Online Lubricant Monitoring System with WSN Based on the Dielectric Permittivity

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Abstract. Through theoretical and experimental methods, the feasibility of the dielectric permittivity as the decay of lubricants evaluation index was verified. To overcome the shortcoming of existing oil monitoring with high costs, complicated operation and poor real-time, it's necessary to develop the wireless online monitoring system. A new type of capacitance sensor for trace moisture measurement was presented. Oil monitoring principle according to the idea of difference was described. Node deploy mode of wireless sensor network is presented in this paper, and asynchronous sleep scheduling algorithm based on the data variation was given. By means of the grey correlation analysis and experiment in allusion to moisture measurement, the results confirm that the accuracy and reliability was improved.

Keywords: Lube · Permittivity · WSN · Grey correlation analysis · Moisture

1 Introduction

The deterioration level of lubricants affects working conditions of the engine directly, and the decay process of the engine lubricating oil is a complicated process. Traditional detecting methods of lubricating oil predominantly use off-line detection, extracting the pre-existing oil sample and bringing it to the special detection mechanism. The off-line detecting method is laborious, time-consuming, costly and requires a long monitoring cycle. Therefore the development of online lubricant monitoring system has very significant theoretical and practical significance.

It shows that moisture in the lubrication system of utility-type unit is one of the important causes leading to the equipment problem, especially in the petrochemical industry. The moisture content in lubricating oil, according to the regulations, should be below 0.03%, and the oil change level is controlled in 0.1%~0.5%. If the standard is not met, lubricating oil will be emulsified, and the lubricating properties of oil will grow poorer, causing parts to rust, axle suspension bush to burn and other machinery accidents. Therefore moisture monitoring in the lubricating oil is particularly important, not only can it monitor the equipment operational condition indirectly, but also provides evidence for the mechanical fault diagnosis.

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2 Related Work

As the lubricant is oxygenized and polluted, the permittivity becomes increasingly apparent; therefore the permittivity can be seen as the comprehensive evaluation index of the lubricant decay extent. Through the reasonable threshold of the permittivity, the rate of lubricants deterioration can be evaluated comprehensively. Among the lubricant physicochemical index, the change of the metal particles, water, and acid substance are the principal factors which affect the lubricant quality decay. Especially the water, whose permittivity is much larger than the lubricants' and other two factors, plays a key role in the permittivity's change [1].

Currently, the moisture content of lubricating oil online measuring is mainly by the capacitive moisture sensor which based on the variable dielectric permittivity. Authors of literature[2-5] discussed the performance of the capacitance sensor with flat, cylindrical, and probe sensors; experiments were carried out to validate correlation models. The structure of the sensor under the condition of high moisture content performance comparatively ideal, and it is appropriate for detecting water well like crude oil, which moisture content is high. But for lubricating oil, which moisture content is extremely insignificant, the situation is completely different. In the first instance, the sensor's capacitance is too minuscule, usually only a few picofarad. Though some improved sensors[6] with a layer of insulating layer on the plate can increase the capacitance to dozens of picofarad, but the capacitance variation caused by the dielectric permittivity change remains unchanged. This does not increase the sensitivity of the sensor, and it is difficult to distinguish for less than 0.1% moisture. Secondly, we cannot ignore the edge effect, parasitic capacitance, stray capacitance for the sensor's minuscule capacitance, as they impact the mapping relationship between moisture content and capacitance. And lastly, though moisture content has noticeable differences in dielectric permittivity measurement between water and oil, but it is not a single-valued function of the lubricating oil dielectric permittivity; the influence of abrasive particle and temperature on dielectric permittivity cannot be ignored. Therefore, in order to improve the sensitivity and accuracy of trace moisture measurement, it needs to be improved for the sensor and methods of measurement.

3 Design of Lubricant Monitoring System

In this section, the lubricants online monitoring system, which focuses on moisture detecting, is described. Details on hardware and software designing are discussed.

3.1 The Capacitance Sensors

A lot of literature and experiments show that moisture content in lubricating oil has significant influence on the dielectric permittivity; it can go as far as offsetting the effect of other impurities on the oil dielectric permittivity in the interval of high moisture content. However, the absolute variation of the dielectric permittivity of oil, with moisture content less than 1000ppm, is very diminutive; it is difficult to measure with the sensor due to its size and structural limitations. To improve the sensitivity of the sensor, the flat capacitor is reformed, and is designed with a parallel plates capacitance sensor which can be adapted according to the requirements. The structure shown in Figure 1, n is 8, representing the capacitor electrode couple number, including 8 pieces of rotary plate and 8 fixed plate, the radius r=14.4mm, plate thickness is 0.5mm, should be used as far as possible to make the maximum plate opposite area. Due to the ideology of difference, there needs to be two identical sensors. But it is difficult to produce the exact equivalent sensor on both the structures due to limitations of the production process. However, you can move the screw-rotating plate to fine-tune the area by strengthening the nut.

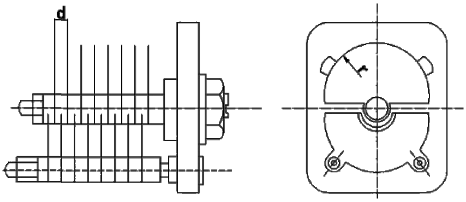

Fig. 1. The structure of sensor

According to research, if consider the influence of edge effect, the plate capacitor expression of limited size is:

$$C = n\varepsilon S\,1\quad \frac{\theta}{\pi}/\mathrm{d} + \frac{n\varepsilon S}{\pi}1 + \ln 1 + \frac{2\pi r}{d} + \ln(1 + \frac{2\pi r}{d}) \tag{1}$$

According to the theory of dielectric permittivity we know that $\varepsilon=\varepsilon_0\varepsilon_r$, replacing the ε in formula 1, we get $C=nK\varepsilon_r$.

In the formula:

θ——rotation angle from moving plate to the fixed plate.
n——the couple of the plate.
ε_0 & ε_r——the permittivity of vacuum and relative permittivity of inter-plate oil
K——sensitivity of capacitance on the relative permittivity of one couple plate.

Holding constant the structure and size of the sensor, dielectric permittivity and capacitance value showed a linear relationship in theory. The original capacitance value increases to n times, and reduces the incidence of the parasitic capacitance, which exists in wire and measuring circuit. Furthermore, sensitivity of the sensor enhanced to n times. However, with higher sensitivity, the stability deteriorates. Additionally, the difficulty of the installation and production increases. Therefore, the value of n and s must be considered.

3.2 The Structure of System

From the above formula (1) we can see, the dielectric permittivity and the capacitance are directly linked. Variable permittivity capacitor transforms the permittivity changes of lubricants to the capacitance changes of capacitive sensors in order to achieve the detection purpose. When the permittivity exceeds the threshold of the system, the system alarm will sound. But to date, none of the methods developed is perfect and all are far from ready to be used in practice systems. So it will be followed by a description of how to set up the network of monitoring system, and details on the sensors' structure are discussed in later sections.

The project, which is part of the Maoming Petrochemical rotating machinery fault diagnosis project, provides one-dimensional fault diagnosis evidence for multi-sensor information fusion. The large units of Maoming Petrochemical are equipped with a lubrication system. Lubricating oil filter is an important part of the lubrication system, and its role is to filter and remove impurity and abrasive particle in the lubricant, and to protect life of operation components.

The design is based on the idea of the differential. Sensors with the same structure are mounted in vital parts such as the oil tank, filter, cooler, and dehydrator. By monitoring the permittivity between different nodes, we can calculate the difference to analyze the impact of numerous factors on the oil dielectric permittivity. So the permittivity increment made by moisture, abrasive particle and thermal can be calculated by measuring the difference of capacitance. The structure of the lubricant monitoring system in Maoming Petrochemical is shown in Figure 2.

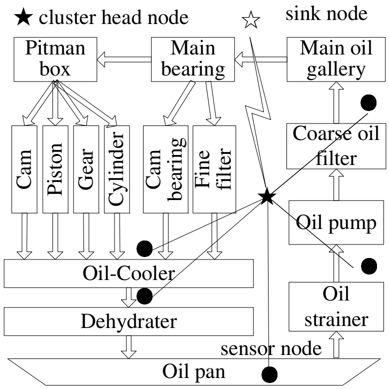

Fig. 2. Diagram of the general design

The monitoring system obtains real-time oil data online generated by sensors mentioned above. Then, it utilizes the Zigbee protocol to communicate between the cluster head node and sensor nodes, by which data is collected. Finally, sink node uses a USB interface and uploads the data to the PC.

The sensor node for each unit is composed of a cluster, using single hop communication between the sensor nodes and the cluster head. The sensor nodes transmit the collected data to the cluster head. Cluster head collects the data from sensor nodes for fusion to remove data redundancy. After that, the cluster head then transfers the data to the sink node. Sensor nodes using regular sleep mechanism wake every ten minutes to collect data from units. And it can also be awakened by the cluster head itself in order to collect data from specific parts of each unit.

When the data is gathered, the sink node uploads the data to the PC by USB interface. Oil expert system can be used for further analysis on the PC, and can also be connected to the larger oil analysis laboratory implementation of remote analysis.

3.3 The Software Design

The diagram of the software is given in figure 3. In order to save the energy of sensor nodes, wireless communication module nodes usually remain dormant and opened only when the value is mutated or when the sink nodes are required to transmit data[7][8]. Considering the energy efficiency and characteristics of oil monitoring, we designed the asynchronous sleep scheduling algorithm based on the data variation as follow. The data are collected by sensor nodes once every ten minutes and compared with preceding data. If changed little, it will be stored in memory and will overwrite the previous data. If the data is mutated, the wireless communication module will power on the wireless communication module for alarm. Sink node will then send the command to WSN to open all nodes when the oil needs to be analyzed, sensor nodes distributed storage data to the cluster-head node, and then send to the sink node by them. Fluids information can be chosen by the sink node at all monitoring points, and can also be separately collected.

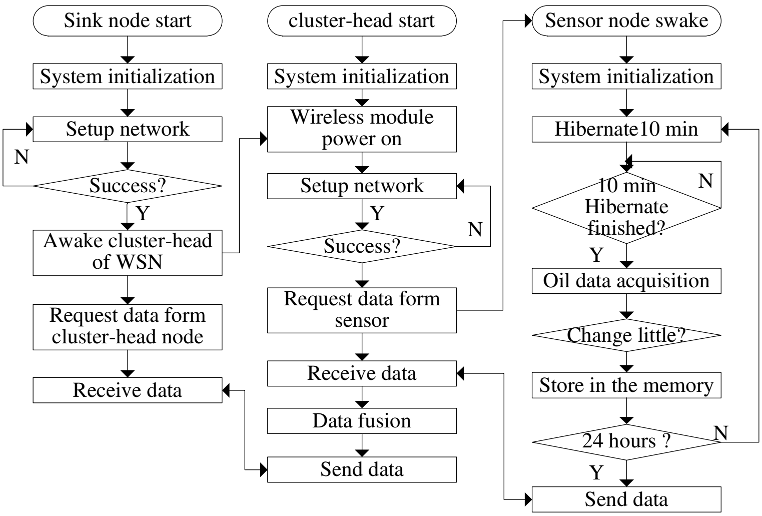

Fig. 3. The flowchart sleep scheduling algorithm

4 Gray Relational Grade Analysis

The dielectric permittivity of the lubricating oil, mainly affected by the moisture, abrasive, temperature and other unknown factors, can give a representative property of physicochemical parameters roundly. It belongs to grey system. The grey system theory put forward the concept of the grey relational grade of various factors, and determines the degree of correlation between factors according to geometry curve similarity of factors. Take water content monitoring for an example, to find out relationship between the sensor output and water content, the bigger correlation degree between factor and moisture content, the more accurate for using it as a monitoring water content index. The major steps are making the original data dimensionless, calculating the correlation coefficient, correlation degree and ranking evaluation index according to the correlation degree.

Set the moisture content as the main sequence Y={Y(k) | k = 1, 2, ……,n}, and factors as sub sequence X_i={X_i(k) | k = 1, 2, ……, n}, i = 1, 2, ……, m.

The physical meaning of each factor is different, so data dimension is inconsistent. In order to eliminate the influence of dimensional and enhance comparability between different dimensions of factors, we need the grey correlation analysis, and first of all the elements of raw data need to be normalization with non-dimensional treatment, its computation formula is[9]:

$$x_i(k) = \frac{x_i(k)}{x_i(l)}, k = 1,2,\cdots\cdots n; i = 0,1,2\cdots\cdots m \tag{2}$$

According to the definition, the correlation coefficient for main sequence Y(k) and sub sequence Xi(k) is

$$\zeta_i(k) = \frac{\min_i \min_k \Delta_i(k) + \rho \max_i \max_k \Delta_i(k)}{\Delta_i(k) + \rho \max_i \max_k \Delta_i(k)} \tag{3}$$

In the formula the ρ is distinguishing coefficient, the smaller the ρ is, the greater the resolution ratio. The resolution is best, the when the ρ≤0.5463 or less, usually take ρ=0.5. The correlation degree of sequence of sub factors represents the relationship to the main sequence, the greater the correlation degree of the factors, the influence is more obvious to the main sequence.

5 Experiment

Results of an experiment focus on moisture content we validated are given to illustrate the proposed technique. In the experiment, the actual sample of lubricating oil is measured regularly from a unit in maoming petrochemical company, model for mobil dte25. Take 20 samples of actual oil, and five of them at room temperature, adding suitable amount of water that making lubricating oil moisture volume fraction were 0.01%, 0.1%, 0.3%, 0.5%, 0.3%. And the real moisture content was measured by Karl fischer moisture meter. Stir well for 10 min making water dissolves in lubricating oil. Measuring the capacitance value C_{x1}. Then filter the oil with the precision of 15 microns, measuring the capacitance value C_{x2}. Experimental data measured in temperatures of 26.7℃, 40℃, 55℃, 70℃. The relations between moisture content and capacitance value under different temperature is shown in figure 4 and 5. Obviously, compared with two figures, we know that coincidence degree is higher when using ΔC_w to represent the moisture content than using a single sensor. Therefore, it can reflect real water content more exactly.

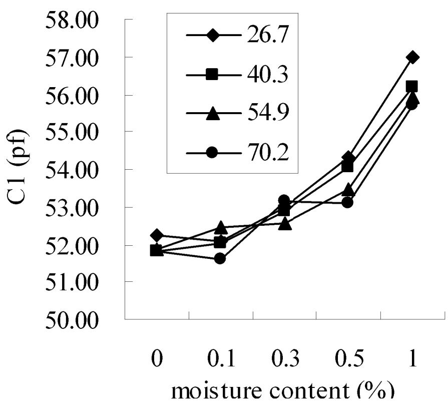

Fig. 4. Relatedness between moisture and C_1

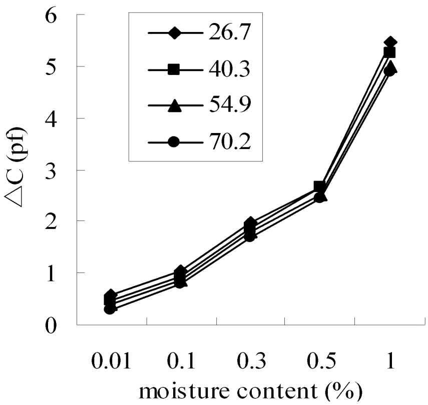

Fig. 5. Relatedness between moisture and ΔC_w

Take water content for main sequence, factors correlation calculated according to the equation 4 shown in table 1. It shows that the capacitance sensor using behind filter can improve the correlation about 10% between moisture content and capacitance. And moisture content represented by ΔC_w can lower the cross sensitivity of sensor for temperature. The correlation would be improved by 10% roughly.

Table 1. The correlation coefficient to moisture content

factor	Temperature	Cx0 (pf)	Cx1 (pf)	Cx2 (pf)	ΔCw (pf)
Correlation coefficient (%)	0.2684	0.2960	0.6833	0.7129	0.8186

The data analysis by the method of least squares in experiment shows that the moisture content and ΔC_w fitting relationship is $Y = 0.08473 + 0.208921 * \Delta C_w$. The relative error between actual and predictive value is shown in table 2.

Table 2. The relative error of predicted value

Real (%)	Predicted value （%）	Absolute errors	relative error (%)
0.01	0.0114	-0.001	-13.7 %
0.1	0.1096	-0.010	-9.6 %
0.3	0.3080	-0.008	-2.7 %
0.5	0.4710	0.029	5.8 %
1	1.0100	-0.010	-1.0 %

The result demonstrates that the more moisture content, the higher the testing precision. The deviation is a little larger when moisture content below 0.01% (100 ppm). But if consider the effect of operational error of experiment, compared with the habitual moisture sensor, it has been able to distinguish the trace moisture in the period of low moisture content.

6 Conclusions

1. In this paper, the design of the capacitance sensor with adjustable plates not only has high sensitivity, but also reduces the volume signally than the sensor with the type of cylinder and plate. And it is suitable for the oil online monitoring.
2. Lube oil monitoring for industrial unit needs a large amount of sensor nodes. This requirement has been fulfilled through WSN. According to the characteristics of slowly changing in monitoring data, the design of asynchronous sleep scheduling algorithm based on the data variation can reduce the network energy consumption and prolong the life cycle of the network.
3. A new way to accurately distinguish the ingredient of contaminants in lubricating oil is proposed. Through the idea of difference, reduces the combined impact of multiple factors on oil permittivity. Take measuring trace moisture in oil for example, the method can improve the correlation between moisture and dielectric, by grey relation analysis and experiment validation. It can predict the moisture content in lubricating more accurately. Through the same way can also measure the content of abrasive particle.

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