Measurement of the resistive leakage current in surge arresters under artificial rain test and impulse voltage subjection

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Abstract: Surge arresters are installed on transmission and distribution lines and in substations between phase and earth in order to improve the lightning performance and reduce the failure rates. High-energy stresses and housing deterioration are the main factors of degradation and damage of surge arresters. Thus, there is need for testing and monitoring the electrical network’s arresters, in order to verify their good condition and their ability to effectively protect the lines. The most common method used, is the measurement of the arresters’ total leakage current (with the isolation of the resistive part), which is an indicator of the arrester’s condition, since every change, deterioration or damage leads to an increase of the resistive leakage current. In the current work, the total leakage current of two 20 kV ZnO surge arresters without gaps is measured and the resistive component for three different cases (brand new arresters, measurements under artificial rain and measurements after impulse voltage subjection) is computed. The analysis of the produced results can be useful in correct diagnosis of arresters’ condition and in more effective schedule maintenance, since any recorded high-resistive currents do not necessarily result arrester’s repair or replacement.

1 Introduction

Lightning strikes are the main reason for outages in overhead transmission lines, distribution lines and in substations. In an effort to maintain high-power quality avoiding damages and disturbances, improving the lightning performance of the system, in addition to the overhead ground wires, surge arresters are installed between phase and earth. Surge arresters are designed to be insulators for nominal operating voltage, conducting at most a few milliamperes of current and good conductors when the voltage of the line exceeds design specifications, passing the energy of the lightning strike to the ground.

Several different types of arresters are available [e.g. gapped silicon carbide (SiC), gapped or non-gapped metal–oxide (MO)] and all perform in a similar manner: they function as high impedances at normal operating voltages and become low impedances during surge conditions. Even though a great number of arresters, which are gapped arresters with resistors, made of SiC are still in use, the arresters installed today are almost all MO arresters without gaps, something which means arresters with resistors made of MO [1]. MO-surge arresters are composed of a series of stacked varistor blocks, enclosed in porcelain or polymeric housing. The distinctive feature of a MO arrester is its extremely nonlinear V–I characteristic, rendering unnecessary the disconnection of the resistors from the line through serial spark gaps, as it is found in the arresters with SiC resistors. In addition MO arresters are inherently faster-acting than the gapped type, since there is no time delay due to series air gaps extinguishing the current [2].
Surge arresters are an essential part of the insulation coordination design of the power system and therefore must be reliable under steady-state as well as surge conditions. Failures have occurred that are suspected of being due to [2, 3]:

- Ingress of moisture, due to bad sealing
- Localised losses and discharging caused by poor inter-disc contact
- Housing deterioration or pollution changing the voltage distribution along the stack
- Mechanical fractures in the MO material due to thermal runaway after a high-current surge
- Damage due to surge current concentration at the edge of the electrode resulting in failure
- Resultant damage to the discs created by previous multiple-stroke lightning surges.

Thus, is obvious the importance of the arresters’ condition monitoring, since this process is capable to guarantee the reliability of the system. However, the monitoring process is expensive, especially for high-voltage systems, exceeding in almost all the cases the value of the arresters’ installation. Furthermore, the risk of measuring errors and measurements’ misinterpretations is high and might lead to unnecessary arrester replacements, which again produce additional expenses in equipment and working time [4]. All those reasons have as a result the application of sample monitoring procedures in contrast to continuous online monitoring systems from electric companies all over the world, considered as more accurate and cost-effective methods. However, the majority of the monitoring methods (either sample or online monitoring) are based on the resistive leakage current measurement, which is an indicator of the arrester’s condition. In the current work the resistive component of the leakage current is measured, using a voltage reference signal. Three different cases for the surge arresters were considered, that is, measurements with brand new arresters, measurements under artificial rain and measurements after impulse voltage subjection. It must be mentioned that this work has been focused on tests under artificial rain in contrast to the several measurements that exist in the technical literature performed under artificial pollution conditions [5, 6]. The behaviour of leakage current’s resistive component during these tests has been presented in detail since rain, that is, moisture on arrester’s polymeric housing, plays an important role in arrester’s condition. The analysis and the discussion of the produced results can be used from electric utility’s engineers in order to easily diagnose arresters’ condition leading to more effective schedule maintenance.

2 Surge arresters characteristics

The most significant technical characteristics of surge arresters according to the IEC 60099-4 are [1, 7]:

a. Continuous operating voltage ($U_{c}$): Designated rms value of power frequency voltage that may be applied continuously between the terminals of the arrester. The continuous operating voltage of the arrester must be higher than the maximum continuous operating voltage of the system.

b. Rated voltage: Maximum permissible rms value of power frequency voltage between arrester terminals at which is designed to operate correctly under temporary overvoltages.

c. Discharge current: Impulse current that flows through the arrester.

d. Residual voltage ($U_{res}$): Peak value of the voltage that appears between arrester terminals when a discharge current is injected.

e. Nominal discharge current: Peak value of lightning current impulse, which is used to classify an arrester.

f. Lightning impulse protective level: Voltage that drops across the arrester when the rated discharge current flows through the arrester.

g. Energy absorption capability: Maximum level of energy injected into the arrester at which it can still cool back down to its normal operating temperature. Standards do not define energy capability of an arrester. In IEC, there exists the term line discharge class, but since this is not enough information, various manufacturers present thermal energy absorption capability in kJ/kV ($U_{i}$), defined as the maximum permissible energy that an arrester may be subjected to two impulses according to IEC clause 8.5.5 [8], without being damaged and without loss of its thermal stability.

3 Methods and diagnostic tests

Nowadays, the determination of the condition of gapless MO arresters is achieved using many alternative methods, such as ultrasonic and radio interference detection [9], partial discharge and electromagnetic radiation measurement [10, 11], thermovision methods [12] and certainly the leakage current measurement. As it has already been mentioned earlier, the majority of diagnostic methods are based on the measurements of the leakage current. The total leakage current of a MO-surge arrester is composed of a capacitive and a resistive part, where the capacitive component is much bigger than the resistive. MO-surge arresters are known to exhibit an increase in resistive leakage current in relation with the arrester’s operating time. Furthermore, the increase rate of resistive leakage current increases, with the increase of the applied voltage and the increase of ambient temperature [8].
Any change, degradation or aging in the arrester results in an increase to the resistive component of the leakage current, while the capacitive part has little change. An increase of the resistive current can be considered as an indicator of the arresters condition, and with the continued operation time it can cause failures or permanent degradation [8]. Therefore it is obvious the importance of the arrester’s resistive leakage current measurement for the diagnosis of its condition, since the total leakage current does not contain important information, except from the case of moisture ingress into arrester, which may affect the peak value of the total current [4].

The leakage current measuring procedures can be divided into two different groups [13]. Online measurements, where the arrester is connected to the system and energised with the service voltage during normal operation, and offline measurements, where the arrester is disconnected from the system and energised with a separate voltage source on site or in a laboratory. Offline measurements can be performed with voltage sources that are specially suited for this purpose, for example, mobile AC or DC test generators. Good accuracy may be obtained by using the offline methods, provided that a sufficiently high test voltage is used. The main disadvantages of this method is the cost of the required equipment and the need for disconnecting the arrester from the system.

Measurements carried out online under normal service voltage are the most common method. For practical and safety reasons, the leakage current is normally accessed only at the earthed end of the arrester. In order to allow measurements of the leakage current that flows in the earth connection, the arrester must be equipped with an insulated earth terminal. Online leakage current measurements are usually made on a temporary basis using portable or permanently installed instruments. Portable instruments are usually connected to the earth terminal of the arrester by means of a clip-on, or permanently installed, current transformer. Long-term measurements of the leakage current may be necessary for more careful investigations, especially if significant changes in the condition of an arrester are revealed by temporary measurements. Remote measurements may be implemented in computerised systems for substation equipment supervision [13].

The most common online methods are the measurement of the total leakage current (which is not a good indicator due to the dominant capacitive current), the direct measurement of the resistive current and the indirect determination of the resistive current by means of harmonic analysis. The direct measurement can be performed using a reference voltage signal (a procedure that demands simultaneous measurement of the voltage) or by an appropriate compensation method. The third harmonic analysis [13], which does not need reference voltage signal, is based on the fact that the leakage current contains harmonics, due to the nonlinearity of the voltage–current characteristic. When the resistive current increases, the amplitude of the harmonics also increases. Main disadvantage of the method is the fact that the measurement is influenced by the voltage harmonics and the practically unknown temperature of the arrester. However, resistive current detection diagnostic methods have been improved and many researchers have presented advanced methods and convenient instruments [3, 6, 14–16].

4 Description of the measurement procedure

In the current work, the resistive leakage current for two 20 kV ZnO silicon rubber (a highly hydrophobic and resistant to UV radiation insulating material) housed surge arresters was computed for three different cases. The electrical and housing characteristics of the arresters are given in Table 1.

Case 1: The arresters were brand new and they had not ever been in operation.

Case 2: Measurement of the total leakage current with artificial rain, according to IEC 60060-1 [17], in order to simulate the effect of natural rain on external insulation of the arrester. The clean arrester is sprayed, using appropriate spray apparatus, for 15 min with water of 100 Ωm resistivity and 25 ± 1°C temperature, falling on it as droplets with a rate of 2 mm/min (avoiding fog and mist) and directed so that vertical and horizontal components of the spray intensity are approximately equal. The measurement of the arrester’s leakage current for the various applied voltage levels was performed during the test.

Case 3: Measurement of the total leakage current after impulse voltage (open circuit generator’s voltage) subjections. Each arrester was subjected to 20, 1.2/50 µs lightning impulse voltages of 20, 40 and 90 kV, with a time interval of 1 min between the impulses.

The experiments were performed in the High Voltage Laboratory of the National Technical University of Athens and in the High Voltage Laboratory of Testing Research and Standards Center of the Hellenic Public Power Corporation S.A. using the circuit of Fig. 1, consisting of a 10 MΩ protective resistance, a capacitor divider (C1 = 1200 pF, C2 = 1200 pF).

Table 1 Electrical and housing data characteristics of the arresters

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>nominal discharge current (8/20 μs), kA</td>
<td>10</td>
</tr>
<tr>
<td>residual voltage (8/20 μs, 10 kA), kV</td>
<td>62.4</td>
</tr>
<tr>
<td>height, mm</td>
<td>552</td>
</tr>
<tr>
<td>insulating material</td>
<td>silicon rubber</td>
</tr>
<tr>
<td>creepage, mm</td>
<td>1168</td>
</tr>
<tr>
<td>number of sheds</td>
<td>6</td>
</tr>
</tbody>
</table>
$C_L = 485 \text{nF}$, a measuring resistance without inductances of $10 \Omega$ and a digital two-channel oscillator. For each arrester and for each one of the three cases four measurements in 12 kV (corresponds to the line voltage), four measurements in 13.2 kV (corresponds to the continuous operating voltage of the arrester) and four measurements in 16.5 kV (corresponds to the rated voltage of the arrester) were performed.

Using the voltage as reference signal, the voltage and the total leakage current waveforms for the pre-mentioned voltage levels were measured with the use of the oscilloscope. The resistive current was the value of the total current at the instant when the voltage was at its peak. This method is commonly used in laboratories for accurate determination of the resistive current, since the reference signal is easily accessible through a voltage divider having a sufficiently small phase shift. In practice, the accuracy is limited mainly by the phase shift of the reference signal and by the deviations in magnitude and phase of the voltage across the nonlinear MO resistors at the earthed end of the arrester. The presence of harmonics in the voltage may further reduce the accuracy of the method. A restriction on the method during online measurements is the need of a reference signal\textsuperscript{13}. However, the scope of this work was not the analysis and the discussion of the measuring procedures, but the analysis of the recorded resistive leakage current measurements on arresters under artificial rain and impulse voltage subjections. Moreover, the study of these measurements could be useful in the more effective evaluation of the arresters’ condition.

### 5 Results and discussion

Figs. 2–5 show some characteristic voltage and current waveforms for each one of the three analysed cases. The current curves seem to have a sinusoidal form, but they are not perfect due to noise and electromagnetic interference. The magnitude of the noise level was almost constant during the tests, something that makes the results comparable. The electromagnetic noise affects significantly the accuracy of the measurements and this is more intense when the test is performed online in a distribution line or in a substation, where the noise level is much higher and not constant. It must be mentioned that the noise is also a function of the measuring resistance, of the grounding system and of the configuration of the system in general.

Tables 2 and 3 show the average computed resistive leakage currents for each one of the three cases for both samples. For each case and voltage level an average value of the resistive leakage current from ten measurements were computed based on oscillator’s waveform. As it was expected, the increase of the AC voltage between the arrester terminals had as a result the increase of the measured resistive leakage current. During the artificial rain test the resistive current increases, but not impressively. The resistive current is obviously higher after the impulse

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**Figure 1** Circuit for the measurement of the total leakage current of a surge arrester

\[ (C_H = 1200 \text{pF}, C_L = 485 \text{nF}, R_m = 10 \text{M\Omega}, R_p = 10 \Omega) \]

**Figure 2** Total leakage current (channel 2) for arrester No. 1 during artificial rain test, applying 16.5 kV (50 Hz AC) between the arrester’s terminal
voltage subjection test, but the increase is not linear, as the applying impulse voltage gets greater. Figs. 6 and 7 show the percentage increase of the resistive leakage current after the artificial rain and the impulse voltages subjection, according to the equation

\[
\text{Increase(\%)} = \frac{I_{R,\text{Case}} - I_{R,\text{Case}_1}}{I_{R,\text{Case}_1}} \times 100 \%
\] (1)

Table 2 Computed resistive currents in milliampere for arrester No. 1 for each one of the three cases

<table>
<thead>
<tr>
<th>Applied AC voltage, kV</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3 (20 kV)</th>
<th>Case 3 (40 kV)</th>
<th>Case 3 (90 kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.078</td>
<td>0.145</td>
<td>0.880</td>
<td>0.588</td>
<td>0.766</td>
</tr>
<tr>
<td>13.2</td>
<td>0.125</td>
<td>0.167</td>
<td>0.688</td>
<td>0.754</td>
<td>0.479</td>
</tr>
<tr>
<td>16.5</td>
<td>0.140</td>
<td>0.172</td>
<td>0.925</td>
<td>0.623</td>
<td>0.744</td>
</tr>
</tbody>
</table>

Table 3 Computed resistive currents in milliampere for arrester No. 2 for each one of the three cases

<table>
<thead>
<tr>
<th>Applied AC voltage, kV</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3 (20 kV)</th>
<th>Case 3 (40 kV)</th>
<th>Case 3 (90 kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.105</td>
<td>0.240</td>
<td>0.866</td>
<td>0.862</td>
<td>0.860</td>
</tr>
<tr>
<td>13.2</td>
<td>0.125</td>
<td>0.163</td>
<td>0.769</td>
<td>0.724</td>
<td>0.666</td>
</tr>
<tr>
<td>16.5</td>
<td>0.151</td>
<td>0.195</td>
<td>0.906</td>
<td>0.760</td>
<td>1.010</td>
</tr>
</tbody>
</table>

Figure 6 Resistive leakage current increase measured in surge arrester No. 1, for each case and voltage level (x-axis: 1, corresponds to 12 kV applied voltage across arrester’s terminals; 2, corresponds to 13.2 kV and 3, corresponds to 16.5 kV)
where $I_{R,\text{Case}_i}$ is the measured resistive current of the $i$th case and $I_{R,\text{Case}_1}$ is the measured resistive current of the Case 1.

The increase of the resistive current had as a result the increase of the varistor temperature, something that does not necessarily lead to degradation or damage of the arrester. The results are useful for online monitoring, since it is shown that higher than normal resistive current values can be owned to moisture on the polymeric housing or to impulse stresses when the measurement is performed almost immediately after impulse voltage subjection. Measurements on a regular basis must be generally performed, in order to conclude into safe results and evaluations for arresters’ condition since such cases where the resistive current is presented higher do not always indicate the need for repair or replacement.

6 Conclusions

The measurement of the total leakage current and the isolation of the resistive component is a laborious procedure. As referred in IEC 60099-5 [13], the use of this method for online monitoring is limited due to the difficulties that arise in the measurement of the total leakage current such as electromagnetic noise and resistive leakage current computation, since this is much smaller than the capacitive component. Furthermore, the accuracy of the method is influenced significantly from the phase shift of the voltage reference signal and the presence of harmonics.

In the present work, the resistance leakage current for two 20 kV ZnO surge arresters was computed for three different cases (measurements on brand new arresters, measurements under artificial rain and measurements after 1.2/50 μs impulse voltage subjection of 20, 40 and 90 kV). The results have shown that the resistive current during the artificial rain test presented a little increase, and after the impulse stresses had significantly higher values without any linear relation. The increase of the resistive current under the artificial rain is owed to the rain drops in the polymeric arrester’s surface. Consequently, an increase to the resistive component value of a surge arrester, which is installed on a distribution or transmission line does not necessarily mean that the arrester is in a bad condition but probably is due to possible moisture on the arrester’s outer surface. In the case of the impulse voltage subjection, and especially when the measurement is performed immediately after the voltage subjection, the resistive current is presented higher, as the temperature of the inner varistor is higher after the voltage strain. Power utilities should take into consideration the above remarks and take measurements on a regular basis, in order to be certain that the increase of the resistive current is due to permanent degradation or damage, and not because of temporary rise of the varistor temperature or moisture on the arresters’ polymeric housing.

The measurements have also shown that the results presented great sensitivity to the grounding system, to the presence of instruments and devices with strong electromagnetic radiation, and to the measuring instruments and the configuration of the measuring system. The measurement of the total leakage current and the computation of the resistive part was difficult and challenging, even though if it was performed in a laboratory, where the conditions were controlled, in contrast with online tests, where the interferences would be more intense. Finally, it has been clear that high measured resistive currents do not necessarily imply a damaged surge arrester and in regular basis measurements must be performed, in order to come in safe conclusions.

7 Acknowledgments

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8 References


