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Key Techniques for On-line Monitoring System of Insulation of Capacitive Equipment

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Abstract: The reliance of electrical equipment depends to a great extent on its insulation. This study has proposed a remote on-line system to monitor the insulation of capacitive equipment. The system adopts an adaptive algorithm based on multiple sampling and a clustering algorithm based on weighted average grey relational analysis is applied to solve the value of dielectric loss (tanδ) which is the primary parameter in assessing insulation. The system involves a three-layer distributed architecture with two working modes of active query and interruption woken up. DSP is used as the data collection controller on the bottom layer; Zigbee and GPRS ensures communication within the system. The upper monitoring center is capable of data monitoring, analyzing, diagnosing and report generating. The test results show that the system has high accuracy and satisfying synchronization.

Key words: Capacitive equipment, on-line monitoring, insulation, tanδ, multiple sampling

INTRODUCTION

The capacitive equipment refers to the equipment whose insulation is capacitive-structured, such as capacitive current transformers, capacitive voltage transformers, capacitive tubes, coupling capacitors and so on. As the number of capacitive equipment accounts for 40~50% of the total in power plants and substations, it is very likely to increase workload in case of blackout and preventive maintenance tests (Liu, 2010). To ensure the smooth operation of electrical system, it is important to improve the reliability of the electrical equipment which to a large extent depends on the insulation capacity of the equipment. The current on-line monitoring system of capacitive equipment insulation falls into two groups according to its hardware structure: the centralized system and the distributed system.

In a centralized monitoring system, all the analog quantities collected are stored in and processed by the host computer, so the system has rich information resources and high automation level. But as a large number of cables are needed to support the sensors in the field, the distortion in signal transmission is relatively high. Other disadvantages include difficulties in maintenance and low expandability (Shen, 2010). As a result, this system is gradually replaced by the distributed monitoring system which features on-site A/D conversion, procession and analysis. Based on Zigbee and GPRS, the remote on-line monitoring system of insulation of capacitive equipment proposed in this study can realize a real-time monitor of different insulation parameters including dielectric loss (tanδ).

MEASUREMENT AND SIMULATION OF DIELECTRIC LOSS TANδ

Multiple sampling and simulation: Dielectric loss tanδ, leakage current and insulated dielectric capacity Cx are three characteristic parameters to measure insulation. As dielectric loss tanδ is determined by the properties of materials and is irrelevant to their shapes and dimensions, tanδis taken as the primary parameter to assess the insulation of the equipment. Since, $\delta = \pi/2-\varphi$ we can measure the phase difference ö first by an algorithm based on adaptive multiple sampling and get the value of tanδ accordingly.

Assuming S(t) is a measured signal from discrete samples, Sr(t) is the reference signal and they are at the same frequency, we obtain:

$$S(t) = A\cos(\omega t+\varphi) \quad (1)$$

where, $S_r(t) = A_r \cos(\omega t)$:

$$\omega = 2\pi f = 2\pi/T \quad (2)$$

Assuming that fs is the sampling frequency, we sample the measured signal at this frequency and get a discrete series S' (t). We can divide a quadrant of a period (T/4) into N equal parts, where N>=1 is an arbitrary integer. Assume we take N samples P1, P2…Pn in every quadrants of a period, the first one taken at the beginning of each part. This results in a uniform sampling frequency fs = 4N/T within one period or we get K = 4N samples per period. This generalization is illustrated in Fig. 1, where P_{ij}

denotes a sample in the i-th quadrant (i = 1, 2, 3, 4) and j denotes the sample number within the i-th quadrant (j = 1, 2, 3, 4, …, N).

From Eq. 1 and 2, we obtain that in the first quadrant (T/4):

$$P_{11} = A\cos\varphi \quad (3)$$

$$P_{12} = A\cos\left(\varphi + \frac{2\pi}{4N}\right) = A\cos\left(\varphi + \frac{\pi}{2N}\right) \quad (4)$$

$$p_{1j} = A\cos\left[\varphi + \left(\frac{2\pi}{4N}\right)(j-1)\right] = A\cos\left[\varphi + \left(\frac{\pi}{2N}\right)(j-1)\right] \quad (5)$$

In a similar way, we can get the following equation in the second, the third and the fourth quadrant respectively:

$$p_{2j} = A\cos\left[\varphi + \left(\frac{\pi}{2N}\right)(j-1) + \frac{\pi}{2}\right] = -A\sin\left[\varphi + \left(\frac{\pi}{2N}\right)(j-1)\right] \quad (6)$$

$$p_{3j} = A\cos\left[\varphi + \left(\frac{\pi}{2N}\right)(j-1) + \pi\right] = -A\cos\left[\varphi + \left(\frac{\pi}{2N}\right)(j-1)\right] \quad (7)$$

$$p_{4j} = A\cos\left[\varphi + \left(\frac{\pi}{2N}\right)(j-1) + \frac{3\pi}{2}\right] = A\sin\left[\varphi + \left(\frac{\pi}{2N}\right)(j-1)\right] \quad (8)$$

From Eq. 5-8, we obtain:

$$\varphi = \text{atan}\,2(-P_{2j}, P_{1j}) - \left(\frac{\pi}{2N}\right)(j-1) \quad (9)$$

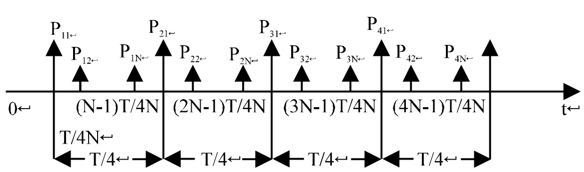

Fig. 1: Multiple sampling

$$\varphi = \text{atan}\,2(P_{4j}, -P_{3j}) - \left(\frac{\pi}{2N}\right)(j-1) \quad (10)$$

We can take an average of the results above and get:

$$\varphi = \frac{1}{2N}\sum_{j=1}^{N}[\text{a}\tan 2(-P_{2J}, P_{1j}) + \text{a}\tan 2(P_{4j}, P_{3j}) - \left(\frac{\pi}{N}\right)(j-1] \quad (11)$$

Suppose the measured signal s(t) is interfered by second harmonic and typical addictive white noise, we can get:

$$s(t) = \sin(2\pi f_0 t + \varphi_1) + Axie \times \sin(2\pi f_1 t + \varphi_2) + Anoise \times randn \quad (12)$$

Next, we conduct a simulation experiment by using MATLAB. Table 1 shows the simulation results. The average estimated phase $\bar{\varphi}$ was calculated together with its standard deviations σ_Φ. Each simulation was performed 10000 times for different values of sampling points, K. Figure 2 is the estimates of improvements.

As is shown in Table 1, the larger the value of sampling points K becomes, the better the measurement

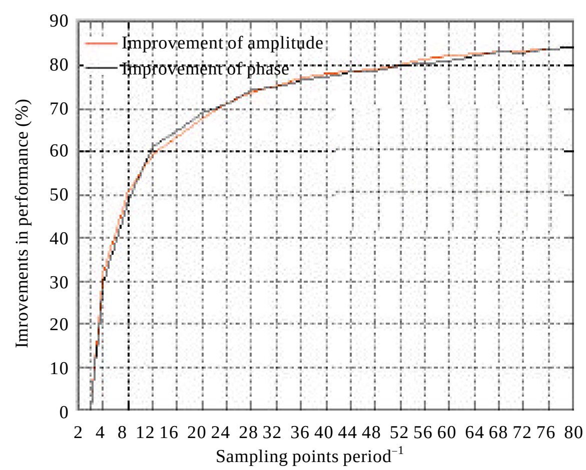

Fig. 2: Estimates of improvements

Table 1: Simulation results

K	$\bar{\varphi}$	σ_Φ	Improvement (%)	K	$\bar{\varphi}$	σ_Φ	Improvement (%)
2	44.9991	0.25843	N/A	44	45.0010	0.05500	78.72
4	44.9929	0.18866	27.00	48	44.9987	0.05231	79.76
8	45.0029	0.12840	50.32	52	45.0011	0.05123	80.18
12	45.0015	0.10770	58.32	56	45.0010	0.04744	81.64
16	44.9958	0.09267	64.14	60	45.0007	0.04698	81.82
20	45.0011	0.08156	68.44	64	45.0000	0.04583	82.27
24	44.9965	0.07543	70.81	68	44.9993	0.04541	82.43
28	44.9973	0.06826	73.59	72	44.9984	0.04240	83.59
32	45.0060	0.06420	75.16	76	45.0011	0.04158	83.91
36	44.9998	0.06110	76.36	80	45.0003	0.03894	84.93
40	45.0025	0.05828	77.45				

accuracy is. From Fig. 2, we can see that when K is larger than 52, a greater than 80% improvement in phase estimations is seen in comparison with that of classic quadrature sampling (with K = 2).

A filter is used to filter the measured signal at the presence of haronic disturbance. Considering the group delay, Kaiser Window is chosen to filter the higher harmonic. Figure 3 shows the design of filter. As the measured signal and reference signal work in the same environment under same filtering condition, phase deviation is not likely to occur. The major error comes from noise interference and quantization error. After improving A/D sampling resolution and increasing samples in each period, phase error (dielectric loss error) is less than 0.003 degree. The quantization error and noise interference can reduce effectively, which allows a more accurate tanδ.

Principle for adaptive measurement: From the simulation experiment we can find that the method of multiple sampling, based on a sampling points of K (K = 4 N, where N>=1 is an arbitrary integer), is very effective in improving the measurement accuracy of phase as the sampling frequency increases.

We should also take into account the relationship between the maximum sampling frequency fsmax and the maximum rated frequency f_{clk}. We obtain:

$$f_{s\,max} \leq f_{clk} \tag{13}$$

When N is a constant, we have:

$$f_{s\,max} = 4Nf_{max} \tag{14}$$

From Eq. 12 and 13, we obtain:

$$4Nf_{max} \leq f_{clk} \tag{15}$$

Or:

$$f_{max} \leq f_{clk}/4N \tag{16}$$

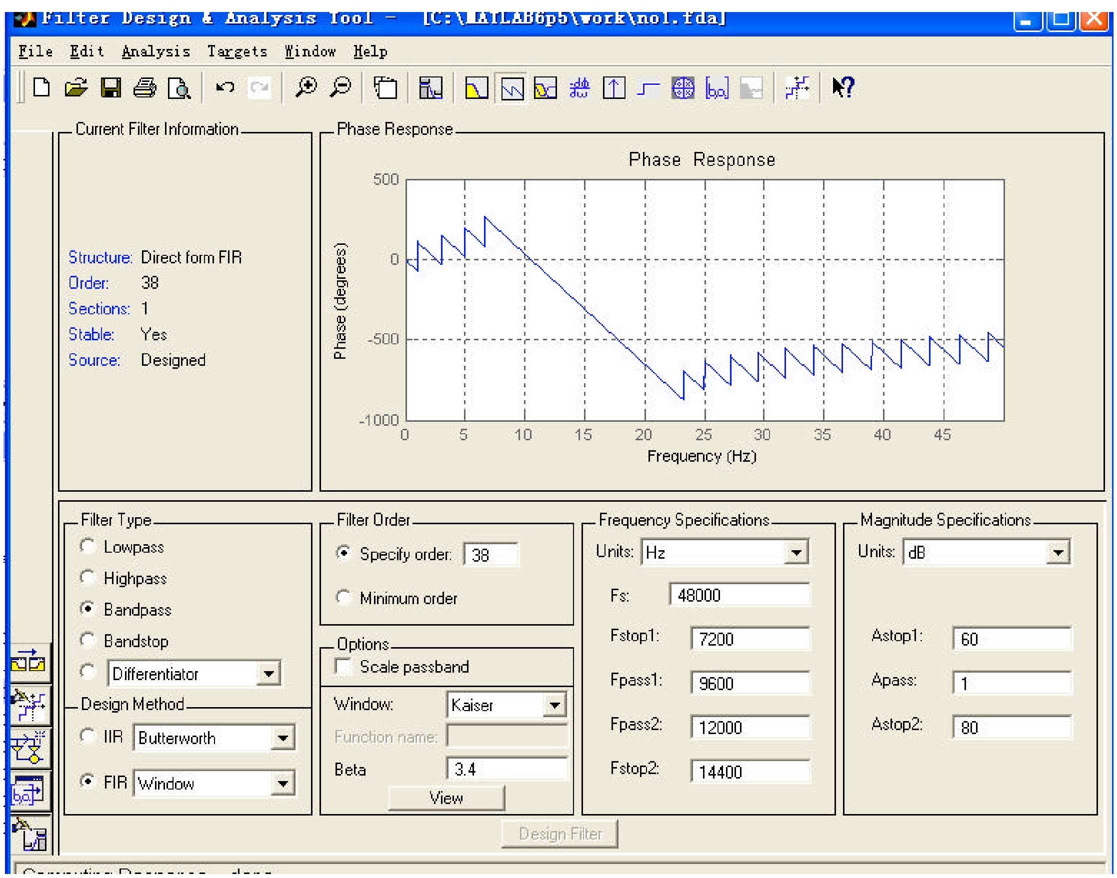

Fig. 3: Design of filter

When frequency f is a constant, we have:

$$f_{s\,max} = 4N_{max}f \quad (17)$$

From Eq. 16 and 17, we get:

$$4N_{max} \leq f_{dk} \quad (18)$$

Or:

$$N_{max} \leq f_{dk}/4f \quad (19)$$

We can get the maximum of N (N_{max}) through modular arithmetic. From Eq. 19, we obtain:

$$N_{max} = \mathrm{mod}(f_{dk}/4f) \quad (20)$$

Clustering algorithm design: We adopt cluster algorithm to assess the valid value of tanδ. This algorithm which stresses the impacts of similar or relevant factors, works in two aspects. One is the factor of tanδin the insulation evaluation. The other deals with the false alarm and false dismissal of tanδ.

Grey relational analysis: Tanδ is an important parameter to assess the equipment insulation performance. The larger tanδ is, the more dielectric loss is and the more likely it is for the equipment to generate heat and to age. However, for the small-volume concentrated defects, the tanδ factor will reduce significantly while temperature and humidity factors rise for leakage current and dielectric capacity. Therefore, it is necessary to set up the database according to different equipment and environment. The database should record the weighed factors such as tanδand other environmental factors. In this way we can have a comprehensive assessment for the equipment insulation.

We chose grey relational analysis theory to analyze and summarize the change of dielectric loss under the influence of different external factors such environmental temperature, humidity and the equipment temperature. This theory is advanced to give a variety of available solutions to those uncertain problems lacking sufficient information and data (Shen, 2010).

Grey relation analysis is an analytic method proposed in this theory. It uses a related quantitative comparison to describe the changes of all factors in a system or within systems as time passes. Its objective is to find out the main factors that influence the target sequence. If there is a correspondence between the changes of certain factor and the target sequence, we assume the two have high correlation and vice versa.

For the calculation of grey correlation degree, we used weighed averages which can tell the influence of environmental factors such as temperature and humidity in different seasons. So, the results can show the aging of insulation more directly and actually.

The steps are as follows:

Step 1: Construct a reference sequence and the comparison sequence. We construct a reference sequence y based on the monitored data of tanδ:

$$y_i = \{y_i(k)\} = \{y_i(1), y_i(2)...y_i(n)\}$$

In this sequence, k = 1, 2,…, n, $y_i(k)$ is the measured tanδat the moment of k and normally n is greater than 1.

We use data of equipment temperature, environmental temperature and humidity to construct a comparison sequence xj. We get:

- $x_j = \{x_j(k)\} = \{x_1(1), x_1(2),...x\ (n)\}$ which stands for changes of the equipment temperature
- $x_2 = \{x_2(k)\} = \{x_2(1), x_2(2),...x_2(n)\}$ which stands for changes of the environmental temperature
- $x_3 = \{x_3(k)\} = \{x_3(1), x_3(2),...x_3(n)\}$ which stands for changes of the environmental humidity

Step 2: Use weighed average to process the above sequences. We can get a new sequence:

$$x'_{ij} = \alpha x_{i1} + \beta x_{i2} + \gamma x_{i3}$$

Here, α, β, γ are weighting coefficients. α is chosen according to the actual service life of equipment and its application situation; β, γ are chosen according to the seasons.

Step 3: Calculate the grey relational coefficient and grey relational degree. The coefficient $L_{ij}(k)$ and relational degree γ_{ij} can be obtained according to Eq. 21 and 22 (ρ = 0.5):

$$L_{ij}(k) = \frac{\min_i \min_j \min_k \left|y'_i(k) - x'_j(k)\right| + \rho \max_i \max_j \max_k \left|y'_i(k) - x'_j(k)\right|}{\left|y'_i(k) - x'_j(k)\right| + \rho \max_i \max_j \max_k \left|y'_i(k) - x'_j(k)\right|} \quad (21)$$

$$\gamma_{ij} = \frac{1}{n}\sum_{i=1}^{n} L_{ij}(k) \quad (22)$$

Step 4: Compare the relational degree. We can compare the value of γ_{ij} to determine which of the three factors (i.e., equipment temperature, environmental temperature and humidity) is more correspondent with the change of tanδ. In this way we can evaluate the insulation performance

False alarm and false dismissal judgment: The other aspects deals with the false alarm and false dismissal of tanδ. We should analyze the value comprehensively to decide if tanδ is beyond the warning threshold. If the value grows high, instead of simply comparing it with the threshold, we must first compare it to the values of the past years and then with those in the same operation environment of the same field. If the excess is remarkable, corresponding measures should be taken to deal with the situation.

OVERALL DESIGN OF ON-LINE MONITORING SYSTEM OF INSULATION OF CAPACITIVE EQUIPMENT

As is illustrated in Fig. 4, the proposed system adopts a structure of 3 layers, namely the field data collection layer, the network layer and the application layer. The DSP chip TMS320F2812 of TI is used as controlling core of terminal nodes to collect data in the field. The dielectric loss tanδ is obtained by multiple sampling algorithm. The terminal nodes collect, process and upload the field data to the Zigbee gateway node. This real-time process can effectively solve the distortion caused by a long-distant transmission of analog data. The network layer uses an ARM9-based gateway and GPRS communication to send the stored and processed information to the user terminal. The monitoring center on the application layer analyzes the data through expert system, neural net and database diagnosis before coming up with the corresponding responsive strategies (Wang, 2011a).

The system has two modes: active query and interruption woken up. If no query is required by the monitoring center or user terminal, the majority of the hardware is in power-down mode and when the insulation parameter in the measured field becomes abnormal, the ZigBee node will be awakened to send the environmental data and node information (such as node number, battery status and etc.) to the gateway node which will store the data and process them and then send the data to the user terminal or monitoring center via GPRS. The user terminal or monitoring center can also inquire the environmental data of certain node by inputting its IEEE address. In such a mode, the power consumption of the system can be noticeably reduced.

TERMINAL NODE DESIGN

Figure 5 shows the design of terminal nodes based on DSP. The processing unit uses TMS320F2812 of DSP chip by TI as the terminal nodes controller. The reference signal is converted into square wave signal after magnification. The signal frequency is measured periodically by frequency-measuring module of DSP through query and the value of N which denotes the number of samplings, is determined by the N-calculating module. Phase-locking frequency-multiplication module, after receiving the value of N, generates a signal of same phase but at a frequency four times that of N. This signal determines time interval for sampling and conversion in data-collection module. The measured signal, after magnification and filtering, is transmitted to the data-processing unit by the low pass filtering in

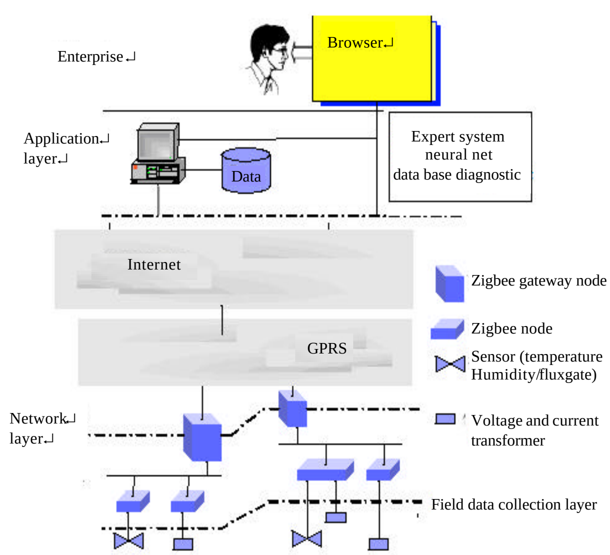

Fig. 4: Online monitoring system of insulation of capacitive equipment

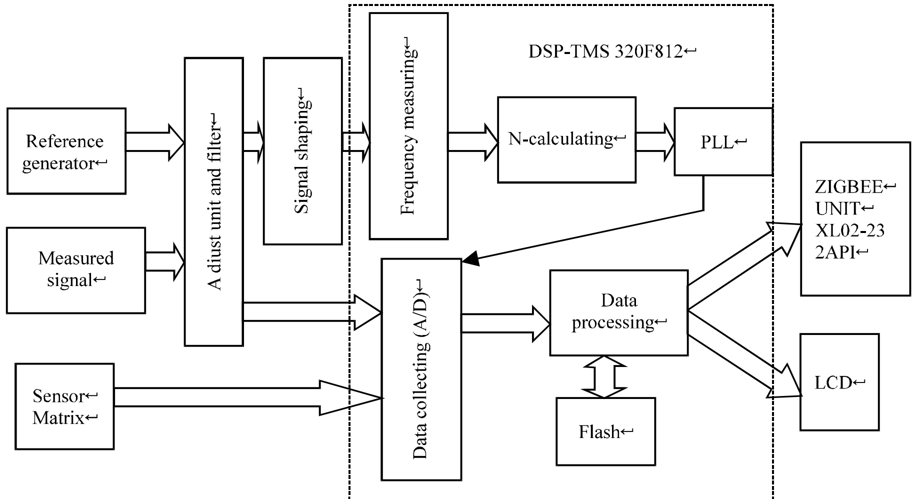

Fig. 5: Terminal node design based on DSP

data-collection unit. Multi-sampling algorithm then calculates and stores the results: the tanδvalue which will be either transmitted to the upper unit for further analysis and process, or to the liquid crystal module to be displayed synchronously.

TMS320F2812 of DSP chip, with rich resources and a150MHz 32-bit DSP kernel processor. can perform the task of controlling and filtering very effectively. The powerful PLL is capable of capturing and phase-locking the frequency of reference signal. The frequency variation of the measured signal is 50 Hz±0.2. The test results reveal that a dynamic range between the two signals is ±50 dB, the sensitivity for output level is 50 mV dB^{-1} and its phase-measuring range can reach 180°.

NETWORK TOPOLOGY DESIGN

We use WSN tree-topology and a multi-layer routing protocol with great expandability.

The WSN tree routing algorithm is a tree structure topology using coordinator as its root. The core of the protocol is to set up a virtual system composed of net address and net depth to represent the real net topology. The root of the tree is the ZigBee coordinator. When a node allows a new node to join the network through itself, they form a parent-child relationship. The child node develops more child-nodes and this in turn forms the large WSN tree. Every new node will get the sole network address distributed by its parent-node. The tree routing algorithm can, thus, achieve routing according to the network address and parent-child relationship. Figure 5 shows the structure of a tree topology (Wang, 2011b, 2013).

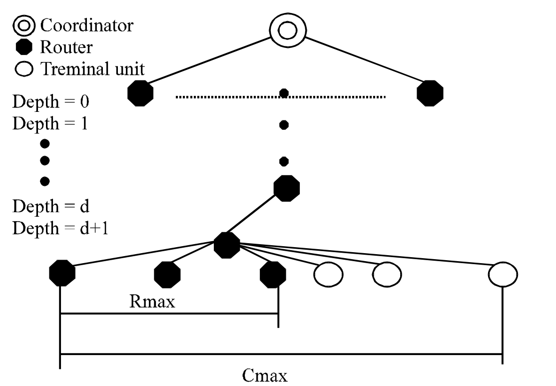

Fig. 6: Tree structure

In the tree routing algorithm, data are transmitted through the tree and the routing is relatively simple. When data need transmitting, the next node can be easily calculated by the equation and this reduces the cost of protocol greatly. This algorithm is also less demanding in node storage space and computing power. If a terminal node needs to send a data packet to another node, it can send the packet directly to the parent of the node which will forward the packet immediately. For example, if a router node needs to forward a packet to a target node D (D as its network address) and the address and depth of the router node is A and d, it will first determine if the target node is its sub-device according to Eq. 23:

$$A<D<A+Cskip(d-1) \quad (23)$$

If it is true, the target device being its sub-device, then the next node address should be:

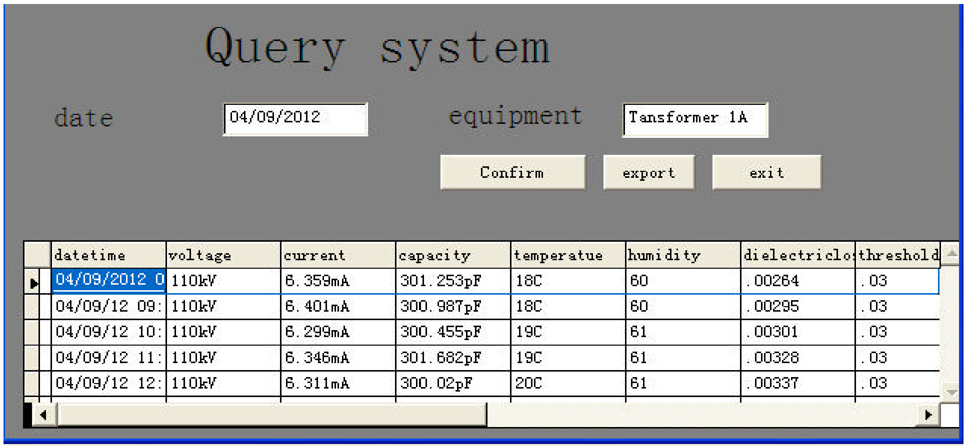

Fig. 7: Interface of information inquiry system

Table 2: Connect relationship of dielectric dissipation value and voltage environment temperature and humidity

	Transformer 1			Transformer 2		
Phase	Temperature	Humidity	Voltage	Temperature	Humidity	Voltage
A	0.635	0.704	0.712	0.675	0.709	0.678
B	0.676	0.692	0.765	0.696	0.724	0.709
C	0.679	0.596	0.769	0.587	0.752	0.609

$$N = \begin{cases} D \\ A+1+\left[\dfrac{D-A+1}{Cskip(d)}\right]\times Cskip(d), \text{others} \end{cases} \tag{24}$$

If the result of Eq. 23 is false, the next node address would be the parent-node of that node and the data will be forwarded through the tree.

EXPERIMENTAL TESTS

Measured parameter: This monitoring system has been running in the bushing shells for a 110 kV main transformers in Jianghan Plain. The measured parameters include busbar voltage, end shield grounding current, equivalent capacitance, dielectric loss, temperature and humidity. Figure 7 shows the interface of the information inquiry system and part of the data in operation. Judging from the measured parameters, the results met the project expectations.

Relational analysis: Again we take the monitored results for the bushing shells as an example. The data (dielectric loss, voltage, current, temperature and humidity) of one month are taken for grey relational analysis. As the disturbance of some uncertain factors may produce false information in monitoring data and therefore influence the sequence changing tendency, a pretreatment of the measured data is conducted first to improve the precision of relational calculation. The data are shown in Table 2.

CONCLUSION

This study has proposed a remote on-line monitoring system of insulation of capacitive equipment. The system is a three-layer distributed architecture with two working modes of active query and interruption woken up. DSP is used as the data collection controller on the bottom layer and the communication is realized by the combination of Zigbee and GPRS. An adaptive method of multiple sampling and cluster algorithm are proposed to obtain and analyze the value of tanδ. The upper monitoring center is capable of data monitoring, analyzing, diagnosing and report generation. The test results show that the system has high accuracy and keeps good synchronization. Further studies may include the quantitative analysis of the impact of more environmental factors on insulation and how to improve the measuring accuracy and transmitting efficiency.

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