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Design of Measurement System and Characteristics Research on the Pulse Current of Composite Insulator

***Abstract**. The composite insulators have been widely used on the power transmission lines. The faulty caused by manufacture techniques, quality defect or organic material degradation comes into being more and more. Measuring the composite insulator' corona pulse current flowing through the grounded wire is an excellent way to monitor the faulty insulator strings on ground. In this paper, the measurement system for detecting pulse current of composite insulator are set up. The wideband current transducer, extraction circuit of pulse current and the circuit of reference signal are designed and manufactured. Based on the experimental system set up in the laboratory, the characteristics of corona pulse are studied. The relationship between applied voltage and pulse current characteristics, the frequency and phase angle range of corona pulse are studied profoundly. Such work provides direction for on-line monitoring composite insulators by pulse current method.*

***Streszczenie.** W artykule analizowano metody badania defektów izolatorów kompozytowych. Mierzono impulsowy prąd wyładowania przepływający przez uziemiony przewód. Przedstawiono układ pomiarowy tego prądu oraz przedstawiono wyniki eksperymentów. Analizowano związek między przyłożonym napięciem a prądem wyładowania, w tym właściwości częstotliwościowe i fazowe tego prądu. (**System pomiarowy do badania prądów wyładowania w izolatorach kompozytowych**).*

Keywords: Composite insulator, Pulse current, Measurement system, Aging condition
Słowa kluczowe: izolatory kompozytowe, defekty, prąd wyładowania

Introduction

In recent decades of years, the composite insulators have been increasingly used for outdoor high voltage insulation since they have some advantages comparing to the porcelain and glass ones, such as light weight, easy installation, contamination performance and so on [1,2]. However, with the extending application and the sudden increase of composite insulators quantity, due to the quality defect, long running period or horrible working environment, the degradation of composite insulators in natural environment is a big concern for the power utilities [3-5]. To find out the hidden trouble and aging condition of composite insulator, avoid the outburst accident and improve the reliability of power system, it is very important to develop the research on on-line diagnostic method for composite insulator.

The aim of diagnostics is, in general, to get relevant information about the state of composite insulator, which means that diagnostics should be an aid in making decisions about if and when maintenance or replacement of insulators should be done. It is basically associated with reducing costs and minimizing risk of damage to people and property. For insulators made of glass or porcelain, several inspection methods are available to detect faulty insulators in service [6]. In the case of composite insulators, the situation is more complex, the knowledge on the degradation of composite insulators is being studied worldwide [7-14]. The methods to assess the working conditions of composite insulators are being studied and created [15], including visual inspection, light emission imaging, thermal measurement, acoustic measurement, electric field distribution measurement, and etc. Though several techniques have been proposed for assessing the state of insulators in service, it is still difficult to accurately correlate measured parameters with presence of defects, thus work on development of diagnostic methods for evaluation of the composite insulator conditions should continue. Nowadays, more and more attentions are paid on the leakage current, partial discharges (PD), radio interference voltage (RIV) or corona pulse current measurement.

An IEEE task force evaluated a number of methods used to detect faulty composite insulators before installation [16]. The results showed that measurements of leakage current, PD and RIV could detect insulators with embedded wires, and RIV was found to be the most sensitive technique since it also could identify insulators containing silver paint. However, the fact that discharges had to be caused by the defects, and not by anything else, restricted applicability of PD and RIV measurements to laboratory environment only.

In Queensland University of Technology (QUT), the approach based on chemical analysis methods was first developed [17]. The work was focused on correlating electrical characteristics with chemical analysis results of the composite insulators and physical observations results. Based on the analysis of the electrical characteristics of composite insulators including leakage current, cumulative current, peaks of leakage current, the authors presents one approach which aims to assess the surface conditions of composite insulators in an easy manner and in short time. But the work mainly developed in the laboratory and it is not practical to be applied in the field.

Although a number of factors are responsible for aging in composite insulator, the leakage current is perhaps most crucial in the aging of contaminated insulator. Several approaches have already been introduced to monitor the leakage current of outdoor insulators, for example, leakage current surge counting, highest leakage peak current recording, and charge measurement, as in [18] and [19]. Meanwhile, spectral analyses of the leakage current in contaminated insulators under fog conditions have been conducted using the fast Fourier transform (FFT) [20] and the autoregressive (AR) method [21]. However, in most cases, only the low-frequency components, namely, the fundamental, 3rd and 5th harmonic components are used for a spectral analysis of the leakage current, owing to the assumption that the low-frequency components contain more important information than the high-frequency components. As a result, most of the high-frequency components are ignored and excluded from the spectrum analysis process. Furthermore, the method proposed in [22] used the high-frequency components to provide important information about the composite insulator. Whereas, the research in [22] mainly focused on predicting flashover and monitoring the contamination conditions, but not aging of outdoor composite insulators.

Measuring the composite insulator' corona pulse current flowing through the grounded line is a excellent way to monitor the faulty insulator strings on ground. It is called pulse current method, in which actually the high-frequency components in leakage current are used for diagnosing the aging condition of composite insulator [23]. However, presently, the research has been concentrated on the determination of aging details and measurement of overall pulse current. There has been little work done on investigations of the corona pulse characteristics. Furthermore, the circuit for extracting pulse current from the whole leakage current has not been reported before.

In this paper, the pulse current method to detect the aging condition of composite insulator is presented. The corresponding circuit for exacting pulse current are introduced. Based on the founded measurement system, the composite insulator' pulse current flowing through grounded line are measured and studied, which could be beneficial to monitor the aging condition of composite insulator on line.

The design and realization of measurement system

The design of composite insulator is integrative. As a whole, the silicone rubber is outside as the weathersheds, at the centre of the insulator system is the fibreglass reinforced polymer rod. Without doubt, the aging of insulator starts from some part of silicone rubber or polymer rod, and then the resistance of aging part will reduce, which means that the voltage applied to these parts will also reduce, therefore the other parts of insulator will withstand more voltage than the normal conditions, which leads to the electric field at some part become larger than before. When the electric field reaches to the enough value, the partial discharge will be inevitable, and then the pulse current will generate. Therefore, the quantity, intensity and phase distribution of corona pulse will be different from the normal insulator's. That is to say, to measure the pulse current of insulator can be used to diagnose the faulty composite insulator. The above is the basic principle of pulse current method.

According to the above introduction, the pulse current method can be realized as the followed, which is also shown in the Fig.1. A wide-band corona pulse current transducer is installed through the grounded wire of tower to extract the leakage current signal. And then the useless component in this signal will be filtered and the useful component will be magnified via a high-pass filter. Finally, the useful pulse current signal will be sampled into the computer by the A/D card. On the other hand, the power frequency component in the leakage current will be gained via an amplifier and band-pass filter, which will be input to the circuit of phase shift and square wave generation, and then a reference signal with the same phase as the voltage of transmission line will be generated, which will be used to trig the A/D card to collect the pulse current signal. The analysis software is used for acquisition of all the individual quasi-integrated pulses and quantifying each of these corona pulses by their magnitude Q, the corresponding phase angle or pulse epoch Φ at which they occur and their number densities or pulse rates N over some chosen interval of time. Thus, a three-dimension plot or image, N-Φ-Q, can be gained, which is regarded as one of the more complete forms of graphical representation of the pulse current distribution and can be used to diagnose the aging condition of composite insulator. As the followed, each part of the measurement system shown in Fig.1 will be introduced in detail. It should be stated firstly that the parameter of R, C shown in the following circuits perhaps has the same symbols, but their value is different.

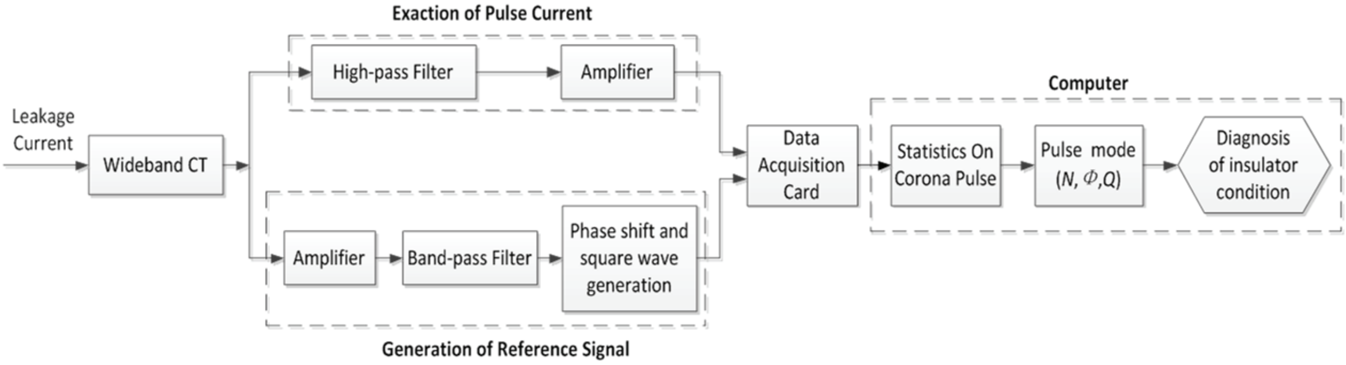


Fig.1. The scheme of measurement system for detecting pulse current of composite insulator

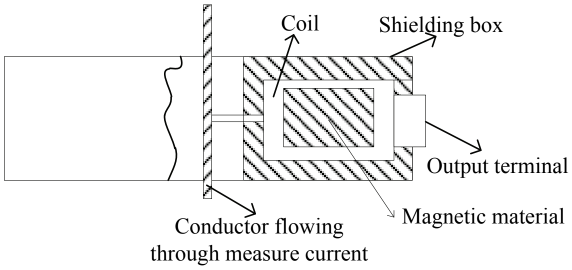
(A) Wideband CT

According to the existing research results [23], the corona pulse current flowing through the grounded line of tower has the characteristics of high frequency and weak signal, that is to say, the pulse current transducer should satisfy with the requirement of wider frequency range and larger magnification times.

The current shunt or Rogowski coil can be used in the measurements of current pulses. The current shunt has a good response characteristic, but a protective circuit is necessary to prevent the measuring instrument from being damaged by the transient over-current of the gap discharge. Moreover, the introduction of a protective circuit will cause oscillation and distortion of the waveform, especially for the measurement of the fast pulse current. A Rogowski coil, isolated from the discharge circuit, is suitable for the measurement of discharge current.

The designed current transducer based on the Rogowski coil works on the principle of electromagnetic coupling. The coil is made of copper wire that is wound in a spiral around a ring-type ferrite magnetic core and then returns to the original point. A type of ferrite of nickel–zinc material with high ρ (resistivity) and low Hc (coercive force) can be used to obtain the performance of broadband and lower loss [24]. The coil is placed around the conductor to couple the pulse signals. A schematic diagram and real picture of the current transducer is shown in Fig.2.

Fig.3 shows the amplitude–frequency response characteristics of the current transducer used to measure the pulse current of composite insulator. From Fig.3 it can be seen that the working frequency band of Rogowski coil with Nickel-zinc is within 6kHz~11MHz, in this frequency scope, the amplitude-frequency response curve is very flat. According to the published references [22,23], the frequency spectrum of pulse current of composite insulator is under 10MHz, that is to say, the designed current transducer's amplitude-frequency response satisfies with the measurement requirement. Furthermore, the response at the 50Hz is not zero, which means that the power frequency component in the leakage current also can be extracted by the current transducer although the amplitude is very little.



(a) schematic diagram

(b) the real object picture

Fig.2. The current transducer

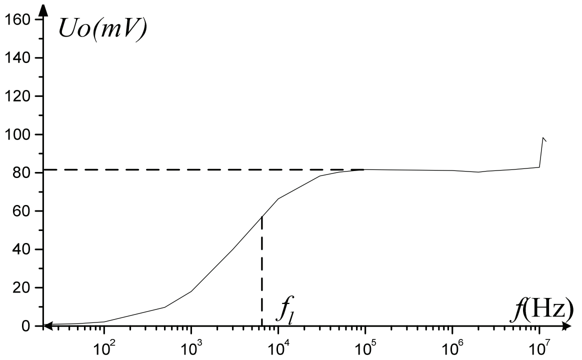


Fig.3. The amplitude–frequency response characteristics of the current transducer

Additional, the linearity of this current transducer is also measured, which is shown in the Fig.4. The frequency of signal used in this measurement is 1MHz. From Fig.4, it can be seen that the error of non-linearity is less than 2% , that is to say, this transducer has excellent linearity.

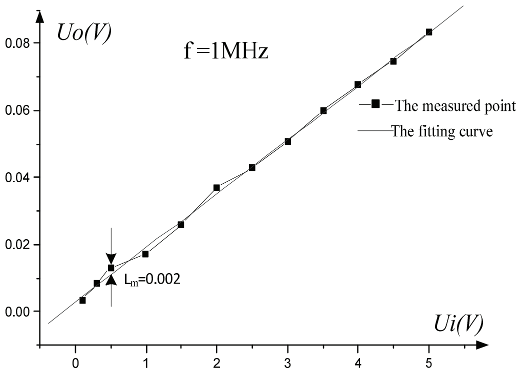


Fig.4. The linearity of current transducer

(B) Extraction circuit of Pulse current

The circuit for extracting pulse component in leakage current consists of two parts, one is high-pass filter, another is high frequency amplifier, which will be introduced in detail as followed.

1) High-pass Filter The corona pulse current is extracted via the current transducer installed through the grounded wire of the tower. However, not only corona signal flows through the grounded wire, but also some other signals do, such as power frequency leakage current, harmonic current, transmission line's corona and etc. In order to analyze the corona pulse current independently, these interference signals must be eliminated, therefore, the signal collected must be filtered by the high-pass filter. As the pulse current method, the statistical characteristics of pulse current's phase and amplitude distribution are mainly applied to diagnose the condition of insulator, and the pulse shape has little influence on the detection result. Therefore, the high-pass filter should have better attenuation under 2MHz to filter the interference signal and the upper cut-off frequency should be as higher as better.

In order to satisfy the above requirement, in this paper, a six order Butterworth filter is adopted, which has the maximally flat pass-band characteristics. a second-order filter section of the Butterworth filter is shown in Fig.5.

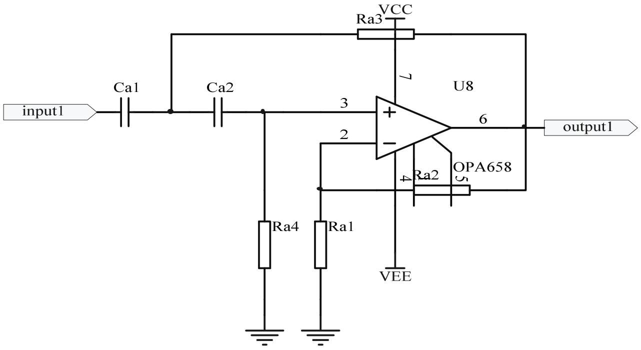


Fig.5. A second-order filter section of high-pass filter

Fig.6 shows the amplitude-frequency characteristic curve of high-pass filter. It can be seen that the lower limit of the cut-off frequency is 2MHz, which is consistent with the design aim.

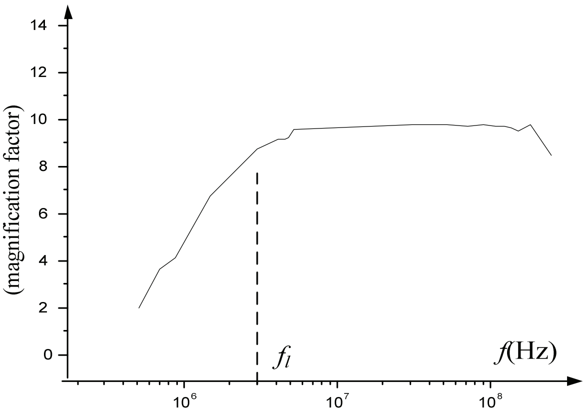


Fig.6. Amplitude-frequency characteristic curve of high-pass filter

2) High frequency amplifier The amplitude of corona pulse current is from μA to mA level, which will be changed to the pulse voltage signal with amplitude of tens of micro-volts to 1 milli-volt via the current transducer and high-pass filter. On the other hand, the corona pulse current has wide range of frequency spectrum. Therefore, the amplifier should have a higher frequency band and gain. In the design, the operational amplifier, OPA658 (unity-gain bandwidth of 900MHz, low power and current-feedback type), is adopted to make up of a high frequency amplifier, which is shown in Fig.7.

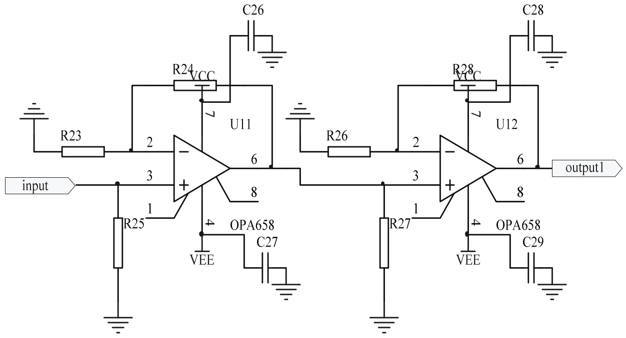


Fig.7. High frequency amplifier

The amplitude-frequency characteristic curve of high frequency amplifier is shown in Fig.8. From Fig.8 it can be seen that the upper cut-off frequency (-3dB) is 20MHz and the working bandwidth is 0-20MHz, which is satisfied with the characteristics of corona pulse current of composite insulator.

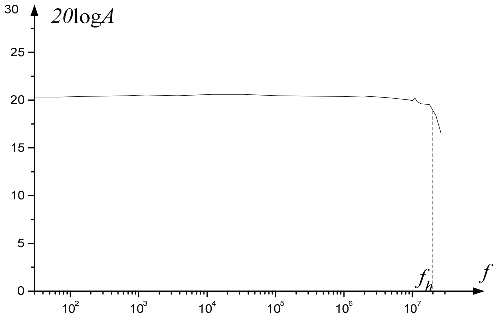


Fig.8. Amplitude-frequency characteristic curve of High frequency amplifier

(C) the circuit for the reference signal

The reference signal is generated from the power-frequency leakage current flowing through the grounded wire of tower. Actually, the frequency of leakage current is consistent with that of the power system, which guarantees that the reference signal's frequency will vary with the power system's frequency. Therefore, the reference signal gained from the power-frequency leakage current can provide a exact phase benchmark, and then the phase statistics of corona pulse can be realized.

The procedure of gaining the reference signal is illustrated in Fig.1. The output of current transducer is enlarged firstly by the high-frequency amplifier (as the same as the amplifier shown in Fig.7), and then the power-frequency component can be extracted from the leakage current via a band-pass filter. Finally, the power frequency component will be changed to a square-wave signal via the circuit of phase shift and square-wave generation. The function of square-wave signal is to trig the followed data acquisition card and control its starting time.

1) Band-pass Filter Fig. 9 shows a typical circuit of band-pass filter based on double T network. Its amplitude-frequency and phase-frequency characteristics are shown in Fig.10.

From Fig.10 it can be seen that the central frequency and band width of band-pass filter is about 50Hz and 5Hz respectively. The frequency fluctuation of power system is within the range of ± 0.2Hz, therefore, the power frequency component of leakage current is always at the range of band-pass, which also means that with the band-pass filter, the power frequency component can be extracted from the whole current flowing through the grounded wire.

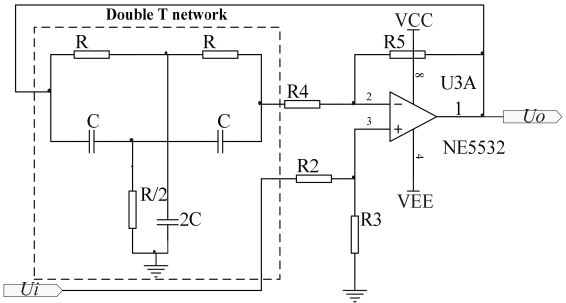


Fig.9. Band-pass filter

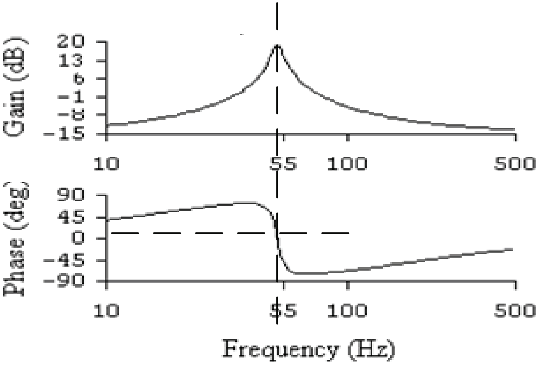


Fig.10. Frequency characteristics of band-pass filter

2) Phase-shift and square wave generation circuit The pulse current method is mainly based on the phase distribution of pulses, therefore, the requirement on phase shift of the power frequency signal extracted by the band-pass filter is very strict. However, from Fig.10 it can be seen that the phase shift of power frequency signal is about 15°, which is very severe, thus the phase of power frequency signal must be shifted to the same phase as the power system's before it is converted to a square wave. The corresponding circuit is shown in Fig.11.

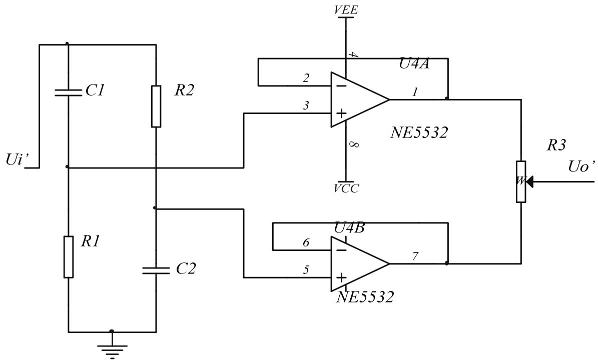


Fig.11. Phase-shift circuit

In Fig.11, commonly, C_1 equals to C_2, R_1 equals to R_2 , moreover, equation $1/j\omega C_i=R_i$ is also tenable, where, i=1、2 and ω is the angular frequency of shifted signal. On the above condition, with the adjustment of the value of R_3, the angle of phase shift could be within ±45°, which means that it is easy to realize phase shift of 15°.

In order to trig the data acquisition card, the output signal of phase-shift circuit must be converted to square wave, which can be realized by the zero-passage comparator and double D trigger. The circuit for square wave converting is shown in Fig.12.

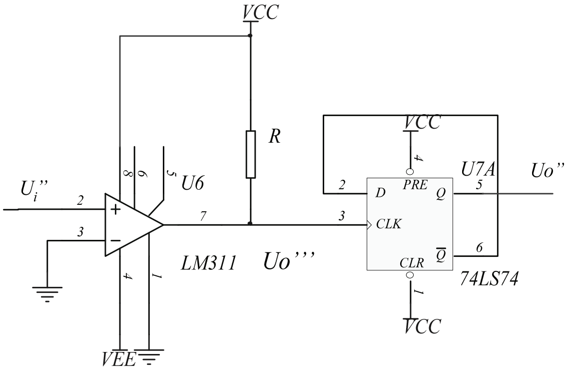


Fig.12. Circuit for square wave converting

Obviously, the square wave, which has the same phase as the input signal U_i of band-pass filter, can be gained from the phase-shift and square wave converting circuit by adjusting the changeable resistor R_3. The experimental result in lab is shown in Fig.13. It can be seen that the phase shift caused by the band-pass filter has been adjusted and the phase difference between the input and output signal decreases to below 1°, which is within the acceptable range.

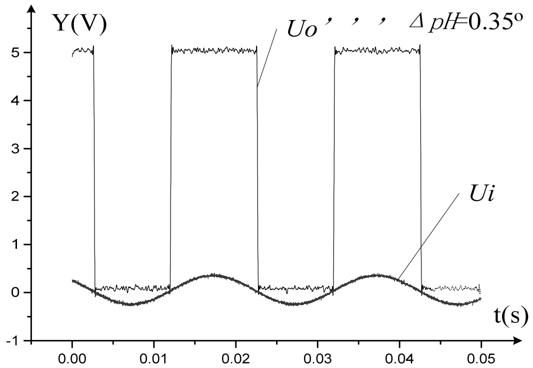


Fig.13. the result of phase shift and square wave conversion

Study on pulse current characteristics of insulator

(A) Test setup

The tests were carried out in a high voltage laboratory. At the condition of one-phase, we measured and analyzed pulse current of two different standard composite insulators respectively. One composite insulator is new, another has been working on the transmitting lines for several years. The experiment scheme is shown in Fig.14.

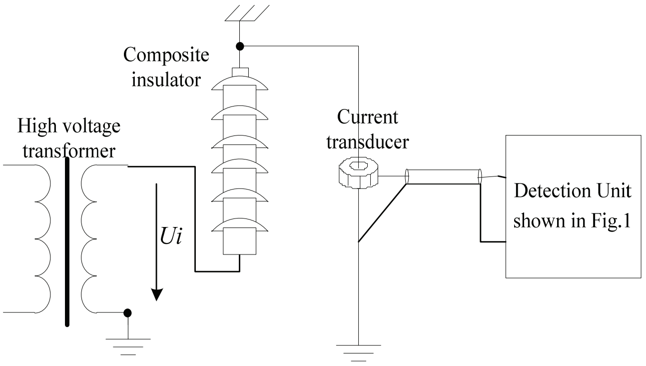


Fig.14. The experiment scheme

The high voltage source can supply 50Hz AC voltage up to 100kV. The grounded line of composite insulator is thrilling through the CT, which is used to acquire the corona pulse current signal and power frequency leakage current. The prototype of detection Instrument is shown in Fig.15.

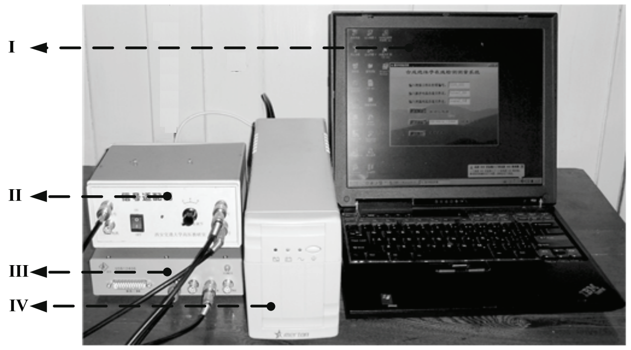


Fig.15 The prototype of detection instrument

I) *Notebook PC*: The core of data sampling, processing and storage. The notebook PC of high performance is chosen, which can realize the quick data processing and long time fieldwork. The running program on the desktop of the PC is the interface of measurement software.

II) *Detection Unit*: The pulse current signals acquired by CT are high-pass filtered, band-pass filtered and magnified through the detection unit, and then the benchmark signal of data acquisition card, leakage current and pulse current can be acquired. This apparatus also can be supplied with the battery. Moreover, it can be seen that there are two output terminals on this apparatus, one is for corona pulse current, another is for square wave signal.

III) Data Acquisition Card Based on USB Interface: The analogy current output through detection unit is changed to digital type by this apparatus, whose starting is trigged by the square wave signal output from the detection unit. Its sampling frequency is up to 40MHz. It is connected to notebook PC via a USB connecting line, and then the measured current is transmitted into notebook PC and saved. The UPS supplies this apparatus.

IV) UPS: It supplies for the detection unit and DAC and it can work for 4 hours continually.

(B) the pulse current characteristics

A new and old 35kV composite insulators are applied to the rating voltage respectively, the experiment scheme is just shown as Fig.14. There, the new one is called as 'N' and the old one as 'O'. Using the above experiment scheme, we measure the pulse current signal of the composite insulators. The collected signals of one power frequency period (800k points) are shown in Fig.16.

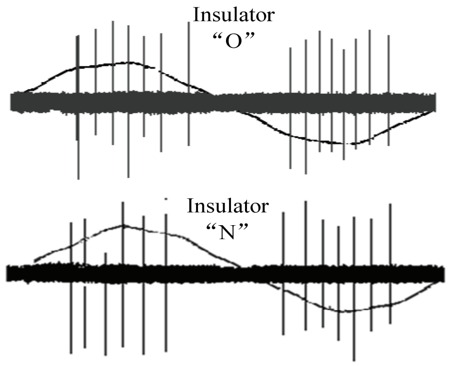


Fig.16. Comparison between Composite insulator 'N' and 'O'

From Fig.16 it can be seen that there are many pulses at the current flowing through grounded line. Now, in order to explore the characteristics of pulse current, only one pulse are reserved and expanded, which is shown in Fig.17.

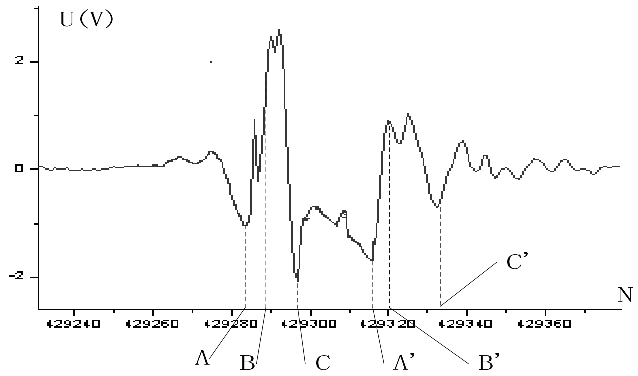


Fig.17. Pulse signal waveform that time axis is expanded

As shown in Fig.17, the values of A, B, C, A', B' and C' are as followed respectively.
A=429284, B=429288, C=429298,
A'=429316, B'=429323, C'=429334.
The sampling frequency of the Data Acquisition Card is 40MHz. The rising time of the first pulse (denoted by A, B and C) shown in Fig.17 is,

t_r=(B-A)/(4.0×10^7)=4/(4.0×10^7)=1.0×10^{-7}s=100ns

The breadth of the first pulse is,

t_T=(C-A)/(4.0×10^7)=14/(4.0×10^7)=4.0×10^{-7}s=350ns

By the same method, the rising time of the second pulse (denoted by A', B' and C') also can be derived, which is as followed,

t_r=(B'-A')/(4.0×10^7)=7/(4.0×10^7)=1.75×10^{-7}s=175ns

The breadth of the second pulse is,

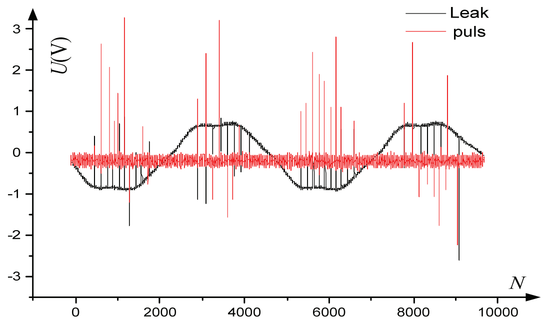
t_T=(C'-A')/(4.0×10^7)=18/(4.0×10^7)=4.5×10^{-7}s=450ns

The experiment indicates that the breadth of corona pulse signal of composite insulator is about 300-500ns, therefore, the frequency range of the corona pulse signal is within 10MHz.

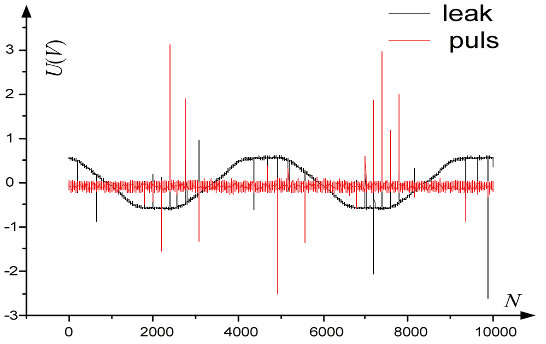
As shown in Fig.16, the magnitude and quantity of the old composite insulator' corona pulse are almost same as that of the new one, this phenomena means that the composite insulator which has been working at the transmitting lines for several years is not aging and damaged and it is also a well-balanced composite insulator. But it is necessary to make clear the pulse current characteristics of the aging composite insulator, therefore, the following work is conducted.

(C) The equivalent aging experiment of the composite insulator

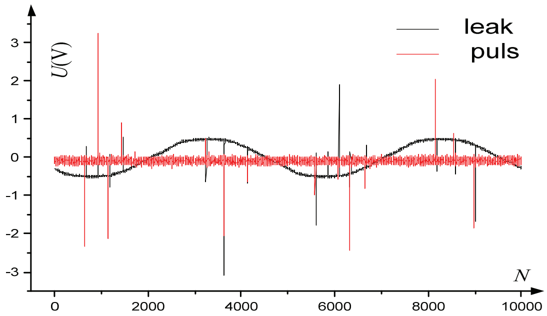
When the composite insulator is aging, it shows that some part of sheath or insulation rod is spoiled, and then the insulation resistance of this part is decreasing, the whole loop impedance becomes small. This will lead to the phenomena of corona take place and corona pulse current become large. For the un-aging composite insulator, in order to simulate the aging condition, we can improve the applied voltage of insulator. In the laboratory, 35 kV, 50 kV, 60 kV and 70kV voltage are applied to the "N" composite insulator and the corona pulse current is measured respectively, the gained waveforms are shown in Fig.18. In Fig.18, the sine wave which has peak pulse is the leakage current acquired by a resistance "R" (not shown in Fig.1) in series with the grounded line.



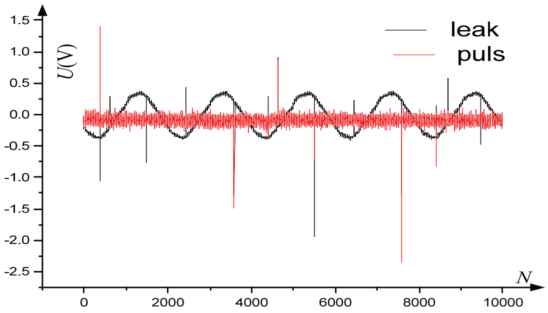
(a) U_i=70kV



(b) U_i=60kV



(c) U_i=50kV



(d) U_i=35kV

Fig.18. The leakage and pulse current of composite insulator at different voltage

From Fig.18 it can be seen that the phase of pulse existing in the leakage current acquired via sampling resistance is as same as that of pulse existing in the pulse current acquired via wideband CT. It indicates that through CT sampling, detection unit magnifying and filtering, the pulse current signal used to diagnose the aging condition of composite insulator can be acquired properly. On the other hand, it also can be seen that with the increase of applied voltage the pulse current magnitude augments, the number of pulses and its spreading phase range both augment. Because the increase of voltage is equivalent to the aging of composite insulator, the above phenomenon indicates that if some part of composite insulator gets aging, the pulse current flowing through the grounded line will vary. That is to say, by the pulse current method the aging condition of composite insulator can be diagnosed and made out.

(D) the phase distribution of corona pulse

The relationship between corona pulse and its phase is shown in Fig.19. The result shows that the corona pulse of composite insulator mainly occurred at the phase range of $60^{o}\sim120^{o}$ and $230^{o}\sim300^{o}$, which is nearby the positive and negative peak position of power frequency voltage.

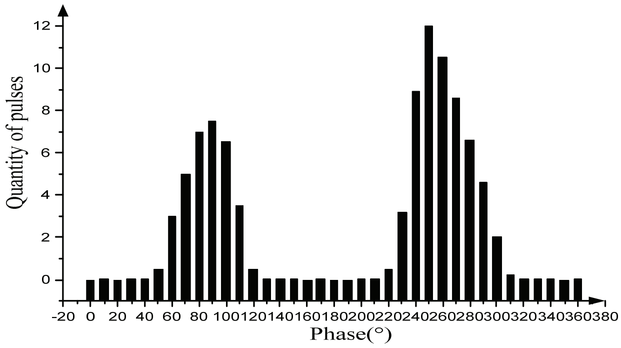


Fig.19 The typical pulse distribution vs. phase angle

Conclusions

In this paper, based on the analysis of principle of pulse current method, the measurement system of composite insulator pulse current is presented, and then wideband CT and each circuit (extraction circuit of pulse current and the circuit of reference signal) are designed and studied, whose performances are satisfied with the requirement of pulse current measurement.

Secondly, the experimental system is set up in the laboratory, and the corona pulse current characteristics of different composite insulators at different voltage is studied, the results show that,

1) The breadth of pulse current is about 300-500ns, which means that the frequency range of the corona pulse signal is within 10MHz;

2) The higher voltage the composite insulator endures, the more amount of pulses can be detected, that is to say, the aging condition of composite has relationship with the pulse current flowing through the grounded wire of tower.

3) The corona pulses mainly occur at the phase range of $60^{o}\sim120^{o}$ and $230^{o}\sim300^{o}$, which is nearby the positive and negative peak position of power frequency voltage.

The study in this paper indicates that the founded measurement system can be used to monitor the condition of composite insulator, the pulse current method is feasible and deserved to study profoundly.

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