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Advance technique for online condition monitoring of surge arresters

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ABSTRACT

Gapless surge arresters (GLSA) constructed with zinc oxide (ZnO) element is connected in electrical power system for protection against surge voltage. For condition monitoring of GLSA conventionally offline and online techniques are available. However, offline techniques are not much useful as it requires system shutdown and hence online techniques are more useful. Online surge arrester monitoring technique based on leakage current analysis is adopted by all stakeholders. However, in this method supply system harmonics plays major roles in measurement accuracy to determine health index. In this paper improved health monitoring indexes for GLSA diagnostic based on ratios of leakage current components has been proposed. The ageing process has been done with application of lightning Impulse current, surface contamination due to salt fog, temperature effect, and moisture ingress. Various experimental tests have been carried out on porcelain and polymer housed surge arresters to evaluate the ability of proposed method. Obtained results of 9 kV, 18 kV, and 30 kV healthy and degraded metal oxide GLSAs have been shown the viability of improved health indexes on surge arrester condition monitoring procedures. The experimental investigation and discussion of the obtained results reflects sufficient and effective trails to utility engineers to determine health of surge arresters and able to effectively schedule further maintenance plan.

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1. INTRODUCTION

Lightning surges are main cause of overvoltage in the power system. Surge arresters are connected to protect the power system against lightning overvoltage. Gapless surge arresters (GLSA) consisting of zinc oxide (ZnO) elements connected in electrical power system for protection of equipment against over voltage. ZnO has non-linear volt-amp (VI) characteristics. GLSAs are frequently used in the distribution system to address overvoltage concerns and mitigate their potential drastic consequences [1], [2]. ZnO surge arresters have been widely used nowadays in overvoltage protection of transmission line systems. The most recently developed ZnO surge arresters do not require serial gaps owing to their excellent nonlinear properties [3]. Due to influence under continuous operating voltage, lightning surges, pollution, and environmental effect performance of GLSA degrades. The degradation phenomenon refers to irreversible change in electrical and

physical properties of ZnO element [4]. It can be concluded that failure of arresters can affect the substation reliability and can cause severe harm to substation reliability or great outage in the network. The equivalent circuit of GLSA consist of ZnO blocks is given in Figure 1. Where, V is the voltage across surge arrester, C represents the equivalent capacitance and R represents the non-linear resistor. Total leakage current (I_T) is flowing through surge arrester. Due to the non-linear characteristics of ZnO blocks a current in the range of 1 mA flows through the surge arrester under normal service condition [5].
I_C and I_R are the capacitive and resistive components of I_T respectively.

The total current (I_T) of the GLSA is given by a vector sum of a capacitive current component (I_C) and resistive current component (I_R):

$$IT = IR + IC \tag{1}$$

hence, the resistive component of total current can be obtained by subtracting capacitive component from total current, that is (2).

$$IR = IT - IC \tag{2}$$

Figure 2 shows phasor diagram of applied voltage, I_T, resistive leakage current (I_R), and capacitive leakage current (I_C). It can be seen I_T leads I_R by angle ɵ and lag I_C by an angle ø. The resistive components of leakage current exceed from its capacitive component with the rise in applied voltage [6]. The capacitive current is attributed to the grading capacitance and permittivity of metal oxide element [7]. Ideally the capacitance of a ZnO element in the range of 60 pF kV/cm^2 to 150 pF kV/cm^2 [8]. Hence, the I_R which generate a Joule effect in the ZnO block, are responsible for the temperature rising, and it is sensitive to the distribution of the voltage in the block. Several techniques make it possible to calculate the I_R value, from the I_T. The resistive current reaches the value of the total current in the moment when the voltage is at its maximum [9].

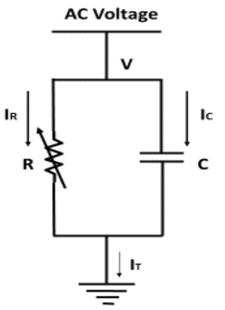


Figure 1. Equivalent circuit of GLSA

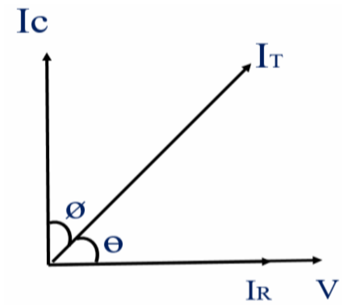


Figure 2. Phasor diagram of leakage current

Resistive component of leakage current is sensitive indicator of change in voltage-current characteristics of metal oxide resistors. Therefore, resistive current is use as effective tool to ascertain condition of metal oxide surge arrester [8], [10]. A leakage current based condition assessment is most extensively opted method to monitor the ageing and deterioration of ZnO surge arrester [11]. The power loss in the surge arrester can be computed based on the leakage current and applied voltage data the following formula can be used to calculate active power loss [12], [13].

$$P = \frac{1}{T}\int_{t}^{t+T} v(t)i(t)dt \tag{3}$$

The power loss measurement is frequently used in the laboratories but is rarely used online because simultaneous leakage current and operating voltage measurements are required [12]. Leakage current measurement is the most commonly applied condition assessment of metal oxide based surge arresters [14]-[17]. The main purpose of most diagnostic techniques are based on resistive current analysis, because the resistive component is a sensitive indicator to determine surge arrester condition [18]. However, in this method compensation of harmonics in supply voltage required to be done for accurate measurement. Many research has been done for compensation of supply harmonics during leakage current measurement. There are method such as arrester temperature and electromagnetic field measurements are used for online testing of arresters [19]-[21], but these methods are less accurate and provides information about temperature of GLSA and electromagnetic field around GLSA hence not much popular. As per research it is supposed that a surge arrester is classified as “aged” if the maximum voltage of V-I characteristic decreased by 10% [16]. However, obtaining V-I characteristic online is challenge. The previous research studies have illustrated that the magnitude of leakage current is mainly affected by the ageing and deterioration of metal oxide GLSA [22], [23]. Earlier, measurement of fifth harmonic resistive current (I_{R5th}) as ageing indicator has been proposed [7]. But compensation of supply harmonic has not been considered. Ratios of third to fifth resistive harmonic components and ratio of resistive to I_T fundamental components have been also proposed [18]. However, in this research, ratios of other current components have not been considered. Hence, there is scope of further research to find out the ageing effect on ratios of all current components. Therefore, in this work for further improvement in health index of surge arrester, online condition monitoring techniques based on current ration analysis of various leakage current components has been proposed. New indexes for GLSA health monitoring based on various current ratios has been proposed. In this paper: i) ratios of I_R to I_T-Ra, ii) ratios of I_{R3rd} to I_T-R_b, iii) ratios of I_{R5th} to I_T-R_C, iv) ratios of I_{R3th} current to I_R–R_d, v) ratios I_{R5th} to I_R– R_e, and vi) ratios of I_{R5th} to I_{R3rd} components–R_f have been proposed. The ratios of these currents are considered for condition assessment of GLSA which improves accuracy of condition monitoring technique. A database of leakage current components has been produced in the laboratory to evaluate the new health monitoring indexes. The data base has been obtained for 9 kV and 18 kV porcelain housed and 30 kV polymer housed ZnO GLSAs for various operating conditions. Such operating conditions includes lightning impulse current application, salt fog, voltage application, and moisture ingress and temperature effects. The experimental results of leakage current measurements of 9 kV, 18 kV, and 30 kV healthy and aged metal oxide GLSAs are analysed, compared and validated for proposed health index technique. Obtained results shows the significant performance of proposed health indexing of ZnO element based GLSAs. Proposed method is validated by offline condition monitoring techniques. Earlier proposed techniques in [7], [18] have been also validated with offline techniques. Experimental results prove effectiveness of proposed method.

2. PROPOSED METHOD

In this paper online condition monitoring techniques based on ratio of various current components has been proposed. Ratios of following leakage current components have been proposed to verify the healthiness of the GLSA.
- Ratio of I_R to I_T–R_a,
- Ratio of I_{R3rd} to I_T–R_b,
- Ratio of I_{R5th} to I_T–R_c,
- Ratio of I_{R3th} current to I_R–R_d,
- Ratio of I_{R5th} to I_R–R_e and
- Ratio of I_{R5th} to I_{R3rd} components–R_f

From the above ratios, overall ratios of all above ratios have been computed by (4):

$$\text{Overall Current Ration (R)} = \sum_{i=1}^{n} \sqrt{R_i^{\,2}} \tag{4}$$

where, $i = a, b, c, d, e, and\ f$.

$$\mathrm{R} = \sqrt{\mathrm{R_a^2 + R_b^2 + R_c^2 + R_d^2 + R_e^2 + R_f^2}} \tag{5}$$

Overall ration “R” derived from above formula has been proposed for detecting the healthiness of GLSA. To validate the proposed methodology detailed experiments have been carried out in the high voltage laboratory on 9 kV, 18 kV, and 30 kV GLSA. The data base has been obtained for 9 kV and 18 kV porcelain housed and 30 kV polymer housed ZnO GLSAs. The obtained results of above method validate the proposed techniques.

3. LABORATORY EXPERIMENTATION

For laboratory experiment 9 kV, 18 kV, and 30 kV GLSAs have been chosen. On different ratings of GLSA various experiments have been performed at research laboratory. The measurement of I_T, I_R, third harmonic, and fifth harmonic component of I_R, on new ZnO based GSLAs has been carried out. The technical specifications of the GLSA used for experiment are given in Table 1.

Table 1. Rating of GLSA

Parameter	Rating		
Rated voltage (Ur)	9 kV	18 kV	30 kV
Maximum continuous operating voltage	8 kV	14.4 kV	24 kV
Nominal discharge current	5 kA	5 kA	10 kA
Maximum residual voltage	27 kV	54 kV	90 kV
Frequency	50 Hz	50 Hz	50 Hz
Basic insulation level (BIL)	75 kVp	150 kVp	170 kVp
External creepage distance	320 mm	650 mm	845 mm

First, on all the healthy GLSAs various condition monitoring tests have been carried out. Thereafter, measurement of I_T, I_R, I_{R3th}, and I_{R5th} have been carried for all three GLSAs. Database of all the test results have been created. All the GLSAs have been kept for rigorous ageing process. After ageing again leakage current measurement and condition monitoring tests have been carried out. From the obtained results the proposed method of ratios of various currents has been validated. The experimental circuit used is given in Figure 3.

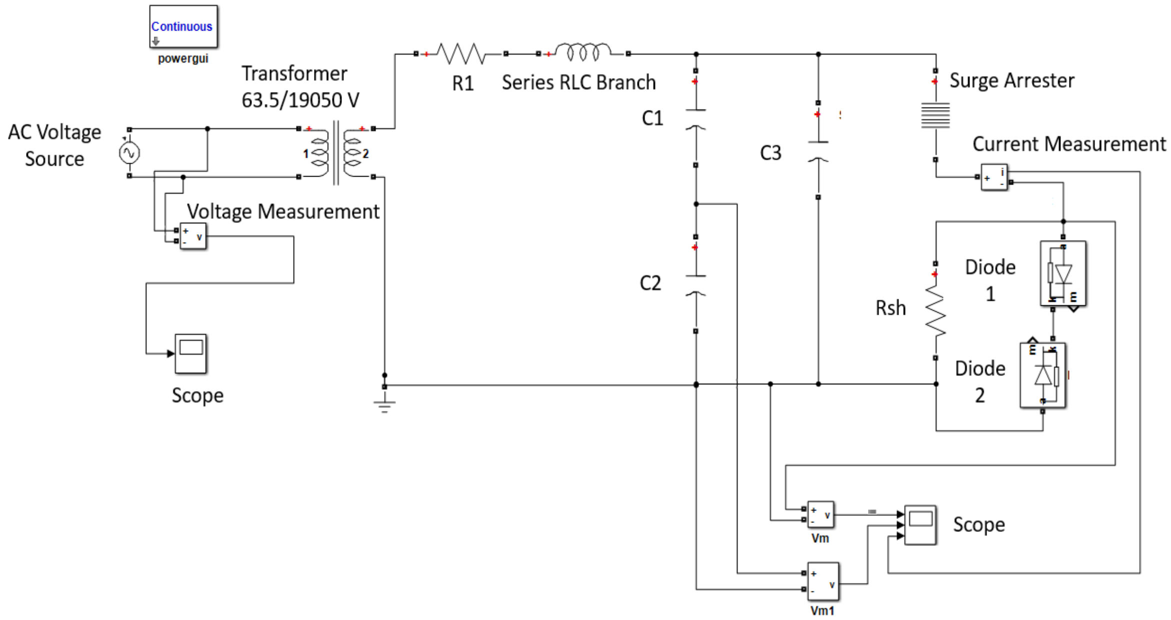


Figure 3. Laboratory experimental circuit for GLSA

Equipment used for each test with detailed methodology is given further. After testing all the GLSAs have been kept for accelerated ageing process. Following tests were carried out on all the GLSAs before and after ageing: i) lightning impulse residual voltage measurement at 1 kAp, 8/20 μS impulse current; ii) measurement of reference voltage at reference current of 1 mA; iii) measurement of capacitance; iv) measurement of tan δ; v) measurement of partial discharge (PD); vi) measurement of I_T; vii) measurement of I_R; viii) measurement of I_{R3rd}; and ix) measurement of I_{R5th}.

For the measurement of impulse residual voltage 800 kVp, 40 kJ impulse voltage test system has been used. Non-inductive current shunts of 1.0 Ω with high resolution impulse analyser used for impulse current measurement. Same test set-up has been used for application of 1 kAp lightning impulse current on all the ratings of surge arresters. The discharge current's amplitude and waveform can have an effect on the residual voltage; the residual voltage must be lower than the protection level of the operating equipment [24]. The reference voltage at reference current of 1 mA measured using 150 kV, 150 kVA, high voltage transformer, 9.8 kΩ resister, 100 kV voltage divider, and digital oscilloscope. For the measurement of various components of leakage current 33 kV, single phase high voltage source used and for measurement of leakage current 10 kΩ non-inductive resistance used. Voltage measurement has been carried out using accurate high voltage probe. 80 kV high voltage PD free transformer, 100 kV capacitive voltage divider, 300 kV coupling capacitor, and digital PD measuring system used for PD measurement. 80 kV high voltage PD free transformer, 50 pF standard capacitor, and bridge used for capacitance and tan δ measurement.

Leakage current was measured on digital oscilloscope and then resistive component of I_T measured as per method given IEC: 60099. The third harmonic and fifth harmonic component of resistive current component obtained by fast Fourier transform (FFT) method on digital oscilloscope [25]. Laboratory experimental set-up has been shown in Figure 4. Measured leakage current and voltage on digital oscilloscope has been shown in Figure 5. The obtained experimental results were recorded and database created.

Figure 4. Experimental set-up

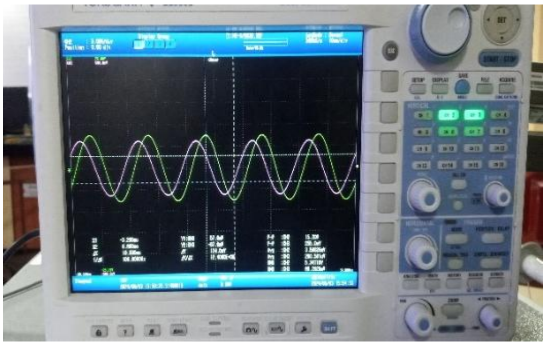


Figure 5. Measured leakage current and voltage

3.1. Accelerated ageing process followed for gapless surge arresters

Accelerated ageing of all the GLSAs have been carried out, the ageing process followed has been given in Figure 6. First all the GLSAs kept in oven at 150 °C for temperature ageing of 168 hours as shown in Figure 7(a). After that impulse current of 1 kA_P has been applied on each GLSA for 500 times as shown in Figure 7(b). Impulse voltage test system has been used for 500 Nos. of application at 1 kAp, 8/20 μS impulse current. After that all three GLSA have been kept in salt fog chamber having volumetric dimension of 15 M^3 used for salt fog for 168 hrs as shown in Figure 7(c). For voltage application under salt fog 50 kV, 1 Amp high voltage source has been used. After that all the three GLSA immersed in normal tap water for 168 hrs as shown in Figure 7(d). After accelerated ageing of GLSA same tests have been repeated. The database of fresh and aged GLSA have been created. Results of the before and after accelerated ageing process has been compared and analysed for verification of healthiness of GLSA.

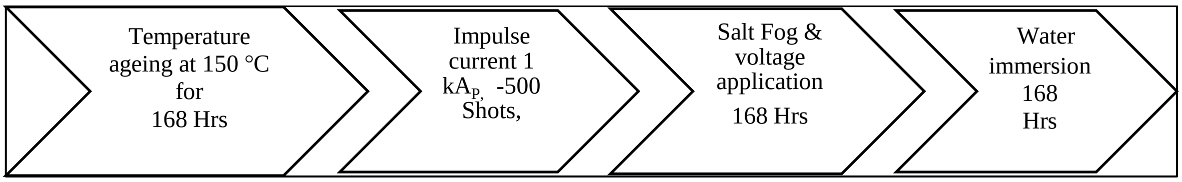
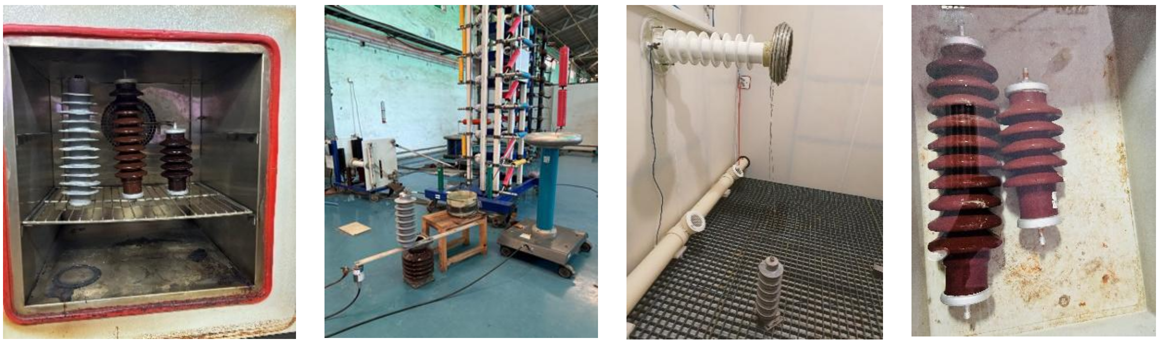


Figure 6. Accelarated ageing process



(a) (b) (c) (d)

Figure 7. GLSA underageing process of temperature, impulse current, salt fog, and water immersion; (a) temperature ageing, (b) impulse current ageing, (c) salt fog ageing, and (d) water immersion ageing

4. RESULTS AND DISCUSSION

Experimental results of all the GLSAs have been recorded. The obtained results before and after ageing process are analysed. Obtained results before ageing process is given in Table 2. As per experimental results, measured impulse residual voltage for all the new surge arresters are within limit. Measured PD quantity, is well within limit for all the new surge arresters. Value capacitance and tan δ does not indicate any abnormalities. The data base of various components of measured leakage current have been created for all three ratings of surge arresters and obtained results does not signify any abnormalities. From the obtained leakage current components reference value of ratios of all current components from R_a to R_f and overall ratio R has been computed. Measured impulse residual voltage after ageing for all surge arresters is reduced after ageing. No significance change observed in the value of measured capacitance of surge arresters. However, significant increment observed in measured tan δ value. PD quantity increased to very high value which conforms ageing effects. The data base of various components of measured leakage current after ageing have been created. Obtained results after ageing process is given in Table 3. All leakage current components shows significantly increased after ageing process. From the obtained leakage current components reference value of ratios of all current components from R_a to R_f and overall ratio R has been computed.

Table 2. Experimental results before ageing

Parameter	9 kV	18 kV	30 kV
Measured lightning impulse residual voltage (kVp)	22.4	41.4	80.18
Measured reference voltage at reference current (kV)	10.2	18.8	30.7
Measured capacitance (pF)	50.823	52.5138	52.9321
Measured tan δ (%)	0.05123	0.07132	0.07532
Measurement of partial discharge (pC)	1.2	1.5	0.8
Measured-I_T (μAp)	126.4	118.5	136.2
Measured-I_R (μAp)	42.12	32.85	45.6
Measured third harmonic resistive leakage current - I_{R3rd} (μAp)	13.47	13.53	15.35
Measured 5th harmonic resistive leakage current - I_{R5th} (μAp)	4.12	4.2	4.32

Table 3. Experimental results after ageing

Parameter	9 kV	18 kV	30 kV
Measured lightning impulse residual voltage (kVp)	20.86	38.92	78.8
Measured reference voltage at reference current (kV)	9.56	17.22	28.12
Measured capacitance (pF)	51.1212	52.3245	51.4532
Measured tan δ (%)	0.06231	0.08231	0.08765
Measurement of partial discharge (pC)	26	35	278.34
Measured-I_T (μAp)	243.32	235.43	358.67
Measured-I_R (μAp)	102.36	110.4	167.37
Measured third harmonic resistive leakage current-I_{R3rd} (μAp)	52.34	48.56	58.71
Measured fifth harmonic component of resistive leakage current-I_{R5th} (μAp)	16.53	15.6	17.89

From the experimental results, measured impulse residual voltage are within specified limit for new surge arresters. Measured PD quantity, is well within limit for all the new surge arresters. Value of capacitance and tan δ does not indicate any abnormalities. The data base of various components of measured leakage current before and after ageing have been created for surge arresters. It can be seen that performance of GLSA degrades due to ageing. As a result, leakage current flowing through the GLSA increased significantly and hence watt loss in GLSA is also increased. Higher power loss increases the temperature of GLSA. While analysis of leakage current of GLSA it is observed that resistive components, third harmonics component of resistive current and fifth harmonics component of resistive current increased significantly. The value of PD quantity is also increased with increased in leakage current. The value of capacitance remains almost same however marginal increase in value of tan δ. After ageing maximum variation is observed in the I_R, third harmonic component of resistive leakage current and fifth harmonic component of resistive leakage current. In this paper, new criteria based on harmonic ratios of measured leakage current have been proposed to identify surge arrester healthiness. As improved health indicator of surge arresters ratios of I_T, I_R, third harmonic component of resistive leakage current and fifth harmonic component of resistive leakage current before and after accelerated process has been computed. Finally, overall ratio of all current has been computed as per formula given in (4). Obtained results before and after ageing have been given in Tables 4 and 5 respectively.

Table 4. Ration of leakage current

Ratio	Current component of GLSA
R_a	Resistive leakage current/total leakage current (I_R/I_T)
R_b	Third harmonic resistive leakage current/total leakage current (I_{R3rd}/I_T)
R_c	Fifth harmonic resistive leakage current/total leakage current (I_{R5th}/I_T)
R_d	Third harmonic resistive leakage current/resistive leakage current (I_{R3rd}/I_R)
R_e	Fifth harmonic resistive leakage current/resistive leakage current I_{R5th}/I_R
R_f	Fifth harmonic resistive leakage current/3rd harmonic resistive leakage current I_{R5th}/I_{R3rd})

Table 5. Ratio of leakage current components of GLSA

Ratio	Before accelerated ageing			After accelerated ageing		
	9 kV	18 kV	30 kV	9 kV	18 kV	30 kV
R_a	0.333	0.277	0.335	0.421	0.469	0.467
R_b	0.107	0.114	0.113	0.215	0.206	0.164
R_c	0.033	0.035	0.032	0.068	0.066	0.050
R_d	0.320	0.412	0.337	0.511	0.440	0.351
R_e	0.098	0.128	0.095	0.161	0.141	0.107
R_f	0.306	0.310	0.281	0.316	0.321	0.305
R	0.573	0.611	0.572	0.784	0.764	0.689

From the computed ratios of various current components it can be seen that the maximum ratio computed for I_R to I_T flowing through the surge arresters. The ratio of I_R to I_T (R_a) obtained from 0.277 to 0.335 before ageing process and after ageing this ratio increased 0.421 to 0.469. Similarly ratio of I_{R3rd} to I_T (R_b) obtained from 0.107 to 0.114 before ageing process and after ageing this ratio increased 0.206 to 0.215. The ratio of I_{R5th} to I_T (R_c) obtained from 0.032 to 0.035 before ageing process and after ageing this ratio increased 0.050 to 0.068. The ratio of I_{R3rd} to I_R (R_d) obtained from 0.32 to 0.412 before ageing process and after ageing this ratio increased 0.351 to 0.511. The ratio of I_{R5th} to I_R (R_e) obtained from 0.095 to 0.128 before ageing process and after ageing this ratio increased 0.107 to 0.161. The ratio of I_{R5th} to I_{R3rd} (R_f) obtained from 0.281 to 0.310 before ageing process and after ageing this ratio increased 0.305 to 0.316. The comparison of ratios of current components for 9 kV, 18 kV, and 30 kV GLSAs have been given in Figures 8-10 respectively.

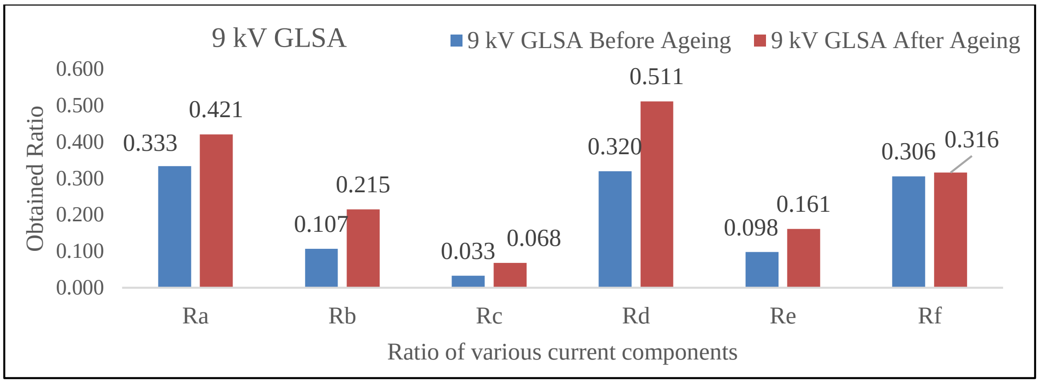


Figure 8. Comparison of ratio of leakage current components for 9 kV GLSA

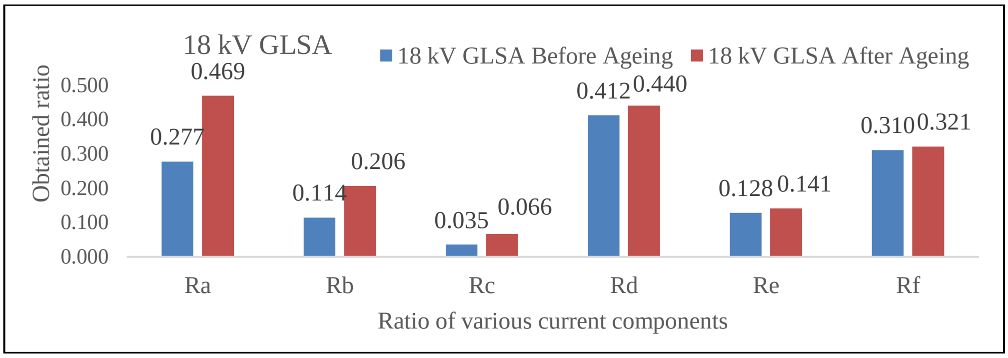


Figure 9. Comparison of ratio of leakage current components for 18 kV GLSA

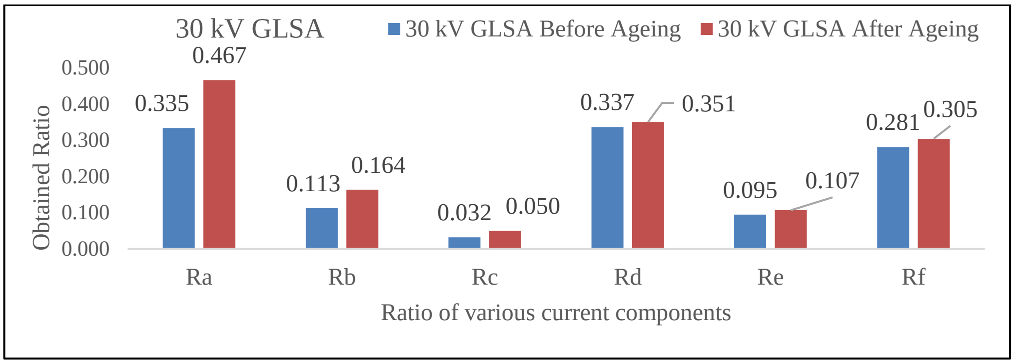


Figure 10. Comparison of ratio of leakage current components for 30 kV GLSA

The overall computed ratios (R_i) before ageing observed 0.573, 0.611, and 0.572 for 9 kV, 18 kV, and 30 kV GLSA respectively. After ageing overall R_i observed 0.784, 0.764, and 0.689 for 9 kV, 18 kV, and 30 kV GLSA respectively. Variation in overall current ratio has been shown in Figure 11.

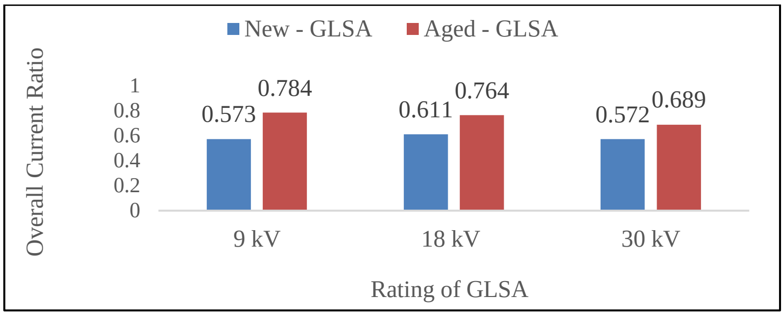


Figure 11. Variation in current ratios

The ratio of I_R to I_T (R_a) increased by 26.2%, 69.2%, and 39.4% for 9 kV, 18 kV, and 30 kV GLSA respectively. Ratio of I_{R3rd} to I_T (R_b) increased by 101.9%, 80.6%, and 45.2% for 9 kV, 18 kV, and 30 kV GLSA respectively. The ratio of I_{R5th} to I_T (R_c) increased by 108.4%, 87%, and 57.3% for 9 kV, 18 kV, and 30 kV GLSA respectively. The ratio of IR3rd to IR (R_d) increased by 59.9%, 6.8%, and 4.2% for 9 kV, 18 kV, and 30 kV GLSA respectively. The ratio of I_{R5th} to I_R (R_e) increased by 65.1%, 10.5%, and 12.8% for 9 kV, 18 kV, and 30 kV GLSA respectively. The ratio of I_{R5th} to I_{R3rd} (R_f) increased by 3.3%, 3.5%, and 8.5% for 9 kV, 18 kV, and 30 kV GLSA respectively. The maximum variation is observed in ratios of I_{R3rd} to I_T and I_{R5th} to I_T.% variation has been shown in Table 6 and comparison has been shown in Figure 12.

Table 6. Variation in current ratios

Ratio	% Variation		
	9 kV GLSA	18 kV GLSA	30 kV GLSA
R_A	26.2	69.2	39.4
R_B	101.9	80.6	45.2
R_C	108.4	87.0	57.3
R_D	59.9	6.8	4.2
R_E	65.1	10.5	12.8
R_F	3.3	3.5	8.3
R	36.77	25.00	20.40

Overall ratio (R_i) increased by 36.77% for 11 kV, 25% for 18 kV, and 20.40% for 30 kV GLSA, which has been shown in Figure 13. The measured partial discharges after ageing has also increased significantly which indicates degradation of surge arresters. The results other health monitoring parameters like reference voltage at reference current, tan δ, impulse residual voltage also indicates degradation of surge arrester. Hence, proposed techniques of criteria of ratios of various current component and overall R_i can be used as effective tool to detect the ageing and degradation of GLSAs.

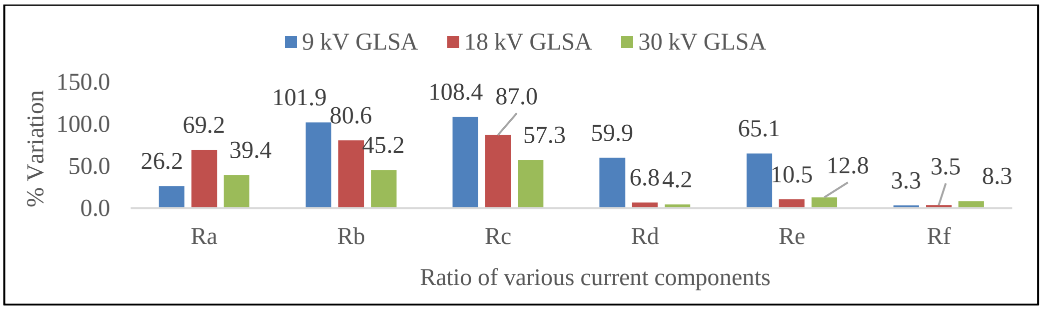


Figure 12. Variation in current ratios

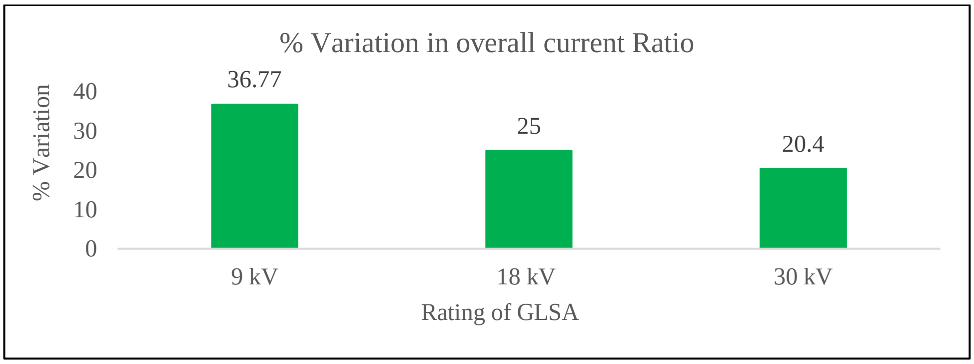


Figure 13. % variation in overall current ratios

5. CONCLUSION

In this paper novel approach based on ratios of various leakage current components has been proposed. New criteria have been proposed to recognize various ageing criteria of impulse current application along with salt fog, temperature, moisture and voltage application as per site conditions. It can be seen that after ageing, I_T, I_R, third harmonic, and fifth harmonic component of resistive leakage current increased. The ageing or condition of surge arresters can be determined by computing ratios of various current components. The value of capacitance does not indicate variation, however value of dissipation factor i.e., tan δ considerably increased after ageing. Proposed new method of ratios of leakage current components i.e., (I_R/I_T), (I_{R3rd}/I_T), (I_{R5th}/I_T), (I_{R3rd}/I_R), (I_{R5th}/I_R), and (I_{R5th}/I_{R3rd}) can be used as improved and effective method as this ratios increased significantly after ageing. Computation of overall ratio from various current components is most effective method as it includes ratios of all current components. The obtained results proves effectiveness of the proposed technique for online condition monitoring of GLSAs. The proposed method of ratios of various leakage current component is also validate by offline condition monitoring techniques, hence this new proposed technique is useful tool to determine the health of surge arresters. In this research supply voltage used are pure sinewave without harmonics hence effects of supply harmonics on various current components ratios has not been considered. This deficiency can be considered for further scope of research.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Anil S. Khopkar	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Kartik S. Pandya		✓				✓		✓		✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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