A Novel Approach to the Ageing Process of Metal Oxide Surge Arresters

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ABSTRACT

Gapless surge arresters constructed with zinc oxide (ZnO) elements, commonly known as Metal Oxide Surge Arresters (MOSA), are widely used for protecting electrical systems from lightning-induced overvoltages. Over time, these arresters are subjected to various environmental and electrical stress factors such as continuous overvoltages, lightning surges, elevated temperatures, pollution, and humidity. These factors contribute to the ageing of the surge arrester, which leads to a degradation in its performance. Thus, assessing the health of a surge arrester is crucial for system reliability, and one of the most effective diagnostic methods is the measurement of leakage current. In this study, the effects of ageing on the performance of MOSA have been investigated through a novel ageing procedure, and its impact on arrester performance has been systematically analyzed. The degradation was evaluated through leakage current measurements, and the results were further validated by conducting standard electrical tests in a high-voltage laboratory.

Keywords-Metal Oxide Surge Arrester (MOSA); ageing; leakage current; resistive leakage current

I. INTRODUCTION

Metal Oxide Surge Arresters (MOSA) are critical components in power systems, designed to protect against switching and lightning-induced overvoltages [1]. In power systems, ensuring system stability and reliability in the face of overvoltage events remains a key concern and a topic of interest [2]. Moreover, the performance of surge arresters deteriorates over time due to ageing and internal insulation breakdown, which may lead to service interruptions and compromised system reliability [3]. Zinc Oxide Surge Arresters (ZnOSA), a widely used type of MOSA, offer effective protection against transient overvoltages [4]. The most recently developed ZnOSA do not require serial gaps thanks to their excellent nonlinear properties [5]. Gapless surge arresters are frequently used in the distribution system to mitigate overvoltage events and their potential consequences [6, 7]. During operation, surge arresters are exposed to multiple stressors, including continuous operating voltages, temperature fluctuations, frequent lightning surges, and harsh environmental conditions such as high humidity and pollution. These factors contribute to the ageing of MOSAs, leading to irreversible changes in the electrical and physical properties of the ZnO elements [8]. The equivalent circuit of a MOSA consists of a nonlinear resistor (R) and a capacitor (C), where the applied voltage V produces a total leakage current (I_T), which is the vector sum of the resistive current (I_R) and the capacitive current (I_C):

$$I_T = I_R + I_C \tag{1}$$

Under normal service conditions, due to the nonlinear characteristics of ZnO blocks, a small leakage current (typically up to 1 mA) flows through the arrester [9]. Authors in [4] showed that the resistive component of leakage current increases significantly more than its capacitive component with an increase in applied voltage. The I_C is influenced by the grading capacitance and the dielectric properties of the ZnO material [3], typically ranging from 60 pF kV/cm^2 to 150 pF kV/cm^2 [10]. The I_R component is particularly important as it leads to internal heating and is highly sensitive to voltage distribution across the ZnO blocks. Several techniques allow for the extraction of the I_R from the I_T. At the voltage peak, the I_R equals the total current [11]. Because the resistive component is a sensitive indicator of changes in the voltage–current characteristics of metal oxide varistors, it serves as an effective diagnostic tool for assessing the condition of MOSAs [10, 12]. While power loss measurements are commonly used in laboratory conditions, they are less practical for online monitoring, as they require simultaneous measurement of both leakage current and operating voltage [13]. Among condition assessment techniques, leakage current measurement remains the most widely adopted method for monitoring MOSA health [14–17]. Various studies have explored condition monitoring of MOSAs based on leakage current analysis, given that surge arresters are classified as "aged" if the maximum voltage of V-I characteristics has decreased by 10 % [16]. Authors in [1] proposed using harmonic ratios of the I_R, considering surface contamination and Ultraviolet (UV) radiation as ageing factors. Authors in [18] analyzed surge arresters submerged in water to examine the effects of moisture ingress. In [19], temperature ageing was conducted by exposing ZnO elements to 135 °C. Most researchers have examined one or two ageing mechanisms in isolation. In our previous work, we investigated the combined effects of temperature, impulse current, salt-fog, and water immersion [20].

In the present work, a novel and comprehensive ageing procedure is employed, combining all major ageing parameters to evaluate their collective impact on MOSA performance. The ageing process includes continuous voltage application, UV exposure, salt-fog, thermal ageing at 150 °C, impulse current application of 1 kA, and water immersion. Experiments were conducted on four 9 kV MOSA samples in a high-voltage laboratory, and the effects of ageing on various performance indicators are presented.

II. EXPERIMENT AND METHODOLOGY

Laboratory experiments were conducted on four ZnOSA samples (S-1, S-2, S-3, and S-4). The technical specifications of the surge arresters are provided in Table I, and the experimental methodology is illustrated in Figure 1. Initially, condition monitoring tests were performed on all four MOSAs. Following this, each arrester underwent an ageing process, the details of which are presented in Figure 2. After the ageing procedures were completed, verification tests were conducted on the aged surge arresters.

TABLE I. RATING OF MOSAS

Rated Voltage (Ur)	9 kV
Maximum Continuous Operating Voltage	8 kV
Nominal Discharge Current	5 kA
Maximum Residual Voltage	27 kVp
External Creepage Distance	320 mm

The following condition monitoring tests have been conducted on all samples.

- Lightning impulse residual voltage measurement at 1 kA peak (8/20 μs impulse current).
- Measurement of reference voltage at reference current.
- Capacitance measurement.
- Tan δ (loss angle) measurement.
- Partial Discharge (PD) measurement.
- I_T measurement.
- I_R measurement.

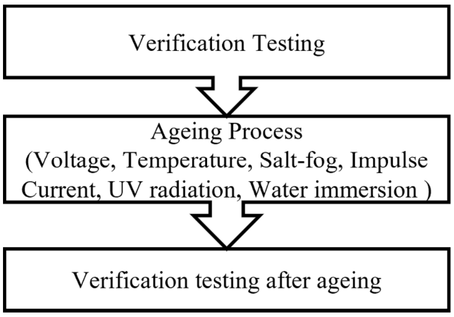

Fig. 1. Methodology and ageing process.

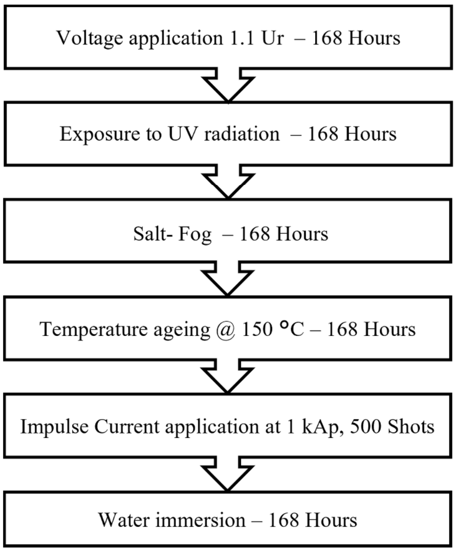

Fig. 2. Ageing process of surge arresters.

Lightning impulse residual voltage measurement has been carried out with an 800 kV_p, 40 kJ impulse voltage test system. Impulse current measurements were obtained using 0.47 Ω resistive shunts and a High-Resolution Impulse Analyzer (HIAS). Residual voltage was captured using a voltage divider. The reference voltage at a reference current of 1 mA was measured using a 150 kV, 1 A High-Voltage Transformer (HVT), a 10 kΩ resistor, a digital oscilloscope, and a 100 kV high-voltage divider. For leakage current measurements, a 0–33 kV single-phase high-voltage source, high-voltage probe, and a high-precision Digital Storage Oscilloscope (DSO) were used. A 10 kΩ non-inductive resistor was employed in the leakage current measurement circuit. For PD measurement, the setup included an 80 kV PD-free HVT, a 100 kV capacitive voltage divider, a 100 kV coupling capacitor, and a digital PD measuring system. For capacitance and Tan δ measurements, a 50 pF standard capacitor, a bridge circuit, and an 80 kV high-voltage source were used. The experimental circuits for leakage current and PD measurements are depicted in Figure 3, and the laboratory setup for leakage current testing is shown in Figure 4. All test results were recorded and compiled into a database.

Then, all samples were subjected to the novel ageing protocol detailed in Figure 2. The experimental setup for salt-fog ageing is shown in Figure 5, the surge arresters undergoing thermal ageing at 150 °C are presented in Figure 6, and those subjected to impulse current ageing at 1 kA are illustrated in Figure 7. Figure 8 displays the surge arresters immersed in water. Upon completion of the ageing process, all diagnostic tests were repeated on each sample to assess the degradation in performance.

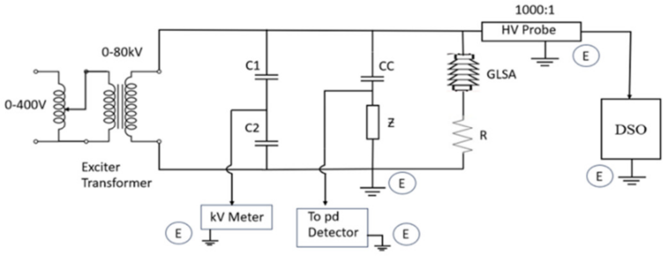

Fig. 3. Experimental circuit for leakage current measurement.

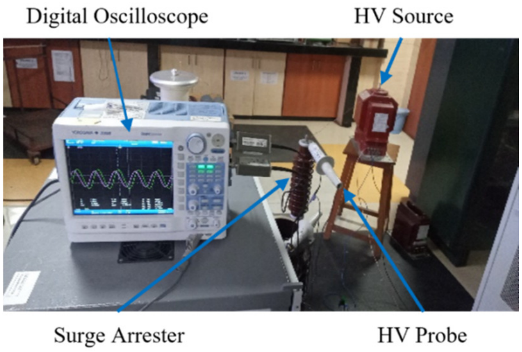

Fig. 4. Laboratory set-up.

Fig. 5. Experimental setup for salt fog ageing.

Fig. 6. Experimental setup for temperature ageing at 150°C.

Fig. 7. Impulse current application at 1 kAp, 500 shots.

Fig. 8. Experimental setup for water immersion ageing.

III. RESULTS AND DISCUSSION

The experimental results for all four MOSA samples prior to ageing are presented in Table II, while post-ageing results are shown in Table III. The initial measurements were found to be within acceptable limits, confirming that the surge arresters met the required operational standards [10, 12]. Following the ageing process, the test results exhibited significant deviations, indicating degradation in the performance of the surge arresters. The percentage variations in key performance parameters are summarized in Table IV and illustrated in Figure 9. After ageing, the performance of surge arresters degraded, increasing the leakage current flowing through them. Specifically:

- Lightning impulse residual voltage decreased by 12.28% to 15.22% across the four samples.
- Reference voltage declined by 11.65% to 14.29%.
- Tan δ increased by 13.56% to 37.90%, indicating potential moisture.
- I_T rose by 60.88% to 85.71%.
- I_R current exhibited the highest variation, increasing by 61.60% to 114.63%.

Previous research focusing solely on UV ageing and pollution in [1] reported a 4.67% increase in I_T and a 7.78% increase in I_R. However, this study did not consider other ageing stressors such as impulse current, voltage stress, thermal ageing, or water immersion. In contrast, results from saltwater exposure experiments in [18] showed a significant 120% increase in I_R, comparable to the variations observed in the present study.

TABLE II. EXPERIMENTAL RESULTS BEFORE THE AGEING PROCESS

Parameter	**Before the ageing process**			
	S-1	***S-2***	***S-3***	***S-4***
Lightning impulse residual voltage (kV_p)	24.2	24.1	24.5	25.3
Reference voltage (V_{ref}) at reference current (kVrms)	10.3	10.25	10.6	10.5
Capacitance (pF)	51.392	52.102	51.245	51.675
Tan δ (%)	0.07916	0.08126	0.08215	0.0804
PD (pC)	1.5	1.7	1.4	1.65
I_R (μA)	123	117	125	118
I_T (μA)	368	336	371	363

TABLE III. EXPERIMENTAL RESULTS AFTER THE AGEING PROCESS

Parameter	**After the ageing process**			
	S-1	***S-2***	***S-3***	***S-4***
Lightning impulse residual voltage (kV_p)	21.18	21.14	21.22	21.45
Reference voltage (V_{ref}) at reference current (kVrms)	9.1	8.9	9.1	9.0
Capacitance (pF)	51.032	51.102	50.743	50.516
Tan δ (%)	0.10916	0.09926	0.09825	0.0913
PD (pC)	178	98	156	122
I_R (μA)	264	228	202	198
I_T (μA)	598	624	661	584

TABLE IV. VARIATION IN MEASURED PARAMETERS AFTER AGEING

Parameter	**Variation in %**			
	S-1	***S-2***	***S-3***	***S-4***
Lightning impulse residual voltage (kV_p)	-12.47	-12.28	-13.39	-15.22
Reference voltage (V_{ref}) at reference current (kVrms)	-11.65	-13.17	-14.15	-14.29
Capacitance (pF)	-0.70	-1.92	-0.98	-2.24
Tan δ (%)	37.90	22.15	19.60	13.56
PD (pC)	11766.67	5664.71	11042.86	7293.94
I_R (μA)	114.63	94.87	61.60	67.80
I_T (μA)	-12.47	-12.28	-13.39	-15.22

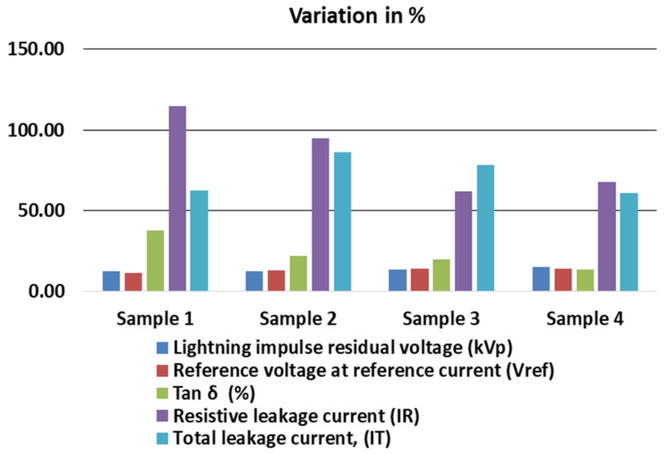

Fig. 9. Ageing process resulting variations.

These findings validate the effectiveness of a combined ageing protocol that includes voltage stress, UV radiation, salt fog, elevated temperature, impulse current, and water immersion. Notably, the results highlight water immersion as a critical ageing factor in the degradation of MOSA.

IV. CONCLUSION

In this study, new ageing criteria were established to evaluate the degradation behavior of Metal Oxide Surge Arresters (MOSAs) under controlled laboratory conditions. Among the various stress factors applied, temperature ageing, salt-fog ageing, and ageing with impulse current emerged as the most critical for MOSA degradation. Ageing led to a significant increase in the total leakage current (I_T), particularly in its resistive component I_R, which rose by 61.60–114.63%. These findings align with earlier research on saltwater immersion ageing [18], which reported leakage current variations of up to 120%. While the capacitance of the arresters remained largely unchanged, a notable increase in the value of Tan δ was observed post-ageing. Furthermore, the reference voltage and impulse residual voltage decreased by more than 10% across all samples, confirming the extent of degradation. In contrast, earlier studies focusing solely on temperature ageing reported smaller variations in reference voltage, typically between 5–10%. Based on the experimental results, it can be concluded that parameters such as partial discharge magnitude, Tan δ, I_T, and resistive leakage current increase because of MOSA degradation, while the impulse residual voltage and reference voltage at rated current decrease. Further research is warranted to isolate and evaluate the effects of individual ageing mechanisms on each of these parameters.

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