World Academy of Science, Engineering and Technology
International Journal of Electrical and Computer Engineering
Vol:18, No:7, 2024

Technique for Online Condition Monitoring of Surge Arrestors

Anil S. Khopkar, Kartik S. Pandya

***Abstract*—**Lightning overvoltage phenomenon in power systems cannot be avoided; however, it can be controlled to certain extent. To prevent system failure, power system equipment must be protected against overvoltage. Metal Oxide Surge Arrestors (MOSA) are connected in the system to provide protection against overvoltages. Under normal working conditions, MOSA function as, insulators, offering a conductive path during overvoltage events. MOSA consists of zinc oxide elements (ZnO Blocks) which has non-linear V-I characteristics. The ZnO blocks are connected in series and fitted in ceramic or polymer housing. Over time, these components degrade due to continuous operation. The degradation of zinc oxide elements increases the leakage current flowing through the surge arrestors. This increased leakage current results in elevated temperatures within the surge arrester, further decreasing the resistance of the zinc oxide elements. Consequently, the leakage current increases, leading to higher temperatures within the MOSA. This cycle creates thermal runaway conditions for the MOSA. Once a surge arrester reaches the thermal runaway condition, it cannot return to normal working conditions. This condition is a primary cause of premature failure of surge arrestors. Given that MOSA constitutes a core protective device for electrical power systems against transients, it contributes significantly to the reliable operation of power system networks. Therefore, periodic condition monitoring of surge arrestors is essential. Both online and offline condition monitoring techniques are available for surge arrestors. Offline condition monitoring techniques are not as popular because they require the removal of surge arrestors from the system, which requires system shutdown. Therefore, online condition monitoring techniques are more commonly used. This paper presents an evaluation technique for the surge arrester condition based on leakage current analysis. The maximum amplitudes of total leakage current (I_T), fundamental resistive leakage current (I_R), and third harmonic resistive leakage current (I^{3rd}) are analyzed as indicators for surge arrester condition monitoring.

***Keywords*—**Metal Oxide Surge Arrester, MOSA, Over voltage, total leakage current, resistive leakage current, third harmonic resistive leakage current, capacitive leakage current.

I. Introduction

TRANSIENTS in the power system are caused by natural lightning and switching operations. This can result in voltages higher than the system voltage. Such overvoltages increase the stress on the system's insulation, which may reduce the insulation's lifespan. Surge arrestors, when connected across the protecting equipment, offer high impedance during normal working voltage, thereby acting as insulators. When lightning or other interference increase peak current or voltage in an electrical circuit, surge arrestors rapidly transition to a low-resistance state and discharge instantaneous energy to earth. This capability allows the surge arrester to limit voltage across protected equipment within tolerable range, thereby preventing damage. Once the overvoltage event subsides, the lightning arrester returns to a high impedance state. To protect equipment from overvoltage, power systems use gapless zinc oxide surge arrestors, commonly known as MOSA. However, prolonged exposure to operating voltage, instantaneous lightning impulse overvoltage, pollution, temperature fluctuations, and humidity can lead to aging of the electrical parameters of the ZnO blocks, which form the core of surge arrestors. This ageing effect can result in deviations from the initial performance index. This leads to an increase in residual voltage ratio, partial discharges, and leakage current flowing through the surge arrester. The diminished performance of surge arrestors adversely affects the normal operation of the electrical power system. Failure of a surge arrester can result in power supply interruptions, damage to other substation equipment, and pose risks to nearby personnel. The functioning of ZnOSA is impacted by aging and insulation breakdown within the arrester. Therefore, it is necessary to protect the ZnOSA from further damage and deterioration, which may could lead to interruptions in electricity transmission and distribution [8]. As such, condition monitoring of MOSA is vital for ensuring the safe and reliable operation of the electrical power system.

In this paper, various online and offline condition monitoring techniques for MOSA have been discussed. The online condition monitoring technique of surge arrestors is based on analysis of leakage current components, ageing processes, and comparison with other condition monitoring tests, all of which are described in detail.

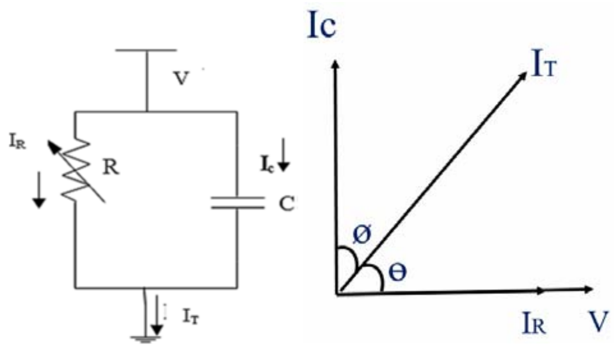
II. Equivalent Circuit of Surge Arrester

Since MOSA operates in the low-current region during normal operation, only a very small power frequency current flow through it. The simplified equivalent circuit of MOSA can be represented as a capacitance branch in parallel with non-linear resistive, as shown in Fig. 1 (a).

The total current (IT) flowing through MOSA can be expressed as the vector sum of a capacitive current component (IC) and a resistive current component (IR). This relationship is shown in (1). The capacitive current component does not deviate with the degradation, while the resistive current component varies with the degradation of MOSA [4].

Anil S. Khopkar is working at Electrical Research and Development Association, India and research scholar of Charotar University of Science and Technology, India (corresponding author, e-mail: anil.khopkar@erda.org).

Kartik S. Pandya is Senior Member – IEEE, Associate Professor, Electrical Engg. Dept., Faculty of Engineering and technology (PIET), Parul University, India.



(a) (b)

Fig. 1 (a) Equivalent circuit of MOSA, and (b) Phasor diagram of total leakage current and applied voltage

$$I_T = I_R + I_C \quad (1)$$

The resistive component of the total current can be obtained by subtracting the capacitive component from the total current, as:

$$I_R = I_T - I_C \quad (2)$$

The phasor diagram of the total leakage current (I_T), resistive leakage current (I_R), capacitive leakage current (I_C), and applied voltage (V) are shown in Fig. 1 (b). From the phasor diagram, it can be seen that the total current (I_T) leads the resistive current (I_R) by an angle θ and lags the capacitive current (I_C) by an angle ø. As the applied voltage increases, the resistive component of the leakage current exceeds its capacitive component [3].

III. Properties of the Leakage Current of MOSA

As per (1), the total leakage current comprises resistive current (I_R) and capacitive current (I_C). Fig. 2 shows a typical laboratory measurement of the leakage current of a single MOSA energized with continuous operating voltage (COV).

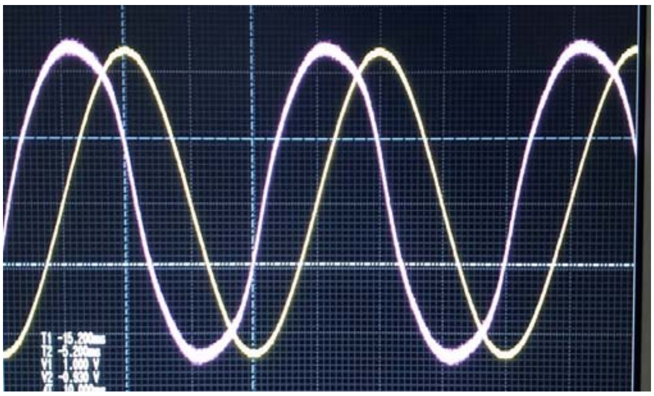


Fig. 2 Typical leakage current of MOSA

The specific capacitance of a resistor element typically ranges from 60 pF kV/cm^2 to 150 pF kV/cm^2, resulting in a capacitive leakage current of about 0.2 mA to 3 mA under normal service conditions. There is no evidence to suggest that the capacitive current would change significantly due to degradation of metal oxide resisters. Therefore, the capacitive current is not a significant indicator of the condition of MOSA. The resistive component of leakage current serves as a sensitive indicator of changes in the voltage-current characteristics of MOSA. Therefore, the resistive current is used as an effective tool to assess the condition of MOSA [2].

Surge Arrester Failure Mode

Under normal operating conditions, surge arrestors are energized at their maximum continuous operating voltage (MCOV). Under this condition, the temperature of the ZnO blocks rises to slightly above ambient. A point is soon reached where the heat being generated by the blocks is perfectly matched by the heat dissipated by the arrester into the surrounding air. However, when the power frequency voltage across the arrester increases due to a system disturbance, fault, or switching operation, it conducts more current and begins to rise in temperature. When the overvoltage is of sufficient magnitude, the heat generated by the MOV (metal oxide varistor) blocks will always be greater than what can be dissipated and there is potential thermal runaway. This thermal runaway condition is a major cause of surge arrester failure.

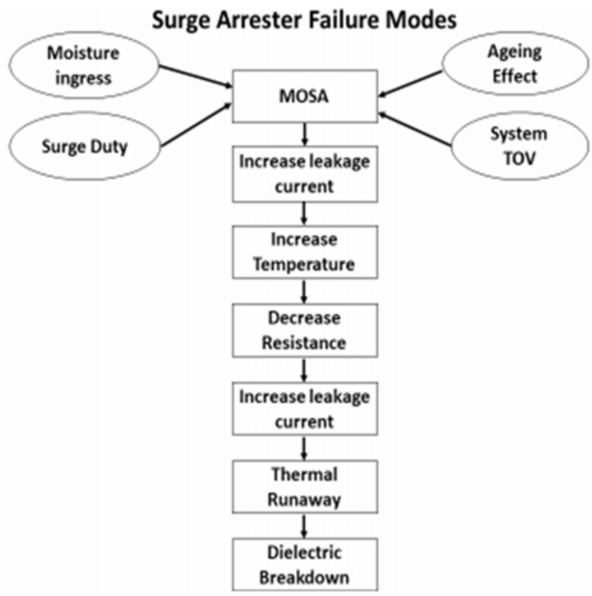


Fig. 3 Surge Arrester Failure mode

IV. Condition Monitoring Techniques of Metal Oxide Surge Arrester

There are several online and offline methods to monitor the health of MOSA. A comparison of the various condition monitoring techniques is shown in Table I [4]. The major drawbacks of the offline methods are that they require the removal of the surge arrester from service, which necessitates a system shutdown.

Therefore, online measurement of total leakage current and extraction of resistive current through analytical methods are the most common approaches. While offline methods may provide accurate results, they require the surge arrester to be taken out of service [6]. Leakage current measurement and analysis remain a popular method [5] for condition monitoring of MOSA. The main approach includes leakage current measurement under an operating voltage with temperature measurement. Extraction of the resistive leakage current from the total leakage current flowing through MOSA is considered as the most suitable method, as it is the most reliable and sensitive method for condition monitoring of MOSA [5]. Additionally, measuring the third harmonic component of the resistive leakage current is suitable and accurate technique to assess the health of surge arrestors.

TABLE I
COMPARISON OF MOSA MONITORING TECHNIQUES

Arrester monitoring technique	Sensitivity	Reliability	Usability
Infrared/Thermal imaging	High	High	Easy
Surge counter	Very low	Very low	Easy
Total leakage current	Low	Low	Easy
Watt loss	High	High	Hard
Resistive current	Very high	Very high	Hard
IR measurement	Low	Medium	Hard
Partial Discharge Test	Low	Low	Hard

Infrared/Thermal Imaging

The degradation of arrester leads to an increase in leakage current, resulting in higher power losses and elevated temperatures of the ZnO blocks. Monitoring of the arrester temperature can be carried out remotely by means of thermal imaging methods. The advantages of using the thermal image measurement include the ability to inspect without having to physically contact the equipment and the ability to utilize it for online monitoring when the equipment is in service and under the operating voltage [9]. Advancements in thermal imaging technology have made online arrester condition assessment increasingly popular. This method is effective because surge arrestors operate relatively close to ambient temperature during steady-state conditions, and the measurements are fast and accurate. The best way to determine if an arrester is not operating properly with this method is to compare the temperature of nearby similar vintage and type arrestors. If the temperature difference exceeds 10 K, it may indicate an issue with the hot arrester. Direct measurement of the metal-oxide resistor temperature gives a fairly accurate indication of the arrester condition, but it requires that the arrester is equipped with special transducers at the time of manufacturing. Therefore, this method is only applicable to surge arrestors that have been specifically with such transducers.

Surge Counter/Spark Gaps

Surge counters are designed to operate above certain thresholds of impulse current amplitude or combinations of current amplitude and duration. However, it is important to note that if the interval between two lightning discharges is very short (less than 50 ms), surge counters may not count every current impulse. Additionally, some counters require power follow current and may not register short impulse currents through metal oxide arrestors. However, it is important to understand that surge counters alone cannot provide specific information about the condition of the arrester. The surge counter should be installed out of easy reach of personnel for safety reasons. The position of the surge counter should allow it to be easily read from ground level with the arrester in service. The earth connection length must be as short as possible. The arrester must have an insulated earth terminal and a conductor between the arrester and counter that is insulated from the earth. Monitoring spark gaps are used to indicate the number and to estimate the amplitude and duration of discharge currents through the arrester. Special expertise is necessary to interpret the marks on the gap accurately. Some spark gaps can be examined with the arrester in service, while other types require that the arrester is de-energized.

Power Loss at MCOV

Power loss may be used for diagnostic indication of arrestors in the same way as the resistive leakage current. The power loss typically ranges from 5 mW/kV to 300 mW/kV at rated voltage and at reference temperature of 20 °C [2]. The temperature and voltage dependencies are practically the same as for the resistive current. The power loss may be expressed in terms of the product of the root mean square (r.m.s.) value of the resistive component of leakage current and the r.m.s. value of the voltage across the arrester. The influence of the harmonics in the voltage is greatly reduced by the multiplication and integration procedure.

Measurement of Resistive Leakage Current

The resistive component of total leakage current can be determined by several methods, which can be further divided into groups [2].

- Method A:
  - A1: Using the applied voltage signal as a reference for direct peak resistive current reading or total current discrimination.
  - A2: Compensating the capacitive component of the leakage current by using a voltage signal.
  - A3: Compensating the capacitive component of the leakage current without using a voltage signal.
  - A4: Compensating the capacitive component of the leakage current by combining the currents of three phases.
- Method B: Indirect determination of the resistive component by means of harmonic analysis of the leakage current. This method can be divided in to three different groups:
  - B1: Third order harmonic analysis of leakage current
  - B2: Third order harmonic analysis with compensation for harmonics in the system voltage.
  - B3: First order harmonic analysis of the leakage current.
- Method C: Direct determination of power losses.

Out of above the methods, method B2: Third harmonic analysis with compensation for harmonics in the system voltage, is suitable for measurement of leakage of surge arrester service condition.

V. EXPERIMENTAL METHODOLOGY

The experiment on 9 kV, MOSA was carried out for various condition monitoring techniques. The experimental setup is shown in Fig. 4, which consists of a 400 V/80 kV, 3 Amp high voltage PD-free transformer. A 100 kV capacitive voltage divider with peak volt meter having dual range of 0-10 kV and 0-100 kV is used for voltage measurement. MOSA is directly connected to the output terminal of the high voltage-transformer in parallel with the voltage divider. At the second end of the surge arrester, a calibrated 4.8 kΩ is connected for the measurement of leakage current.

Fig. 4 Experimental set-up for measurement of leakage current

For the experiment, the following major equipment was used:

a. High voltage transformer: 80 kV, 240 kVA
b. Voltage divider with peak voltmeter:100 kV
c. PD detector
d. Capacitance and tan delta bridge
e. Coupling capacitor: 100 kV
f. Impulse voltage generator
g. Digital oscilloscope
h. Environmental chamber

The technical specifications of the surge arrester include:

a. Rated voltage: 9 kV
b. Continuous operating voltage: 7.06 kV
c. Nominal discharge current : 5 kA
d. Maximum residual voltage: 26 kV
e. External creepage distance: 240 mm

Experiments were conducted on three samples of 9 kV surge arrestors. The following tests were conducted on surge arrestors of the same rating.

a. Leakage current measurement
b. Partial discharge measurement
c. Reference voltage at reference current
d. Lightning impulse residual voltage measurement at 500 A measurement
e. Measurement of capacitance and tan δ

Ageing Process

All three surge arrestors were mounted vertically in the weather ageing test chamber. Enough clearance was maintained between the roof and the surrounding walls of the chamber. The surge arrestors were mounted in a way so as to avoid electrical field disturbance from each other.

The test parameters maintained include:

- Applied voltage: 10 kV
- Ageing duration: 1000 h
- Water flow rate: 0.4 l/h/m^3 ± 0.1 l/h/m^3
- Size of droplets: 5 µm to 10 µm
- Temperature: 20 °C ± 5 K
- NaCl content of water: Between 1 kg/m^3 to 10 kg/m^3

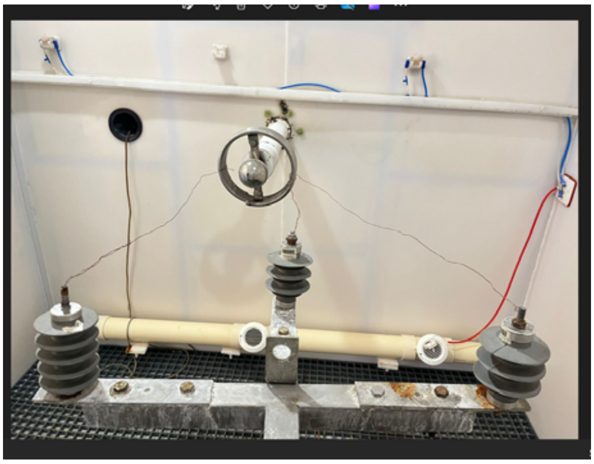


Fig. 5 Surge arrester under weather ageing

Following the above ageing process, similar tests were carried out on surge arrestors.

VI. Results and Discussion

The results obtained for each of the test parameters before and after the ageing process are compared and analyzed. The results for each of tests conducted are given in Tables II-XIII.

Measured total leakage current, resistive leakage current, third harmonic resistive leakage current and partial discharge for samples 1, 2, and 3 are presented in Tables II, III, and IV, respectively.

TABLE II
Measured Leakage Current of MOSA –Sample 1

kV	IT (µA)	IR (µA)	IR 3rd (µA)	PD (pC)
4	91.7	16.2	2.1	0.3
5	121.6	25.3	3.2	0.3
6	150.4	41.9	5.3	0.3
7	174.9	50.2	7.4	0.3
8	210.6	59.3	10.6	0.3
9	261.3	174.9	35.5	0.3
10	605.8	472.2	60.5	0.3
10.33	1006.6	600.4	88.3	0.4

The test results obtained after ageing are given below. The measured total leakage current, resistive leakage current, third harmonic resistive leakage current and partial discharge for samples 1, 2, and 3 are given in Tables VIII-X, respectively.

TABLE III
MEASURED LEAKAGE CURRENT OF MOSA-SAMPLE 2

kV	IT (μA)	IR (μA)	IR 3rd (μA)	PD (pC)
4	90.7	14.8	3.8	0.2
5	120.3	24.3	4.5	0.2
6	148.2	42.3	5.5	0.2
7	180.1	55.2	7.5	0.3
8	205.3	60.3	12.6	0.3
9	255.2	165.5	55.2	0.5
10	548.4	480.2	76.6	0.6
10.33	970.6	643.3	91.1	0.8

TABLE IV
MEASURED LEAKAGE CURRENT OF MOSA – SAMPLE 3

kV	IT (μA)	IR (μA)	IR 3rd (μA)	PD (pC)
4	91.7	18.2	2.9	0.5
5	131.6	28.6	4.2	0.5
6	160.4	45.3	6.3	0.5
7	178.2	51.3	8.4	0.6
8	215.3	58.5	9.6	0.6
9	274.9	178.5	63.4	0.7
10	598.3	482.3	75.4	0.8
10.33	986.5	632.4	93.3	1.5

TABLE V
REFERENCE VOLTAGE AT REFERENCE CURRENT

Sample No.	Ref. Current	Ref. Voltage
1	1 mA	10.1 kV
2	1 mA	9.80 kV
3	1 mA	10.2 kV

TABLE VI
MEASURED LIGHTNING IMPULSE RESIDUAL VOLTAGE

Sample No.	Impulse Current	Residual Voltage
1	500 A	25.50 kVp
2	500 A	25.20 kVp
3	500 A	25.80 kVp

TABLE VII
MEASURED CAPACITANCE AND TAN Δ

Sample No.	Voltage	Capacitance (pF)	Tan δ (%)
1	6.35 kV	42.912	0.097942
	7.00 kV	43.125	0.111242
2	6.35 kV	44.247	0.104656
	7.00 kV	44.211	0.116521
3	6.35 kV	43.431	0.111245
	7.00 kV	43.481	0.124114

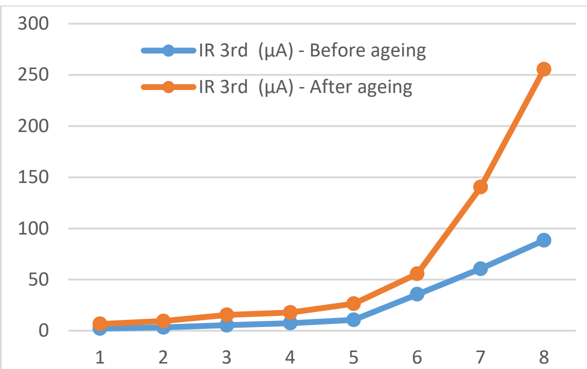


Fig. 6 Third harmonic resistive leakage current of surge arrester before and after ageing process

TABLE VIII
MEASURED LEAKAGE CURRENT OF MOSA – SAMPLE 1

kV	IT (μA)	IR (μA)	IR 3rd (μA)	PD (pC)
4	95.7	18.2	6.6	0.5
5	131.1	32.3	9.4	0.5
6	161.4	55.5	15.4	3.2
7	188.9	67.4	17.8	5.6
8	282.6	87.2	26.4	6.2
9	388.5	198.5	55.6	8.9
10	990.8	489.3	140.3	10.2
10.33	1098.4	871.4	255.4	18

TABLE IX
MEASURED LEAKAGE CURRENT OF MOSA – SAMPLE 2

kV	IT (μA)	IR (μA)	IR 3rd (μA)	PD (pC)
4	92.1	16.2	5.2	0.8
5	145.2	30.3	7.8	1.6
6	172.2	46.1	17.2	2.5
7	210.2	78.2	28.5	4.1
8	298.2	95.2	48.5	5.6
9	404.3	165.5	95.5	14.3
10	1005.3	480.2	135.2	18.2
10.33	1150.3	898.3	281.2	32.5

TABLE X
MEASURED LEAKAGE CURRENT OF MOSA - SAMPLE 3

kV	IT (μA)	IR (μA)	IR 3rd (μA)	PD (pC)
4	92.5	18.8	2.1	1
5	125.5	25.3	4.1	1.5
6	152.4	45.1	8.9	5.3
7	195.4	75.2	12.2	8.2
8	265.5	86.5	28.6	15.5
9	386.6	145.2	55.2	18.6
10	877.1	456.2	135.2	22.5
10.33	1120.3	835.3	261.2	25.5

TABLE XI
REFERENCE VOLTAGE AT REFERENCE CURRENT

Sample No.	Ref. Current	Ref. Voltage
1	1 mA	10.1
2	1 mA	8.8
3	1 mA	9.8

TABLE XII
MEASURED LIGHTNING IMPULSE RESIDUAL VOLTAGE

Sample No.	Impulse Current	Residual Voltage
1	500 A	23.8
2	500 A	22.2
3	500 A	24.1

TABLE XIII
MEASURED CAPACITANCE AND TAN Δ

Sample No.	Voltage	Capacitance (pF)	Tan δ (%)
1	6.35 kV	41.342	0.101154
	7.00 kV	42.653	0.124242
2	6.35 kV	43.523	1.153447
	7.00 kV	44.125	0.191581
3	6.35 kV	44.235	0.111245
	7.00 kV	44.99	0.124114

Based on the above results, it can be seen that after weather ageing of surge arrestors for 1000 hours, the current flowing them increased significantly. Total leakage current flowing through surge arrester has also significantly increased. Additionally, the measured resistive leakage current and third harmonic components of the resistive leakage current increased significantly. Moreover, the quantity of internal partial discharges has exceeded the specified limit. The measured value for the internal partial discharge should not exceed 10 pC [1].

The measured value of the dissipation factor (tan δ) is also increased. However, the value of measured capacitance remains the almost same, indicating that the capacitive current does not increase due to ageing effects and subsequent degradation of the surge arrester. The value of the reference voltage at a reference current of 1 mA and the impulse residual voltage at 500 A have also been marginally reduced. This reduction is due to the increased leakage current caused by ageing effects. The weather ageing of surge arrestors was conducted according to standard procedures, considering actual site conditions.

The degradation of surge arrestors is primarily caused by moisture ingress and continuous voltage stresses during operation. Consequently, after the ageing process, due to degradation of MOSA, the measured values of leakage current, partial discharges and tan δ increased significantly. Such degradations can be effectively detected through the measurement of total leakage current, the extraction of resistive leakage current from total leakage current, and analysis of third harmonic resistive leakage current. It is worth noting that when applied voltage is purely sinusoidal, the measured leakage current contains only the fundamental component. However, when applied voltage includes n^{th} order harmonic components, the leakage current consists of fundamental and n^{th} order harmonic components [7]. Therefore, compensation for supply harmonics is necessary during measurement.

VI. Conclusion

In this paper, various condition monitoring techniques for surge arrestors are discussed. It can be seen that after ageing, surge arrestors exhibit a significant increase in total leakage current flowing through them. Additionally, the resistive current and third harmonic components of resistive leakage current, as well as the quantity of partial discharges and the dissipation factor (tan δ), show significant increases, serving as indicators of surge arrester degradation.

Therefore, for online condition monitoring of surge arrestors, measuring total leakage current and extracting resistive leakage current using analytical methods prove to be useful techniques. These methods are common and reliable, providing valuable insights into the condition of the surge arrestor. Monitoring trends in resistive leakage current and third harmonic leakage current are equally valuable tools for detecting degradation.

Therefore, for online condition monitoring of surge arrestors, the measurement of total leakage current, resistive leakage current and analysis of third harmonic leakage current are useful techniques. These methods are the most common and reliable method, providing valuable insights into the condition of the surge arrestor. Monitoring trends in resistive leakage current and third harmonic leakage current are equally useful tools for detecting degradation. Further research could focus on refining techniques for extraction and analysis of resistive leakage current from total leakage current, as well as on modeling of MOSA. Validating these methods through simulation in software is further scope of research.

Acknowledgment

The authors wish to thank the Management of Electrical Research and Development Association (ERDA), Vadodara – India for permission to present this paper. Authors also wish to thank CHARUSAT university for their guidance and support to publish this paper.

References

[1] Surge Arrestors – *Metal oxide surge arrestors without gaps for a.c. systems,* IEC Standard 60099-4, 2014.

[2] Surge Arrestors – *Selection and Application Recommendation",* IEC Standard 60099-5, 2018.

[3] Abdullah Munir, Z. Abdul Malek and Rai Naved Arshad, *"Resistive component extraction of leakage current in metal oxide surge arrester: A hybrid method".* Elsevier Journal, Measurement 173 (2021) 108588.

[4] Z. Abdul Malek, Novizon Yusoff, Mohd Fairoz and Mohd Yousuf, *"Filed Experience on Surge Arrester Condition monitoring – Modified Shifted Current Method".* UPEC 2010, 31st August – 3rd Sept. 2010.

[5] S. Mohammed Arshad, Asanka S. Rodrigo, *"Modified phase shifting of leakage current to condition monitoring of metal oxide surge arrestors in power system."* Mortuwa Engineering Research Conference (MERC on), 978-1-5386-4417-1/18, 2018, IEEE pp 300-305. 2018.

[6] M. Khodsuz and M. Mirzaie, *"Monitoring and identification of metal-oxide Surge Arrester conditions using multi-layer support vector machine."* IET Journal, Vol 15 iss 16, pp.2501-2508, 2015.

[7] M. Khodsuz, M. Mirzaie and S. Seyyedbarzegar' *"Metal oxide surge arrester condition monitoring based on analysis of leakage current component",* Elsevier Journal, Electrical Power and Energy systems 66, pp. 188-193, 2015.

[8] Syeda Sakin Haider, Hania Ahmed, Umme Aaiman, Syda Shakeel and Abdullah Munir, *"Online condition monitoring of 120 kV Zinc Oxide Surge arrestors using correlation method,"* MDPI, Engineering proceedings, 2023, 46,42, MDPI journal.

[9] Behnam Ranjbar, Ali Devarshi, Rahman Dashti and Hamid Reza Shaker, *"A survey of diagnostic and condition monitoring of metal oxide surge arrester in power distribution network",* MDPI, Energeis, 2022, 15,8091.