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On-line Monitoring System of Capacitive Equipment Dielectric Loss

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Abstract

To ensure capacitive equipment working safely and reliably, an on-line monitoring system of capacitive equipment dielectric loss was developed. The insulation situation was estimated accurately through long-distance synchronous sampling (using IRIG-B code synchronous clock), seamless connection of data between devices (using Intelligent Electronic Device (IED)), communication following IEC61850 protocol, and data analysis (using fault diagnosis algorithm). Running results showed that the system not only can accurately monitor the information, such as leakage current, dielectric loss, and equivalent capacitance, which reflect the working condition of capacitive equipment, but also can transmit data to the on-line monitoring data center through the IEC61850 protocol. The operating data, monitoring on CVTs in 330kV substation, showed the great improvement of this system on credibility, accuracy, and stability. What's more, it also proved the great value of using and promoting this system.

Keywords: *capacitive equipment, dielectric loss, on-line monitoring, intelligent electronic device (IED), IEC61850 protocol*

1 . Introduction

The safe and reliable operation of the equipments in substation is the foundation for the fast development of national economy [1]. Capacitive equipment accounted for about 30% to 40% of the total substation equipments, whose isolation condition is directly related to the safe operation of the substation. Therefore, it is of great significance to carrying on the on-line monitoring [2]. As the strategy of smart grid is putting forward, intelligent substation requires signal to be digitization, communication mode to be networking, information to be shared and standardization [3]. On the one hand, traditional condition overhauling can't realize fault in time. On the other hand, it also can't meet the requirement of information and resources sharing in intelligent substation. According to the characteristics of capacitive equipment on-line monitoring, a whole structure and hardware design of intelligent monitoring terminal is proposed. In order to make communication protocol meet the requirement of State Grid Corporation, a design of corresponding IED is proposed as well, which follows the IEC61850 protocol. Meanwhile, collected data are dealt with grey relational algorithm, thus the efficiency of monitoring and reliability of fault diagnosis are ensured.

2 Theory and Structure

2.1. Algorithm of Monitoring

Dielectric loss factor is calculated by tangent δ, which is the complement angle of phase difference between current flowing through and voltage across the device [4]. In general, $\tan\delta$, capacitive equipment dielectric loss factor, is so small that the measurement can be certain affected by noise jamming, harmonic frequency changing, and harmonic waveform distortion rate. Harmonic analysis method is adopted to extract capacitive equipment dielectric loss angle, which make the dielectric loss factor $\tan\delta$ is not affected by the influence of harmonic component. In this system, the calculation of dielectric loss factor is completed by IED, the implementation process is as follows:

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After A/D conversion, analog signals are converted into discrete series of voltage and current, expressed as x(n) and y(n) (0<n<N, N is the number of samples). Afterwards deal X(n) with DFT(Discrete Fourier Transform):

$$X(k) = DFT(x(n)) = \sum_{n=0}^{N-1} x(n)\, e^{-j\frac{2\pi}{N}kn} = x(n)(\cos\frac{2\pi kn}{N} + j\sin\frac{-2\pi kn}{N}) \quad (1)$$

So the real part and imaginary part of voltage is:

$$X_R(k) = \sum_{n=0}^{N-1} x(n)\cos\frac{2\pi kn}{N} \qquad X_I(k) = \sum_{n=0}^{N-1} x(n)\sin\frac{-2\pi kn}{N} \quad (2)$$

Phase of voltage signal can be calculated according the real part and imaginary part:

$$\alpha_1 = \tan^{-1}\frac{X_I(k)}{X_R(k)} \quad (3)$$

Phase of current signal, β_1, can be obtained through the same method. IED of capacitive equipments monitoring calculates $\tan\delta$ through dielectric loss factor calculation formula:

$$\tan\delta = \tan[\pi/2 - (\beta_1 - \alpha_1)] \quad (4)$$

Due to fundamental wave is mainly extracted in this method, the effects of harmonic component are inhibited and measurement accuracy is improved.

2.2. Algorithm of Fault Diagnosis

The dielectric loss factor is pretty small, which range from 0.001 to 0.03, so it is easily be corrupted by noise. The analysis result of insulating situation shows that: The influence of external environment factors, especially temperature and humidity, can affect the data much more obviously when the insulating property of capacitive equipment is on a good condition [5]. However, with the reduction of equipment's insulating performance and the raise of equipment's temperature, the influence of the equipment's own temperature on $\tan\delta$ is greater than temperature and humidity of external environment. Given all those fact, the insulation property of capacitive equipment is analysed and judged accurately through gray correlation analysis, which can analyze the relationship between dielectric loss series and each external environment factor series.

(1) Building model of measured data series and comparative data series: among that, monitored dielectric loss factor $\tan\delta$ series is regarded as measured data series, expressed as, and site environment temperature and humidity data is regarded asX_0 comparative data series, expressed as X_j:

$$X_0 = \{x_0(k)\} = \{x_0(1), x_0(2), \ldots, x_0(n)\} \; X_j = \{x_j(k)\} = \{x_j(1), x_j(2), \ldots, x_j(n)\} \quad (5)$$

k=1,2,…,n; j=1,2,3,4; $X_j(k)$ present respectively the factors such as humidity and temperature of site, equipment's own temperature, interface contamination.

(2) Determining the correlation coefficient:

$$\zeta(k) = \frac{\min_j \min_k |x_0(k) - x_j(k)| + \rho \max_j \max_k |x_0(k) - x_j(k)|}{|x_0(k) - x_j(k)| + \max_j \max_k |x_0(k) - x_j(k)|} \quad (6)$$

Define: $\Delta_{min} = \max_j \max_k |x_0(k) - x_j(k)|$ $\quad \Delta_{max} = \max_j \max_k |x_0(k) - x_j(k)|$

So:

$$\zeta_j(k) = \frac{\Delta_{min} + \rho\Delta_{max}}{|x_0(k) - x_j(k)| + \Delta_{max}} \quad (7)$$

Above the formula, $\zeta_j(k)$ is correlation coefficient of comparative data series X_j refer to measured data series X_0 on point k, $1 \le k \le n$; $|x_0(k) - x_j(k)|$ is the absolute difference between $X_0(k)$ and $X_j(k)$ on the Kth element, Δ_{min} is minimum difference, while Δ_{max} is maximum difference . $\rho \in [0,1]$, as the system discriminating coefficient, indicate the indirect effecting degree of every factor on correlation.

(3) Calculate relevancy:

$$\gamma_j = \frac{1}{n}\sum_{k=1}^{n}\zeta_j(k) \quad (8)$$

Through relevancy γ_j estimate the degree of relevance between X0(k) and Xj(k). After successively calculating each influence parameter of certain relevancy and relative coefficient, a factor, among equipment's own temperature, external environment's temperature and humidity, interface contamination, is finally confirmed, which is the closest to variation tendency of monitor series, tanδ, so the insulation property of capacitive equipment is judged accurately.

2.3. System Structure

According to the structure of smart gird, the implementation of the function is divided into three parts: monitoring terminals in process layer, IED of capacitive equipment monitoring in spacer layer, and monitoring host in substation control layer [6, 7]. The whole structure of the system is shown in Figure 1.

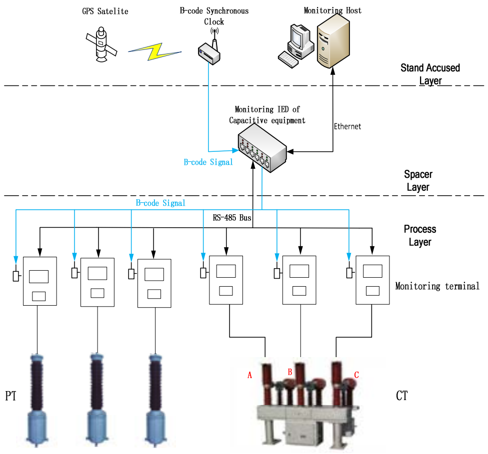

Figure 1. Whole Structure of System

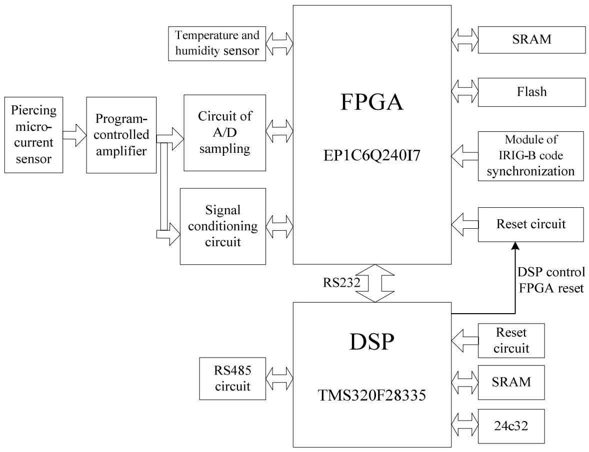

Figure 2. Hardware Principle

The working process of the whole system is: monitoring host in Substation Control Layer gives measuring instructions, which are transmitted to every terminal monitors in Process Layer through IED. Receiving IRIG-B code as a synchronous clock, terminals measure reference voltage and leakage current at the same time. After every terminal finished measurement and data processing, IED ask every terminal for collected data, and obtain dielectric loss, leakage current, equivalent capacity by dealing these data. Then IED, in Spacer Layer, will pack data and upload them to monitoring host following IEC61850 proctoco. After receiving data and analyzing through expert software, monitoring host will judge the operating state and store data into data base for historical analysis.

3. System Implementation

The accuracy of dielectric loss measurement is greatly influenced by external factors due to complex site condition, so the requirements for monitoring device are high. Monitoring terminal adopted dual-core structure of FPGA and DSP, achieved long-distance synchronous sampling through IRIG-B code. IED of capacitive equipment monitoring adopted dual-core structure of ARM and DSP, which have strong power on control and operation.

3.1. Hardware of Monitoring Terminal

As shown in Figure 2. FPGA accomplishes function such as measuring reference voltage and leakage current, decoding synchronous clock, controlling A/D conversion, and communicating through RS-232. The main function of DSP include: dealing the data with FFT (Fast Fourier transform), sending handshake signals to FPGA regularly to determine whether working properly, and reset when the device running abnormal. In addition, DSP communicate with IED through RS485.

3.2. Signal Collection

The accuracy of the sensor is of vital important for the result of measurement [8], because the leakage current of capacitive equipments is usually in mA level even in uA level. Using permalloy as the core material, adopting deep negative feedback technology to realize automatic compensation for core, the sensor used in this system can obtains leakage current from 500uA to 700mA accurately, on the condition of phase error less than 0.01°, which can meet the requirement in accuracy completely [9].

3.3. IRIG-B Code Decoding Unit

IRIG-B code is decoded by FPGA instead of traditional decoding chip, as well as in order to avoid unstable errors affecting the accuracy of measurement [10, 11]. Shown as follows:

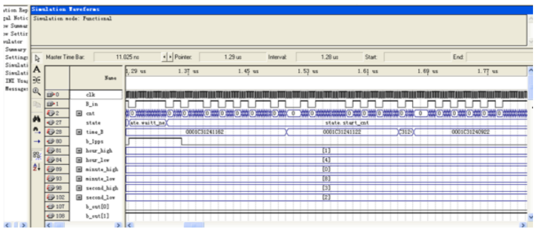

Figure 3. IRIG-B Time-Decoding

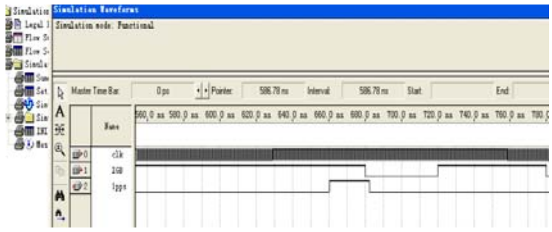

Figure 4. IRIG-B Synchronous Pulse-Decoding

The simulations show that the decoding error of synchronous pulse is no more than 2ns, while 50ns when measured by oscilloscope in actual circuit. And it can completely meet the requirement of monitoring capacitive equipment.

3.4. A/D Sampling Unit

After IED send collection command, A/D sampling unit is enabled. When 1PPS (1 pulse per second signal generated by IRIG-B code synchronous clock) reaches, A/D sampling unit will execute 512-point sampling according to the sample rate, which is calculated based on system-frequency [12, 13].

3.5. On-Line Monitoring IED of Capacitive Equipment

3.5.1. Construction of IED

As shown in Figure 5, the system uses the ARM and DSP double CPU architectures as the hardware core. ARM with additional peripheral devices, such as keyboard, liquid crystal, Ethernet communication and other hardware equipment are all used to complete the management and control the whole system. Taking advantage of high-speed computing and a variety of peripheral characteristics on the chip, DSP is used to complete calculating and analyzing of collected data. The way of communicate between DSP and ARM is SPI.

Implementation process of IED is shown in Figure 6: when ARM receives collecting command, DSP transmits it to terminal. After that, DSP demands for data by polling through RS485, then calculating the value of dielecbn tric loss and amplitude of leakage current. ARM will store the data transmitted by DSP through SPI, and transmitted data capsulated to host on substation control layer through Ethernet.

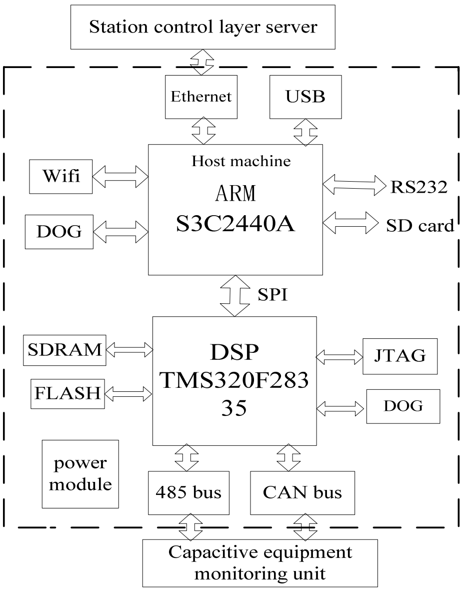

Figure 5. Hardware of IED

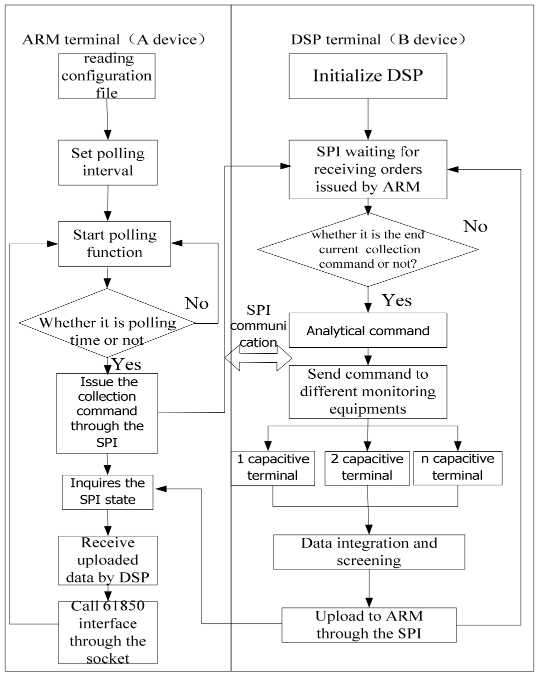

Figure 6. Software Process

3.5.2. IEC61850 Protocol Implementation

Following IEC61850, On-line monitoring IED of capacitive equipment builds model about principles in the function object, according to the data and data property related to the same function object, expressing what and how to communicate [14]. The first thing of building model to IED is to describe the function completely: describe each monitoring terminal as one object of IED and build the smallest function unit as one logical node [15]. Layered module is shown in Figure 7, and the description of all logical nodes, according to IEC61850, is shown is char.1.

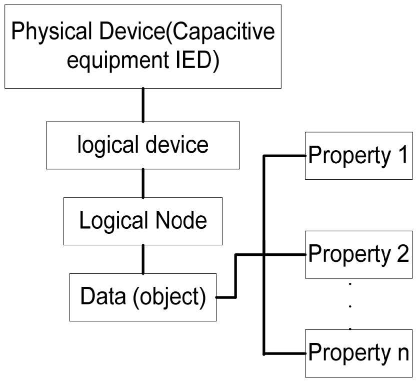

Figure 7. Layered Module of IED

Table 1. Description of Logical Nodes

Property Name	Property Type	Description
EEHealth	INS	Health of external device
EEName	DPL	Nameplate of external device
OpTmh	INS	Operation time
Vol	MV	Voltage of CVT
LosFact	MV	Dielectric loss factor
Hz	MV	System frequency
Amp	SAV	Leakage current
React	MV	Equivalent capacitance
EnvTmp	MV	Environmental temperature
EnvHum	MV	Environmental humid

4. Operation Results and Analysis
4.1. Operation Results

The system has been successfully installed and operating in 330kV substation, shown as following pictures. Major monitoring program was insulation property on-line monitoring of CVT. Virtual monitoring parameter is as following: dielectric loss, the leakage current of terminal screen, resistive current, capacitative current, and equivalence capacitance.

Figure 8. Structure of Ternimal Device

Figure 9. IED of Capacitive Equipment

Figure 10. Monitoring Terminal on CVT

Figure 11. Monitoring Terminal on PT

Figure 12 shows the three-phase dielectric loss variation trend of 330kV CVT from 28th January to 29th January, 2013. As shown below, dielectric loss is generally range from 0.004 to 0.02. As CVT's three phases operate under same level of voltage and similar operating environment, so the variation trend of dielectric loss is approximately same.

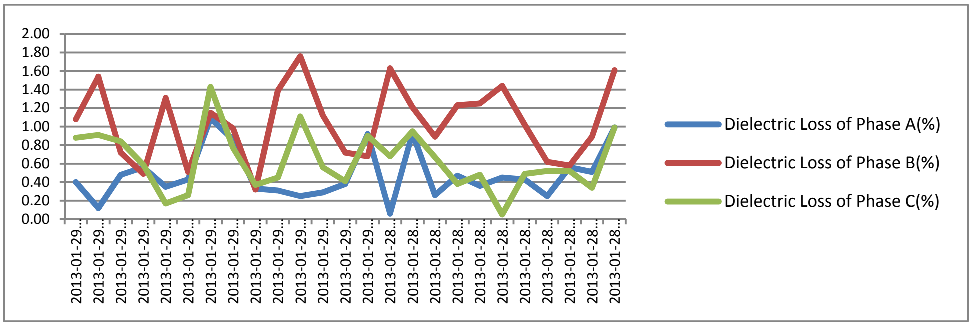

Figure 12. Three-phase Dielectric Loss Variation Trend of 330kV CVT

The variation trend of 330kV CVT's three-phase leakage current is shown Figure 13, from 28th January to 29th January, 2013. As shown below, dielectric loss is one of the virtual parameter which can reflect insulation property, ranging from 3.12mA to 3.20mA. Insulation condition of capacitive equipment can be judged through the value and variation trend of leakage current. Meanwhile, it can validate effectiveness of each other with dielectric loss.

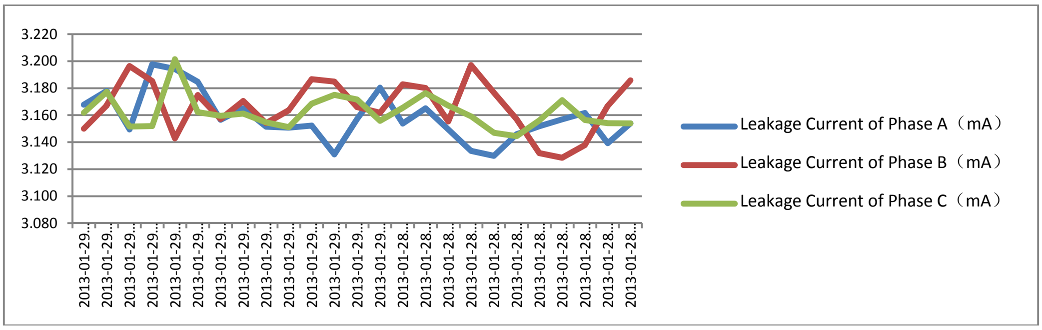

Figure 13.Three-phase Leakage Current Variation Trend of 330kV CVT

4.2. Analysis

In order to verify the accuracy of the system, two terminals were used to monitoring one simulate current signal at the same time, taking one of them as the reference device. The result is shown in Table 2.

Table 2. Experimental Results

NO.	Dielectric Loss Factor Error(%)	NO.	Dielectric Loss Factor Error(%)
1	0.0012	7	0.0004
2	0.0061	8	0.0017
3	0.0013	9	0.0014
4	0.0020	10	0.0057
5	0.0032	11	0.0047
6	0.0050	12	0.0038

The result shows that the dielectric loss factor error is no more than 0.01%, much lower than tranditional measurement using phase-lock loop or others, and can completely match the international requirement of dielectric loss factor monitoring.

5.Conclusion

Based on IEC61850 protocol, a system of capacitive equipment on-line monitoring and fault diagnosis is proposed in this paper, which takes advantage of IED. The system consists of intelligent monitoring terminal, online monitoring IED, and monitoring host. The intelligent monitoring terminal, which adopts FPGA and DSP dual-core structure, is good at collecting and digitalizing analog signal immediately. Adopting ARM and DSP dual-core structure, IED of capacitive equipment on-line monitoring manages the transmission of instructions and control of terminals in process layer, taking advantage of its good ability on controlling and computing. With synchronous error no more than 50ns, long-distance synchronous sampling of each monitoring terminal, is achieved by using high-accuracy IRIG-B code. RS485 bus is adopted to realize command transmission and data communication between monitoring terminals and IED, through which can overcome the electromagnetic interference on condition of high voltage, meanwhile, it can ensure the reliability and real-time ability of data transmission. What's more, the fault diagnosis method of expert software can judge the running condition of capacitive equipment accurately. Running results of system operated in Ningxia shows that the system can measure the operating condition of capacitive equipment accurately, ensure equipments to operate safe and stable, provide a reliable guarantee for the safe and stable operation of the substation.

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