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Development of Distributed On-line Monitoring System for Dielectric Loss Tangent of High Voltage Capacitive Apparatus

***Abstract**. This paper presents a distributed measuring system for on-line monitoring of dielectric loss factor tan δ, and capacitance of HV apparatus. The method employs the Discrete Fourier Transform (DFT) which is performed on the scaled down analog voltage and current signals obtained using digital signal processing (DSP) technology. The measuring unit of the on-line monitoring system takes a series of measures in the hardware circuit design to improve the effectiveness of the DFT algorithm. The lab test results of measuring unit show that the measuring unit has high precision of measurement based on the DFT method. Field tests at a regional substation to evaluate the insulation of two groups of 220kV current transformer units using the developed system.*

***Streszczenie.** W artykule opisano system pomiaru rozproszonego do monitorowania on-line współczynnika strat dielektrycznych i pojemności w aparatach HV. W metodzie wykorzystano Dyskretną Transformatę Fouriera. W celu poprawy dokładności i skuteczności DFT, dokonywana jest seria pomiarów. Wyniki badań laboratoryjnych oraz w rzeczywistej podstacji, wykazały wysoką precyzję rozwiązania. (**Budowa systemu rozproszonego monitorowania on-line współczynnika strat dielektrycznych w wysokonapięciowych aparatach pojemnościowych**).*

Keywords: dielectric loss factor ; discrete Fourier Transform ; distributed measuring system ; DSP ; on-line monitoring
Słowa kluczowe: współczynnik strat dielektrycznych, Dyskretna Transformata Fourier'a, system pomiaru rozproszonego, DSP, monitorowanie on-line.

Introduction

To ensure the safe and reliable operation of a power system it is necessary to monitor periodically the insulation condition of HV apparatus. This may be accomplished by measuring partial discharge levels and/or dielectric loss factor and capacitance using conventional well-established time based maintenance. However, the implementation of these routine tests requires removal of equipment from service. This disadvantage may be overcome by using on-line monitoring methods. On-line measurements also offer the possibility of continuous monitoring of the condition of apparatus insulation under operating conditions.

On-line methods for measurement of dielectric loss factor utilize the current flowing through and/or the voltage signal applied to the test object. The various techniques reported in the literature differ in the manner in which the signals are acquired and the handling of the gathered data to obtain results. In the work reported in this paper a distributed on-line monitoring system has been developed based on digital signal processing (DSP) technology. A method based on harmonic analysis using Discrete Fourier transform (DFT) has been used. To improve the effectiveness of the DFT algorithm, a few difficulties were overcome when comes to use the most fundamental method in digital spectrum analysis.

The on-line monitoring system detect the following parameters: running voltage, frequency, insulation current (current pass through capacitance of equipment), capacitance, dielectric loss factor tan δ, the current and voltage harmonic components of the 3rd ,5th and 7th ,environment temperature and humidity etc.

Principle of Measurement

Fig.1 and Fig.2 show the principle diagram of measuring unit of the on-line monitoring system. Insulation current of equipment is the main signal detected by a current transducer with high accuracy. The signals should be pre-processed by hardware, which involves differential amplifier (used to suppress common mode interference), synchronous six channel A/D converter. At the same time the running voltage signal from the secondary of the potential transformer (PT) is also detected. With the help of DFT algorithm, the fundamental frequency signals of the current and voltage were obtained. Afterwards, dielectric loss factor tan δ could be derived by compare the fundamental phase angle of these two signals.

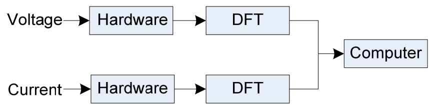

Fig.1 Principle diagram of on-line monitoring system for capacitive type equipment

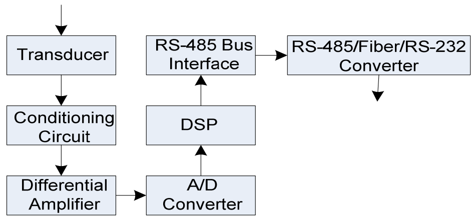

Fig.2 Principle diagram of hardware

Suppose $u(t)$ and $i(t)$ are simultaneously measured continuous voltage and current signals from single-phase power equipment, then their Fourier series can be written a general form as follow.

$$f(t) = a_0 + \sum_{n=1}^{\infty}(a_n \cos(n\omega_0 t) + b_n \sin(n\omega_0 t)) \tag{1}$$

where a_0 is the dc component of the $f(t)$ signal. The harmonics of this $f(t)$ signal have frequencies $n\omega_0$, where ω_0 is the fundamental frequency and n=1, 2, 3,…. Through Fourier analysis, the constants ω_0, a_0 , a_n , b_n can be determined by the following equations.

$$\omega_0 = 2\pi/T \tag{2}$$

$$a_0 = \frac{1}{T}\int_0^T f(t)dt \tag{3}$$

$$a_n = \frac{2}{T}\int_0^T f(t)\cos n\omega_0 t dt \tag{4}$$

$$b_n = \frac{2}{T}\int_0^T f(t)\sin n\omega_0 t dt \tag{5}$$

$$\delta = \pi/2 - (\phi_i - \phi_u) \tag{6}$$

The amplitude of the n th harmonics at a frequency $n\omega_0$ will be $A_n = \sqrt{a_n^2 + b_n^2}$. In addition to the amplitude, the phase angle φ_n can be calculated by $\varphi_n = \arctan(-b_n / a_n)$.

The fundamental amplitude of the voltage and current signals, and the fundamental phase angles U, I, φ_u, φ_i can be calculated through the above equations. Finally, the dielectric loss angle can be directly expressed by equation (6).

The measuring unit of the distributed on-line monitoring system only sample one period of the current and voltage signals. And after that, it only calculates the 1st, 3rd, 5th and 7th harmonics. By using this method, it saves more time than using FFT.

Hardware Design

The hardware frame diagram of the measuring unit for dielectric loss factor tan δ is shown in Fig.2. It is made up of the following detail modules: DSP module, ADC module, differential amplifier module, frequency trace module, signal conditioning module, communication module, power supply module etc.

When performing the DFT on the sampled data, non-simultaneous sampling and the lack of synchronization between sampling rate and signal period are believed to the main source of error in the measurement of the magnitude and the phase of the signals. To improve the effectiveness of the DFT algorithm, two measures were taken in the design of the measuring unit.

A. Simultaneous Sampling

Although DSP or microprocessor inner A/D converter has multiple analog input channels, there is only one converter in the ADC module. It is very difficult to sample the current and voltage at the same time. To accomplish the synchronization of all the input analog signals, a special ADC was adopted. It eliminates the necessity of calibration to account for the time difference due to the non-simultaneous sampling. The ADC contains six 16-bit, fast, low power, successive approximation ADCs all in the one package. The ADC features throughput rates up to 250 kbps. The conversion process and data acquisition are controlled using CONVST signals and an internal oscillator. Three CONVST pins allow independent simultaneous sampling of the three ADC pairs. The ADC has both a high speed parallel and serial interface allowing the devices to interface with microprocessors or DSP.

B. Synchronization and Frequency Fluctuation Tracing

In the procedure measuring dielectric loss factor which uses the method-fundamental wave phase detachment, the most important thing is to guarantee the 2^N sample dots exactly in one power system frequency period, thus, the error influence that frequency spectrum leakage brings can be decreased, in the power system, the system frequency fluctuates around 50Hz, frequency trace is needed while sample 2^N fixed dots which is dispersed data in one period, in order to confirm the actual sampling frequency. Because the fluctuating of power system frequency is slowness, the measuring unit adopts pretty simple measuring frequency circuit to realize sample synchronously. By means of voltage comparator, make the voltage signal from sampling to be square wave signal, and input the square wave to the capture pin of the Event Manager (EM is one module of the DSP). Before start the conversion process of the ADC, DSP measuring the time interval between the two adjacent rising edges or falling edges of the square wave signal, and the interval is the power system period T. After get the period of the power system, the hardware program can dynamically set the sampling frequency of the ADC by the CPU timer of the DSP so that the 2^N sample dots exactly acquired in one period. In this work, 128 sample dots were acquired in one period.

One phase of the voltage signal is chosen as the reference signal and data sampling starts at a random location on the voltage reference waveform, called the trigger point. The results of the measurements are based on averaging the measurements over a specific number of sampled cycles.

Laboratory Tests

Laboratory test were carried out to evaluate the accuracy and effectiveness of the DFT algorithm. To perform the evaluation, conditioning circuits bypassed, the dielectric loss factor angle was measured. Through the dielectric loss factor calculation equation (6), the phase angle between the current and voltage can be calculated by $\pi/2 - \delta$.

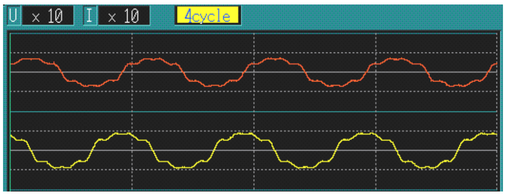

Fig.3 Voltage and current signals with 10 percent of 3rd, 5th and 7th harmonics (the upper waveform is voltage signal)

Two voltage signals (Current signals were conditioned to voltage signals before inputting to the differential amplifiers) were supplied directly to the input of the differential amplifiers from the Electrical Power Standard 6100A (FLUKE), the phase angle of the two signal were adjusted ranging from 0 to 180 degree. By varying the phase angle of the current and voltage with a step of 20 degree, the precision of the angle measurement is limited to $\pm$0.06% no matter harmonics free or contaminated with specific harmonic components. Fig.3 and Fig.4 show the waveforms contained specific harmonic components.

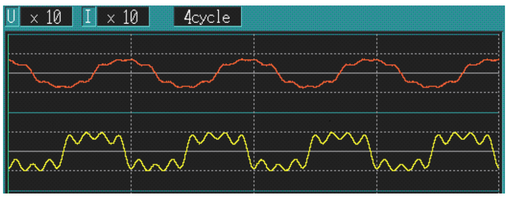

Fig.4 Voltage signal with 10 percent of 3rd, 5th and 7th harmonics and current signal with 20 percent of 3rd and 5th harmonics, 30 percent of 7th harmonic

Basic Description of the Distributed on-line Monitoring System

The distributed on-line monitoring system reported in this paper is based on the half duplex RS-485 bus and fiber communication technology. The schematic diagram of the system is shown in Fig.5. First, the analog signals are passed through a signal conditioning circuit which provides the transient protection and isolation of the input analog signals. A 16-bit resolution ADC is used to implement simultaneous sampling of the analog and current signals.

Finally, the algorithm of the DFT is performed inside the DSP chip and the digital computation of the dielectric loss factor and capacitance are ready for uploading to the computer. In addition to the values of the dielectric loss factor and capacitance, the waveforms of the voltage, current, temperature, humidity and frequency signals and the harmonic components of the voltage and current can be displayed.

The computer can send out some commands based on the protocol, such as start sampling, stop sampling, upload data, reset DSP etc, to control the measuring units. There is no communication between different measuring units. The first measuring unit is to measure the temperature and humidity of the environment. And the rest measuring units are used to measure the different group of HV apparatus under monitoring.

The onsite twisted pair daisy chain RS-485 network is connected through fiber-optic cable to the control room. Compared with systems based on electrical cables, the approach of optical fiber communications has advantages, the most important of which are: Fiber-optic cables are immune to problems of electrical cables such as ground loops or electromagnetic interference (EMI). High voltage signals are completed isolated between the onsite electrical cables and the control computer in the control room.

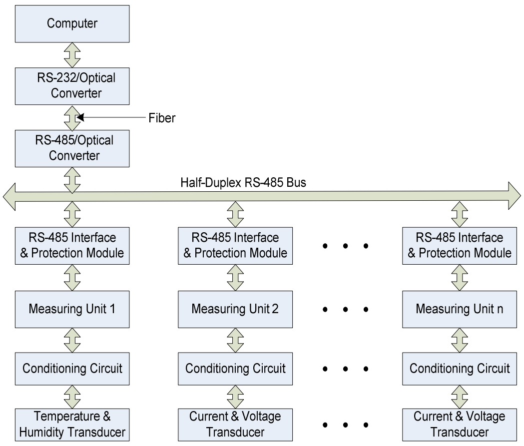

Fig.5 the schematic diagram of the distributed on-line monitoring system

On-line Measurements

As shown in Fig.6, the voltage signal was obtained from the secondary side of the potential transformer and resistive dividers. The current signal was derived from the voltage across the combination of a resistor R and the current signal scaling circuit. The resistor R was included to provide a safe voltage connection, and current signal scaling circuit functions as a shunt resistor with transient protection feature. A Pulse withstand chip resistor Rd was employed as damping resistor. It was verified by experiments that the setup of Fig.7 provided adequate transient protection.

The on-line monitoring system was installed to evaluate the insulation of two groups of 220kV CT units at local substation. Fig.8 shows an illustration of the graphic user interface, and the readouts and display that it provides. Table 1 shows the corrected data, which takes into account phase shifts introduced by the signal conditioning circuit, the PT, the shunt resistor, resistor R2 and neighbour transmission lines etc. Table2 shows the off line test results measured by the Schering Bridge Insturment.

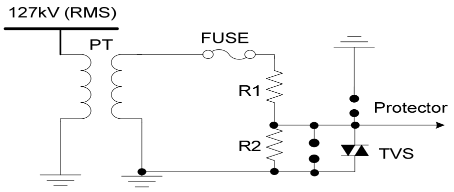

Fig.6 Arrangement for delivering voltage signal (single phase).

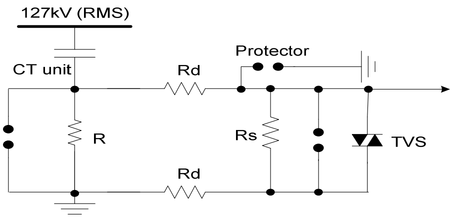

Fig.7 Arrangement for delivering current signal (single phase)

Table.1 On-line measured results of the dissipation tan δ (%) and capacitance C (pF) after correction.

Group one			Group two		
Phase	tan δ	C	Phase	tan δ	C
A	0.215	1109.1	A	0.233	283.7
B	0.225	1095.6	B	0.229	283.1
C	0.208	1103.2	C	0.234	281.7

Table.2 Off line results of the dissipation tan δ (%) and capacitance C (pF)

Group one			Group two		
Phase	tan δ	C	Phase	tan δ	C
A	0.22	1109.0	A	0.23	284.0
B	0.22	1100.0	B	0.22	283.0
C	0.21	1104.0	C	0.23	282.0

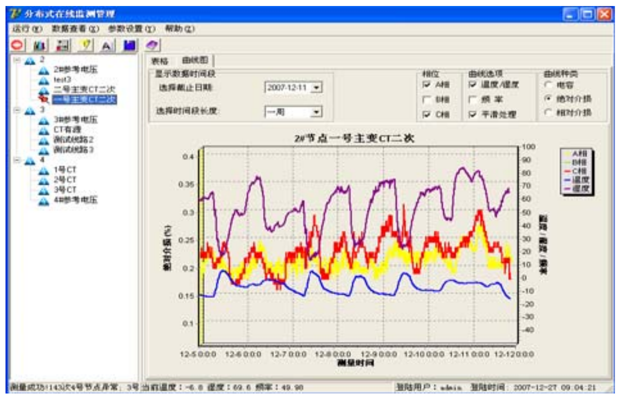

Fig.8 Graphic user interface of the system

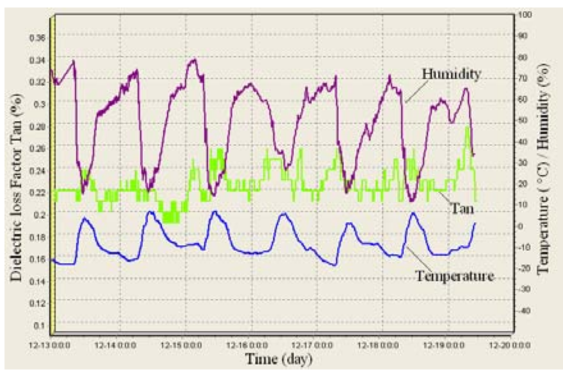

Fig.9 Continuous monitoring results of current transformer (Group one phase B)

Fig.9 shows the continuous monitoring results of one of the current transformer in a whole week. For clearness here only present a single phase tan δ versus temperature and humidity. The graph shows that tan δ may fluctuate a little bit with variation of temperature and humidity. The variation of the of the dielectric loss factor tan δ is ranging from 0.19 to 0.28 percent.

Conclusion

The developed measuring unit of the on-line monitoring system can effectively improve the simultaneous sample between multi-channel voltage and current signals. And the dynamic sampling rate setting method can trace the frequency fluctuation and improve the synchronization between the sampling rate and signal period. The measures adopted by this paper not only can improve the effectiveness of the DFT algorithm, but also can withstand frequency fluctuation.

It has been verified that the measurement precision of the measuring unit is ± 0.06% for dielectric loss angle ranging from 0 to 180 degree. This precision is obtained by improving the effectiveness of the DFT algorithm and averaging the measurements over a specific number of sampled cycles. The errors caused by the trigger point locations and harmonics were greatly reduced.

The distributed on-line monitoring system has high precision of measurement, strong ability of anti-interferences, steady and reliable running performance. The suitability of the developed system for on-line application has been demonstrated.

Acknowledgments

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