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Fault Analysis and Adaptive Design of Wind Turbine Lubrication System

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Abstract

Wind turbines work in harsh environments and have changeable loads. The reliability and service life of the wind turbine gearbox has become an important factor for maintaining its safe, stable, and reliable economic operation. The production practice shows that the failure of the wind turbine gearbox is closely related to the structure and performance of the lubrication system. In this paper, the fault tree of the wind turbine gearbox lubrication system is established. It is pointed out that the temperature, state, and lubrication intensity of the lubricating oil are not well adapted to the working condition of the gear box, which leads to frequent gearbox breakdowns until its failure. The heat dissipation power consumption of the lubrication system is determined by calculating the heat balance of the lubrication system. By introducing the AI control method, the adaptive lubrication system framework of the wind turbine gear box is constructed from the aspects of oil temperature, oil pressure, oil level, and oil quality, which can automatically adjust the lubrication intensity according to the working condition of the wind turbine, so as to improve the lubrication effect of the wind turbine gear box. The research work in this paper plays an important role in optimizing the performance of the lubrication system, reducing the failure of the lubrication system, and reducing the operation and maintenance cost of wind turbines.

Keywords: lubrication system fault tree; adaptive design; wind turbine

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1. Introduction

Wind energy is the fastest growing renewable energy technology. The technology is relatively mature, and it is a widely promoted and commercialized energy industry. China's wind energy reserves are at the forefront of the world, and their distribution area is relatively wide. The distribution of wind farms in Guangdong, Hunan and North China to the Inner Mongolia Autonomous Region and Heilongjiang Province in the south covers a large area with a wide operating temperature. The reliability of the lubrication system is especially significant important. In recent years, large-scale wind turbines have become the developmental trend of high-power wind turbines. The operation of the gearbox needs to withstand greater load on the stability of the lubrication system. The continuous accumulation of lubrication system failure occurs from time to time, reducing the efficiency of the unit and seriously affecting the economic benefits of wind farm owners [1]. According to the "Report on the Operation Quality of Wind Power Equipment in China," the gearbox is a key component of frequent faults. Lubrication system failure is the main type of gearbox in the type of fault that has been identified, and the proportion of lubrication system failure increases year by year. However, the corresponding gearbox lubrication technology is still not perfect [2]. Therefore, it is necessary to systematically summarize the faults of the wind turbine gearbox lubrication system and to establish the fault tree of the gearbox lubrication system. Based on the analysis of the fault tree of the lubrication system, a corresponding solution to the common fault types is proposed after the lubrication system design for reference.

2. Wind Turbine Lubrication System Overview

Wind turbine gearbox lubrication using splash lubrication and forced lubrication combination of lubrication is shown in Figure 1.

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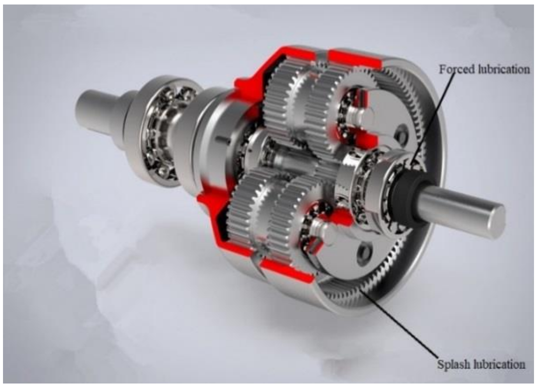

Figure 1. Gear box lubrication

Splash lubrication is the use of gear box operation of the main shaft gear and planetary gear and other pieces of movement. The lubrication of splash lubrication varies with the speed of the gear box. The faster the gear rotates, the greater the lubrication is. Therefore, the lubrication effect is worse when the gear speed is slower. Due to the larger torque transmitted by the main shaft of the wind generator, there is a need to increase the force lubrication system to ensure lubrication [3].

The forced lubrication system mainly includes the oil storage device, oil supply device, filter device, cooling and heating device, lubricating line, and various kinds of sensors [4], as shown in Table 1.

Table 1. The forced lubrication system

Components of the lubrication system	Main function	Effect of failure
Oil storage device	Store lubricating oil	Lube oil leakage
Oil supply device	Pressurization for lubricating oil	Low oil pressure in lubricating system
Filter device	Remove impurities from lubricating oil	Excessive impurities in lubricating oil aggravate the wear of moving parts
Cooling and heating device	Maintain the normal working temperature of the lubricating oil	Oil temperature anomaly
Lubricating line	For conveying lubricating oil	Oil pressure anomaly, lubricating oil leakage
Sensor	Testing lubrication system	System misreport

3. Wind Turbine Lubrication System Common Fault Analysis

According to the working principle and working status of the wind turbine lubrication system, the common faults of the wind turbine gearbox lubrication system are analyzed, which is helpful to find the deficiencies of the lubrication system and address them.

3.1. Abnormal Temperature of Oil

From the operating condition of the wind farm feedback unit, the wind turbine lubrication system often fails because of the abnormal oil temperature. The abnormal oil temperature can be embodied in two cases, which are too high oil temperature and too low oil temperature. The following reasons for high oil temperature and low oil temperature are analyzed.

The main cause of excessive oil temperature is the long and full load operation of the gear box, the damage of the gear box components, and the insufficient capacity of the cooling system. The heat source of the lubricating oil is the heat produced by the bearing and the gear in the gear box. When the heat is not dispersed well, the temperature of the gearbox becomes uncontrollably high [5].

The main reason for low oil temperature is that the temperature of the environment is too low. Wind turbines are generally set up on mountains, open fields, high altitudes, and high speed areas in order to obtain higher wind speeds. The area year-round temperature is low, which causes winds to greatly influence the engine lubricating system. There is a need for a lubricating oil heating system to heat the lubricating oil in advance, so as to reach the working temperature. If a fault occurs in the lubricating oil heating system, it will lead to the oil temperature being too low, reduce the lubrication effect, and increase the burden on the oil supply system to improve the reliability of wind turbines [6].

3.2. Oil Pressure Anomaly

Oil pressure anomaly is one of the main faults of wind generator lubrication systems. If oil pressure is too high, there will be a risk of pipeline rupture. This will cause great pressure on the oil pump and can easily lead to mechanical failure, resulting in downtime. Low oil pressure is very difficult to ensure the thickness of the oil film, reducing the lubrication effect and affecting the efficiency of the lubrication system.

The causes of high pressure are as follows: excessive impurities in the lubricating oil pipeline lead to oil pipeline blockage, which will increase the pressure in the filter pipeline; the bypass valve does not open or opens only a small volume, which leads to the front end of the filter pressure circuit increasing; the lubricating oil viscosity is too high, resulting in high oil pressure in the mechanical gear pump and gear pump oil outlet [7].

The main reasons for low oil pressure are as follows: abnormal work of the oil supply system, the leakage of lubricating oil, and the low viscosity of the lubricating oil.

The abnormal performance of the oil supply system involves the two aspects of mechanical pump failure and electric pump failure.

The mechanical pump is driven by the spindle of the gear box. It may be mechanically damaged because of the excessive viscosity of the lubricating oil and the blockage of the oil path. Low level of oil can also cause the oil pump to not suck in oil or breathe in some air or foam, which can also lead to low oil pressure in the lubricating system. When the wear of the main and passive gear is serious, it will also cause a decrease in the efficiency of the mechanical pump to affect the oil pressure of the lubricating system [8].

The electric pump is powered by the circuit system and drives the motor to drive the oil pump to pressurize the lubrication system. The main faults of the electric pump system are as follows: the overheating of the motor, the overload of the motor, the non-start of the motor, and the noise of the vibration. Due to operating in a closed environment, poor motor cooling can cause motor overheating; electronic component failure or burnout failure can also cause motor overheating; power supply voltage instability can cause the motor temperature to be too high; motor or internal short circuit power circuit breakers will lead to a sharp rise in the temperature of the motor. The electric pump system will also be overloaded because of the abnormal work of the dragged gear pump. If the motor does not start, it may be a power supply system circuit fault. If the oil pressure is too high or there are too many bubbles in the lubricating oil, there will be greater vibration and noise during the process of lubricating oil pressurization.

The reasons for the leakage of the lubricating oil are the aging damage of the seal ring, the improper installation of the pipe joint, and the breakage of the pipeline. When the viscosity of the lubricating oil is too high, or the lubricating oil pipeline is blocked, the oil pressure of the lubricating system or part of the pipeline is too high, which leads to the leakage of the lubricating oil.

When the oil viscosity is too low, the oil pressure at the nozzle is not easy to maintain. When the oil pressure is too low, the thickness of the oil film is not large enough, resulting in excessive wear of the gear box. When the viscosity of the oil is too low, the leakage phenomenon of the lubricating oil will happen more easily, which will affect the reliability of the gearbox.

3.3. Anomaly of Oil Level

Abnormal oil level includes high oil level and low oil level. Excessive lubricating oil may be added to the sensor fault or misoperation, which causes high oil level to affect the stability of the lubrication system. Low oil level is caused when a lack of lubricating oil and high viscosity of lubricating oil result in misinformation of the oil level sensor. The lubricating system may reduce the system oil slowly because of the oil leakage of each part, causing the system oil level to be too low to alarm. When the viscosity of the lubricating oil is too high, the judgment of the oil level sensor will be affected, and the misjudgment of the low oil level causes the shutdown of the wind turbine.

3.4. Poor Oil Quality

The wind power generator in the running process may be rated power long-term work state. The lubrication system oil temperature will rise, increasing the chemical activity of the lubricating oil and air oxidation reaction and greatly reducing the lubrication effect. The filtering system abnormal work will also affect the lubricating oil. When the filter is blocked or there is high viscosity of lubricating oil from the bypass valve, the impurities in the lubricating oil will not be filtered out. The impurities in the lubricating oil will aggravate the bearings and gears in the gear box. When water enters the lubrication system, the gear is stirring under the lubricating oil emulsification metamorphoses quickly, seriously affecting the reliability of the wind turbine.

According to the common failure analysis of the wind turbine lubrication system, we established the fault tree of the Figure 2 wind turbine lubrication system and took the failure of the wind turbine lubrication system as the top event. Combined with the fault phenomena and the cause of the failure, it provided a basis for troubleshooting and maintaining the wind turbine lubrication system. The fault tree model events are shown in Table 2 [9].

Table 2. Fault tree model event

Serial number	Event description	Serial number	Event description
A1	Oil temperature anomaly	X8	Low viscosity of lubricating oil
A2	Oil pressure anomaly	X9	Serious wear and tear of the main and passive gear
A3	Anomaly of oil level	X10	Inhalation of foam or air
A4	Poor oil quality	X11	Oil road blockage
B1	Oil temperature too high	X12	High viscosity of lubricating oil
B2	Oil temperature too Low	X13	Poor heat dissipation
B3	Oil pressure too high	X14	Electronic component failure
B4	Oil pressure too low	X15	Power supply voltage anomaly
B5	Oil level too high	X16	Circuit short circuit or circuit breakage
B6	Oil level too low	X17	Oil road blockage
C1	Mechanical pump failure	X18	High viscosity of lubricating oil
C2	Electric pump failure	X19	Abnormal work of a dragged gear pump
C3	Lube oil leakage	X20	line fault
D1	Mechanical overload	X21	Oil pressure too high
D2	Motor overheating	X22	Overabundance of bubbles in lubricating oil
D3	motor overload	X23	Seal ring damage
D4	Motor does not start	X24	Pipe joint loosening
D5	Larger vibration noise	X25	Lubricating oil pipeline breakage
X1	Long term full load operation	X26	Overabundance of oil
X2	Gear box component damage	X27	Insufficient oil
X3	Work anomaly of cooling system	X28	The viscosity of the lubricating oil is too high to cause misreport
X4	Low ambient temperature	X29	Long term high temperature lead to lubricating oil
X5	Abnormal heating system of lubricating oil	X30	Filtering system work exception
X6	High viscosity of lubricating oil	X31	Lubricating oil modification emulsification
X7	Filter system bypass valve pressure is too high		

Wind turbines generally operate in harsh environments. In the work process, they will face a variety of complex loads. As an example, for a 2.5MW wind generator produced by a domestic company, the cut-in speed is 4m/s, the rated wind speed is 13m/s, and the cut-out speed is 25m/s. However, there are sometimes extreme wind speeds up to 30m/s, and the wind speed in fifteen seconds can be increased from 0m/s to 30m/s in extreme wind conditions. The spindle speed will rise from the normal work of 20r/min to 25r/min or even faster. The spindle speed and torque fluctuation of the bearing become more severe at this time, and it is easy to cause the high temperature of the gear case. Because of its special location, there will be great fluctuations in the temperature range of lubricating oil for the lubricating system during normal operation of the wind, generally at -15℃-65 ℃. When the temperature is too low due to the increase in viscosity of the lubricating oil, a great burden on the oil supply system is liable to cause high oil pressure or mechanical failure of the oil pump, which affects the reliability of the normal operation of the wind turbine [10].

In Figure 3, faults of wind turbine type statistics can be seen. The probability of failure of the lubricating system is very high, and the following problems exist in the lubrication system:

The oil temperature of the lubrication system cannot be adjusted adaptively.

The lubrication strength of the lubrication system cannot change with spindle speed.

The lubrication system filter equipment cannot change accuracy with the oil state.

The wind turbine workplace is bad, maintenance is difficult, and maintenance costs are high, which affects the economic benefits of wind farms, so it is necessary to establish an adaptive lubrication system to ensure the normal operation of wind turbines.

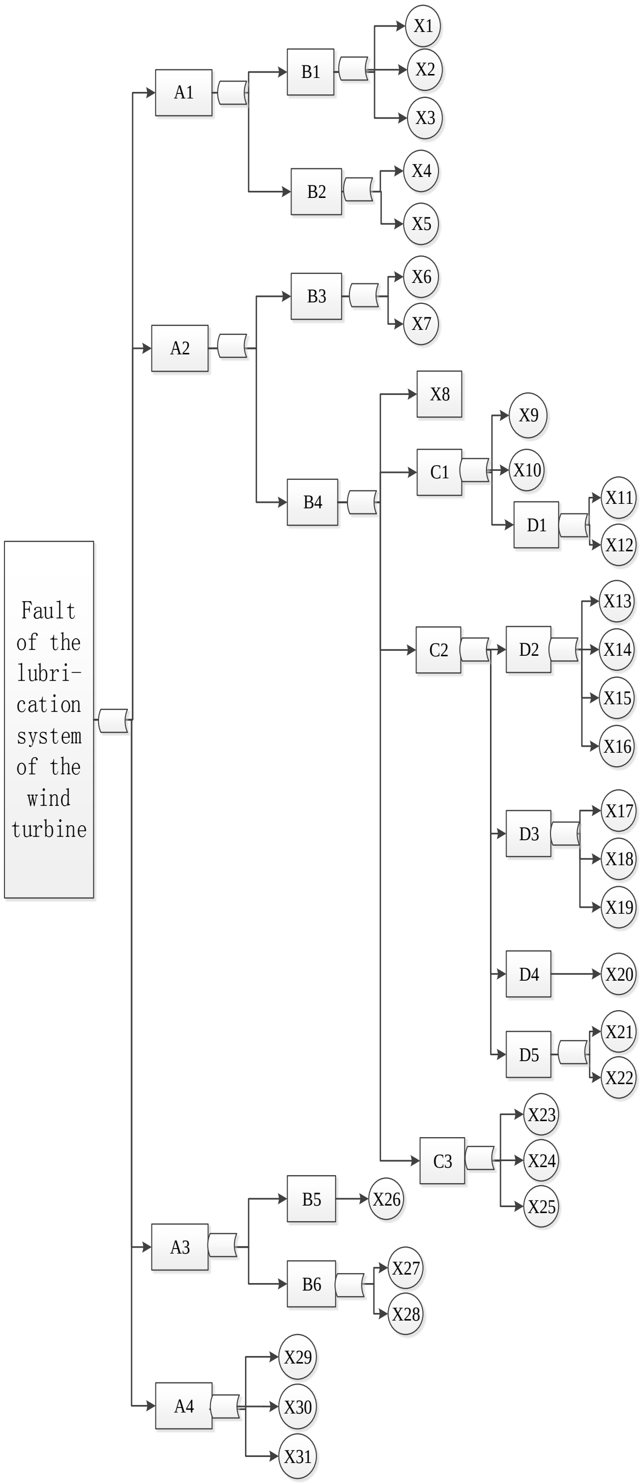

Figure 2. Fault tree of wind turbine lubrication system

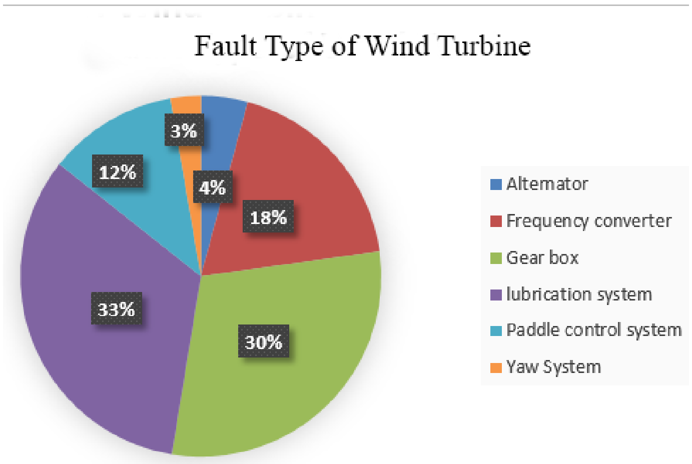

Figure 3. Fault type of wind turbine

4. Adaptive Design of Lubrication System

The self-adaptive lubrication system is intended to introduce an artificial intelligence method that can autonomously analyze internal and external environments [11]. When extreme weather conditions are encountered, it can independently improve the controllable operating environment, optimize its own lubrication status, and ensure that the lubrication system is at high temperature, low temperature, full load, etc. The normal work under special circumstances improves the adaptability of the environment. Compared with the existing lubrication system, the damage can be minimized, the adverse effects of the extreme environment on the lubrication system can be effectively reduced, the gear box of the wind turbine can be adequately lubricated, and the wind turbine's service life can be extended [12].

4.1. Structural Design of Lubricating System

The adaptive lubrication system mainly includes the oil storage system, oil supply system, filtration system, cooling system, heating system, sensor, solenoid valve, oil circuit, and so on. An adaptive lubrication system is designed, as shown in Figure 4.

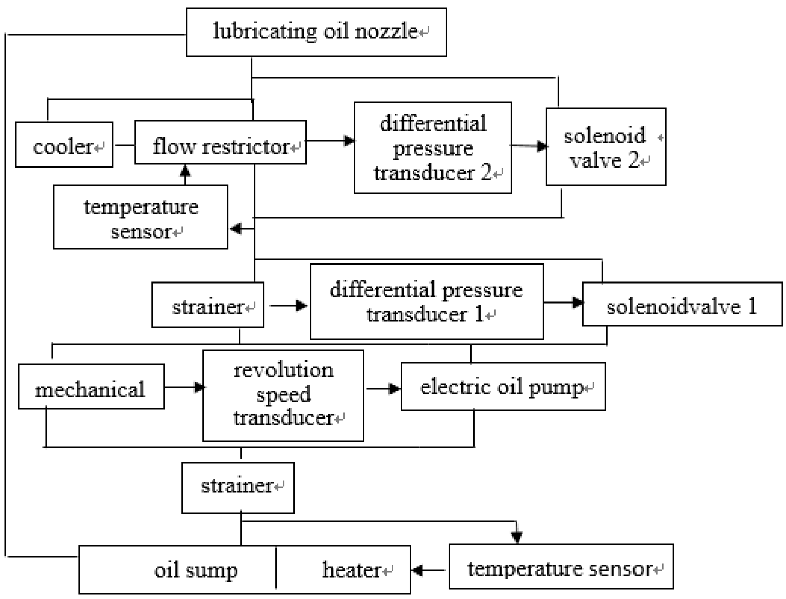

Figure 4. Adaptive lubrication system—represent oil road→represent signal

4.2. Heat Balance Calculation of Lubricating System

Calculating the heat generation of the gearbox and the cooling of the cooler is the key to designing the lubrication system.

When the speed of the wind turbine increases rapidly, the gearbox will generate a large amount of heat. Because the working environment is relatively closed, we believe that the heat generated will be emitted through the cooling system. Therefore, it is very important to determine the power of the cooling system. If the power of the cooling system is too large, it will cause unnecessary workload to the lubrication system. If the cooling system power is too small, the temperature of the gear box will be too high. The following calculation method can provide the heat of the gear box and an accurate calculation of the cooling capacity of the cooling system. It provides scientific guidance for the design of the radiator of the adaptive lubrication system, ensuring that the lubrication system does not overheat when working under extreme conditions, thereby improving the working stability of the lubrication system [13].

The heat generated by the bearing is divided into two parts, the bearing fixed thermal power Pb0 and the thermal power Pb1 varying with the load.

$$v_{oil} n < 2000\text{mm}^2 / (s \times min) \text{ ,}$$

$$P_{b0} = 1.6 \times 10^{-8} f_0 d_m^3 \omega \quad (1)$$

$$v_{oil} n > 2000\text{mm}^2 / (s \times min)$$

$$P_{b0} = 10^{-10} f_0 (v_{\text{oil}} n)^{2/3} d_m^3 \omega \quad (2)$$

v_{oil} is the viscosity of the lubricating oil at working temperature. n is the bearing speed (r/min). f_0 is the coefficient associated with the form and lubrication of the bearing. d_m is the bearing middle diameter (mm). ω is the degree of the bearing angular speed (rad/s). The bearing coefficient f_0 value is shown in Table 3.

Table 3. Bearing coefficient f_0 value table

Bearing type	Lubricating type		
	Oil mist	Oil bath	Oil jet lubrication
Deep groove ball bearing single row	1	2	4
Double row	2	4	8

The gearbox input shaft bearing speed is slower, $v_{\text{oil}} \times n < 2000\text{mm}^2 / (s \times min)$. The input shaft bearing thermal power calculation formula is selected (1). The generator rated speed is faster, $v_{\text{oil}} \times n > 2000\text{mm}^2 / (s \times min)$, so the output shaft bearing thermal power calculation formula is selected (2).

The formula for calculating the heating power P_{b1} with the change of the load is as follows:

$$P_{b1} = f_1 P_1 d_m \omega \times 10^{-3} \quad (3)$$

f_1 is the bearing coefficient, and P_1 is the dynamic load of the equivalent bearing. Coefficient f_1 and the equivalent shaft bearing P_1 value are shown in Table 4.

Table 4. Bearing coefficient and equivalent shaft bearing value table

Bearing type	f_1	P_1
Deep groove ball bearing	0.0003(P_0/ C_0)0.4	1.4$Y_2$$Fa-0.1Fr$
Angle contact ball bearing single row	0.001(P_0/ C_0)0.33	Fa-0.1Fr
Double row	0.001(P_0/ C_0)0.33	1.4$Y_2$$Fa-0.1Fr$
P_0 is bearing equivalent static load P_1 is a bearing equivalent dynamic load C_0 is the basic rated static load of the bearing Fa is the axial load of bearing Radial load of Fr bearing If $P_1 < Fr$, $P_1 = Fr$		

To sum up, the power of the single bearing in the gear box is as follows:

$$P_{bi} = P_{b0i} + P_{b1i} \tag{4}$$

The total heat power produced by the work of the bearing in the gearbox is:

$$P_b = \sum_{i=1}^{n} (P_{b0i} + P_{b1i}) \tag{5}$$

The formula for calculating the thermal power of a single gear P_g is:

$$p_g = pf\mu_z(1/z_1 \pm 1/z_2) \tag{6}$$

$h_a \leq m_n$, $f = 2.3$; $h_a = (1\sim1.8)\times m_n$, $f = 3.1$.

P is the rated power of the wind turbine gearbox, and f is related to the addendum and the gear method. h_a is the gear tooth height. m_n is a gear normal modulus. z_1 and z_2 are the number of gear teeth. "+" is for gears, and "-" is for internal gears. μ_z is associated with the friction coefficient of the gear, and $\mu_z = 1.25\mu$. μ is the coefficient of friction of gear meshing. The formula used in the classical Buckingham semi-empirical formula is the following:

$$\mu = 0.05e^{-0.125v} + 0.002\sqrt{v} \tag{7}$$

v is the circumferential speed of the gear.

The relation between the peripheral speed and friction factor is shown in Figure 5.

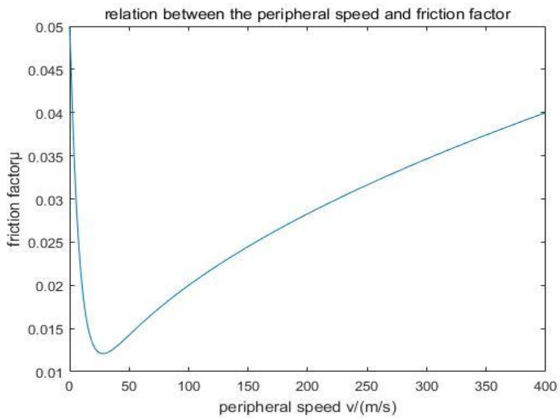

Figure 5. Relation between the peripheral speed and friction factor

Therefore, the total heat power of the gear box is as follows:

$$P_g = \sum_{i=1}^{n} p_{gi} \tag{8}$$

n is the number of gears.

The total heat producing power of the gearbox is:

$$P = P_b + P_g \tag{9}$$

$$P = \sum_{i=1}^{n}(P_{b0i} + P_{b1i} + P_{b2i}) + \sum_{i=1}^{n} p_{gi} \tag{10}$$

For the heat dissipation of the lubrication system, we only consider the cooling of the lubricating system cooler. The formula for calculating the heat dissipation power of the radiator P_s is as follows:

$$P_s = h_c A(t_w - t_f) \tag{11}$$

h_c is the heat transfer coefficient $(\mathrm{W/(m^2 \times K)})$, because the heat transfer coefficient of the cooling system of the wind turbine is forced convection, and the heat transfer coefficient is only related to the air velocity. A is the heat transfer area $(\mathrm{m^2})$.

For the cooler, t_w is the temperature of the radiator (K) and t_f is the intake temperature (K).

In order to maintain the reliability of the operation of the wind turbine lubrication system and keep the lubricating oil in the normal temperature range, the heat dissipation power must be greater than the heating power, that is, $P_s > P$. Otherwise, the oil temperature of the lubrication system of the wind turbine will be too high [14].

4.3. Control Principle of Adaptive Lubrication System

An adaptive lubrication system is designed, as shown in Figure 6.

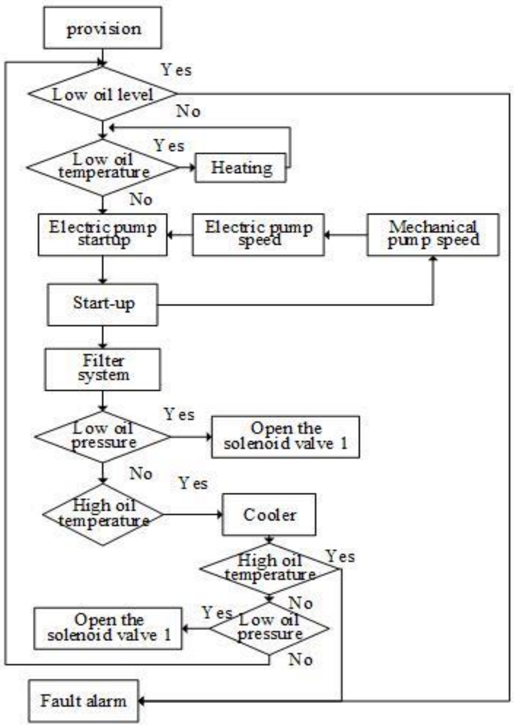

Figure 6. Lubrication system control chart

In order to prevent the oil pan in the precipitation of impurities, the lubricating oil filter design between the oil supply system of oil pump and oil pan is used to filter large impurities, in order to ensure the strength of the lubrication system can increase with the increasing speed of the gear. The speed sensor is connected in the mechanical pump, collecting the mechanical pump speed and transferring to the electric pump. The electric pump speed can change with the mechanical pump speed due to mechanical power from the spindle, so the power supply system can work as the gear box power increases. The temperature sensor and the lubricating oil in the oil pan heating device in the oil pan side are connected when the oil temperature is too low. The lubricating oil heating device begins to work in parallel. Besides the filter differential pressure sensor, both ends of the oil filter can control the filter parallel electromagnetic bypass valve opening degree when the pressure is too large and add the current limiting valve in parallel with the lubricating oil cooler. Direct fuel injection service occurs if the temperature is normal. There is a high temperature when the electromagnetic valve oil flow is distributed through the cooler. In order to ensure the necessary lubrication effect, the cooler plug installed in the cooler at both ends of the pressure sensor control solenoid opens valve 2.

5. Conclusions

This paper establishes the fault tree of the wind turbine gear box lubrication system. It is pointed out that the incompatibility of lubricating oil temperature, lubrication intensity, and oil state with the working condition of the gear box are the main factors of frequent failures of the gear box.

The calculation method of the gear box heating power and the cooling power of the cooler are determined, and a theoretical basis is established for the design and maintenance of the wind turbine lubrication system.

By introducing the AI control method, the adaptive lubrication system framework of the wind turbine gear box is constructed from the aspects of oil temperature, oil pressure, oil level, and oil quality. It can independently adjust the intensity of lubrication, according to the wind turbine work situation. It is also beneficial to improve the lubrication system stability and wind turbine failure-free operation time and decrease the operation and maintenance cost of wind turbines.

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