A Review of Leakage Current-based Condition Assessment of Gapless Surge Arresters

***Abstract*—A review of leakage current-based condition assessment of metal oxide gapless surge arresters is presented in this study. The fundamental principles that establish the relation between the electrical condition diagnosis of these transient overvoltage units and the resistive current component is discussed. The commonly applied techniques of resistive current extraction from the leakage current are revisited in this work. The problematic influence of supply harmonics on leakage current evaluation and the challenges related to practical measurements of the instantaneous power-based technique of assessing the resistive leakage current when the supply voltage is distorted.**

keywords - Metal oxide surge arrester, resistive current, accelerated ageing, harmonic-distortion, weibull probability density function.

I. INTRODUCTION

The application of metal oxide-based gapless surge arresters (GSA) in power networks is essential practice to ensure equipment safety and system reliability [1, 2]. In the course of power network operation metal oxide arrester-based (GSA) devices are reportedly prone to electrical failure, which could lead to reduced surge protection capabilities and to high risk of insulation breakdown, equipment damage or substation fire [3, 4]. For these reasons, the health condition of surge protective devices (SPD's) is monitored and assessed at regular time-intervals in order to ensure adequate transient clamping performance. Leakage current - based diagnostic methodology consists of one of the most commonly applied on-line condition assessment of gapless arresters [5 - 7]. However, the implementation of this methodology in AC power networks poses significant challenges with respect to accurate extraction of resistive component from measured leakage current, and the commonly reported interference of power system voltage harmonics with leakage current-based techniques of arrester's condition evaluation [8 - 11]. In this study, an analytical survey of the fundamental theoretical concepts and implementation challenges related to resistive current measurement in metal oxide-based GSA is conducted in order to determine the most practically accurate measurement of the resistive current. The findings obtained support the resistive current component as the GSA failure indicator parameter, and suggests that the active power or watt loss-based estimation of the resistive current component can be adopted unless measurement of the applied voltage is safe and practical.

II. THE RESISTIVE CURRENT EXTRACTION TECHNIQUES

The leakage current in metal oxide-based GSA consists of two fundamental current components: the capacitive component which consist of 95$\%$ of the leakage current and the resistive component consists of 2$\%$ - 5$\%$ content of the leakage current [12].

The applied voltage stress and the environmental temperature in which gapless arresters operate consist of major ageing factors in this family of SPD's [13, 14]. Therefore, the dependence of the resistive current on the supply voltage and temperature [15, 16], makes this current component to be the key indicator of the heath status of metal oxide arrester's ageing process. Based on the current components of the leakage current, the metal oxide arrester could described as indicated in figure 1. The current components could be expressed as follows:

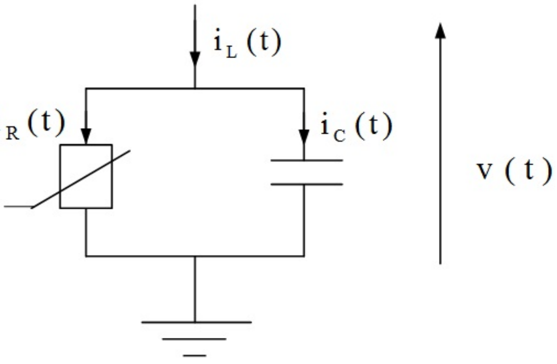

Fig. 1. Basic description of Metal Oxide Arrester.

$$i_L(t) = i_R(t) + i_C(t) \tag{1}$$

Where: I_L is the measured leakage current, $i_R(t)$ is the resistive current and $i_C(t)$ is the capacitive current component.

$$i_R(t) = f(V;T) \tag{2}$$

Where: $f(V;T)$ is a function of the supply voltage (V) and temperature (T).

To determine the health status of gapless arresters the resistive component has to be extracting from the leakage current. This requires compensation of the capacitive component. The following proposed extraction techniques are discussed:

A. The Constant Phase shift Method

The theoretical basis of this methodology is rested on the fact that the phase shift relationship between the fundamental capacitive component and the measured leakage current is constant and insensitive to the ageing process of metal oxide arrester devices [17, 18]. Based on this relationship, the resistive component can therefore be obtained by subtracting the capacitive component from the leakage current. The constant phase relationship that forms the basis of this technique is shown in figure 2. According to this method, the resistive current extraction suggests compensation of the fundamental capacitive component which could therefore be represented in terms of the following phasor equations:

$$I_R = I_L - I_L \cos\phi_{C_1} = I_L\left(1 - \cos\phi_{C_1}\right) \tag{3}$$

Where: I_R is the phasor resistive component, I_L is the phasor leakage current and $\cos\phi_{C_1}$ is the constant phase angle between the leakage current and the fundamental capacitive component.

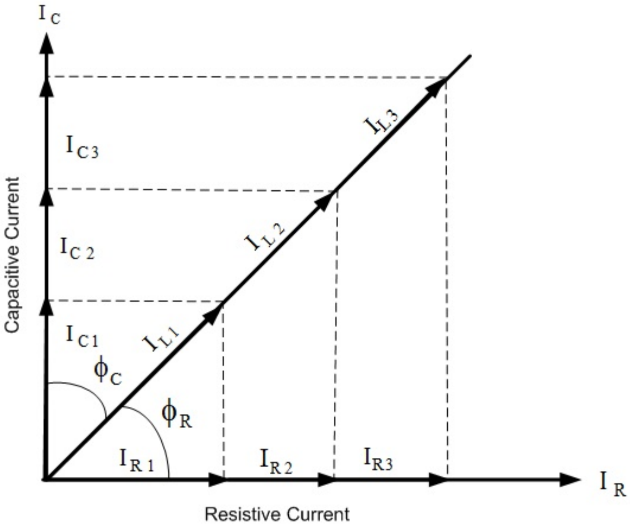

Fig. 2. Phase Relationship between Capacitive Component and Leakage Current.

Although this measurement approach requires no voltage measurement and appears to be theoretically simple, it does suffer fundamental flaws with respect to the validity of constant phase shift claim as well as on the presence of capacitive harmonic current components that constitute the capacitive current component when the supply voltage is distorted. A study conducted in [17] shows that the phase shift measured in similar arresters may differ and therefore may lead to resistive current measurement error. Furthermore, the constant phase shift method does not account for harmonic components in the supply voltage which cause the capacitive component not to consist of the fundamental only.

B. The Modified Shift Current Method

The theoretical basis promoted in this measurement technique resides on 180^o phase-shifted capacitive current injection to the measured leakage current in order to compensate for the capacitive current component [19, 20]. This could be mathematically expressed as follows:

$$i_L = i_C \cos\omega t + i_R\left(t\right) + i_C \cos\left(\omega t - \pi\right) \tag{4}$$

Where: i_L is the leakage current, $i_C \cos\left(\omega t - \pi\right)$ is the phase-shifted capacitive current injected and i_R is the resistive current component.

This method just as the previous one does not require voltage measurement and could be done on field. However, capacitive current compensation such as indicated in this method is applicable in cases with sinusoidal applied voltage across the arrester devices. In non-sinusoidal or distorted networks this method is prone to measurement errors.

C. The Multi-Coefficient Compensation Method

The multi-coefficient compensation method such as proposed in [21] builds on the variable coefficient compensation approach. The theoretical concept of this technique is based on multi-compensation of harmonic capacitive current components that result from non-sinusoidal supply voltage applied across metal oxide arresters. Therefore, the resistive leakage current is expressed as follows:

$$i_R = i_L - \sum_{h=1}^{n} k_h \cdot \cos\left(h\omega t + \theta_h\right) \tag{5}$$

Where: i_R is the resistive current, i_L is the measured leakage current, h is the harmonic order, n is the number of harmonic components, θ_h is the phase angle of the h^{th}- order harmonic and k_h is the multi-coefficient compensation.

The multi-coefficient compensation is expressed as follows:

$$k_h = \frac{\int_0^{2\pi} i_L \cdot cos\left(h\omega t + \theta_h\right) d\omega t}{\int_0^{2\pi} \cos^2\left(h\omega t + \theta_h\right) d\omega t} \tag{6}$$

This measurement approach doeas not require voltage measurement and extends current compensation to harmonic capacitive currents created in case of non-sinusoidal applied voltage. Although harmonics in the applied voltage give rise to harmonic capacitive currents, the same phenomenon is also applicable to harmonic resistive currents [22, 23]. Furthermore, the practical implementation of the multi-coefficient compensation method is expensive.

D. Harmonic Current Compensation Method

This method combines the Fourier decomposition of the measured leakage current and harmonic compensation. Since the third harmonic current (THC) of the measured leakage current and the third harmonic resistive current (THRC) show similar dependance pattern to the applied voltage and ambient temperature [24, 25], the THC is sometimes monitored to assess the health condition of metal oxide arresters. In non-sinusoidal systems, compensation is required to eliminate the supply-induced THC.

$$THRC \approx I_R^3 = I_L^3 - k \cdot \frac{I_i^3}{I_i^1} \cdot I_L^1 \tag{7}$$

Where: I_R^3 is the THC or the equivalent THRC, I_L^3 is the magnitude of the total third harmonic current measured, I_i^3 is the induced THC, I_i^1 is the induced fundamental component and I_L^1 is the fundamental component of the leakage current.

This indirect measurement technique is quite common given its low cost and easy practical implementation. The Fast Fourier Transform (FFT) is an important step in this method as it is used to produce the frequency components of measured the time-domain signal. This is followed by supply-induced harmonic current compensation. Supply-induced harmonic current as indicated previously is quite common when the applied voltage across arrester has harmonic content. However, the major issue related to this form of condition assessment is its dependance on the knowledge of the THRC which may requires other aproaches to be attempted. Generally, the rated THC of metal oxide-based GSA is not provided, and when measured it consist of low current values which may lead to erronous interpretation of the actual condition of the arrester devices.

E. The Active Power Measurement

This methodology is based on the proportional relationship that binds the active power and the resistive or active component of the current flow [26, 27]. This fundamentally requires both the current and voltage signals to be systematically measured. Considering system harmonics, the leakage current and the non-sinusoidal voltage across the arrester are given in equations (8) and (9), respectively.

$$i_L(t) = \sum_{h=0}^{n} \sqrt{2} i_{L_{max}} \sin\left[(2h+1)\,\omega t + \phi_{(2h+1)}\right] \tag{8}$$

Where: $i_L(t)$ is the instantaneous leakage current, $i_{L_{max}}$ is the maximum value of the leakage current, h is the harmonic order and n is an integer.

And the non-sinusoidal voltage is given as:

$$v(t) = \sum_{h=0}^{n} \sqrt{2} v_{max} \sin\left[(2h+1)\,\omega t + \alpha_{(2h+1)}\right] \tag{9}$$

Where: $v(t)$ is the instantaneous voltage across the arrester device, v_{max} is the maximum value of the applied voltage, h is the harmonic order and n is an integer.

The instantaneous power could therefore be obtained by using the product of equations (8) and (9). This yields the following equation:

$$p(t) = v(t) \cdot i_L(t) \tag{10}$$

Where: $p(t)$ is the instantaneous power into the metal oxide arrester device.

The instantaneous power obtained in equation (10) consisted of both the active and reactive power components. The active component could therefore be expressed on the basis the following equation:

$$P_{active} = \sum_{h=0}^{n} V_{2h+1} \cdot I_L \cos\left[\alpha_{(2h+1)} - \phi_{(2h+1)}\right] \tag{11}$$

Where: P_{active} is the active power component, V_{2h+1} is the phasor component of the applied voltage and $I_L \cos\left[\alpha_{(2h+1)} - \phi_{(2h+1)}\right]$ is the resistive current component of the leakage current.

The resistive current such as measured in this method is inclusive of all resistive harmonic current components. This is therefore written as follows:

$$I_R = \sum_{h=0}^{n} I_L \cos\left[\alpha_{(2h+1)} - \phi_{(2h+1)}\right] \tag{12}$$

The active power measurement approach essentially makes use of the IEEE power theories and definitions applicable in non-sinusoidal circuits such as described in [28, 29]. The capacitive current compensation such as required in previous techniques is not required in this methodology. The knowledge of the voltage signal or waveform in this method cannot be avoided. Therefore the application of the active power measurement is not recommended in circuits or networks where voltage measurement is impractical.

F. The Least Square-based Methodology

In this method such as detailed in [30], the time-domain expressions of the leakage current as well as its resistive and capacitive components are obtained, followed by the least squares application in order to estimate the capacitance and resistance of the metal oxide arrester. These parameters are used in the time-domain equations to simultaneously obtain the resistive, capacitive and the leakage currents. The time-domain equation of the resistive current is given as follows:

$$i_R(t) = G(v)\, v(t) = \sum_{k=0}^{n} G_{2k} \cdot v(t)^{2k+1} \tag{13}$$

Where: $G(v)$ is the non-linear conductance, G_{2k} is the $2k^{th}$ circuit parameter and $v(t)$ is the voltage across the arrester.

The least square-based approach introduces an algorithm that supports and resolve the time-domain resistive, capacitive and leakage current equations. The capacitive current compensation is therefore not applicable in this method. Although the time-domain approach is technically sound and commandable, this method should be improved to support the presence of harmonics in the applied voltage system. Just as the active power measurement, this method requires knowledge of the applied voltage.

III. CONCLUSION

A review of major approaches or techniques applied for resistive current extraction from measured leakage current is presented in this study. The fundamental concepts that guide and support the described techniques of measurement of the resistive current are therefore discussed. The following observations are therefore made:

1) The orthogonality between the resistive and capacitive current components is not enough to facilitate capacitive current compensation.
2) System voltage harmonics impose the need for full compensation of capacitive current components as well as of harmonic resistive current components.
3) Current compensation techniques do not require knowledge of the applied voltage across arrester devices. However, this may prove to be detrimental to this method since distortion on the system voltage will introduce significant measurement errors.
4) If applicable, the applied voltage should also be monitored for accurate estimation of the resistive current.

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