. CONCLUSION

Throughout the paper, the transfer function model in the control theory is used to model the drive mechanism of the wind turbine, and a possible model is explored from the perspective of the dynamic model. Moreover, the common broken tooth faults in the speed increasing gearbox in the wind turbine are analyzed, and the influence of the fault transmission on the whole transmission system is analyzed. Finally, through the analysis, the dynamic changes of the physical quantities of the high-speed shaft speed, the generator rotor speed, and the electromagnetic torque of the generator are obtained.

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