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NEW METHOD FOR MEASUREMENT OF THE RESISTIVE LEAKAGE CURRENTS OF METAL-OXIDE SURGE ARRESTERS IN SERVICE

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Abstract - Various methods for determination of the condition of ZnO surge arresters by means of measurement of the arresters leakage current are discussed. A new method, which is based on harmonic analysis of the leakage current, is presented. The main advantage of the new method is the low sensitivity to harmonics in the system voltage.

Keywords: metal-oxide, zinc-oxide, ZnO, surge arrester, leakage current, resistive current.

INTRODUCTION

Although a ZnO surge arrester requires no ordinary maintenance, it may be desirable from a utility point of view to check the condition of the surge arresters at regular time intervals. For practical and economical reasons, it is preferred that the check can be carried out without deenergizing or disconnecting the arrester, especially when high-voltage surge arresters are considered. This restriction obviously reduces the number of available methods for checking the state of a surge arrester.

Several ways of monitoring the state of a ZnO surge arrester in service have been presented in the past. Most methods are based on measuring the leakage current in the ground connection of the arrester [1,2] since it is well known that the resistive component of the continuous leakage current is a good indicator of the surge arrester condition. A considerable increase in the continuous resistive current may be caused either by moisture ingress due to sealing problems, or by premature ageing of the ZnO varistors, in contrast to a transient rise in the resistive leakage current caused by a temporary increase in varistor temperature.

In this paper, a new method is presented for harmonic analysis of the arrester leakage current where the influence of harmonics in the system voltage is minimized. The presence of harmonics in the voltage have presented a great problem to earlier methods based on harmonic analysis, since these harmonics may interfere with the harmonics generated by the nonlinear resistance of the arrester. The favourable effect of the new method is achieved by introduction of a field probe which allows a compensation for the harmonic currents generated by the harmonics in the voltage.

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ELECTRICAL PROPERTIES OF A ZnO SURGE ARRESTER IN THE LEAKAGE CURRENT REGION

For the discussions in this paper, it is necessary to define a voltage level close to the knee-point of the voltage-current characteristic of a varistor, where the resistive current component starts to be predominant. In accordance with the suggested new IEC standard, the reference voltage may be used for this purpose. In practice, the reference voltage is very close to the rated voltage of most high-voltage surge arresters, or the duty-cycle rating for metal-oxide surge arresters according to the ANSI/IEEE standard. The actual continuous operating voltage is usually in the range 0.6 to 0.8 p.u. of the rated, or reference voltage.

For comparison purposes, the reference voltage is in the following defined at a resistive current of 3 mA_{peak} for a 75 mm diameter varistor. For other varistor diameters, the current amplitude is adjusted accordingly.

Electrical Representation of a ZnO Varistor

The electrical properties of a ZnO varistor in the leakage current range may be represented by the simplified model shown in Figure 1.

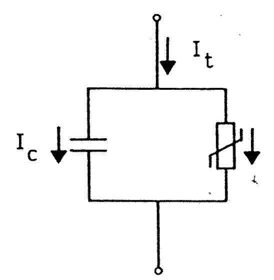

Fig. 1. Electrical representation of a ZnO varistor.

The typical specific capacitance of a ZnO varistor is 75 pF•kV/cm^2. Typical values of the capacitive current range from 0.5 to 3 mA_{peak} depending on the varistor diameter. For a complete surge arrester, the capacitive current is dependent on the number of varistor columns in parallel, the stray capacitancies, and the actual operating voltage.

The resistive component of the leakage current of a varistor is at the same time in the range 50 to 250 μA_{peak}. Typical resistive leakage currents for a 75 mm diameter ZnO varistor are shown in Figure 2 for two temperatures, +20°C and +50°C. The applied voltage is expressed in p.u. of the reference voltage of the varistor.

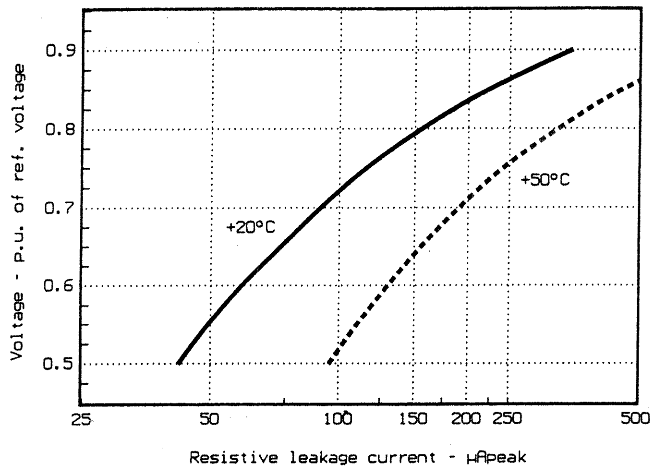

Fig. 2. Typical resistive leakage currents for a 75 mm diameter ZnO varistor.

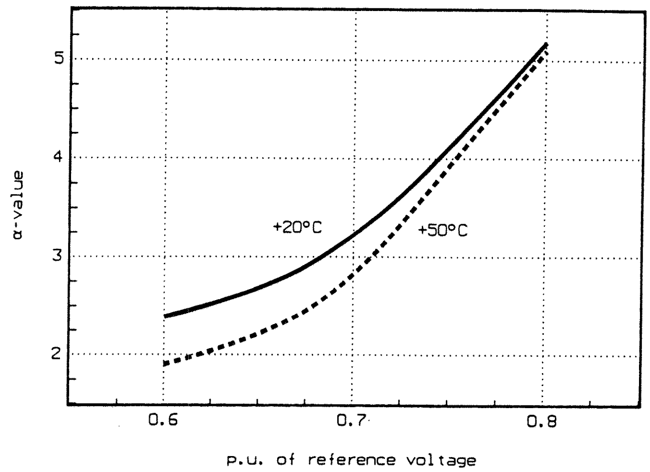

Fig. 3. Typical α-values in the leakage current region.

The resistive characteristics of a varistor may be expressed in terms of the α-value:

$$I_r = k \cdot U^{\alpha} \quad (1)$$

where I_r is the resistive current
U is the voltage
k is a material-specific constant
α is a function of temperature and voltage

In a normal application, the surge arrester operates at a continuous voltage stress of between 0.6 and 0.8 p.u. of the rated voltage. Since the rated voltage in this context may be considered practically equal to the reference voltage, the α-values of Eq. 1 can be obtained from Figure 2. The results are presented in Figure 3, where it can be seen that the α-value is between 2 and 5 at normal operating voltages. However, the characteristics in the leakage current range may vary from one varistor manufacturer to another.

EXISTING METHODS FOR MEASUREMENT OF SURGE ARRESTER LEAKAGE CURRENTS IN SERVICE

The different methods utilized to give a measure of the resistive leakage current in normal operating conditions are described in the following sections.

Measurement of the Total Leakage Current

Measurement of the total leakage current is commonly implemented by means of a permanently installed mA-meter, which shows the average of the rectified leakage current, or by a portable instrument for average and peak level measurements. The sensitivity of this method to an increase in the resistive component of the leakage current, was studied by application of the varistor model shown in Figure 1. The capacitive current component was assumed to be 1 mA_{peak}, and the resistive component was varied from 50 to 500 μA_{peak}. The increase in the average leakage current is shown in Figure 4. The results are valid for all α-values between 2 and 5.

As seen in Figure 4, a resistive current of 500 μA_{peak} gives a 10 % higher reading, but at 250 μA_{peak} the increase is only 3 %, which means it is hardly visible on an instrument. Peak level measurements are even less sensitive; a resistive

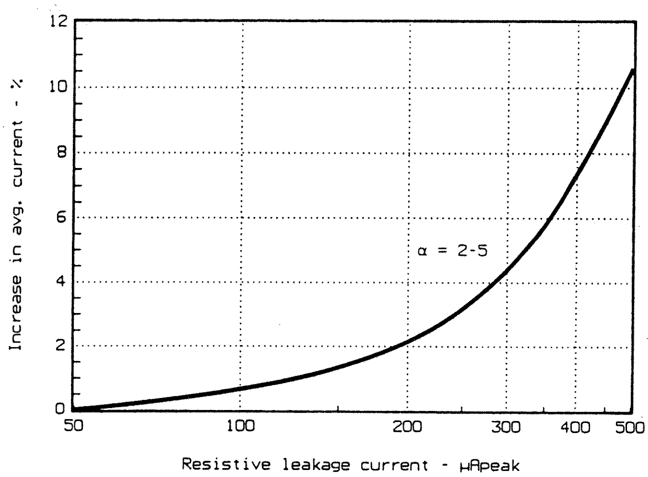

Fig. 4. Increase in average leakage current.

current of 700 μA_{peak} is required to increase the peak level by 5 %. Considering normal variations in the system voltage, which also influence the average and peak levels, it is obvious that this method is definitely inadequate for determining the condition of a surge arrester.

Direct Measurement of the Resistive Leakage Current

A direct determination of the resistive leakage current component is the most desirable method since it allows an immediate comparison with the expected resistive current level at the prevailing operating conditions.

The resistive component of the current is found by registrating the leakage current at the instant when the voltage across the arrester is at its peak. However, this method is usually hard to apply in practice. First, it requires that the voltage across the arrester is measured simultaneously with the leakage current and, secondly, that the phase-shift of the voltage measurement is negligible. Furthermore, it is required that potential transformers fulfilling this requirement, are present in all phases, and that connections can be made during operation of the system.

From this, it is clear that a direct measurement of the resistive leakage current is possible to perform in special cases, but the method is not suitable for checking the condition of arresters on a regular basis.

Harmonic Analysis of the Leakage Current

Due to the nonlinear resistance of the ZnO varistors, the leakage current contains harmonics when the arrester is energized with a sinusoidal voltage. Since the amplitudes of the harmonic currents increase with the resistive component of the leakage current, the harmonic content can be used as an indicator of the arresters condition. Different implementations of this method have been presented in the past: Determination of the ratio of the sum of the harmonics to the total leakage current [1], and measurements of the third-order harmonic current alone [2].

The presence of harmonics in the system voltage may, however, interfere with the harmonics generated by the nonlinear resistance of the surge arrester. The amount of harmonics in the system voltage varies with the type of load and with the system voltage level. For the higher voltage levels considered in this paper, about 60 kV and above, it is generally recommended that the third-order harmonic content is below 1 to 1.5 % [3,4].

For an arrester with a typical capacitive leakage current of 1 mA_{peak}, a 1 % third-order harmonic in the voltage generates a capacitive harmonic current of 30 μA_{peak}. As will be shown later in the paper, this harmonic current is on the same order of magnitude as the typical third-order harmonic current generated by the nonlinear resistance of the arrester. Thus, large errors may be introduced in the determination of the third-order harmonic current by this method.

NEW METHOD FOR HARMONIC ANALYSIS OF SURGE ARRESTER LEAKAGE CURRENTS

The new method for harmonic analysis of the leakage current is based on a compensation technique, where the third-order harmonic current generated by harmonics in the system voltage is eliminated in order to obtain the third-order current component generated by the surge arrester alone. Furthermore, a relation is established between the third-order harmonic of the resistive current, and the total resistive current. (In the following, I_n denotes the n:th-order harmonic of the current I.)

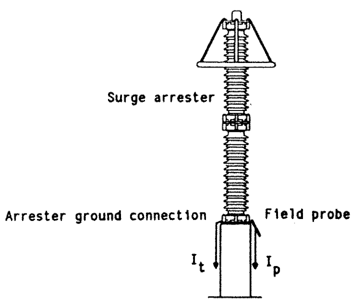

Fig. 5. Total leakage current and field probe current at the base of a surge arrester.

Referring to Figure 1, a third-order harmonic in the voltage generates a capacitive current component I_{3c} of the same frequency. The contribution of this current to the total third-order harmonic current I_{3t} may be significant, as previously discussed. If, however, the capacitive third-order harmonic current I_{3c} is subtracted from the total third-order harmonic current I_{3t}, the third-order harmonic current I_{3r} generated by the non-linear resistance of the arrester is obtained:

$$\bar{I}_{3r}=\bar{I}_{3t}-\bar{I}_{3c} \qquad (2)$$

The current I_{3r} is in the following referred to as the resistive third-order harmonic leakage current. The amplitude and phase angle of the current $I3_t$ can be obtained by Fourier transformation of the total leakage current I_t measured in the ground connection of a surge arrester, as shown in Figure 5.

The capacitive third-order harmonic current I_{3c}, on the other hand, can not be directly determined. It is, however, possible to perform an indirect determination of I_{3c} by means of electric field measurements, as discussed in the following section.

Determination of the Capacitive Harmonic Current

The capacitive third-order harmonic current I_{3c} can be determined by measuring the current I_p induced in a field probe positioned in the electric field surrounding the surge arrester, as shown in Figure 5. After Fourier transformation of I_p, the third-order harmonic current I_{3p} is obtained.

If the amplitude and phase angle of I_{3p} can be related to I_{3c}, the resistive third-order harmonic current I_{3r} can de found according to Eq. 2.

The current I_{3c} depends mainly on the third-order harmonic in the voltage in the phase to which the arrester is connected, and to some extent on the voltages in the adjacent phases by the influence of stray capacitancies. The probe current I_{3p}, on the other hand, depends only on stray capacitances, which means that I_{3p} is more influenced by the adjacent phases. The methods used to relate the phase and amplitude of I_{3p} to I_{3c} are discussed in the following sections.

Phase Angle of Capacitive Harmonic Current

It is reasonable to assume that the third-order harmonics in the phase voltages has the same phase angle ϕ_3 with respect to the fundamental frequency of each phase. If only the fundamental frequency and the third-order harmonic are considered, this can be expressed as:

$$U_n(t)=U_{1n}\cdot\cos(2\pi ft + n\cdot 2\pi/3) + U_{3n}\cdot\cos(3\cdot 2\pi f\cdot t + 3\cdot n\cdot 2\pi/3 + \phi_3) \qquad (3)$$

where n=0,1,2 for the three phases
f is the fundamental frequency

Here, the main advantage with third-order harmonic analysis of the leakage current can be observed. As can be seen in Eq. 3, all three third-order harmonic voltages U_{3n} differ in phase angle by a multiple of 2π rad, and can therefore be seen as a zero-sequence voltage with a frequency three times the fundamental frequency of the system. Thus, I_{3p} has the same phase angle as I_{3c} independent of the position of the field probe.

Amplitude of Capacitive Harmonic Current

Since the capacitance of the field probe is generally not known, a scaling procedure for I_{3p} has to be introduced, thus enabling the amplitude of I_{3c} to be determined. The scaling is based on a comparison of the fundamental frequency components I_{1t} and I_{1p}. The method is justified since I_{1t} is predominantly capacitive, which means that the amplitude is not very sensitive to an increase in the resistive current component. This is shown in Figure 6 where the amplitude of the fundamental component I_{1t} is shown as a function of the resistive current I_r for α-values between 2 and 5. The capacitive current component I_c is assumed to be 1 mA_{peak} and the typical resistive current is therefore in the range 50 to 250 μA_{peak}.

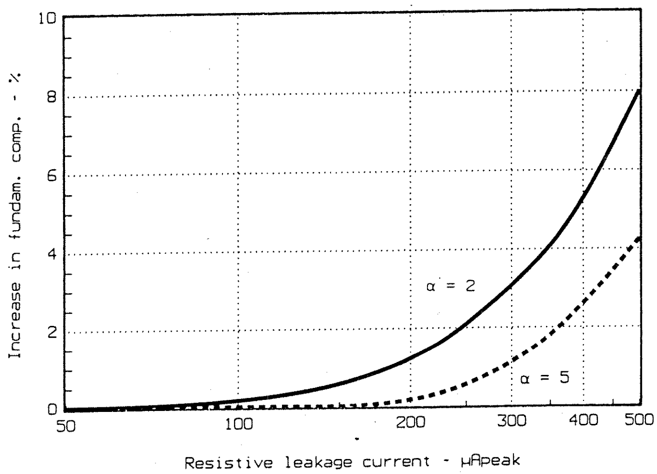

Fig. 6. Increase in fundamental frequency component vs. the resistive current amplitude.

As seen in Figure 6, the increase in the fundamental current is only a few percent within the practical range of resistive currents. Thus, I_{1t} can be considered practically equal to I_{1c}, and the relation between the amplitudes of the fundamental frequency components I_{1t} and I_{1p} can be expressed as:

$$k_1=I_{1t}/I_{1p} \tag{4}$$

The capacitive third order harmonic current can now be scaled according to Eq. 5:

$$I_{3c}=k_3 \cdot I_{3p} \tag{5}$$

The multiplier k_3 is introduced since k_3 is not always equal to k_1, as will be discussed in the following. Referring to Eq. 4 and 5, and assuming that I_{1t} is practically equal to I_{1c}, k_3 may be expressed as:

$$k_3=k_1 \cdot I_{1p}/I_{1c} \cdot I_{3c}/I_{3p} \tag{6}$$

For each frequency, the currents are proportional to the electric field strengths. Thus, Eq. 6 can be rewritten:

$$k_3=k_1 \cdot E_{1p}/E_{1c} \cdot E_{3c}/E_{3p} \tag{7}$$

In a single-phase application, the relation between the fundamental frequency and third-order harmonic electric field components is constant and independent of the location in space. This means that k_3 is equal to k_1.

In a three-phase application, however, the relation between the electric field components depends on the position in space. This is due to the phase shift (2π/3 rad) between the the fundamental frequency components of the three phase voltages. For the third-order harmonic components, there is no corresponding phase shift, as discussed previously. As a consequence, k_3 is not generally equal to k_1 in a three-phase application.

Electric Field Calculations

To determine the relation between k_1 and k_3 at the location of the field probe, the electric fields at the base of the arrester were calculated for two typical three-phase surge arrester configurations. In order to cover a large range of phase spacings, arrester heights, number of arrester units etc., the calculations were carried out for two system voltages: 145 kV (single-unit arrester) and 420 kV (three-unit arrester).

The geometries of the surge arrester configurations are given in Table I. The arresters are assumed to be positioned close to a wall simulating a large grounded object, e.g. a transformer. It should be noted that the effect of the wall on the electric field strength is small compared to the effect of the adjacent phases.

TABLE I

GEOMETRIES FOR ELECTRIC FIELD CALCULATIONS

Dimensions	145 kV	420 kV
Phase spacing (m)	1.5	5.0
Arrester piedestal height (m)	2.0	2.0
Total arrester height (m)*	3.3	6.4
Distance to grounded wall (m)	1.1	3.0

* incl. piedestal

The electric field strengths at the base of the arresters, where the field probe is positioned, were calculated using a BEM (boundary element method) computer program developed specifically for three-dimensional, three-phase applications [5]. For the calculations, the arresters were energized with the normalized voltages shown in Table II.

TABLE II

NORMALIZED VOLTAGES FOR ELECTRIC FIELD CALCULATIONS

Frequency component	Phase no. 1	2	3
Fundamental	-50 + j87	100	-50 - j87
3rd order harm.	100	100	100

Results obtained from the electric field calculations are shown in Figure 7 in terms of equipotential lines around the base of phase no. 2 of the 145 kV arrester.

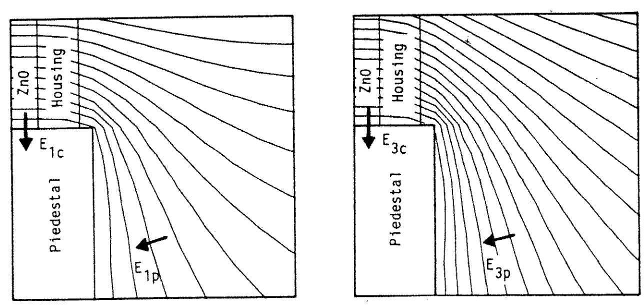

Fig. 7. Fundamental frequency and third-order harmonic fields at arrester base.

The field strength ratios E_{1p}/E_{1c} and E_{3c}/E_{3p} of Eq. 7 can be determined directly from Figure 7. The field strengths E_{1c} and E_{3c} are found at the bottom of the ZnO columns, while E_{1p} and E_{3p} are found at the assumed position of the field probe, 10 cm below the base of the arrester and 5 cm outside the piedestal.

The results of the electric field calculations for the two surge arrester configurations are presented in Table III in terms of the ratio k_3/k_1.

TABLE III

CALCULATED RATIOS OF ELECTRIC FIELD STRENGTHS

Surge arrester configuration	Phase no. 1	2	3
145 kV	0.70	0.69	0.70
420 kV	0.82	0.80	0.82

Despite the large differences in surge arrester configuration (phases spacings, single-unit vs. three-unit arresters etc.), the ratio of k_3/k_1 is fairly constant, as seen in Table III. For practical use, it is therefore possible to apply one single ratio, e.g. 0.75, to be used for both center and outer phases at all system voltage levels.

Determination of Resistive Third-Order Harmonic Current

Referring to Eq. 2, 4 and 5, the resistive third-order harmonic leakage current of an arrester can now be determined from Eq. 8:

$$\bar{I}_{3r}=\bar{I}_{3t} - 0.75 \cdot I_{1t}/I_{1p} \cdot \bar{I}_{3p} \tag{8}$$

As previously discussed, the resisitive third-order harmonic leakage current can be used to determine the condition of a surge arrester during normal operation. However, the method is limited to comparative measurements only, since the expected resistive third-order harmonic current for the arrester is not generally known. On the other hand, the expected total resistive current for a surge arrester, as a function of the applied voltage stress and varistor temperature (see Figure 2), can usually be obtained from the manufacturer. In the following section, the relationship between the resistive third-order harmonic current and the total resistive current, is discussed.

Determination of the Total Resistive Leakage Current

With reference to the simplified model of a ZnO varistor shown in Figure 1, the relation between the total resistive current I_r, as given by Eq. 1, and the third-order harmonic current I_{3r}, was calculated theoretically for α-values ranging from 2 to 5. The result is shown in Figure 8.

By using the typical relations between the voltage stress and the α-value shown in Figure 3, it is possible to redraw Figure 8 in such a way that the ratio of the total resistive current to the resistive third-order harmonic current can be expressed as a function of the voltage stress. This was done in Figure 9 for varistor temperatures of +20°C and +50°C.

RESULTS FROM MEASUREMENTS ON VARISTORS

The theoretical relations between the total resistive leakage current and the resistive third-order harmonic leakage current obtained in the previous section were compared with results from laboratory measurements on varistors.

The test program comprised varistors of different diameters from several manufacturers. The measurements were performed on both new and aged varistors at room temperature as well as higher temperatures. Tests were

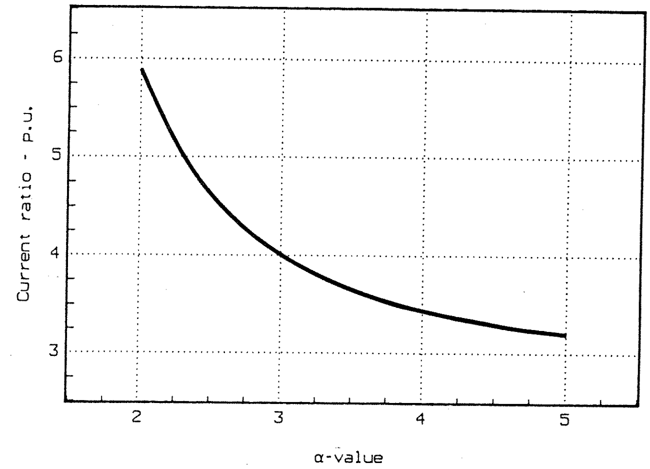

Fig. 8. Ratio of total resistive current to the resistive third-order harmonic current as a function of the α-value.

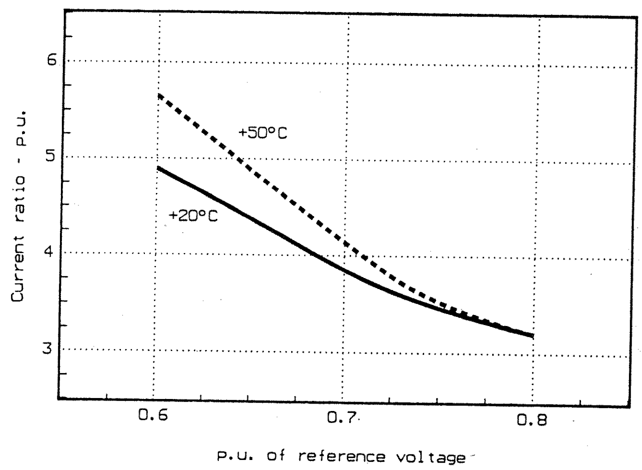

Fig. 9. Ratio of total resistive current to the resistive third-order harmonic current as a function of the voltage stress.

also carried out with an increased harmonic content in the test voltage.

The total leakage current was measured simultaneously by two separate devices; a digital oscilloscope for measurement of the total resistive leakage current, and a computer-based system for determination of the resistive third-order harmonic leakage current.

The oscilloscope was connected to a resistive shunt for current measurement, and to a resistive voltage divider for measurement of the test voltage. The computer-based system was connected to a field probe attached close to the high-voltage conductor feeding the varistor, and to a current transformer. The leakage current was measured according to the zero-flux method [1].

The varistors were energized with test voltages ranging from 0.6 to 0.8 p.u. of the reference voltages, thus representing the voltage stress region usually found in normal surge arrester applications.

The first test was performed at room temperature on varistors from four different manufacturers. The varistor diameters varied from 41 to 75 mm and the reference voltages were in the range 2.9 to 4.4 kV_{rms}. The aim of the test was to determine the ratio of the total resistive current to the third-order harmonic current as a function of the applied voltage stress. The third-order harmonic content in the test voltage was low, about 0.2 %.

The results are presented in Figure 10. For make A, seven varistors of various diameters were used, therefore, the mean value at each voltage stress is given along with the standard deviation. For make B, C and D, only one varistor was used.

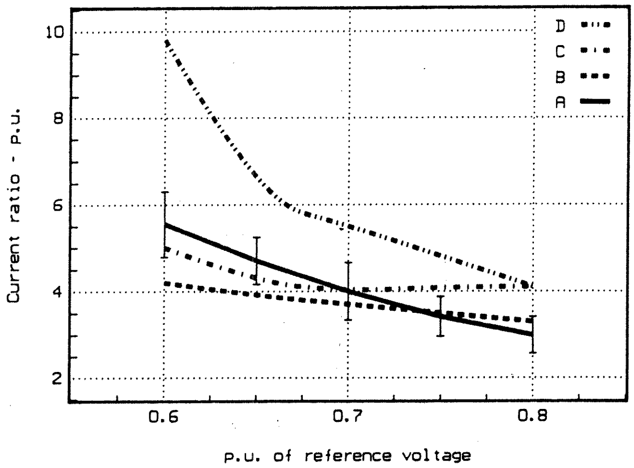

Fig. 10. Ratio of total resistive current to third-order harmonic current for varistors of make A, B, C and D.

The influence of varistor ageing on the total resistive to third-order harmonic current ratio was determined from measurements on a 75 mm diameter varistor of make A. The varistor, without a protective surface coating, was aged by exposition to a special non-oxygen atmosphere before the test, resulting in a ten-fold increase in the resistive leakage current. The result of this test is seen in Figure 11 for varistor temperatures of +20°C and +50°C. The temperature dependence was determined by measurements on a none-aged 75 mm diameter varistor of make A. Result for varistor temperatures of +20°C and +50°C are shown in Figure 11.

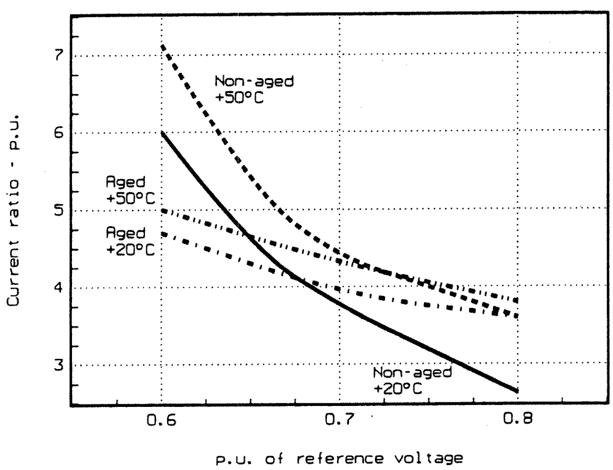

Fig. 11. Ratio of total resistive current to third-order harmonic current for aged and non-aged varistors at different temperatures.

Finally, the sensitivity of the new measuring method to a high harmonic content in the voltage was determined by adding a third-order harmonic voltage to the applied test voltage. This was done by connecting an additional transformer in series with the high-voltage winding of the test transformer. By feeding the transformer from an LF-generator via a high-power audio amplifier, it was possible to obtain up to 3 % of third-order harmonic content in the test voltage.

The tests were carried out on a 75 mm diameter varistor of make A with a third-order harmonic content of 0.2, 1, 2 and 3 %. The phase angle of the harmonic was slowly varied with respect to the fundamental frequency of the test voltage. As the phase angle of the third-order harmonic was varied, the total resistive current varied also, especially for the higher harmonic contents. The total resistive current was taken as the mean of two readings on the oscilloscope; when the harmonic was in phase with the fundamental frequency, and when it was in opposite phase to the fundamental frequency of the voltage. The resistive third-order harmonic current was taken as the mean of ten consecutive analyses while the phase angle varied. The ratios of these two mean levels are shown in Figure 12. The shapes of the test voltage and the total leakage current for a 3 % harmonic content in the voltage as measured by the oscilloscope, is shown in Figure 13.

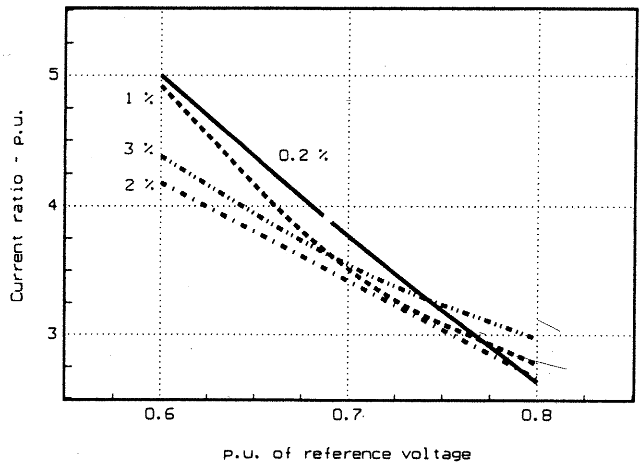

Fig. 12. Mean ratio of total resistive current to third-order harmonic current for different harmonic contents in the test voltage.

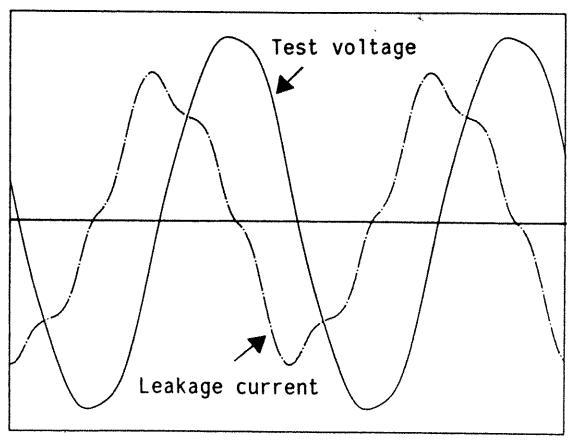

Fig. 13. Test voltage and total leakage current at a harmonic content of 3 % in the test voltage.

The tests show that the ratio of resistive third-order harmonic current to total resistive current is fairly stable, despite the distorded waveform.

NEW INSTRUMENT FOR LEAKAGE CURRENT MEASUREMENTS

The new method for leakage current measurements was implemented in a new microcomputer based leakage current monitor, developed and designed especially for in-service measurements of the continuous leakage current of gapless ZnO surge arresters. The leakage current monitor is intended to be connected to a permanently installed surge counter with a built-in current transformer, and it consists of three main parts, as shown in Figure 14:

- A current probe attached to the connector on the surge counter. The current probe includes electronic circuitry for measurement of the leakage current by means of the zero-flux method.
- A field probe, positioned near the base of the arrester, and connected to the current probe via a coax cable and an adaptor. The current induced in the field probe is taken to the adaptor, which contains a measuring resistor and protection circuitry. The field probe signal is further amplified in the current probe.
- A leakage current instrument with built-in microprocessor for determination of the resistive component of the leakage current according to the method described.

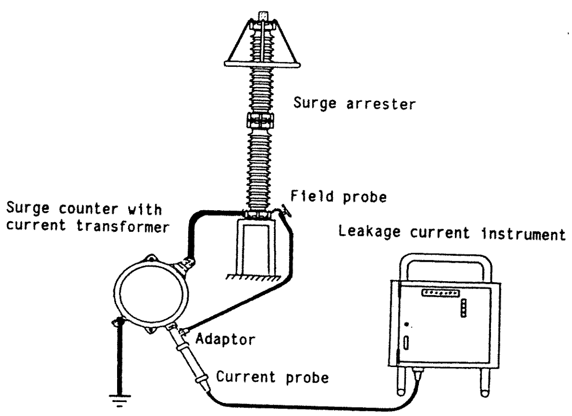

Fig. 14. Principal design of the leakage current monitoring equipment.

Application of the Leakage Current Monitor

The leakage current monitor is intended to be connected to a permanently installed surge counter having a built-in current transformer. This type of surge counter represents a short circuit between its main terminals. In case another type of surge counter with an internal impedance greater than a few ohms is installed, the measurement may be carried out by connecting, in parallel, the first type of surge counter on a temporary basis.

The leakage current monitor may be used in three different ways:

- As a portable instrument for checking the conditions of the surge arresters on a regular basis.
- To monitor the condition of an arrester during a shorter or longer period of time, for instance to investigate in more detail the behaviour of an arrester which shows a leakage current higher than expected. Thus, temporary increases in the resistive leakage current caused by high temperature may be distinguished from the continuous level.
- Permanently installed for continuous registration of the leakage current in surge arresters that are of very great importance to the operation reliability of the system.

To enable temporary or permanent outdoor use, the equipment is made completely weather-proof and provided with a heater that will be automatically switched on if the temperature becomes too low.

When used as a portable measuring equipment the field probe is mounted on a rod of the telescope type made of insulating material, making in-service installation on arresters possible.

Description of the Leakage Current Instrument

Figure 15 shows a block diagram of the instrument. The input signals, proportional to the total leakage current and the field probe current, pass through autoranging circuits where the signal levels are adjusted to the microprocessor analog input range. The signals are filtered before entering the multiplexer (MUX) and analog/digital (A/D) converter part of the microprocessor.

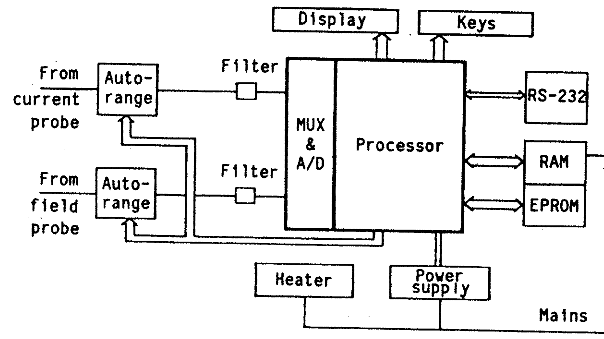

Fig. 15. Block diagram of instrument unit.

The computer program controlling the instrument and calculating the resistive leakage current, is stored in the EPROM. Measured values are stored in the RAM with battery backup to prevent loss of data when the power supply is off.

The operator communicates with the instrument via four keyboard switches and a display, allowing the operator to set up instrument parameters, read instrument settings and data, or to output stored data to a personal computer via the RS-232 interface.

The shape of the total leakage current and the field probe current can be studied via oscilloscope output connectors.

Leakage Current Data Handling

Every ten minutes the leakage current monitor stores the measured resistive leakage current value into the internal memory (RAM). The stored value is the mean of five measurements made within the 10-minute period.

A reference value, corresponding to the expected (or nominal) resistive leakage current of the arrester is set at the beginning of the measurements, and stored in the instrument. The successive measurement results are presented in p.u. of the reference value.

The influence of possible external leakage currents occurring on the arrester housing due to pollution is suppressed and will not influence the leakage current mean values stored. The effect of pollution resulting in an increased resistive leakage current due to increased temperature is, however, included in the mean values.

Data stored in the memory for reading on the display include:

- all 10-minute recordings for the last hour.
- one-hour mean values for the last 24 hours.
- mean value for the last week.
- 24-hour mean values for the last month.

- monthly mean values for the last year.
- yearly mean values.

Data stored in the memory for output to the RS-232 interface for reading by a personal computer comprise, in addition, all 10-minute values for the last week.

Protection of the Leakage Current Monitor

To study the influence of severe high-frequency disturbances on the operational reliability of the leakage current monitor, tests were carried out by disconnector switch operations in a 300 kV outdoor substation. A 300 kV busbar was connected and disconnected several times by pantograph disconnectors. During the tests, the leakage current monitor was connected to one of the surge arresters.

The transients caused by the restriking disconnectors disrupted the measuring cycle of the leakage current monitor. However, all recorded data remained unchanged and the instrument automatically retained correct operation afterwards.

The ability of the leakage current monitor to withstand transients occurring during lightning discharges was verified by a 100 kA, 4/10 µs high-current impulse applied to the surge counter. The leakage current monitor, connected to the surge counter in the normal manner, showed the same behaviour as during the disconnector test described above.

Measurements on Surge Arresters in a Substation

The new measuring method was tested in several substations at various system voltage levels. In one case it was possible to make a comparison with a direct measurement of the resistive leakage currents of the arresters.

These measurements were carried out in a 300 kV substation on two surge arresters (outer and center phase) during normal operation. The arresters are of make A with a rated voltage of 264 kV. The operating voltage at the time of the leakage current measurements was equal to a voltage stress of 0.66 p.u. of the rated (or reference) voltage. At this voltage stress, and at the prevailing ambient temperature (-5°C), the expected resistive leakage current of this varistor type is in the range 40 to 50 μA_{peak}. The third-order harmonic content in the system voltage was 0.3 % at the time of the measurement.

The resistive leakage currents of the arresters were measured in two ways; by a direct measurement of the resistive current, as it was described in a previous section, and by the new method for harmonic analysis of the leakage current.

For the direct determination of the resistive current, the voltage across the arrester was measured using the existing capacitive voltage transformers (CVT). The arrester leakage current was measured by means of the current transformer built-in to the surge counter, together with a zero-flux measuring unit [1]. It was assured that the phase shift of the voltage and current measurements were small enough to allow an sufficiently accurate determination of the total resistive current of the arrester.

TABLE IV

RESULTS FROM MEASUREMENTS ON 300 kV SURGE ARRESTERS IN A SUBSTATION

Phase designation	Direct measurement ($\hat{\mu A}$)	New method ($\hat{\mu A}$)
Outer	42	31-36
Center	43	27-30

For converting the resistive third-order harmonic current measured by the leakage current monitor, to the total resistive current, the harmonic current was multiplied by a conversion factor derived from Figures 10 (results for make A at +20°C) and 11 (influence of temperature). At the prevailing voltage stress and temperature, the factor was estimated to about 3.5 - 4. The results obtained by the two measuring methods are summarized in Table IV. The results are the average levels of two readings for each method.

DISCUSSIONS AND CONCLUSIONS

As mentioned earlier, a 1 % third-order harmonic content in the voltage generates a capacitive third-order harmonic current of 30 μA_{peak} in a typical surge arrester application. Referring to Figure 10, this corresponds to a total resistive leakage current of more than 100 μA_{peak}, which is on the same order of magnitude as the expected resistive current of a typical surge arrester. Thus, if harmonic analysis of the total leakage current is used without the compensation technique described in the paper, large errors are introduced by the presence of harmonics in the voltage. The error depends on the phase relation between the harmonic in the voltage and the harmonic current generated by the arrester, and may very well reach 100 %.

On the other hand, the measurements carried out on varistors show that a reasonable accuracy may be expected also at high harmonic contents in the voltage, if the new method for harmonic analysis of the leakage current is adopted.

Measurements on Varistors

The theoretically calculated ratios of total resistive current to third-order harmonic current shown in Figure 9 (valid for make A) agree fairly well with the measured ratios shown in Figure 10 for the same make.

The differences seen in Figure 10 between the varistors of various make can be attributed to the different leakage current characteristics resulting from different manufacturing processes. If the method is used for measurements of the absolute resistive current level, it is therefore necessary to determine the current ratios of Figure 10 for each varistor make, preferably based on several varistor samples. For checking surge arresters on a regular basis by comparative measurements, the ratios are not important.

The influences of ageing and increased varistor temperature (the second may obviously follow from the first) shown in Figure 11, indicate that the total resistive leakage current may still be determined with good accuracy, despite the fact that the resistive characteristics of the varistors are affected by both phenomena.

As seen in Figure 12, the influence on the average current ratios by a large third-order harmonic content in the voltage, does not affect the accuracy of the measuring method in any significant way. The effect of higher-order harmonics is eliminated by the Fourier transformation. It may therefore be concluded that the new method for harmonic analysis of the leakage current is inherently insensitive to the presence of harmonics in the voltage.

Three-Phase Applications

The electric field calculations showed that the variations in the ratio of k_3 to k_1 is quite small considering the large differences in the geometries of the two surge arrester applications studied. Since the ratio is fairly close to one, it indicates good coupling between the electric fields appearing inside the varistors and at the position of the field probe. This leads to the conclusion that the proposed ratio of 0.75 can be used generally for three-phase applications.

It should be realized that the resistive leakage current in the ground connection of a surge arrester is influenced by the actual voltage distribution along the varistor column. The voltage stress and, correspondingly, the resistive current, is usually slightly higher at the top of the arrester and lower at the base. When the total voltage across the arrester is used as reference for measuring the resistive current, as for the direct method, the measured resistive current level is close to the average level along the varistor column. When the new method for leakage current measurement is applied, on the other hand, the slightly lower resistive current appearing in the lower part of the arrester is obtained. Thus, the resistive current measured by the new method is slightly lower than expected for the average voltage stress of the complete arrester, which explains the discrepancies found in Table IV between the results for the two measurement methods.

Error Estimation for Total Resistive Leakage Current

It can be concluded from Figures 10, 11 and 12, that the margin of error in the ratio of the total resistive current to the resistive third-order harmonic current is on the order of 20 to 25 % at a given voltage stress. However, for comparative measurements on the same surge arrester at regular time intervals, a significantly better accuracy can be expected, since only the influence of varistor temperature has to be considered in addition to variations in the operating voltage level.

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