Influence of Harmonics Voltage on MOSA Current Extraction Methods

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Abstract

The most common monitoring method of metal–oxide surge arrester is based on leakage current measurement, particularly, the component of resistive leakage current. Nowadays, there are several analytical methods used to extract the resistive leakage current. These analytical methods need both current and voltage signals. However, in fact, electrical system voltage contains harmonics and because of these harmonics, it may affect the accuracy of resistive leakage current extraction methods in different ways. The calculated results may be in error or incorrect. It can lead to erroneous evaluation or fault assessment. This paper compares the extracted results both amplitude and signal between three different methods; improve compensation method, harmonic analysis method and current orthogonality method. The results have showed that voltage harmonics not affect resistive leakage current amplitude. However, they have an effect on current waveforms. The waveshapes obtained from different methods are not the same. Current orthogonality method gives the most accurate results because its algorithm calculates current on all frequencies and includes non-linear behavior of metal oxide material.

Keywords: metal–oxide surge arrester, resistive leakage current, resistive leakage current extraction methods, harmonics voltage

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1. Introduction

All high voltage equipment is vitally important in power system so they should be monitored and protected. Metal–oxide surge arrester (MOSA) is one of a significant protective device used to protect other electrical apparatus from surgevoltage. Nevertheless, metal–oxide surge arrester is subjected to the environment conditions and overvoltage when it has been used and these may result in degradation [1]. Thus, performance monitoring and evaluation of metal–oxide surge arresters is needed. Several off-line and on-line monitoring methods used to detect and assess surge arrester's conditions such as V-I characteristic curve analysis [2], visual inspection, thermal image, and partial discharge test [3]. Typically, the most common method is based on the measurement of leakage current. As leakage current, especially, the resistive leakage current, is well known that it is directly related to the degree of surge arrester's deterioration [4].

The total leakage current is given from two components: resistive current and capacitive current. Various analytical methods such as improve compensation method, harmonic analysis method and current orthogonality method used to extract the resistive leakage current from the total leakage current. These methods need both current and voltage signals. In fact, electrical system voltage contains other frequency components (3^{rd}, 5^{th}, 7^{th}, etc). These harmonics have an effect on total leakage current which is used as an indicator to assess MOSA's condition [5, 6]. Moreover, as the different methods have dissimilar algorithms to decompose resistive leakage current, voltage harmonics have great influence on the extraction methods in different ways. The calculated results may be different or inaccurate and in the end it can lead to the wrong assessment of surge arrester condition.

This paper attempts to clarify the influence of harmonics voltage on resistive leakage current extraction methods and offer guidance for choosing the extraction method which is suitable for the measured data, different conditions or limitation of each algorithm.

2. Current Extraction Method

In this paper, total leakage current was extracted by three analytical methods consist of improve compensation method, harmonic analysis method and current orthogonality method [7, 8].

2.1 Improve Compensation Method (ICM)

Voltage and total leakage current of surge arrester were extracted to DC and each harmonic component as following,

$$v_t(t) = V_0 + \sum_{k=1}^{\infty} V_k sin(k\omega t + \alpha_k) \quad (1)$$

$$i_t(t) = I_0 + \sum_{k=1}^{\infty} I_k sin(k\omega t + \beta_k) \quad (2)$$

where

V_0 is DC component of voltage (V)

I_0 is DC component of leakage current (A)

V_k is k harmonic peak value of voltage (V)

I_k is k harmonic peak value of leakage current (A)

α_k is phase angle of voltage (rad)

β_k is phase angle of leakage current (rad)

ω is angular frequency (rad/s)

The capacitive and resistive leakage current can be calculated by (3) and (4),

$$i_{c,k}(t) = G_k V_{sf,k}(t) \quad (3)$$

$$i_{r,k}(t) = i_{t,k}(t) - G_k V_{sf,k}(t) \quad (4)$$

The constant G_k is the compensating coefficient of k harmonic and its value is assumed that is equal to a multiply of a constant obtained from fundamental frequency (G_1) which can be obtained by solving (5),

$$\int_0^T [V_{sf,k}(t)(i_{t,k}(t) - G_k V_{sf,k}(t))]dt = 0 \quad (5)$$

where

$V_{sf,k}(t)$ is k harmonic of voltage that 90° phase shift with respect to $V_k(t)$

$i_{r,k}(t)$ is k harmonic of resistive leakage current

$i_{c,k}(t)$ is k harmonic of capacitive leakage current

$i_{t,k}(t)$ is k harmonic of total leakage current

2.2 Harmonic Analysis Method (HAM)

Referred to voltage and leakage current that applied to MOSA, the equations of both signals can be presented by (1) and (2). In addition, this method suggests that resistive leakage current is in-phase with terminal voltage and capacitive leakage current leads terminal voltage by 90 degree which are represented, respectively, as

$$i_c(t) = \sum_{k=1}^{\infty} I_{c_k} cos(k\omega t + \alpha_k) \quad (6)$$

$$i_r(t) = I_0 + \sum_{k=1}^{\infty} I_{r_k} sin(k\omega t + \alpha_k) \quad (7)$$

The total leakage current can be given as,

$$i_t(t) = I_0 + \sum_{k=1}^{\infty} I_{r_k} sin(k\omega t + \alpha_k) + \sum_{k=1}^{\infty} I_{c_k} cos(k\omega t + \alpha_k) \quad (8)$$

where

i_{r_k} is harmonic peak value of resistive leakage current

i_{c_k} is k harmonic peak value of capacitive leakage current

From (8), multiplying both sides by $sin(k\omega t + \alpha_k)$ and integrating over a period, the peak resistive leakage current is obtained by,

$$I_{r_k} = I_k[cos(\beta_k)cos(\alpha_k) + sin(\beta_k)sin(\alpha_k)] \quad (9)$$

Then multiplying both sides of (8) again by $cos(kwt + \alpha_k)$ and integrating over a period, the peak capacitive leakage current is written as,

$$I_{c_k} = I_k[sin(\beta_k)cos(\alpha_k) + cos(\beta_k)sin(\alpha_k)] \quad (10)$$

2.3 Current Orthogonality Method (COM)

This method is based on the orthogonality between resistive leakage current and capacitive leakage current. Assume i_C' is equal to the capacitive leakage current when a capacitor is equal to one Farad, and then it can be expressed as follows,

$$i_c'(t) = \frac{i_c(t)}{C} = \frac{dV_t(t)}{dt} \quad (11)$$

Integrating the product of leakage currents $i_t(t)$ and i_C' over one period of the voltage signal, we get

$$B = \int_0^T i_c'(t) i_t(t) dt \quad (12)$$

From (11), (12) and orthogonal property between resistive and capacitive leakage current, then (12) becomes,

$$B = \int_0^T i_c'(t)(i_r(t) + Ci_c'(t))dt = C\int_0^T i_c'(t)^2 dt \quad (13)$$

Then the capacitance of MOSA (C) is expressed as

$$C = \frac{\int_0^T i_c'(t) i_t(t) dt}{\int_0^T i_c'(t)^2 dt} \quad (14)$$

Additionally, $i_c'(t)$ is equal to the differential of the voltage signal $V(t)$ and it can be expressed as (15)

$$i_c'(t) = \sum_{k=1}^{\infty} k\omega V_k sin(k\omega t + \alpha_k + \frac{\pi}{2}) \quad (15)$$

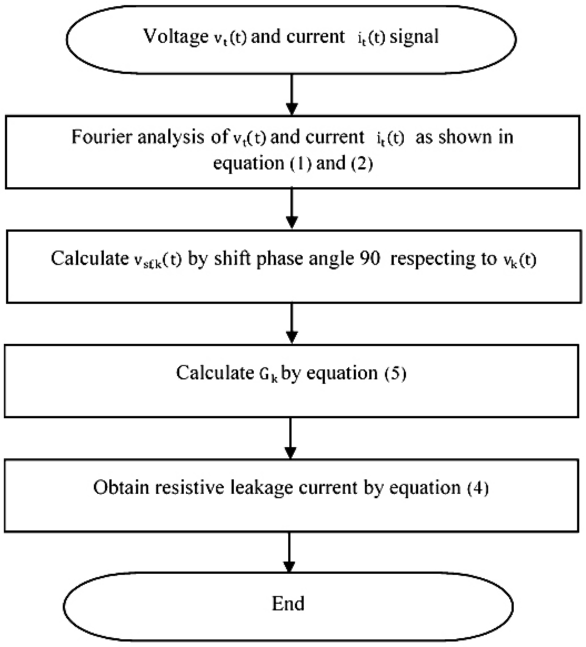
Therefore, the resistive leakage current is gotten as the following

$$i_r(t) = i_t(t) - Ci_c'(t) \quad (16)$$

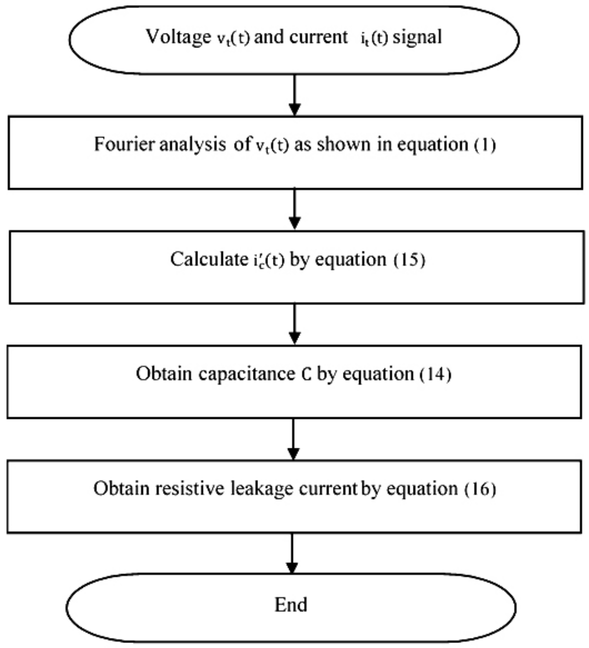
From the methods that are mentioned above, the calculation procedure of each method is presented in Figure 1.

3. Experiment

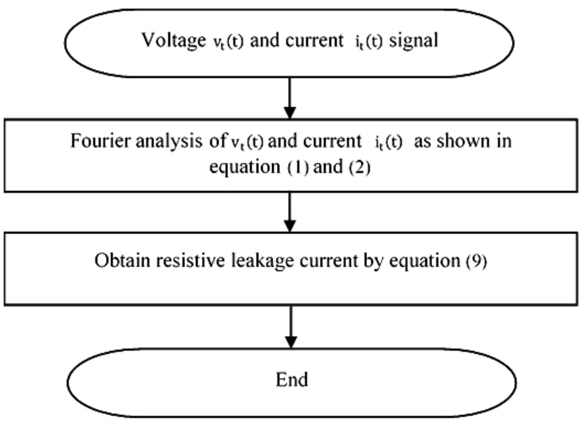
The experiment was set up and performed for measuring leakage current of surge arrester. Figure 2 shows the experiment setting up which consists of power supply, low voltage transformer, high voltage transformer, current limiting and surge arrester. In



(a) Improve Compensation Method (ICM)



(c) Current Orthogonality Method (COM)



(b) Harmonic Analysis Method (HAM)

Figure 1 Flowchart for resistive leakage current extraction

addition, two important signals are measured. Leakage current was measured by using a shunt resister and applied voltage using a capacitive voltage divider. Both signals were directly captured and shown on a digital storage oscilloscope.

The voltage source that used in this experiment is divided into two types: non-harmonic source and harmonic source. Non-harmonic source generates pure sinusoidal voltage and harmonic source generates voltage waveform which has harmonics. Moreover, the test objects used in this work are arresters equipped in Thailand's electrical distribution system.

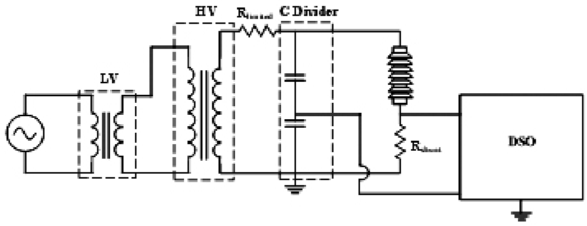


Figure 2 Experiment setting up

To investigate the effect of harmonics voltage on current extraction methods, measured leakage current and voltage were extracted by using three analysis methods: Improve compensation method, Harmonic analysis method and Current orthogonality method. All results are compared with tested current. Eventually, the magnitude and waveform of extracted leakage current results were considered.

4. Results

4.1 Non-harmonic voltage source

After extracting tested voltage by Fourier analysis, its spectrum is shown in Figure 3. It can be clearly seen that main component of voltage is the fundamental component. Other harmonic orders are not significant and their values are less than 1%.

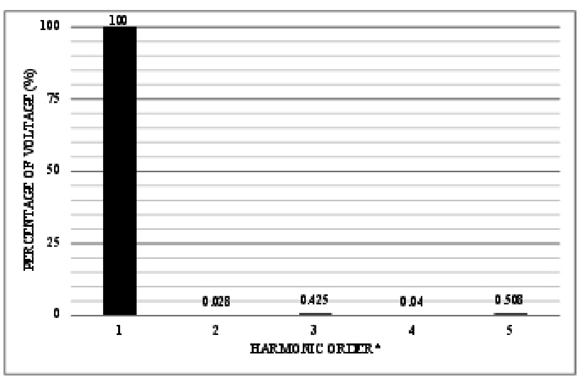


Figure 3 Voltage spectrum of non-harmonic voltage source

* 1^{st} or fundamental frequency is equal to 50 Hz

The leakage current was extracted by the analytical methods that are mentioned above. Example results of leakage current obtained from surge arrester used in 22 kV distribution system are presented in table 1.

Table 1 the leakage current in case of non-harmonic voltage source

	$I_{t-measurement}$ = 0.224718 mA		
	Extraction Methods		
Leakage Current (mA) *	ICM	HAM	COM
I_t	0.224549	0.224549	0.224718
I_r	0.150069	0.150069	0.150413
I_c	0.167027	0.167038	0.168839

* Magnitude in root mean square

From table 1, the magnitudes of resistive, capacitive, and total leakage current from each method were not different. The variation is less than 1.812 μA. In addition, their waveforms were quite the same. The examples of extracted current are shown in Figure 4 to 6.

However, due to very small harmonic as shown in Figure 3, they affect leakage current calculation process. This results in non-smooth waveforms.

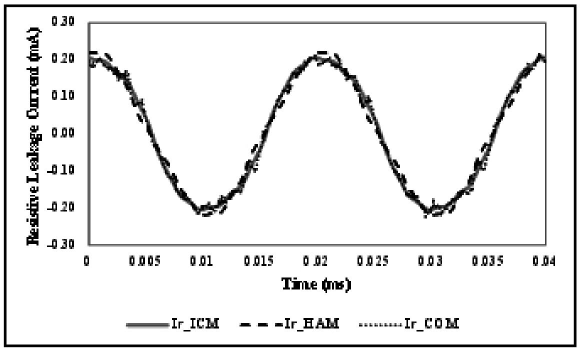


Figure 4 Resistive leakage current waveform in case of non-harmonic source

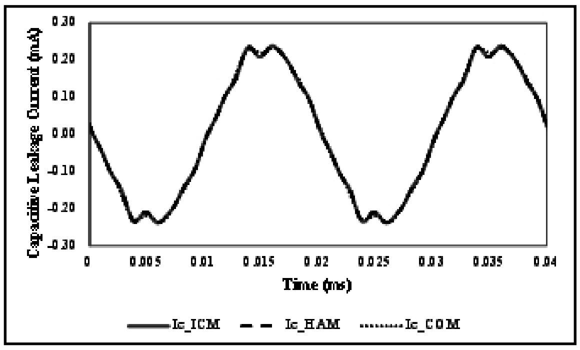


Figure 5 Capacitive leakage current waveform in case of non-harmonic source

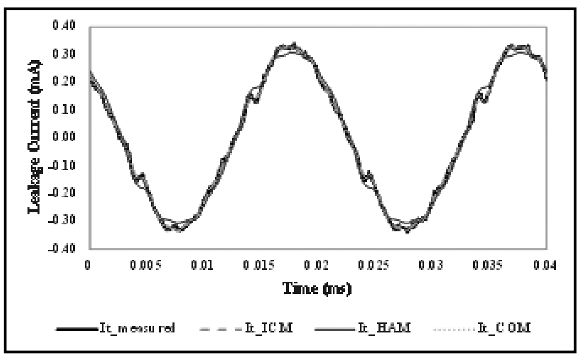


Figure 6 Leakage current waveform in case of non-harmonic source

In case of non-harmonic source, resistive leakage current calculated by three analytical methods is mostly obtained from fundamental frequency. Hence, the equation of resistive leakage current is reduced to the same form which comprises amplitude and cosine of current.

4.2 Harmonic voltage source

Voltage that was applied across surge arrester has harmonics and its spectrum obtained from Fourier analysis is shown in Figure 7.

From Figure 7, there are two important harmonic orders which are the fundamental and third harmonics with the percentage of 100 and 10, respectively.

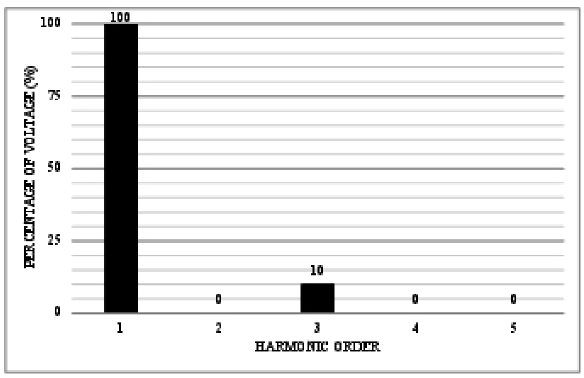


Figure 7 Voltage spectrum of harmonic voltage source

Considering the extracted current in table 2, it presents the magnitude of leakage current obtained from surge arrester for 11 kV distribution system.

Table 2 leakage current in case of harmonic voltage source

	$I_{t\_measurement}$ = 0.187306 mA		
	Extraction Methods		
Leakage Current (mA) *	ICM	HAM	COM
I_t	0.187227	0.187227	0.187306
I_r	0.074362	0.074362	0.078019
I_c	0.171826	0.171827	0.170278

Although the magnitude of resistive, capacitive, and total leakage current were still in the same order, the waveforms which acquired by three methods were totally different. Extracted current waveforms are shown in Figure 8 to 10.

From Figure 8, resistive leakage current's waveshapes gained by each method were different. Although the waveforms are different, the value of important characteristics such as period and phase are the same.

With regarding to HAM, resistive leakage current calculated by eq. (9) just computes only current component which is in-phase with voltage.

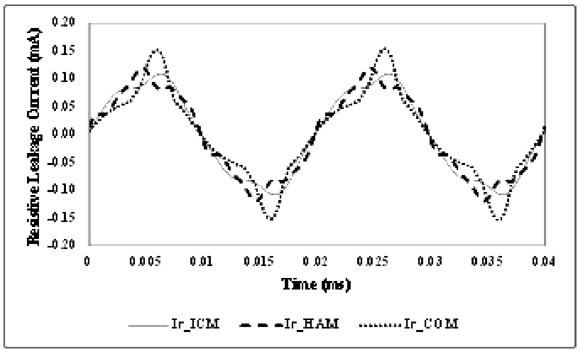


Figure 8 Resistive leakage current waveform in case of harmonic source

In contrast, resistive leakage current's calculation by ICM needs to compute value of capacitive leakage current first. It can be seen from eq. (4) that capacitive leakage current depends on compensating coefficient and voltage signal. According to eq. (5), the compensating coefficient (G_k) has many values and their values depend on frequency. Additionally, resistive leakage current of COM is calculated by using eq. (16) which depends on voltage and the actual capacitance (*C*). This capacitance has only one value and its value is computed from leakage current of every frequency. Eventually, these different algorithms result in different results.

Considering Figure 9, capacitive current waveforms acquired by ICM and COM are nearly identical. There is a little different. On the other hand, HAM provided totally different waveform. To compare the total leakage current waveforms, resistive and capacitive leakage current were combined. Comparison between calculated and tested current waveforms is shown in Figure 10.

From Figure 10, it is obviously seen that HAM has highest distortion. Thus, HAM is not suitable for leakage current analyzation when system voltage contains harmonics. When consider between COM and ICM, in the power system frequency, the value of capacitance is believed that is not a frequency-dependent.

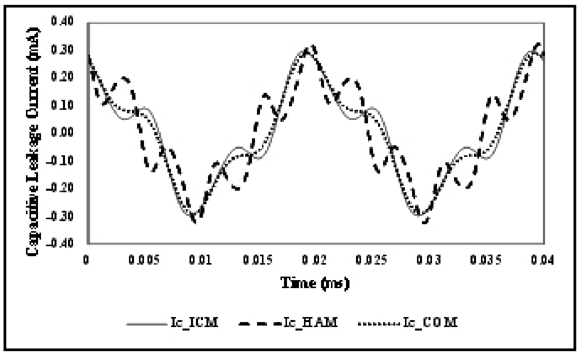


Figure 9 Capacitive leakage current waveform in case of harmonic source

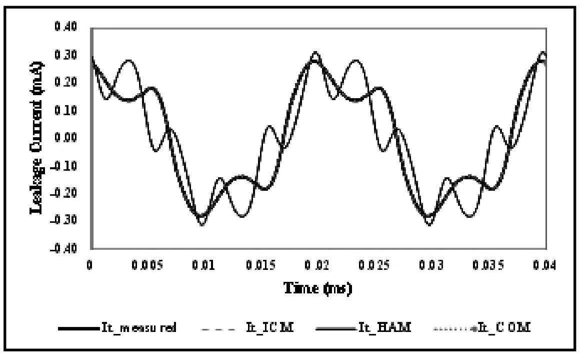


Figure 10 Leakage current waveform in case of harmonic source

Therefore, COM would be recommended on this condition. Furthermore, in fact, harmonic has always existed in electrical power system and the element of MOSA has a highly non-linear voltage-current characteristic. This non-linear behavior will generate more harmonics than found in voltage signal. However, extracted current calculated by COM always includes the effect of nonlinear relationship between voltage and leakage current. Consequently, COM is the most suitable for current extraction on voltage harmonics source.

5. Conclusion

From the extracted results, in case of non-harmonic voltage source, the results are clearly showed that although leakage current was extracted by different algorithms, there are no difference between magnitude and waveform. Thus, all extracted methods can be used on this condition. By contrast, current waveforms have distortion when voltage source compose of harmonics. From the results, HAM is not suitable for voltage source included harmonics.

We suggest that HAM is the most suitable method using for current extraction in case of non-harmonic source because this method has less complexity and calculation process. It is appropriate for a system which is limited by processor speed and less memory size. In contrast, COM would be recommended when it calculates in case of harmonic source because its algorithm calculates current on all frequencies and includes non-linear behavior of metal oxide material. However, COM is complex compu-tational procedure. It requires high performance devices.

Finally, it would be better to develop computing program or analyzing system which can select appropriate method on different conditions based on the quantity level of harmonic contents.

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