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Surge Arrester Monitoring under Different Operating Conditions Using Bees-ANFIS

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Abstract: The essential role of surge arresters is equipment protection against over-voltages to increase system reliability. Different monitoring techniques have been used to diagnose surge arrester condition. Leakage current analysis methods by the extraction resistive and capacitive components of leakage current are a conventional method for surge arrester monitoring. Insufficient appropriate thresholds are most important restriction of these kinds of methods. In this paper, the impact of pollution, ultraviolet aging and varistors fault on harmonic spectrum of leakage current have been evaluated experimentally. Real tests and examinations have been done on different metal oxide surge arresters to investigate effects of mentioned factors on leakage current harmonics. To show results performance, bees-adaptive network based fuzzy inference system has been applied.

Keywords: Surge Arrester, Harmonics Analysis, Leakage Current, Diagnostic, Bees-ANFIS.

1 Introduction

GAPLESS surge arresters (SA) have been used widely in utilities for switching or lightning surges energy stress elimination. Also it can be able to limit surge magnitude to a satisfactory margin. The major factors of unpredicted outages and equipment failures are switching and lightning over-voltages [1-2]. Therefore, SA can be implemented as a powerful device to increase the continuity and reliability of high voltage apparatuses. Consequently surge arrester property performance can be restricted utility or substation tools failures [3-5]. Therefore, condition monitoring of surge arresters is an essential process to distinguish and evaluate their conditions. With the aim of conditions monitoring of SAs various online and offline methods have been offered [6-14]. Determination of surge arrester condition via leakage current evaluating is the most practical online techniques. In this way, harmonic analysis especially 3rd order harmonic is a main parameter for SA monitoring in online methods [6-9]. Decomposition of leakage current requires surge arrester applied voltage measuring for obtaining resistive or capacitive components. Impression of voltage harmonics amplitudes and phase angles is major drawback of leakage current measuring methods. Also, diagnostic approaches based on resistive current harmonics and serviceable equipment have been developed [15-20]. Considering that many monitoring techniques based on leakage current analysis have been represented but need of more accurate indicators are required [6], [15-17]. In this article, the effects of several conditions such as exterior pollution, varistor degradation and ultraviolet (UV) aging have been examined on harmonic contents of SA leakage current. It can help the operator in preventive and predictive maintenance activities. A features database for the different investigated conditions based on experimental tests on polymer housed surge arresters in high voltage laboratory has been collected. Based on obtained real signals, the performance of introduced results is evaluated by bees-ANFIS.

2 Measuring Process

Metal oxide varistors are ceramic resistors with high

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nonlinear V-I characteristic, which are suitable for transient overvoltage repression. The nonlinear resistivity of varistor is a natural property of this composite ceramic resistor. According to the nonlinear V-I characteristic of varistors, MOSA functions can be divided as follow:

- Don't operate under normal operating voltages. (Small leakage current goes through surge arrester)
- Operate during overvoltage without causing a fault. (Large leakage current goes through surge arrester).

The simplified equivalent circuit of MOSA at low current region is shown in Fig. 1 which it is comprised of nonlinear resistive branch in parallel with capacitive one. Under normal operating voltage, a small total leakage current passes through the MOSA. This current subdivides into resistive and capacitive components.

To extract proper features, the experimental test setup was arranged to analyse surge arresters conditions effects on total leakage current (TLC) and its components (resistive and capacitive). Total measurement decomposition to resistive and capacitive currents has been performed by the explained method in [20]. This method is an extraction method based on orthogonality between the capacitive and the resistive components.

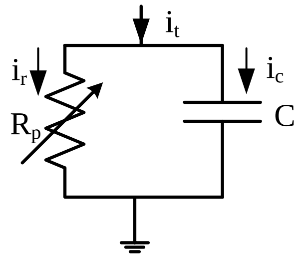
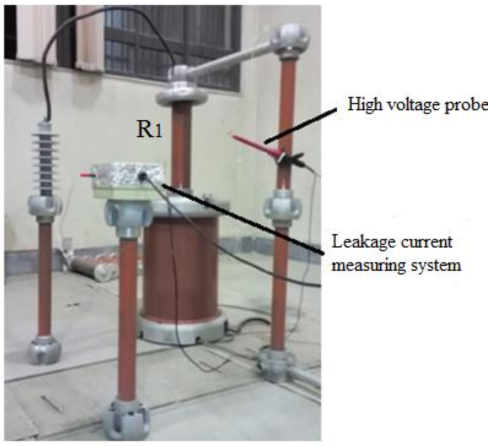


Fig. 1 The block diagram of the considered hybrid micro grid.

2.1 Experimental Setup

To achieve required tests, as shown in Fig. 2, experimental test setup has been arranged. In this figure, high voltage setup comprises of a transformer with variable output between 0-100 kV, protective resistor (R_1), voltage measuring tool and leakage current measuring system. Voltage measuring tool implements high voltage probe for voltage measuring. This probe can measure high voltage signals directly and also the AC voltage measuring level of this probe is 40 kV. Leakage current measuring system consists of protective Zener diodes and a measuring resistor (R_{sh} = 470 Ω). Back to back connected Zener diodes have been used for overvoltage protection and R_{sh} for measuring leakage current. This resistor has been serried with surge arrester and its voltage drop has been measured. So leakage current can be achieved directly.

The details of LC measuring device has been shown in Fig. 2.b. Measured TLC and voltage have been transported to the analysis software by digital oscilloscope during experimental tests. 20 kV polymer surge arresters have been utilized for leakage current measuring under different conditions corresponded to typical failures and excellent condition (clean virgin samples). The manufactured data of evaluated surge arresters have been represented in Table 1.



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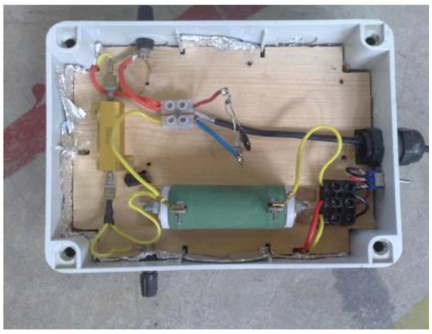


(b)

Fig. 2 Voltage and current measuring experimental preparation; a) experimental setup and b) leakage current measuring device.

Table 1 Surge arresters characteristics.

Surge arrester type	A	B	C
Rated voltage (kV)	25	25	24
Creepage distance (mm)	800	750	800
Shed numbers	8	10	16
Maximum residual voltage (kV)	70	70	71
impulse current- 8/20µs (kA)	10	10	10
Zinc oxide varistor numbers	7	7	6

2.2 Experimental Tests

Good condition was the first considered investigation on studied surge arresters during experimental tests. In this situation, the SAs were untapped and clear. Other defective conditions are UV aged, aged-polluted and virgin-polluted samples and SAs with degraded varistors in active column. The influence of UV aging on polymer housed surge arrester leakage current has been investigated in this article. Therefore, according to IEC60507 [21], SAs have been exposed to UV_C radiation for 3000 hours to do aging process. Fig. 3 shows the sequence of aging test.

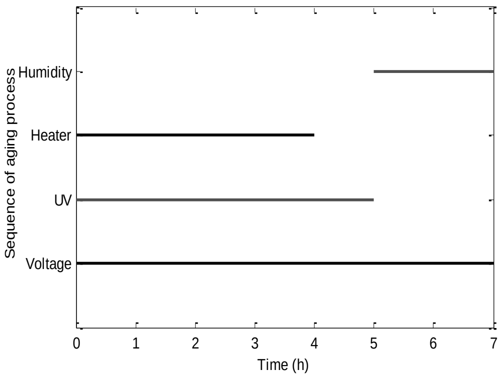


Fig. 3 The sequence of aging test.

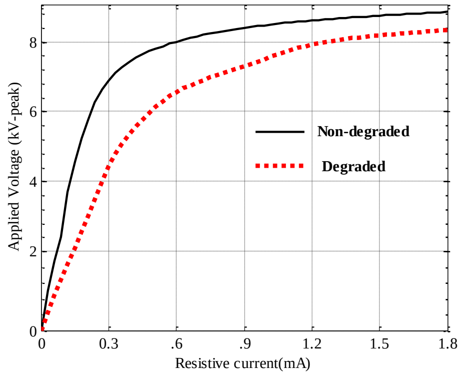
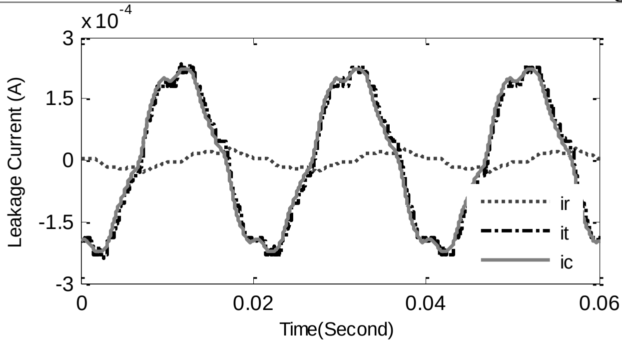


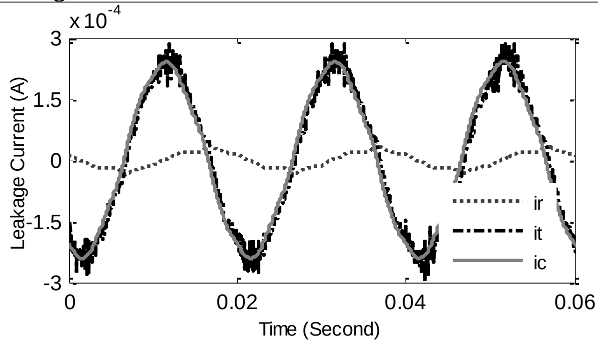
Fig. 4 V-I characteristics of aged and virgin zinc oxide varistors.

Table 2 Different considered Scenarios for surge arrester condition assessment.

Scenario 1: Clean Aged and Virgin Housed SA.

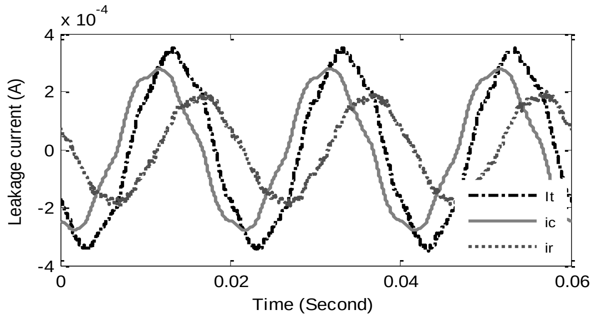


LC of clean-virgin **A surge** arrester.

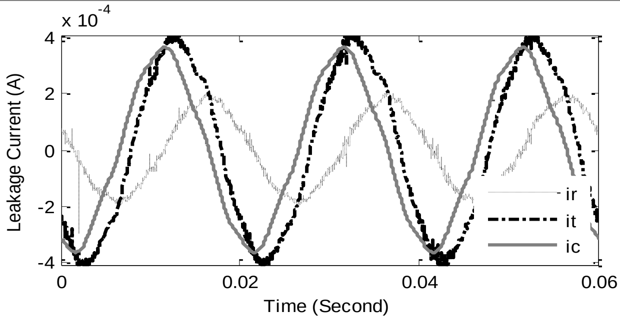


LC of Aged A surge arrester.

Scenario 2: Polluted Aged and Virgin SA.

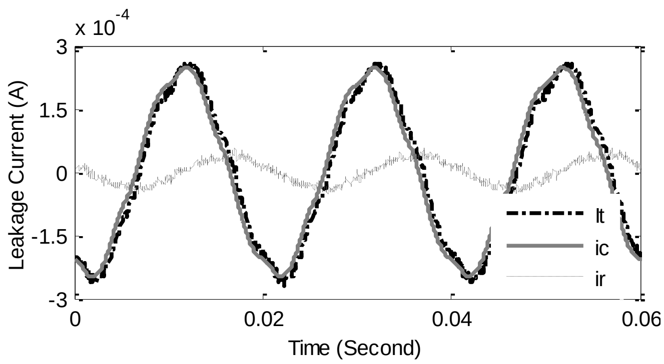


LC of virgin-light polluted A surge arrester (85% humidity).



LC of Aged-light polluted A surge arrester (85% humidity).

Scenario 3:Degraded Varistor in Active Column.



TLC and its components of **A** surge arrester with degraded varistor.

2.3 Experimental Tests

Good condition was the first considered investigation on studied surge arresters during experimental tests. In this situation, the SAs were untapped and clear. Other defective conditions are UV aged, aged-polluted and virgin-polluted samples and SAs with degraded varistors in active column. The influence of UV aging on polymer housed surge arrester leakage current has been investigated in this article. Therefore, according to IEC60507 [21], SAs have been exposed to UV_C radiation for 3000 hours to do aging process. Fig. 3 shows the sequence of aging test.

Pollution occurrence on the SA housing has been investigated experimentally via solid layer technique in high voltage lab. Different kinds of liquid have been prepared to contaminate the surge arresters exterior surfaces. Equivalent Salt Deposit Density (ESDD) has been applied as an indicator to calculate polluted layer severity levels on surge arrester surface according to IEC60507 [21]. To consider varistor degradation effect on leakage current, degraded varistors have been detached from worked SA in high voltage power system for 15 years and have been located in three different locations of new surge arrester active columns. Voltage-current data of degraded and new varistors has been shown in Fig. 4.

3 Different Scenarios for Leakage Current Investigation

In this segment, TLC harmonics and their components have been measured experimentally for 11.54 kV (rms phase to ground) under mentioned different situations. For this purpose, three scenarios have been considered and Table 2 shows the typically waveforms of TLCs and their decomposed parts.

3.1 Scenario 1

In this scenario, the influences of surface aging have been studied on surge arrester TLC and its components. Table 3 shows the harmonic components of clean SA leakage current before and after UV radiation presence. It should be mentioned that in order to be confident about measured values, each experimental has been repeated more times and the average data has been used to determine values of each specific situations. As revealed in Table 3, fundamental, third and fifth resistive components, which considerably affect resistive leakage current magnitude, depend on the SA surface condition. Fundamental and third harmonics of aged SAs are greater than virgin samples whereas fifth order harmonic diminishes.

To show resistive harmonic content dependency of surface aging, A surge arrester was occasionally removed from the aging chamber and its leakage current was measured in several times. After measuring, the sample was returned to aging chamber to age. Fig. 5 shows harmonic components of measured resistive leakage currents during aging process.

Table 3 Harmonic spectrum analysis of virgin and UV aged surge arrester.

LC components (μA)	Surge Arrester A		Surge Arrester B		Surge Arrester C	
	Virgin	Aged	Virgin	Aged	Virgin	Aged
i_{t1}	223.77	234.23	226	230	250	272
i_{t3}	4.847	3.413	3.511	3.131	3.81	2.76
i_{t5}	20.63	9.74	14.33	6.68	18.49	7.11
i_{r1}	21.488	23.16	24.58	26.13	69.69	71.55
i_{r3}	0.5103	1.2657	1.292	1.649	1.047	1.702
i_{r5}	4.315	1.819	2.915	2.857	3.941	1.685

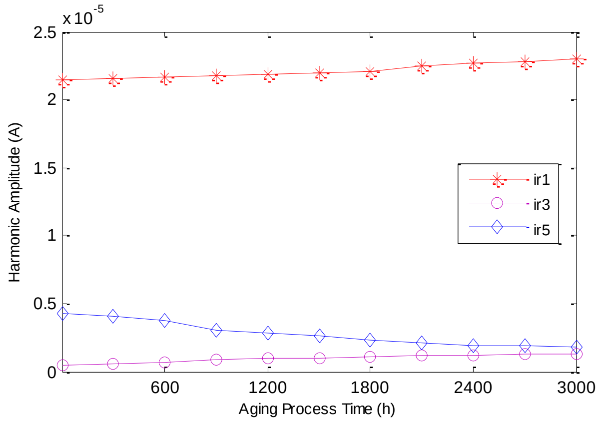
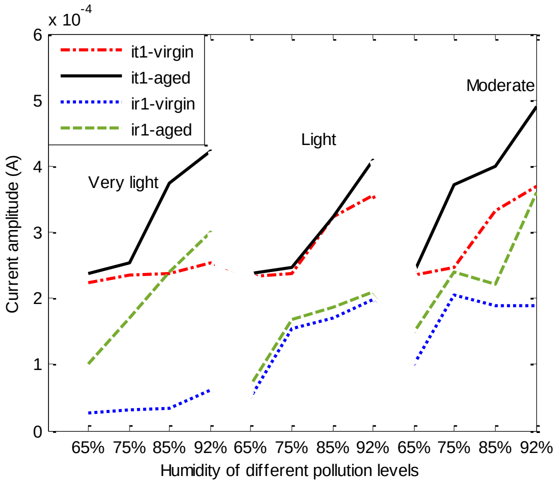


Fig. 5 Harmonic components of resistive leakage current during aging process.

3.2 Scenario 2

In this scenario, the influences of pollution on TLC and its components have been evaluated. For this purpose, leakage currents of aged and virgin SAs in different pollution levels have been measured experimentally. Fig. 6 shows harmonic spectrum analysis of A surge arrester in polluted and aged-polluted situations. Moreover, the leakage currents harmonics of B surge arrester are represented in Fig. 7.



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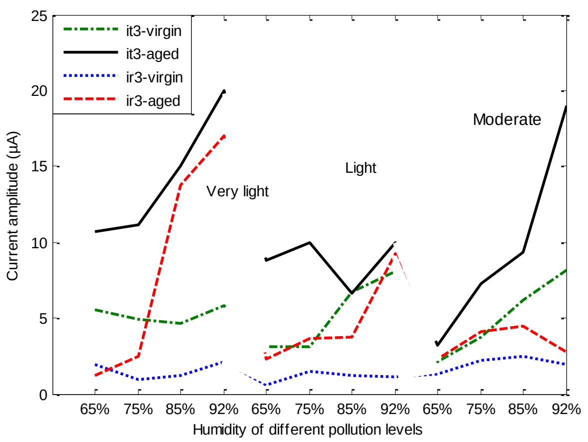

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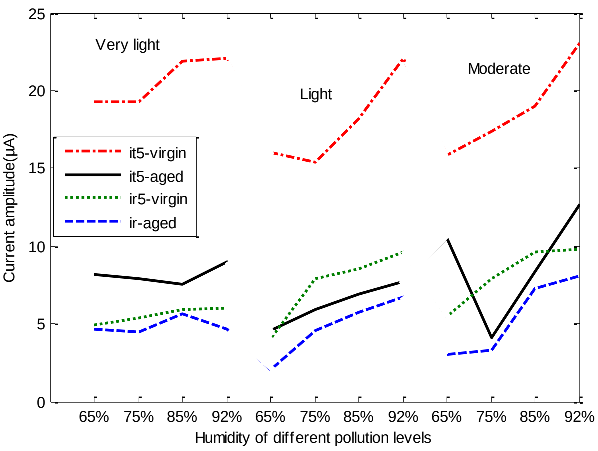

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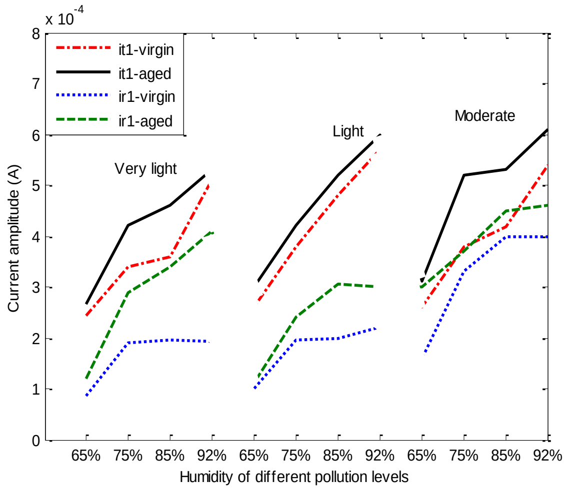
Fig. 6 Leakage current harmonics spectrum of A surge arrester; a) Fundamental order harmonic analysis, b) Third order harmonic analysis, and c) Fifth order harmonic analysis.



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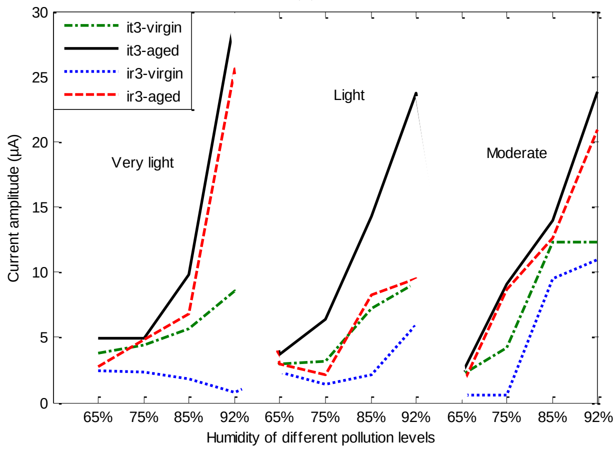

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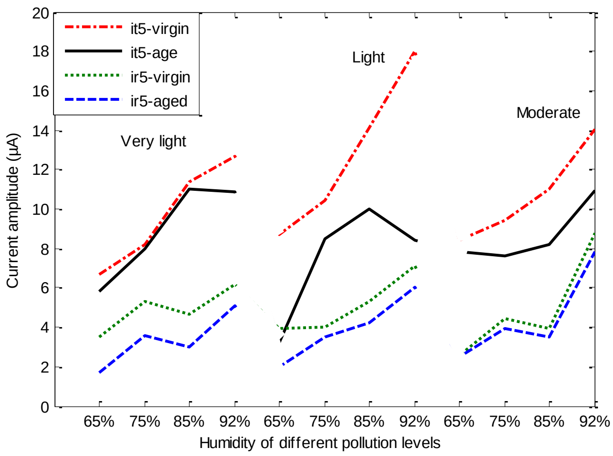

(c)

Fig. 7 Leakage currents harmonics spectrum of B surge arresters a) Fundamental order harmonic analysis, b) Third order harmonic analysis, and c) Fifth order harmonic analysis.

It concludes harmonic analysis of polluted aged and contaminated virgin ones. Consistent with the results, it is clear that TLC fundamental order harmonic and also resistive component to be mainly impressed by pollution that leading to the TLC distortions. Moreover, more severely pollution levels, due to the housing conductivity increment, bring about flow of higher ir_1 and it_1. Also, in aged exterior surfaces samples due to hydrophobic losses causing by UV aging, ir_1 and it_1 have increased more than virgin polluted ones. Moreover, ir_3, it_3, ir_5 and it_5 have correlation with the ageing (especially ir_3 and ir_5) and can be used to recognize aged samples from virgin ones. A great rise in third harmonics of total and resistive current and a diminution in their fifth harmonics have been made by UV aging.

3.3 Scenario 3

To investigate varistors degradation effects on SA leakage current, a degraded ZnO block has been located in three various positions of active column in A surge arrester with seven varistors. Harmonics spectrum analyses of the measured currents are represented in Table 4. According to the represented results of leakage currents, it is seen that degradation had effects on harmonic components of resistive and total leakage current equated with the clean virgin harmonics. ir_1 and it_1 are more dominant in the case of varistor degradation and so degradation fault can be discerned of aged and virgin clean surge arresters based on these two factors. It is clear that the 3rd and 5th order harmonics of resistive current simulates well the degradation level compared to the virgin samples. In addition, it_3 and it_5 in degraded condition decrease relative to virgin clean samples.

4 Introduced Parameters Performance Using ANFIS

ANFIS is a type of artificial neural network regarding to the Takagi–Sugeno interference method [22]. This method has been used as an useful method to approximate nonlinear functions. Neural networks and fuzzy logic attitudes combines in ANFIS and so it is able to capture the profits of both in a single structure [23, 24]. To use ANFIS in a further optimum way, the best parameters can be obtained by cross validation technique [24]. Cross-validation is a technique which can give a vision how the statistical analysis results will be generalized as a self-determining data. It is principally applied for prediction and estimation goals. To limit over fitting problems, cross validation is used to define a dataset for model testing in the training stage [24]. ANFIS still requirements impressive parameter training and rule-base optimization methods to do efficiently when the inputs number increment. Therefore many researchers have evaluated optimizing in the ANFIS rule-base. In this paper, the bees algorithm (BA) has been used to achieve optimum radius vector. The BA is a swarm intelligence approach for function optimization for both continuous and combinatorial optimization problems. It mimics the food foraging behaviour of honey bees. One iteration consists of both local exploitation and global search. In its basic version, the algorithm performs a local or exploration combined with global random search and can be used for optimization. The basic BA uses a number of parameters that can be tuned to achieve better optimization results. These include the number of scout bees, best and elite bees and the number of recruited bees around the best and elite patches. In addition, it needs the search neighbourhood size of each patch and the stopping condition.

As indicated, the SA operating characteristics change under use as a consequence of several factors. In this paper, external pollution, UV aging and varistor fault effects have been investigated to analyse currents behaviours of three types tested SAs. In relation to the obtained results, contamination and degradation lead to an intense variation in ir_1 and it_1. Moreover, ir_3 and ir_5 have good dependency to the ageing and degradation situations and finally it3 and it_5 have good coordinate to distinguish degraded condition from aged polluted one. For comprehensive investigation, Fig. 8 shows the averages of ir_1 and ir_3 that achieved from laboratory tests on A surge arrester graphically. Fig. 9 presents a summary of the proposed technique that has been applied to evaluate the accuracy of obtained results.

Table 4 Degraded varistor harmonic spectrum analysis.

LC components(μA)	Degraded varistor position			Clean virgin	Clean Aged
	1st location	2nd location	3rd location		
i_{t1}	248.9	247.8	247	223.7	233.4
i_{t3}	2.8	3.03	2.8	4.84	3.413
i_{t5}	12.01	12.9	12.4	20.63	9.74
i_{r1}	38.5	38	37.84	21.4	23.16
i_{r3}	2.051	1.762	1.102	0.5103	1.2657
i_{r5}	1.489	1.728	2.519	4.315	1.819

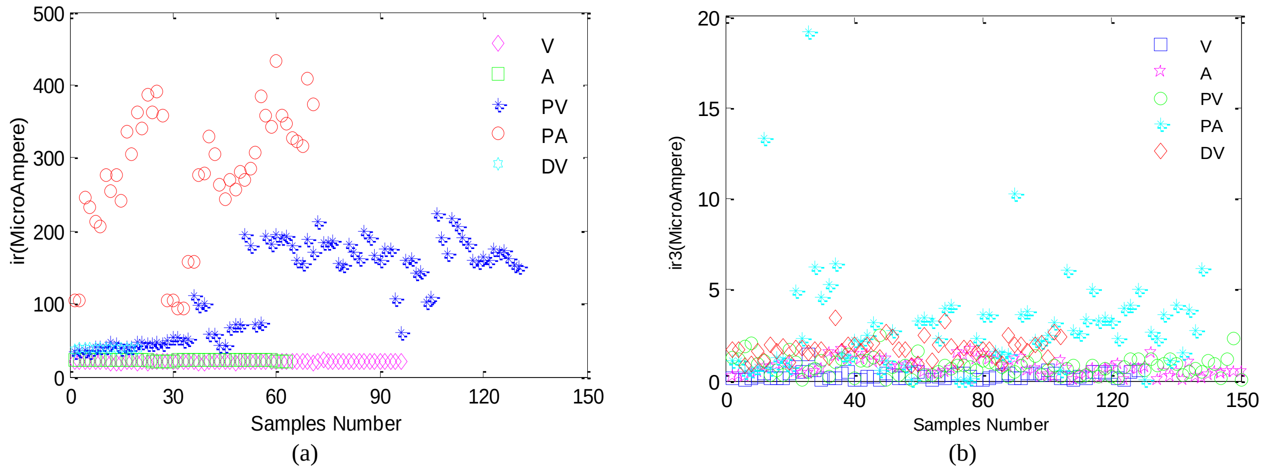

Fig. 8 The dispersion of measured data (a): i_{r1} (b): i_{r3}.
PA: Polluted-Aged, A: Clean-Aged, V: Clean-virgin, DV: Degraded-varistor, PV: Polluted- virgin

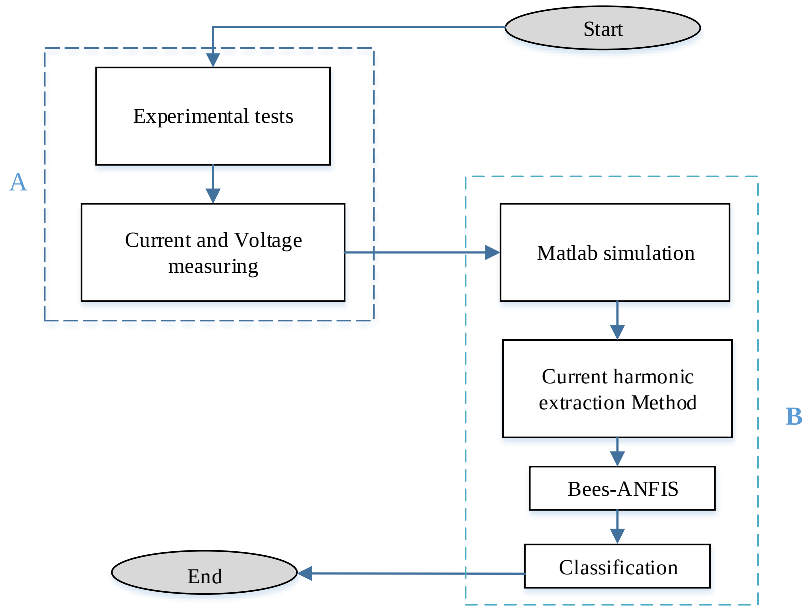

Fig. 9 A summary of the classifier via leakage current measuring.

For this purpose, the aforesaid dataset of the different conditions of a surge arrester was used which 40% of experimental data have been implemented for testing and the remaining for classifier training. The k-fold cross validation technique has been implemented to show the validity of obtained data from experimental test [22-24]. The samples are accidentally divided into k equal sized subsamples so that one subsample is applied for model testing and the rest subsamples are used as training data.

4.1 Performance of ANFIS With and Without Optimization

In this manuscript bees-ANFIS has been used to show the accuracy of the obtained indicators. In fact, the ability of measured data and proposed criteria has been evaluated with ANFIS recognizer. If the ANFIS model is correctly trained based on input data, the output can be achieved exactly. The capability to correlate both data and existing specialist knowledge about the problems, precise and fast learning, good generalization capability features have made neuro-fuzzy systems popular [25]. ANFIS still requirements impressive parameter training and rule-base optimization methods to do efficiently when the inputs number increment. Moreover, the standard gradient based learning via two pass learning algorithm is prone slow and prone to get stuck in local minima. Therefore many researchers have evaluated optimizing in the ANFIS rule-base. At first, the efficiency of the system with no optimization algorithm has been studied. Next, the bees algorithm (BA) has been used to achieve optimum radius vector.

Table 5 shows the recognition accuracy of tested samples. It can be seen that ANFIS with unprocessed data achieves 92.71% recognition accuracy. Combining

Table 5 Recognition accuracy of the recognizer.

Classifier	Input size	Recognition accuracy (%)	Run time (S)
ANFIS	6	92.71	0.2
BA-ANFIS	6	96.12	5

Table 6 The confusion matrix of best result (96.12%).

	First Pattern	Second Pattern	Third Pattern	Forth Pattern	Fifth Pattern
First Pattern	54	0	0	0	0
Second Pattern	0	34	0	0	0
Third Pattern	0	0	36	0	1
Forth Pattern	0	0	1	32	2
Fifth Pattern	0	0	1	1	29

the BA with the ANFIS significantly improves the classification performance relative to the stand-alone ANFIS model. It can be seen that BA-ANFIS with unprocessed data achieves 96.12% recognition accuracy.

The confusion matrix has been represented in Table 6 to show recognizer performance. The diagonal values represent the accuracy of classifier performance and remaining values show system error for each input group. For instance, the quantity of 32 in forth row shows the correct action of classifier of forth input. Also the quantity of 1 and 2 represents that it had wrong performance and this pattern has been classified incorrectly with third and fifth inputs.

5 Conclusion

In this paper, different operating conditions of SAs have been investigated experimentally. It has been done to represent monitoring features for SA diagnostic. The most important findings are as follows:

- Since it is not essential to extract internal and external leakage currents due to the strong relationship of i_{r3} and i_{r5} with the surface ageing, therefore resistive harmonic components of total leakage current can be implemented as powerful criteria to identify ageing level of SA.
- ir_1 and it_1 are more dominant in the cases of varistor degradation and exterior pollution. They can be considered as an efficient criteria to distinguish clean condition from pollution and degradation ones.
- The classification of degraded varistor from aged polluted samples is complicated. These conditions lead to similar changes in i_{r1}, i_{t1}, i_{r3} and i_{r5}. It was observed that 3rd and 5th order harmonics of TLC simulates well the degradation level compared to the virgin samples. Degraded samples have been recognized from contaminated aged situations via i_{t3} and i_{t5} variation.
- The capability of results is evaluated by ANFIS. Results show the ability of introduced parameters for SA condition monitoring. The recognition accuracy without optimization was 92.71%.whereas using BA, the recognition accuracy increased to 96.12%.

Acknowledgment

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