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PS3 Developments of Rotating Machines and Operational Experience

Research on Non-Invasive Condition Monitoring-Based Predictive Maintenance of Electric Motors

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SUMMARY

With the development of science and technology and intelligent industrial applications, the concept and technology of equipment maintenance have been developed from defect-based maintenance to preventive maintenance to predictive maintenance. Predictive maintenance is a new generation of active maintenance technology for industrial equipment, which could integrate condition monitoring, fault diagnosis, trend analysis, fault prediction, and intelligent operation and maintenance.

The existing maintenance strategies for electric motors have limited capability for intelligent predictive maintenance. To address this problem, this paper proposes a new predictive maintenance expert system based on non-invasive condition monitoring. The system mainly performs two functions. On the one hand, the health condition of the mechanical structure of the motor is diagnosed online by analyzing the three-phase instantaneous average power of the motor. This method can overcome the deficiencies of existing methods in identifying the fault characteristic signals from the motor current. On the other hand, the electrical insulation performance of the motor is diagnosed online by analyzing the PD (Partial Discharge) characteristics of the motor winding. This method can solve the problem that the offline PD test cannot monitor the insulation health condition during equipment operation. At the same time, based on artificial intelligence technology, the historical parameters of the equipment are compared with the condition monitoring results to analyze and predict the trend of the equipment health condition, which could provide a reliable guarantee for the economic and stable operation of the motor.

Moreover, the paper systematically analyzes the principle and structure of the expert system. Specifically, the system is capable of the following online condition monitoring and fault diagnosis functionalities: ① Non-invasive signal acquisition. The motor-related signals are collected at the circuit breaker, the terminal box, or the body of the motor. ② Selection and analysis of fault characteristic signals. Motor fault diagnosis is achieved by analyzing the fault characteristic signals, such as the three-sequence component of the current, the voltage and power of the motor, the eccentric fault frequency, and the initial phase of the PD signal. ③ Condition evaluation and prediction. On the one hand, based on mathematical modelling methods, the analysis and evaluation of equipment health condition are completed by fault diagnosis through the analysis of the signals extracted for condition monitoring. On the other hand, based on artificial intelligence methods, the trend analysis and

prediction of equipment health condition are completed by comparing the historical parameters of the equipment with the condition monitoring results.
In summary, the expert system can obtain the motor fault feature signals in the initial stage of the fault. Then, comprehensive and accurate fault evaluation and prediction can be achieved by combining the feature parameters of the equipment and the historical trend of the corresponding fault characteristic signal. Finally, the goal of predictive maintenance can be achieved.

KEYWORDS

Electrical insulation fault; mechanical structure failure; motor; predictive maintenance; non-invasive diagnosis

1.0 PREFACE

Equipment maintenance has been an epoch-making progress from defect maintenance to preventive maintenance. However, with the development of science and technology from industrialization to intelligence, the maintenance system based on preventive maintenance has exposed the discomfort in the application process: It is not easy to maintain a balance between insufficient maintenance and excessive maintenance. Predictive maintenance is a new innovative maintenance mode of industrial equipment, which integrates condition monitoring, fault diagnosis, trend analysis, fault prediction, and intelligent operation and maintenance.

2.0 CURRENT SITUATION OF MOTOR MAINTENANCE STRATEGY

Motor failure can be caused by various factors, such as design or manufacturing quality, installation, operation, or maintenance. The traditional motor maintenance strategy is based on passive relay protection, focused on preventive maintenance, and supplemented by defect maintenance. This maintenance strategy cannot prevent the occurrence of accidents, but can only take remedial action after the accident to reduce the expansion of the losses caused by the accident.

Some enterprises had begun to consider simple active monitoring maintenance schemes for critical motors. For example, increasing the engineer's daily inspection frequency or installing probe has been used to monitor the condition of electric motors. These probes need to be installed in the motor winding, bearing or accessories structure, which would bring additional harm to the motor and structure. For example, on the one hand, the use of additional probes may affect the compact structure or rigidity of the motor. On the other hand, harsh environment may affect the accuracy of the sampled signal or the normal operation of the sampler, and ultimately affect the monitoring performance. In addition, the signal sampler must be installed on the site of the motor. For the motor in the unreachable area, these signal probes might be unable to accurately and reliably transmit the signal to the APU (Analytic Processing Unit) due to the harsh environment. Therefore, the predictive maintenance based on intrusive condition monitoring is not popularized.

The expert system of motor predictive maintenance based on non-intrusive condition monitoring is brought forward in this paper, which is based on motor online condition diagnosis. It mainly includes three units: ① Non-intrusive signal sampling in which motor-related signals are collected at the motor circuit breaker. ② Fault characteristic signal processing and analysis in which the fault characteristic signals include the three-sequence component of the motor, the eccentric fault frequency, and the initial phase of the PD signal. ③ Condition evaluation and prediction. On the one hand, based on mathematical modelling methods, the analysis and evaluation of equipment health condition are achieved by fault analysis and diagnosis of the signals extracted for condition monitoring. On the other hand, based on artificial intelligence methods, the trend analysis and prediction of equipment health condition are achieved by comparing the historical parameters of the equipment with condition monitoring results.

3.0 EXPERT SYSTEM FOR ONLINE DIAGNOSIS OF MOTOR FAULTS

Condition monitoring is the core of the online fault diagnosis expert system for motors, which must solve the following problems:

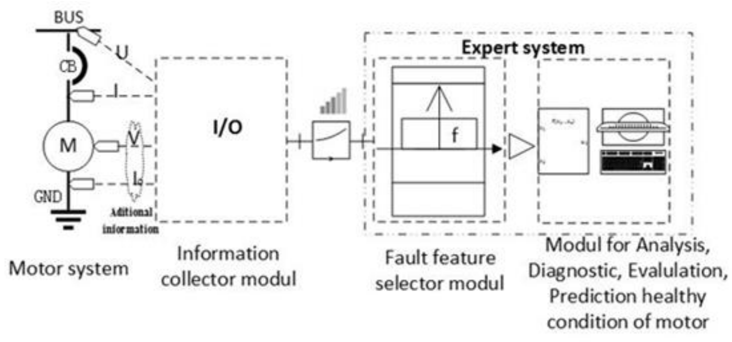

Fig1. Exerpert system diagram for diagnostic motor on-line

1) Fault mechanism analysis, which would process the condition monitoring signals to reflect the mechanism of motor abnormal condition. These condition monitoring signals will include various quantities, such as electrical quantities (e.g., current, voltage, or their combination signals), mechanical quantities (e.g., vibration), thermal quantities (e.g., temperature, pressure, or flow), chemical composition, etc.

2) Signal sampling and processing, which would select the sensors used to collect the samples of the condition monitoring signals and transmit the samples to the signal processing unit with no distortion.

3) Feature extraction, which extracts the fault feature information from the condition monitoring signals analyzes and evaluates the signals based on the fault mechanism, and then draws conclusion about the fault.

The functional block diagram of the online motor fault diagnosis expert system is shown in Fig1.

3.1 Classification of typical motor faults

The motor is mainly composed of rotor and stator. Any improper maintenance and use, such as frequent start, long-term overload, motor damp, mechanical collision, may cause failure of the motor. The main faults of motor generally occur on bearing, rotor, and coil. These faults usually make the electromagnetic characteristics of the motor change directly or indirectly and form unique fault characteristics. The quantity, locations, and nature of the faults in 182 high voltage motors (manufactured by the same manufacturer) from 8 power plants in the Northeast China Power Grid are listed in Table 1[1].

Table 1 Fault characteristics and classification statistics of three-phase asynchronous motor (Northeast China Power Grid)

No.	Site	Nature of fault	Classification of defects	Failure quantity	Failure rate（%）	Equivalent failure rate（%）
1	Stator	Loss of main insulation	Equivalent to stator inter-turn short circuit	14	23.3	43.2%
2		Loss of winding connection wire		8	13.3	
3		Inter-turn short-circuit		2	3.3	
4		Leading wire short circuit		2	3.3	
5	Rotor	Cage breaking, welding-off	Rotor bar broken	22	36.7	36.7
6		Sweeping chamber	Air-gap eccentricity	5	8.3	20
7		Bearing failure		7	11.7	

Combined with the statistical data of relevant motor fault studies published by Electric Power Research Institute (EPRI), there are 37% stator fault, 10% rotor fault, 41% bearing fault, 12% other faults. This paper summarizes the common faults of squirrel cage asynchronous motors and the characteristics of the final development of the faults, which can mainly be divided into three kinds: Stator inter-turn short circuit fault (28%), rotor broken-bar fault (6%), air gap eccentricity fault (42%), and other faults are shown in Table 2.

Table 2 Three-phase asynchronous motor fault classification statistics (EPRI)

No.	Classification of fault mechanism	Symptom of fault	Fault rate	Probability subtotal
1	Stator inter-turn short circuit	Inter-turn insulation	23%	28%
2		Grounding insulation	4%	
3		Iron core	1%	
4	Rotor bar broken	Rotor bar and end ring fault	5%	6%
5		Iron core	1%	
6	Air gap eccentricity (dynamic eccentricity and static eccentricity)	Bearing failure	38%	42%
		Rotary shaft or coupling failure	4%	

Considering the motors in operation, the three main faults, i.e., motor stator inter-turn short circuit, rotor broken-bar, and air gap eccentricity constitute about 76% total fault in motors. These faults make the motor electromagnetic power frequency characteristics superimposed multi-frequency or even high frequency characteristic signals. The harm of these faults is more than 95%.

Therefore, by analyzing the electromagnetic characteristic signal of motor and combining the characteristic information of three kinds of faults, the faults of motor mechanical structure can be all monitored and diagnosed. For motor winding insulation, the stator winding fault caused by aging or mechanical damage can be diagnosed comprehensively in the early or incipient stage of motor winding insulation fault through the insulation diagnosis device based on the online PD principle. Hence, engineers will have more time to develop mitigation strategies to prevent motor faults. In addition, the motor vibration caused by rotor eccentricity detected by using the electromagnetic spectrum can eliminate the external interference or dynamic error more significantly than that caused by mechanical vibration.

3.2 Fault mechanism analysis of motor

3.2.1 Electromagnetic theory design of motor

When the motor is designed and manufactured normally, the theoretical symmetry of three-phase winding is required to ensure the stability of mechanical properties. Therefore, the three-phase current of the motor with normal and stable operation will be symmetrical under the action of three-phase symmetrical power supply. Thus, it can be concluded that:

The fundamental magnetomotive force expression of the three-phase synthesis is:

$$\mathrm{f}_1(\theta, t) = 1.35\frac{N_1 k_{w1}}{p} I_\varphi \cos(\omega t - \theta); \qquad (2\text{-}1)$$

The expression of the three-phase harmonic magnetomotive force is:

$$\mathrm{f}_\nu(\theta, t) = \frac{1}{\nu} 1.35\frac{N_1 k_{w\nu}}{p} I_\varphi \cos(\omega t - \nu\theta); \qquad (2\text{-}2)$$

where ν is the harmonic number; p is the magnetic pole number; N_1 is the number of turns of the line group; k_{w1} and $k_{w\nu}$ are the coefficients of the fundamental wave and harmonic line group, respectively; and k is a natural number.[2]

For three symmetrical currents, it can be proved that:

When $\nu = 6k - 3$, the harmonic magnetomotive force is 0;

When $\nu = 6k - 1$, the harmonic magnetomotive force is opposite to the fundamental magnetomotive force, which is called the reverse magnetomotive force;

When $\nu = 6k + 1$, the harmonic magnetomotive force is the same as the fundamental magnetomotive force, which is called the forward magnetomotive force.

Due to the existence of harmonic magnetomotive force, additional loss, vibration and noise will be caused in the AC motor, and harmful additional torque will also be generated for the induction motor, which will deteriorate its performance. Therefore, in the actual design, the distribution and short-pitch winding are used to weaken the influence of harmonic magnetomotive force, so that the motor could operate stably under normal symmetrical voltage, and the additional loss, vibration and noise could be greatly reduced.

3.2.2 Motor rotor fault

When the motor rotor fails, such as bearing, rotor failure or abnormal installation, the dynamic and / or static eccentricity of air gap (generally referred to as composite eccentricity) will be caused, which will break the balanced and stable magnetomotive force in the theoretical design of the motor. This imbalance has little effect on the fundamental wave magnetomotive force, but will seriously break the harmonic magnetomotive force balance. The most direct expression is the abnormal increase of additional loss, vibration and noise. Traditional fault diagnosis methods (vibration measurement, temperature measurement, noise measurement) are used to analyse the fault feature to judge the failure. In fact, the measured signals are not the most direct signal source, but the characterization signal derived from the energy conversion. The feature information is easily lost and will be limited by the accuracy of the measuring instrument and the interference of external noise. Assuming that the air gap length under composite eccentricity is:

$$\delta(\theta, t) = \delta_m[1 - k_s \cos\theta - k_d \cos(\omega_r t - \theta)] \qquad (2\text{-}3)$$

where δ_m is the average air gap length; k_s is the static eccentricity; k_d is the dynamic eccentricity;$\omega_r = (1 - s)\omega/p$ is the rotor rotation angular frequency.[3]

After theoretical analysis, it can be proven that the characteristic frequency component with the frequency of $f_1 \pm f_r$ will be induced in the stator winding with the composite eccentricity fault. The interactions between the current components at these frequencies and the air-gap magnetic field could make the torque and speed of the motor fluctuate. The fluctuation frequency is $f_1 \pm mf_r$, which is the characteristic frequency of eccentric fault, where m is a natural number.

The reciprocal of the air gap is simplified, and the lower order term is taken after Fourier expansion, and the following equation can be obtained:

$$\frac{1}{\delta} = \frac{1}{\delta_m}[1 + k_s \cos\theta + k_d \cos(\omega_r t - \theta)] \qquad (2\text{-}4)$$

3.2.3 Motor Stator Fault

When the motor stator fails, such as inter-turn, inter-phase short circuit or broken circuit, the symmetry of the stator winding will be broken. The air gap magnetic potential generated by the stator winding is transformed into an elliptical one. The elliptical magnetic potential can be decomposed into a positive rotation component $\overrightarrow{F_{11}}$ and a reverse component $\overrightarrow{F_{12}}$, with the same rotational speed and opposite direction. The positive rotation component $\overrightarrow{F_{11}}$ induces the AC potential with frequency of power frequency f_1 in the stator winding and induces the potential and current with frequency of sf_1 multipled with slip ratio in the rotor winding. The rotor magnetic potential generated by the rotor current at this frequency is denoted as $\overrightarrow{F_{21}}$, which is relatively static with $\overrightarrow{F_{11}}$. The reversal component $\overrightarrow{F_{12}}$ also induces the AC potential with frequency f_1 in the stator winding, but the phase sequence is opposite, so the negative sequence component is generated in the stator three-phase current. Therefore, negative sequence component is the fault feature of stator winding fault. Similarly, when the three-phase voltage of the input motor is asymmetric, the negative sequence component will also be generated when it acts on the motor with symmetrical winding. Therefore, the negative sequence component is a sufficient rather than a necessary condition for the stator winding fault.

When the fault is minor, the proportion to the negative sequence component is relatively small, and the damage to the motor is not serious. The traditional relay protection could not achieve the frequency analysis intelligently and accurately. To ensure the stability of equipment operation and the reliability of protection setting, the motor had to be kept in operation with small faults. For serious short-circuit fault or open-circuit fault, the negative sequence protection or zero sequence protection of relay protection will trip. The fault would develop and deteriorate until the fault current exceeds the equipment margin in short-circuit phase, and the winding could break the winding or iron core for overheating. Then, the short-circuit protection or blocking protection (main protection) would immediately trip to remove the fault, which is used to prevent the over-current or overload protection (backup protection) of the motor from overheating. To prevent the influence of relay protection on the stable and reliable operation of equipment, the motor must be allowed to be slightly damaged before removing the fault, which is the purpose of relay protection setting calculation.

3.2.4 Stator winding insulation fault

The dielectric constant varies with insulating media, and the insulation strength is also different. There is no voltage breakdown under normal insulation strength in the same vertical line. Once the material is mixed with low insulation strength, the overall insulation strength on the same vertical line would be reduced due to the decrease of its shared voltage, which would lead to a voltage breakdown at the weak insulation strength, which is namely PD. In addition, with the amplitude of AC voltage waveform changing, the PD will appear intermittent pulse discharge process, in the voltage peak and valley near the first occurs, back to zero PD will stop. The schematic diagram is shown in Figure 2.

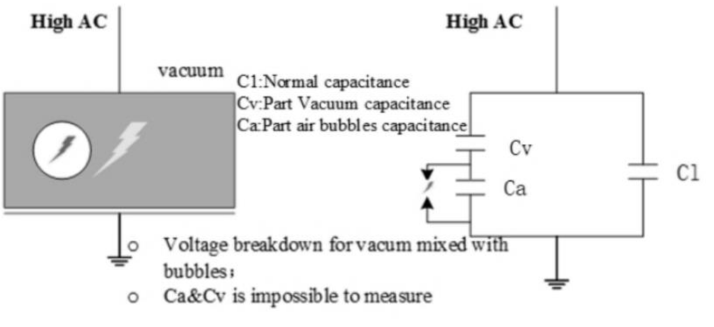

Fig.2 circuit diagram of insulation PD

The insulation condition of the electrical equipment is usually expressed by the following characteristics: ①The quantity and discharge position of the PD, ② dielectric loss factor (tgδ), ③ leakage current, ④ variation of equipment capacitance. Motor stator winding insulation is a solid material, PD is generally in the position of uneven dielectric insulation. In the early fault, PD will not lead to breakdown the whole insulation structure with a part fault breakdown. This kind of discharge is a pulse with a duration less than 1 μs, and the PD frequency is about 30 MHz (the specific frequency is related to insulating material) in general motors. At the same operating voltage, the weaker the insulation strength, the earlier and more serious the discharge. The online diagnosis of insulation fault is to diagnose the insulation health by monitoring the strength of PD.

When the internal aging of the insulating layer is reduced, it could be detected by the traditional offline PD test (corona test). The evaluation criteria are as follows: The maximum discharge quantity Q_m would increase slowly with the increase of voltage. For the same electrical equipment, under the same voltage and the same time interval, the greater the number of PD pulses is, the larger discharge pulse amplitude is, and the larger Q_m is, with the lower insulation strength. The relationship curve between the PD voltage and the maximum quantity is shown in Fig. 3. Q_m can be measured in the offline condition, but it is difficult to measure Q_m in the online condition. Therefore, although the insulation offline diagnosis theory is relatively mature, there are still some difficulties in the promotion and application of insulation online diagnosis.

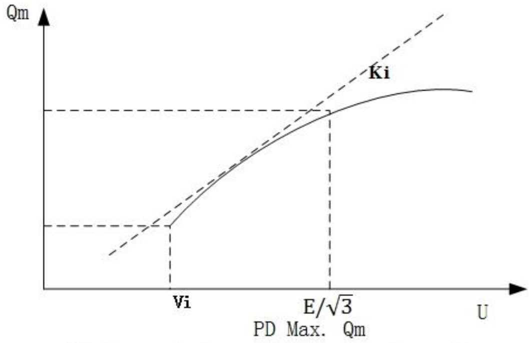

Fig.3 curve between PD voltage and max. Qm

In addition, the initial voltage V_i of PD directly reflects the insulation strength. The slope K_i of the curve is related to the deterioration degree of the insulating material, and the maximum discharge amount is related to the capacitance of the insulating material. Therefore, the initial voltage V_i can be used as the fault feature of insulation deterioration. In this way, for the PD characteristics of insulation, the deterioration degree of insulation strength can be identified by the composition or position of the fundamental wave and the pulse waveform of PD.

3.3 Mathematical modelling of motor fault

3.3.1 Mathematical Modelling Analysis of Motor Mechanical Structure Fault [4]

Combined with the above mechanism analysis results, combined with various fault conditions, the mathematical analysis is carried out according to the Fourier expansion, and the simplified expression of a phase current of motor (only containing the low-order harmonic component near the fundamental wave, ignoring the high-order harmonic component) can be obtained:

$i_a = I_{p1}\cos(\omega_1 t - \varphi_1) + I_{n1}\cos(2\omega_1 t - \varphi_{n1}) + I_{bp1}\cos[(1-2s)\omega_1 t - \varphi_{bp1}] + I_{bn1}\cos[(1+2s)\omega_1 t - \varphi_{bn1}] + I_{ecp1}\cos[(\omega_1 - \omega_r)t - \varphi_{ecp1}] + I_{ecn1}\cos[(\omega_1 - \omega_r)t - \varphi_{ecn1}]$
（3-1）

where I_{p1} 、 I_{n1} are the amplitude of positive sequence and negative sequence components corresponding to stator winding inter-turn and inter-phase short-circuit faults; I_{bp1} 、 I_{bn1} are the amplitudes of positive sequence and negative sequence components corresponding to broken bar faults; I_{ecp1}、 I_{ecn1} are the amplitude of positive sequence and negative sequence current components corresponding to eccentric faults; φ_1、 φ_{n1}、 φ_{bp1}、 φ_{bn1}、 φ_{ecp1}、 φ_{ecn1} are the initial phase of the above current components; $\omega_1=2\pi f_1$、 $\omega_r=2\pi f_r$ are the angular velocities of stator and rotor.

Based on the above analysis, it can be proved that the current of motor could reflect the fault characteristics of motor. The amplitude of motor current is so small as to the voltage and varies with the fluctuation of the voltage, so that motor health condition is not easy to diagnose by directly monitoring motor current. Assuming that the average three-phase instantaneous power p3 (t) is:

$$p_3(t) = \sqrt{3}(u_{AB}i_A + u_{BC}i_B + u_{CA}i_C)/3 \qquad (3\text{-}2)$$

where u_{AB}、 u_{BC}、 u_{CA} are the line voltage of the motor， i_A、 i_B、 i_C are the corresponding line current. The detail is as （3-1）、（3-2）：

$$p_3(t) = \frac{\sqrt{3}}{2}U_{p1}\{I_{p1}\cos\varphi_p + I_{n1}\cos(2\omega_1 t - \varphi_n) + \sum_{k=1}^{\infty}[I_{bpk}\cos(2ks\omega_1 t + \beta_{bpk}) + I_{bnk}\cos(2ks\omega_1 t - \beta_{bnk})] + \sum_{m=1}^{\infty}[I_{ecnm}\cos(2ks\omega_r t + \beta_{ecnm}) + I_{ecpm}\cos(2ks\omega_r t - \beta_{ecpm})]\}$$
（3-3）

Obviously, all kinds of fault characteristic components could be fully reflected in the expression, and the characteristics are simple and clear. At the same time, it could avoid the deficiencies of current as a fault characteristic signal (because the characteristic spectrum is very close to the fundamental frequency in spectrum analysis, it is easy to be annihilated). In the case of keeping the fundamental voltage as one multiplication factor unchanged, the other factor is the current in various operation conditions (with the occurrence of faults, the characteristic current components of various faults will be superimposed respectively). In normal conditions, there is only the fundamental component $I_{p1}\cos\varphi$， while the negative sequence characteristic component $I_{n1}\cos(2\omega_1 t - \varphi_n)$ is monitored in the stator inter-turn short circuit, and the characteristic component $\sum_{k=1}^{\infty}[I_{bpk}\cos(2ks\omega_1 t + \beta_{bpk}) + I_{bnk}\cos(2ks\omega_1 t - \beta_{bpk})]$ is monitored ksf1 in the rotor bar broken, and the characteristic component $\sum_{k=1}^{\infty}[I_{ecnm}\cos(m\omega_r t + \beta_{ecnm}) + I_{ecpm}\cos(m\omega_r t - \beta_{ecpm})]$ is monitored $m\omega_r = m(1-s)\omega_1/p$ in the air gap eccentricity.

3.3.2 Mathematical Analysis of Electrical Insulation Faults of Motors

Combined with the above theoretical analysis, it can be proved that the electrical insulation fault would cause PD when the voltage increases to a certain value, then PD would be stronger with the higher voltage and badder insulation.

Table 3 For general high voltage AC motor insulation comprehensive judgment standard is as follows[5] :

Test item	Critical parameter	Voltage class (KV)	Critical （pulse number） （unit）	
			Attention	Failure
PD tests	maximum discharge Qm	3.3	2500~5000	>5000
		4.0	2500~5000(5)	>5000(10)
		6.6	5000~10000	>10000
		11.0	5000~10000	>10000

Discharge power P: Equal to the average pulse power of a single apparent charge q_i between the two ends of the sample within the selected reference time interval T_{ref}.

$$\mathrm{P} = \frac{1}{T_{ref}}(q_1 u_1 + q_2 u_2 + q_3 u_3 \ldots q_1 u_1) \qquad (3\text{-}4)$$

where u_1, u_2, …, u_i is the instantaneous value of the test voltage, t_i is the instantaneous discharge time, q_i is the single apparent charge.

The characteristic waveform of insulation could be composed of the fundamental waveform of voltage and the PD pulse waveform in online insulation diagnosis. $\mathrm{U} = U_1 + U_p$, where U_1 is the fundamental voltage waveform, U_p PD pulse waveform, which could couple voltage waveform by the capacitor, couple current waveform by CT, couple vibration waveform by the vibration probe, and could be used to describe the voltage time domain waveform as following expression:

$$U = U_1 \cos(\omega_1 t - \varphi_1) + U_p \cos(\omega_p t - \varphi_{p1}) \qquad (3-5)$$

where ω_p is the pulse frequency, generally around 30MHz and above, the cycle is less 1μs, where ω_p is generally greater $20000\,\omega_1$. In fact, the discharge power is difficult to measure online, but the deterioration degree of insulation strength could be evaluated with the pulse position of PD, as shown in Fig. 4.

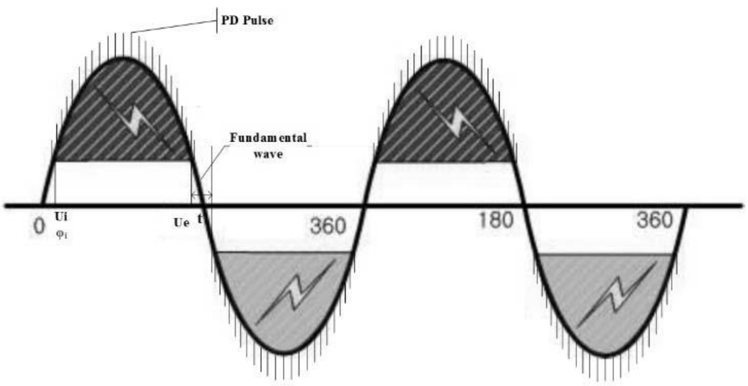

Fig. 4 PD Wave

When the voltage is stable and the PD does not break down seriously, the relationship between the number of pulses and the PD time of the power supply fundamental wave is staic. So the severity of the PD can be verified by monitoring phase angle of the initial voltage U_i and the extinction voltage U_e of the PD pulse (the extinction time of the PD pulse in each cycle can be calculated by monitoring the time or phase of the pulse on the winding power frequency voltage curve). This diagnosis result could more accurately discripe the severity of equipment insulation deterioration. The insulation strength given here could only be a relative value, and accurate evaluation must be given by comparing with the relative historical parameters of the equipment.

3.4 Motor Fault Feature Information

Based on the above analysis, we can know the main faults of squirrel cage asynchronous motor are composed of stator inter-turn short circuit, rotor broken bar and air gap eccentricity and winding insulation fault. The feature information corresponding to these fault conditions is as following:

- ✓ The stator inter-turn short circuit corresponds to the negative sequence component in the current, and the average instantaneous power is the DC component.

- ✓ The characteristic frequency component of (1±2ks) f_1 is in the current with broken rotor bar or end ring fault, and the average instantaneous power is ksf1 component.
- ✓ The air gap eccentricity corresponds to the characteristic frequency component of $f_1 \pm mf_r$ in the stator current, and the average instantaneous power is $m(1-s)\omega_1/p$ component.
- ✓ Once the winding insulation fault occurs, the PD pulse component in the corresponding electrical quantity is the pulse interruption time or phase angle in this diagnosis.

3.5 Application of motor fault online diagnosis

The predictive maintenance expert system of motor based on non-invasive condition monitoring is designed to realize the online monitoring, diagnosis and health status evaluation and prediction of motor, which mainly includes two parts: the local device and sensor used for signal acquisition, measurement and display. The remote part is mainly used for engineer stations with functions of data calculation, analysis, evaluation and prediction.

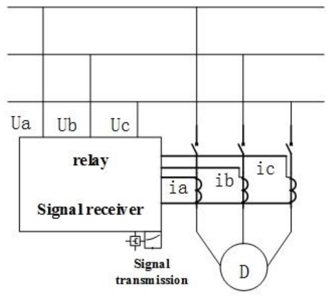

Fig.5 diagram of electrical signal collection

3.5.1 Diagnosis of Motor Electromagnetic Fault Features

FThe signal acquisition circuit can be shared with the traditional relay protection signal acquisition circuit or the electrical measurement circuit of the motor. At the same time, the corresponding fault characteristic quantities are extracted from these signals. The schematic diagram of signal acquisition is referred to 5.

For the fault diagnosis of electromagnetic abnormal changes caused by mechanical defects of the motor, the effect of this device is particularly superior. The block diagram of the motor predictive maintenance expert system is shown in Figure 6.

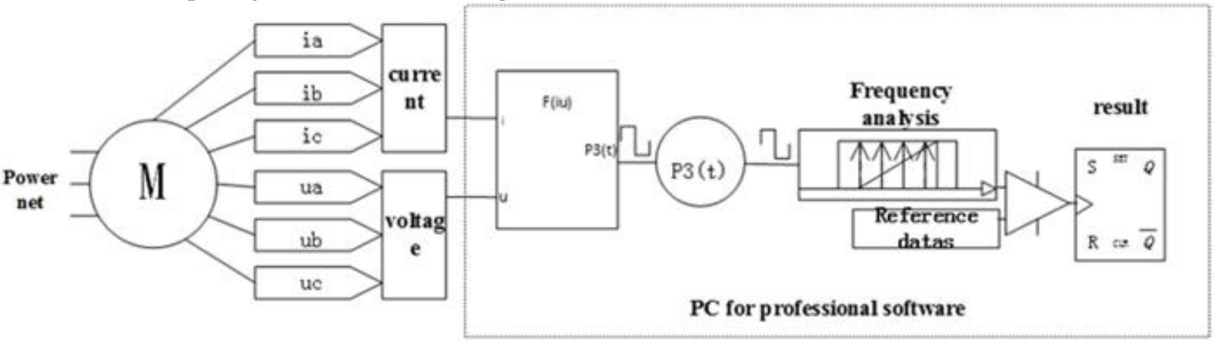

Fig. 6 diagram of diagnosising fault with motor

For the judgment of electrical insulation fault, electromagnetic principle is not as accurate and fast as PD principle. In addition, for equipment in unreachable areas, it is no need to install more field equipment, only share current and voltage signals in the relay protection device circuit near the motor inlet switch. The relevant signals collected by the signal acquisition device are identified and packaged into data files. On the one hand, they can be uploaded to the cloud through the network to enrich the inventory of the data center. On the other hand, they can also complete data transmission directly through WIFI or other ways, so that the engineer station can realize the remote call of data.

As the core of the expert system, the engineer station uses special software for a series of data processing and analysis, and compares the calculation results with the theoretical results, so as to draw the evaluation conclusion. For the data without a unified verification standard, we can predict the performance of each device through artificial intelligence and give a recommended evaluation scheme or diagnostic results based on historical trends.

3.5.2 Application of on-line diagnosis of motor insulation

Once the motor insulation defects deteriorate, PD will gradually appear, and the PD signal has the following obvious characteristics: High frequency, wide frequency, narrow band, multi-frequency superposition. According to the different structure of the motor and the form of field installation, PD signals can be extracted by three ways: ① Capacitance coupling to extract PD voltage pulse. ② PD current pulse is extracted by electro-ground current infiltration. ③ Vibration pulse extraction by PD shock vibration. The signal acquisition schematic is shown in Figure 7. In view of the particularity of PD signals, high frequency, high saturation response, high resolution and high sensitivity sensors must be selected for signal acquisition.

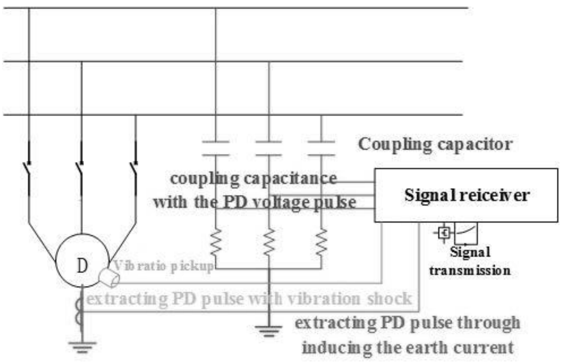

Fig. 7 diagram of PD signal collection

There is no uniform standard for the comparison and judgment of PD signals. Therefore, the final diagnosis and evaluation must be based on the historical PD data of the equipment and the material itself. The trend of PD characteristics of insulation materials according to normal aging is shown in Figure 8.

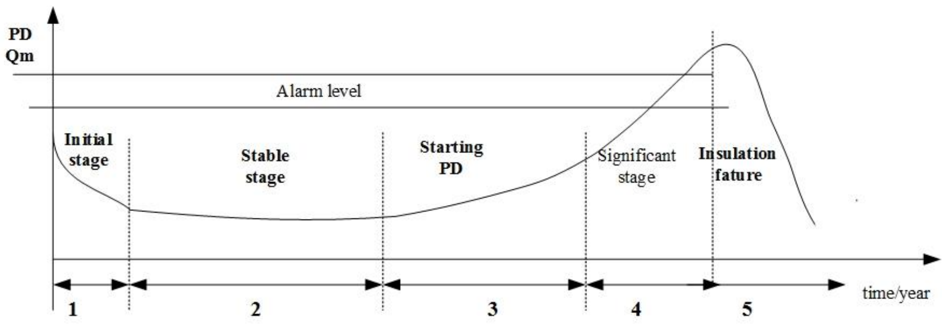

Fig. 8 diagram of PD trend

3.6 Evaluation of motor diagnostic results

System analysis software: The main functions are to conduct comprehensive analysis, judgment and data storage of electrical signals and PD pulse signals. The expert system of professional system analysis software is installed to identify and read the signal package file of signal acquisition module, and then analyze and calculate the full function of analysis, digital display, waveform display, FFT analysis, wavelet analysis, fundamental frequency spectrum analysis, decibels analysis, storage, sampling rate adjustment, and form a data file to establish a professional database.

The evaluation of motor diagnosis results is mainly based on two aspects: 1) For the parameters of the existing measurement standards, based on the existing evaluation criteria. 2) For parameters without ready-made measurement standards, these parameters can be basically defined as equipment characteristic parameters. In the evaluation, it is also necessary to determine the benchmark database according to the change trend of the corresponding historical parameters of the equipment itself. For the first operation, we must also make full use of offline detection results to set the basic alarm value and outage maintenance value. Subsequently, artificial intelligence deep learning can be used to improve and enhance the key sensitive parameters such as alarm value and outage maintenance value, so as to evaluate the health status of the motor more accurately and effectively.

4.0 CONCLUSION

The real-time online monitoring of the main motors is carried out by using the complete on-site control system and the comprehensive online diagnosis technology of the motors. The relevant parameter database is established by the special software of the expert system, and the operation parameters of the system are analyzed. At the same time, through the intelligent calculation using artificial intelligence, the health operation status of the motors is evaluated, and the health trend of the motors is predicted. It is recommended that the motor maintenance timeline and plan can realize the predictive maintenance of the motor. Of course, it is also necessary to track the operation of the system and equipment to see how to accurately judge and predict the life and failure of the motor based on data analysis avoid equipment failure caused by unexpected shutdown. At the same time, the basic parameters of inspection and parameter correction are set to ensure that the evaluation and prediction accurate and effective, which is the goal of the motor predictive maintenance expert system.

Although the current experimental results are not ideal, the diagnostic cases cannot be shown to the readers more clearly, mainly because the sensitivity of some sensors in the laboratory is not enough. But I firmly believe that on the basis of this theory, I will soon overcome this problem.

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