A New Approach to On-Line Monitoring Device for ZnO Surge Arresters

Bok-Hee Lee[†] , Hyoung-Jun Gil* and Sung-Man Kang*

Abstract - This paper describes a new approach to the algorithm and fundamental characteristics of the device for monitoring the leakage currents flowing through zinc oxide (ZnO) surge arresters. In order to obtain a technique for a new on-line monitoring device that can be used in the deterioration diagnosis of ZnO surge arresters, the new algorithm and on-line leakage current detection device for extracting the resistive and capacitive currents using the phase shift addition method were proposed. The computer-based on-line monitoring device can sense accurately the power frequency leakage currents flowing through ZnO surge arresters. The on-line leakage current monitoring device of ZnO surge arresters proposed in this work has the high sensitivity compared to the third harmonic leakage current detection devices. As a consequence, it was found that the proposed leakage current monitoring device would be useful for forecasting the defects and degradation of ZnO surge arresters.

Keywords: ZnO surge arrester, Leakage currents, Deterioration diagnosis, On-line monitoring device, Phase shift addition method, Surge protective device.

1. Introduction

The key role of surge arresters in electric power systems is to protect transmission lines and generation and distribution equipments from overvoltage and to absorb a substantial amount of electric energy resulting from overvoltage, lightning and switching surges. The lightning surge arrester should be an insulator at any voltage below the protected voltage, and a good conductor at any voltage above to pass the energy of the lightning strike to ground.[1] However, Zinc oxide blocks do not have infinite impedance so it will draw a continuous quiescent current at normal working voltage levels. The absorption of high lightning and switching surge voltages can lead to performance degradation of ZnO surge arresters and increase leakage currents. The guidelines are need for electrical engineers to estimate the residual lifetime of lightning surge arresters in service to improve the reliability of electric power supply.[2-3].

ZnO surge arresters are well known to lead an increase of the resistive current with time and the increase of the resistive current with increasing the applied voltage and temperature.[4-6] The increase of the leakage currents flowing through ZnO surge arresters results in a thermally unstable state that may lead to a serious problem. Therefore, it is very important to develop a technique for the diagnosis of the deterioration of ZnO surge arresters in order to maintain normal operation conditions. Diagnostic techniques are therefore essential to assess ZnO surge arresters in service

Some techniques of monitoring the deterioration of ZnO surge arresters such as the compensation circuit method and the third harmonic leakage current detection method have been developed.[7,8] To ensure the safety and continuity of power supply, non-contact leakage current detectors and on-line monitoring techniques are preferred. The compensation circuit method can detect the resistive leakage current flowing through ZnO surge arrester blocks precisely, but it is appropriate in laboratory test rather than in service. The third harmonic current detection method can cause some errors by the external factors such as the harmonic components and the capacitive third order harmonic current depending on stray capacitance included in power system voltages and currents.[9].

Thus it is essentially necessary to develop the techniques of evaluating the degradation of ZnO surge arresters. The most proper method for diagnosing ZnO surge arresters is to measure the resistive leakage current in service immediately. The measurement of the working voltages is expensive and not possible in actual power systems. In order to develop a technique for evaluating the deterioration of ZnO surge arresters in service, this work focuses on the computer-based on-line monitoring device that can detect the resistive leakage current flowing through ZnO surge arresters precisely. The resistive leakage current measurement is a core factor in diagnosing ZnO surge arresters. The phase shift addition leakage current detection device, which can directly extract the resistive current component from the leakage current without the measurement of the voltage across the ZnO

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surge arrester in service, was designed and constructed. The experimental results obtained from the laboratory tests are presented.

2. A New Approach to Leakage Current Detection

The behaviors of a ZnO surge arrester without gap are explained by the equivalent circuit of the series-parallel *R-L-C* networks as illustrated in Fig. 1. This may be used for predicting the dependence of leakage current on applied voltage and frequency.[10]

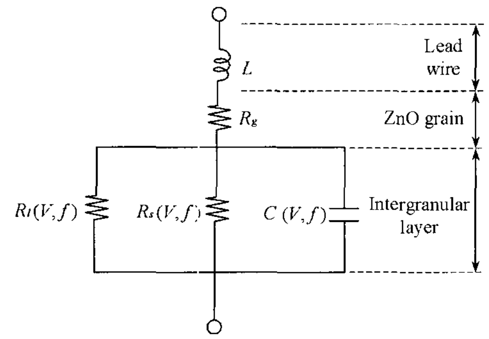
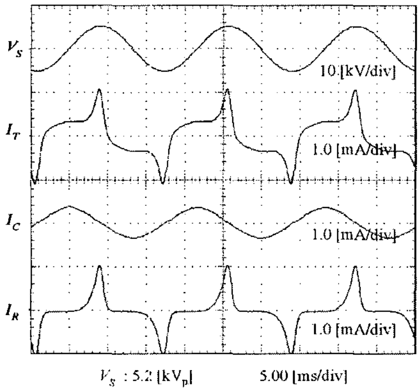


Fig. 1 Equivalent circuit of ZnO surge arrester block.

The series resistance R_g indicates ZnO grain resistance. The series inductance L is due to packaging and the length of the leads. Because the inductance of 1 μH/m is assumed, the effect of the inductance is negligible. The parallel resistance $R_l(V,f)$ is weak frequency-dependent and strong voltage-dependent, and the resistance $R_s\,(V, f\,)$ is strong frequency-dependent and weak voltage-dependent. The capacitance C is weakly dependent on the applied voltage, temperature and frequency.



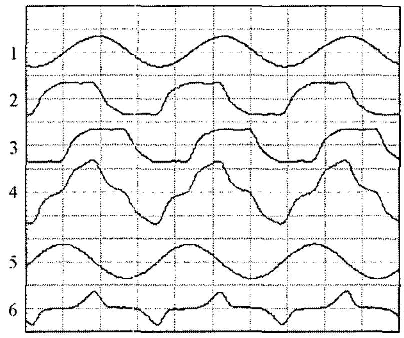
V_S : 5.2 [kV$_p$] 5.00 [ms/div]
I_T : 1 [mA$_p$], I_C : 0.36 [mA$_p$], I_R : 1 [mA$_p$]

Fig. 2 Typical waveforms of the applied voltage and leakage currents measured by the compensation circuit leakage current detection device: V_S is the applied voltage, I_T the total leakage current, I_C the capacitive current, and I_R the resistive leakage current.

At low voltages, losses are determined by $R_s(V,f)$, but, at high voltages, losses are governed by $R_l(V,f)$. Also, at very high conduction domain, the behaviors of ZnO surge arrester blocks are chiefly characterized by the grain resistance R_g. ZnO surge arrester blocks behaves like a parallel RC network at working voltage levels. That is, the ZnO arrester block leakage current under power frequency voltage is composed of the resistive and capacitive components.

Fig. 2 displays typical waveforms of the applied voltage, total leakage currents, capacitive and resistive currents flowing through ZnO surge arrester blocks under a 60 Hz power frequency voltage. The leakage currents were measured by the compensation circuit leakage current detection device in the previous work.[11] The magnitude of the capacitive leakage current is much greater than that of the resistive leakage current in the low conduction domain. Typical magnitudes of the resistive leakage current of ZnO surge arrester blocks under normal operating voltages range from 0.05 to 0.250 mA$_p$.[9].

The capacitive leakage current reveals the fundamental frequency of the applied voltage and its phase is 90° leading. That is, the capacitive current leads the applied voltage by one-quarter period. The resistive leakage current is the non-sinusoidal waveform, which has the fundamental frequency component. Also, the leakage current waveform in the positive half period is the same as that in the negative half period. The peak points of the resistive leakage current under power frequency voltage are consistent with those of the applied voltage. The phase shift addition method, which can find the peak time of the voltage across the surge arrester without measuring the applied voltage, is proposed. Waveforms of the applied voltage, measured leakage current, phase-shifted current,



Vertical axis;: 1 : 5 kV/div, 2~6 : 0.5 mA
Horizontal axis; 5 ms/div

Fig. 3 Waveforms of the applied voltage, measured leakage current, calculated capacitive and resistive leakage currents: 1 Applied voltage; 2 Total leakage current; 3 Phase-shifted current by a quarter period; 4 Addition current; 5 Capacitive current; 6 Resistive current.

calculated capacitive and resistive leakage currents for the purpose of the explanation of the phase shift addition method were shown in Fig. 3.

The sequences for calculating the peak time of applied voltage and the resistive and capacitive currents from the measured leakage current are as follows; ⓐ The leakage current flowing through ZnO surge arrester blocks at the 60 Hz power frequency voltage is measured. ⓑ The measured leakage current is shifted by one-quarter period with lagging phase. ⓒ The 90° lagging phase-shifted leakage current is added to the measured leakage current. The peak points of the current waveform obtained by adding the 90° lagging phase-shifted current to the measured leakage current are consistent with those of applied voltage as seen in Fig. 3. ⓓ The peak value of the resistive leakage current corresponds to the value of the measured leakage current at the instant of the peak time of the added current waveform. ⓔ The resultant resistive and capacitive leakage currents are calculated by combining the measured and phase-shifted leakage current waveforms. The algorithm for calculating the resistive and capacitive currents is described in Sec. 3.2.

3. Monitoring System

3.1 Measurement setup

The leakage currents flowing through a ZnO surge arrester blocks at the power frequency voltage are composed of the resistive and capacitive leakage currents. Nonlinear *V-I* characteristic curves of ZnO surge arresters are changed by the deterioration that is becoming clear to detect the resistive component and/or the third-order harmonic of the leakage current. The total leakage current is of no interest for the degradation of ZnO surge arrester. On-line monitoring systems must detect the variations in the resistive leakage current with time. The resistive leakage current at the power frequency voltage is extracted by subtracting the capacitive current component from the total leakage current.

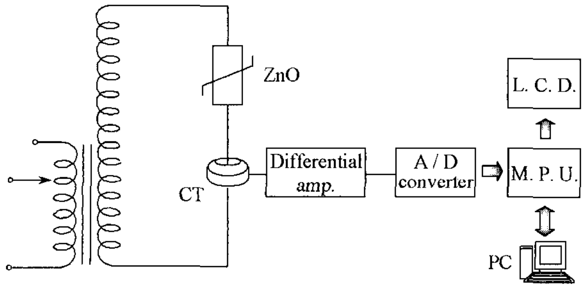


Fig. 4 Configuration of the leakage current detection device using the phase shift addition method.

Fig. 4 shows a configuration of the computer-based leakage current detection device using the phase shift addition method. This approach is not in need of the third-order harmonic current detection, the capacitive current compensation and the measurement of working voltages. The on-line leakage current monitoring device based on the phase shift addition method in service is composed of two parts. One is the signal sensing and processing part composed of the leakage current sensor, the differential amplifier and the low pass filter, and the other is the A/D converter and personal computer. The current sensor signal is amplified and integrated, resulting in a signal which is proportional to the ZnO leakage current. The phase shift addition method is not need to take out ZnO surge arresters from the power systems under test.

Experiments were performed on ZnO arrester blocks taken from the 18 kV-rated distribution surge arresters, and the specifications of the specimens used in this work were tabulated in Table 1.

Table 1 Specifications of the ZnO blocks used in this work

Diameter	33 [㎜]
Thickness	29 [㎜]
Rated voltage	3 [kV_{rms}]
Rated discharge current	5 [kA_{crest}]
Maximum continuous working voltage	2.55 [kV_{rms}]
Nominal conduction voltage	DC 5.0~5.39 [kV] at 1 [mA]

3.2 Algorithm for control of data processing and acquisition

The ZnO leakage current is measured by the current probe. The current signal is processed by the differential amplifier and the low pass filter before entering the A/D converter. Filtered leakage current signal is converted to digital signal by the A/D converter.

Fig. 5 shows a circuit diagram of the micro-processor unit for signal processing. The microprocessor unit consists of the A/D converter with resolution of 10 bit, the clock frequency of 16 MHz and the data bus of 8 bit. The current signals transmitted at the A/D converter are divide into the total leakage current and resistive components by the proposed algorithm calculating the time at the peak voltage using phase shift addition method, and the peak values of the total and resistive leakage currents are displayed on the 4×12 line LCD. Also, the waveforms of the total, resistive and capacitive leakage currents calculated by the proposed algorithm are displayed on PC monitor. The green LED is on under normal operating states. When the ZnO leakage current is greater than the nominal conduction current of 1 mA, the green LED is on and the red LED is off.

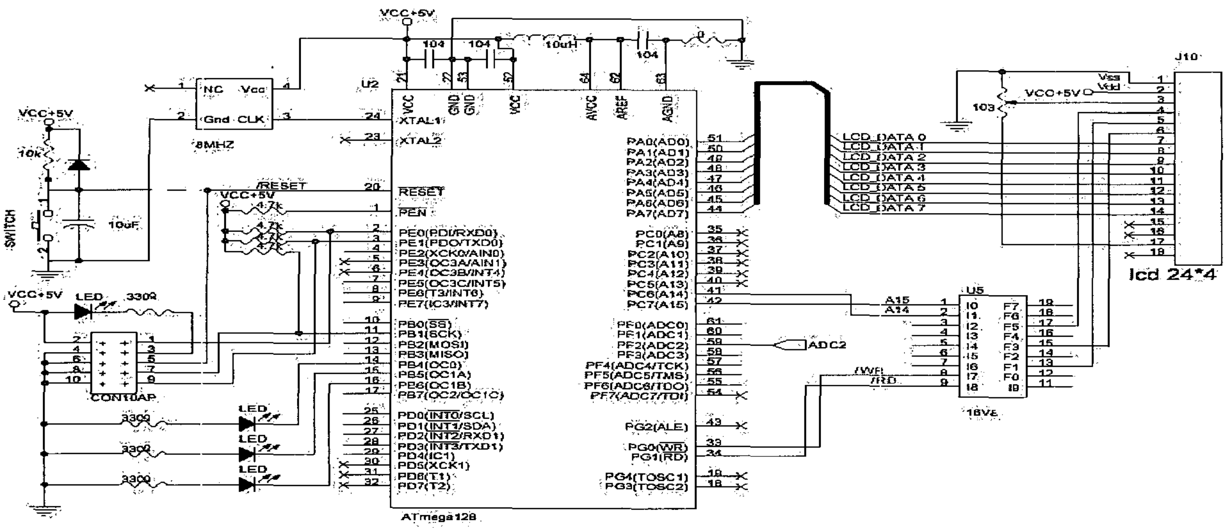


Fig. 5 Circuit diagram of the micro-processor unit.

As shown in the block diagram of Fig. 6, the algorithm for the phase-shift addition leakage current detection method could be summarized as follows;

After measuring the total leakage current signal [$f(\omega t)$], the software calculates the phase-shifted current waveforms [$f(\omega t-\pi/2)$] delayed with respect to the total leakage current as a quarter period [$\theta=\pi/2$] of working frequency. Here, we can give the addition waveforms [$f(\omega t)+f(\omega t-\pi/2)$]. The value of the total leakage current at the phase [θ_p] corresponding to the peak value of the addition waveform is the peak value of the resistive current [$f(\theta_p)$] and the value of the total leakage current at the phase [$\theta_p+\pi/2$] prior to the one-quarter period of θ_p is the peak value of the capacitive current [$f(\theta_p+\pi/2)$]. Because the fundamental frequency of the capacitive current is the same as the addition waveform, the capacitive current waveform can be calculated. As a result, the resistive current waveform is extracted by subtracting the capacitive current from the total leakage current.

4. Results and Discussion

4.1 Leakage currents calculated by the phase shift addition method

To display the leakage current waveforms on PC monitor transmitted from the on-line monitoring system using the phase shift addition method, the program using LabVIEW tools for analyzing the leakage currents of ZnO surge arresters was developed. The total leakage current waveform, its phase shift waveform by a one-quarter, the addition waveform of the above two waveforms, and the waveforms of resistive and capacitive currents are displayed on the user screen of the monitoring software.

Fig. 7 shows typical measured leakage current

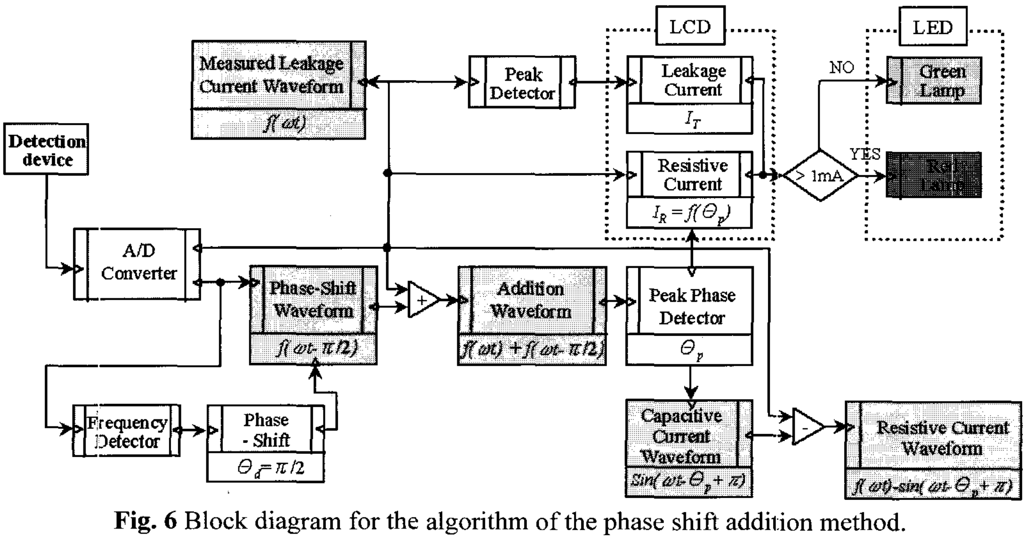
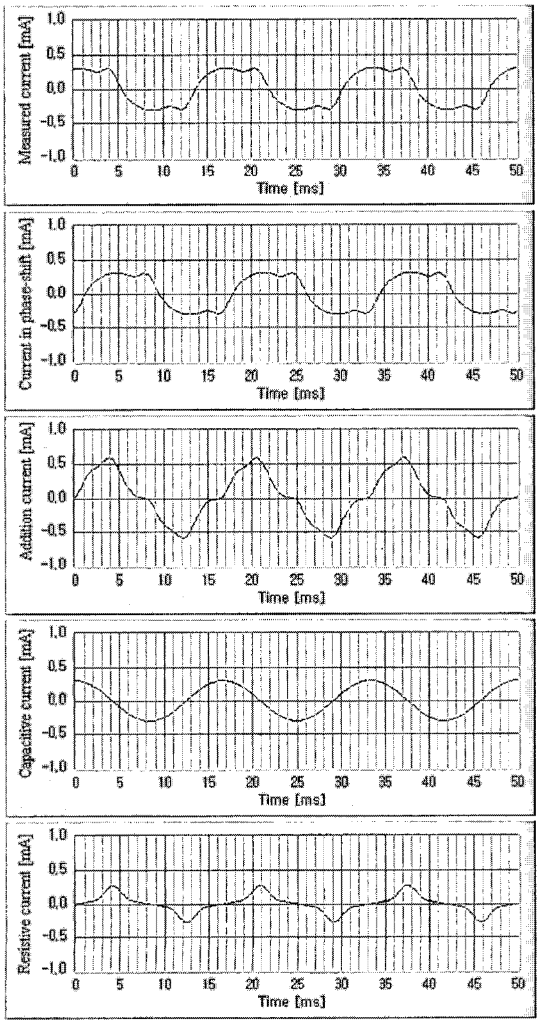


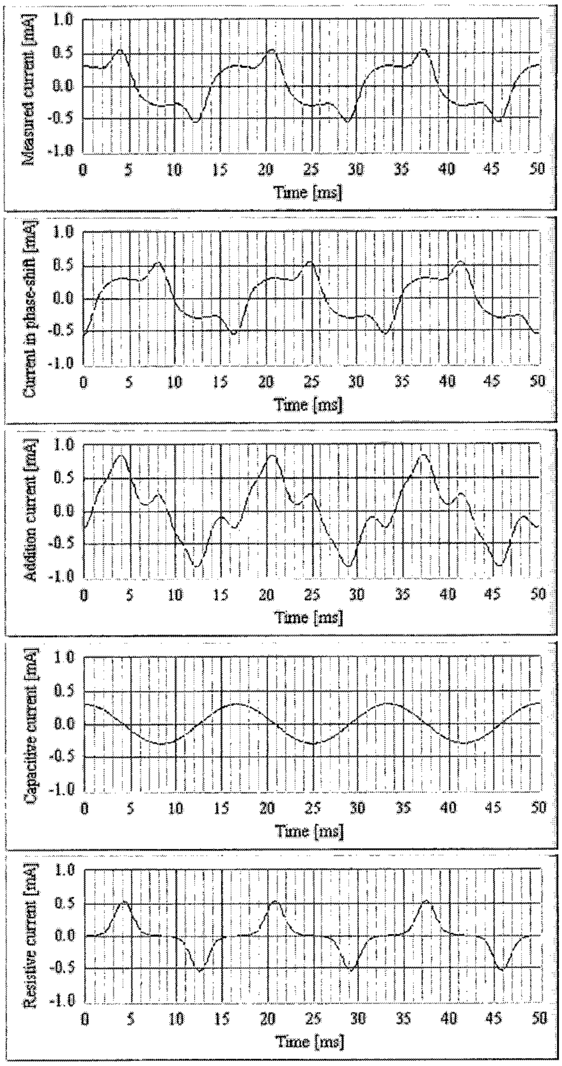
Fig. 6 Block diagram for the algorithm of the phase shift addition method.

waveforms, their phase-shift current waveforms by a one-quarter, the waveform produced by adding the phase-shift current to the measured leakage current waveform and the calculated resistive and capacitive current waveforms. Also, these waveforms can display simultaneously on the same screen.

When the voltage of 3.4 kV$_{rms}$ is applied, then the peaks of the resistive leakage currents are approximately equal to those of the capacitive current. But, the phase difference between the resistive and capacitive currents is one-quarter period. The distortion of leakage current waveform becomes more severe with increasing the applied voltage. The peaks of the resistive leakage current at higher voltage levels is greater than those of the capacitive current as is shown in Fig. 7(b). Also, the peak value of the resistive leakage current at the applied voltage of 3.7 kV$_{rms}$ is approximately 0.55 mA$_p$, approximately 2 times compared to the value at the applied voltage of 3.4 kV$_{rms}$. In addition, the peak values of the resistive leakage current waveform calculated from the phase shift addition method are good agreement with those of the measured leakage current.



(a) Applied voltage of 3.4 kV$_{rms}$



(b) Applied voltage of 3.7 kV$_{rms}$.

Fig. 7 Typical measured leakage current waveforms, their phase-shift current waveforms, the waveform produced by adding the phase-shift current to the measured leakage current waveform and the calculated resistive and capacitive current waveforms.

We can see clearly in Fig. 7 that the measure leakage current at the peak phase of the resultant waveform obtained by adding the phase shift current to the measured leakage current is the same as the peak value of the resistive leakage current. It may therefore be concluded that the resistive leakage current can be directly calculated from the measured leakage current using the proposed on-line leakage current monitor based on the phase shift addition method.

4.2 Changes in the ZnO arrester block leakage currents

Measurements of the responsitivity of the proposed phase shift addition leakage current detection device were carried out at the 60 Hz power frequency applied voltage. Also, the performance of the phase shift leakage current detection device was compared with that of the third-order harmonic leakage current detection device and the leakage current detection device with compensation circuit. *V-I* characteristic curves obtained by the different measuring methods were illustrated in Fig. 8. Data of the *V-I* curves indicate the peak values for both the resistive leakage currents and applied voltages. The third-order harmonic component of the leakage current flowing through ZnO arrester block using the third-order harmonic leakage current detection device proposed in the previous work, was plotted for comparison.[12] The results of the resistive leakage current measured by the phase shift addition method are good agreement with the data by the compensation circuit method.

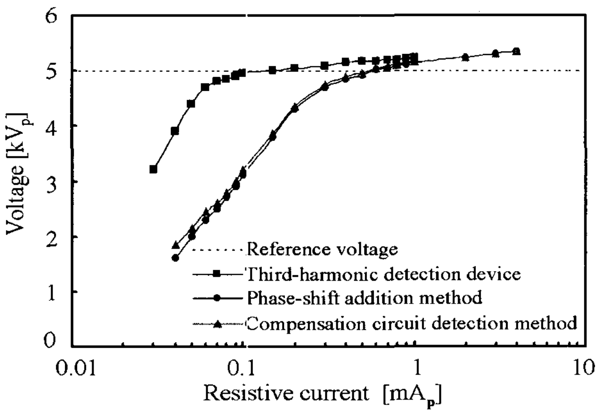


Fig. 8 Leakage current of the ZnO arrester block as a function of applied voltage.

The *V-I* characteristics of ZnO surge arrester blocks are classified into two categories of the low and high conduction regions. At the applied voltage of lower than the reference voltage, the leakage voltage is nearly proportioned to the applied voltage and the ZnO blocks behave like a lumped resistor of high resistance. But, in the high conduction region, the leakage current increases steeply with the applied voltage. The degradation of ZnO surge arresters leads to an increase of the resistive leakage current that includes amount of the third harmonic current. i.e., degraded ZnO arrester blocks have larger values of the resistive current and the third-order harmonic than fine ones. The detection of the resistive and third harmonic leakage currents may be desirable to evaluate the deterioration of ZnO surge arresters.

Also, the response curve of the phase shift addition current detection device is similar to that of the compensation circuit method that is proper to detect the resistive leakage current flowing through ZnO blocks accurately. The proposed leakage current monitoring device based on the phase shift addition method has a high sensitivity compared with the third-harmonic-current-measuring devices. In a word, the diagnosis of the deterioration of ZnO surge arresters is performed in the low conduction region. The magnitude of the resistive leakage current is significantly higher than that of the 3rd harmonic current. Consequently, it can alternatively be used for the deterioration diagnosis of ZnO surge arresters.

5. Conculsion

The new ZnO arrester leakage current detection device based on the phase shift addition method together with a data acquisition system and analysis program was developed. The computer-aided leakage detection device using the phase shift addition method can directly measure the resistive leakage current flowing through ZnO surge arrester without measuring the voltage across the surge arrester in service. The response sensitivity of the leakage current detection device was considerably improved. As a consequence, this leads to the conclusion that the developed on-line monitoring device of ZnO arrester block leakage current is applicable to provide the accurate degradation diagnosis and simplified on-site testing equipments of ZnO surge arresters in actual power systems

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References

[1] L.M. Faulkenberry, W. Coffer, Electrical Power Distribution and Transmission, Prectice Hall, Inc. pp.189~196, 1996.

[2] S. Shirakawa, F. Endo, H. Kitajima, S. Kobayashi, K. Kurita, K. Goto, M. Sakai, "Maintenance of surge arrester by a portable arrester leakage current detector", IEEE Trans. Vol.PD-3, No.3, pp.998~1003, 1988.

[3] W. G. carlson, Dr. T. K. Gupta, A. Sweetana, "A procedure for estimating the life time of gapless metal oxide surge arresters for AC application", IEEE Trans Vol.PWRD-1, No.2, 67~74, 1986.

[4] M. Matsuoka, "Nonohmic properties of Zinc Oxide Ceramics", Japanese Journal of Applied Physics, Vol. 10, No. 6, pp.736~741, 1971.

[5] M. Oyama, I. Ohshima, M. Honda, "Life performance of zinc-oxide elements under DC voltage", IEEE Trans. Vol.PAS-101, No.6, pp.1364~1368, 1982.

[6] K. Sato, Y. Takada and H. Maehama, "Electrical Conduction of ZnO Varistors under Continuous DC Stress", Japanese Journal of Applied Physics, Vol. 19, No. 5, pp.909~915, 1980.
[7] C.A. Spellman, A. Haddad, "A technique for on-line monitoring of ZnO arresters", Proc. 10th ISH, Vol.4, pp.148~151, 1997.
[8] T. Klein, W. Kohler, K. Feser, W. Schmidt, and R. Bebensee, "A New Monitoring System for Metal Oxide Surge Arresters", Proc. 11th ISH, Paper 2. 302, 1999.
[9] J. Lundquist, L. Stenstrom, A. Schei and B. Hansen, "New Method for Measurement of the Resistive Leakage Currents of Metal-Oxide Surge Arresters in Service", IEEE Trans. Vol.PD-5, No.4, pp.1811~1822, 1990.
[10] A. Haddad, J. Fuentes-Rosado, D. M. German, and R. T. Warwes, "Characterisation of ZnO surge arrester elements with direct and power frequency voltages", IEE Proc., Vol.137, Pt. A, No.5, pp.269~279, 1990.
[11] Bok-Hee Lee, Sung-Man Kang, Ju-Hong Eom, Tatsuo Kawamura, "A Monitoring Device of Leakage Currents Flowing through ZnO Surge Arresters" Japanese Journal of Applied Physics, Vol.42, Pt 1, No.4A, pp.1568~1574, 2003.
[12] Bok-Hee Lee and Sung-Man Kang, "A new on-line leakage current monitoring system of ZnO Surge Arresters" Materials Science and Engineering B, accepted for publication on Dec. 2004.

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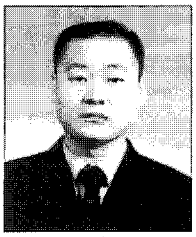

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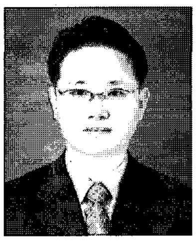

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