LEAKAGE CURRENT BASED ONLINE CONDITION MONITORING OF METAL OXIDE SURGE ARRESTERS WITH HARMONICS COMPENSATION

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ABSTRACT

Metal oxide surge arresters (MOSA) are used as overvoltage limiting devices to protect the transmission and distribution system from high voltage surges caused by severe lightning and switching operations. Their health and hence condition monitoring are vital to ensure the reliability of the power system. Any deterioration of the non-linear properties of a MOSA is known to cause a corresponding increase in the resistive leakage current, especially the odd harmonic components of the resistive current. The arrester resistive leakage current level is a known and reliable indicator of MOSA deterioration, provided it can be successfully extracted from the arrester total leakage current. The currently available resistive leakage current extraction techniques are divided into either system voltage independent or system voltage dependent. Even though the extraction is made simpler by having a simultaneous arrester voltage signal, the voltage measurement is either difficult or prohibitive. Several previously proposed voltage independent extraction techniques suffer from inaccuracies. In addition, the presence of harmonics in the supply voltage also affects the accuracy of the extraction techniques. The research aims to improve the accuracy of the MOSA resistive leakage current extraction by means of a modified shifted current method-circuit based method (MSCM-CBM) hybrid technique, a thumb-rule based technique for compensating the effects of voltage's harmonics, and a condition monitoring technique using the resistive fifth harmonic leakage current, I_{R5th}, as an ageing indicator of MOSA. The MSCM-CBM hybrid method was developed and tested on Simulink software and then experimentally applied on 120 kV rated MOSAs. Results show that the resistive current extracted by the proposed hybrid method is 3.2 % more accurate than that for the modified shifted current method. The execution of the proposed thumb-rule technique is based on the determination of the total harmonic distortion of both the system voltage and the MOSA total leakage current. The proposed thumb-rule technique is at least 10.5 % more accurate than the existing compensation techniques. The condition monitoring technique of MOSA based on the resistive fifth harmonic is found to be less sensitive towards the voltage harmonics as compared to that using the third harmonic current. Results show that the proposed fifth harmonic-based ageing indicator of MOSA is 1.6 % more accurate than that for the existing third harmonic-based indicator. It is also found that the trend of I_{R5th} variation with respect to the applied arrester terminal voltage and arrester ageing is similar to that of I_{R3rd}. The performance of the proposed I_{R5th} based condition monitoring of MOSA was also validated using the maximum temperature and power loss measurements. The improved accuracies provided by the MSCM-CBM based hybrid method, rule of thumb-based compensation and I_{R5th} based condition monitoring may provide a solution for better and more efficient MOSA condition monitoring.

ABSTRAK

Penangkap Pusuan Metal Oksida (MOSA) digunakan sebagai peranti pengehad voltan lampau untuk melindungi sistem penghantaran dan pengagihan daripada pusuan voltan tinggi yang disebabkan oleh kilat yang teruk dan operasi pensuisan. Kesihatan dan pemantauan keadaan peranti tersebut adalah penting untuk memastikan kebolehpercayaan sistem kuasa. Sebarang kemerosotan ciri tak linear MOSA memang diketahui menyebabkan peningkatan yang sepadan dalam arus bocor rintangan, terutamanya komponen harmonik ganjil arus rintangan. Paras arus bocor rintangan penangkap pusuan merupakan penunjuk kemerosotan MOSA yang diketahui dan boleh dipercayai, dengan syarat ia berjaya diekstrak daripada jumlah arus bocor penangkap. Teknik pengekstrakan arus bocor rintangan yang tersedia pada masa ini dibahagikan kepada sama ada bebas dari voltan sistem atau bergantung kepada voltan sistem. Walaupun pengekstrakan boleh dibuat lebih mudah jika pada masa yang sama ada isyarat voltan penangkap, pengukuran voltan pula adalah sama ada sukar atau terlarang. Beberapa teknik pengekstrakan bebas voltan yang dicadangkan sebelum ini mengalami ketidaktepatan. Selain itu, kehadiran harmonik dalam voltan bekalan juga mempengaruhi ketepatan teknik pengekstrakan. Penyelidikan ini bertujuan untuk meningkatkan ketepatan pengekstrakan arus bocor rintangan MOSA dengan teknik hibrid antara kaedah arus anjakan yang diubah suai dan kaedah berasaskan litar (MSCM-CBM), teknik berasaskan peraturan ibu jari untuk pampasan kesan harmonik voltan, dan satu teknik pemantauan keadaan menggunakan arus bocor rintangan harmonik kelima, I_{R5th}, sebagai penunjuk penuaan MOSA. Kaedah hibrid MSCM-CBM telah dibangunkan dan diuji pada perisian Simulink dan kemudian digunakan secara ujikaji ke atas MOSA berkadar 120 kV. Keputusan menunjukkan bahawa arus rintangan yang diekstrak oleh kaedah hibrid yang dicadangkan adalah 3.2% lebih tepat daripada kaedah arus anjakan yang diubah suai. Pelaksanaan teknik peraturan ibu jari yang dicadangkan adalah berdasarkan penentuan jumlah herotan harmonik kedua-dua voltan sistem dan jumlah arus bocor MOSA. Teknik peraturan ibu jari yang dicadangkan adalah sekurang-kurangnya 10.5 % lebih tepat daripada teknik pampasan sedia ada. Teknik pemantauan keadaan MOSA dibangunkan berdasarkan harmonik kelima rintangan didapati kurang sensitif terhadap harmonik voltan berbanding dengan yang menggunakan arus harmonik ketiga. Keputusan menunjukkan bahawa penunjuk penuaan berasaskan harmonik kelima yang dicadangkan bagi MOSA adalah 1.6 % lebih tepat daripada penunjuk berasaskan harmonik ketiga yang sedia ada. Ia juga didapati bahawa arah aliran variasi I_{R5th} dengan perubahan voltan terminal penangkap dan penuaan penangkap adalah serupa dengan I_{R3rd}. Prestasi pemantauan keadaan berasaskan I_{R5th} yang dicadangkan bagi MOSA juga telah disahkan dengan menggunakan pengukuran suhu dan kehilangan kuasa maksimum. Ketepatan yang lebih baik yang disediakan oleh kaedah hibrid berasaskan MSCM-CBM, pampasan berasaskan peraturan ibu jari dan pemantauan keadaan berasaskan I_{R5th} mungkin menyediakan penyelesaian bagi pemantauan keadaan MOSA yang lebih baik dan cekap.

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LIST OF ABBREVIATIONS

ABB	-	Asea Brown Boveri Corporation
ANN	-	Artificial Neural Network
BNC	-	Bayonet Neill–Concelman
Bi_2O_3	-	Bismuth trioxide
CBM	-	Circuit-based Analytical Method
CCCM	-	Capacitive Current Compensation Method
CM	-	Conventional Method
CMS	-	Condition Monitoring System
COM	-	Current Orthogonality Method
CoO	-	Cobalt Oxide
Cr_2O_3	-	Chromium Oxide
DSO	-	Digital Oscilloscope
EOA	-	Evolutionary Optimization Algorithm
FFT	-	Fast Fourier Transformation
FPM	-	Field Probe Method
GA	-	Genetic Algorithm
ICCM	-	Improved Capacitive Current Method
ITDM	-	Improved Time Delay Method
LCM	-	Leakage Current Measurement
LSM	-	Least Square Method
MOSA	-	Metal Oxide Surge Arrester
MnO	-	Manganese Dioxide
MSCM	-	Modified Shifted Current Method
MLRM	-	Multiple Linear Regression Method
NEC	-	Nippon Electric Company
OF	-	Objective Function
OVM	-	Orthogonal Vector Method
SA	-	Surge Arrester
Sb_2O_3	-	Antimony Oxide
SVM	-	Support Vector Machine

THD	-	Total Harmonic Distortion
TOHM	-	Third Order Harmonic Analysis Method
TNB	-	Tenaga Nasional Berhad

LIST OF SYMBOLS

A	-	Area of the MOSA disc
C	-	Capacitance in the surge arrester model
D	-	Depth of the current sensor
d	-	Height of the column of MOSA
f	-	Fundamental frequency
H	-	Harmonic order
Hi	-	Height of the current sensor
I_C	-	Total capacitive leakage current of the MOSA in case-I of the system voltage
I_{CVH}	-	Peak magnitude of the capacitive current harmonics induced by the voltage distortion
I_{C3}, I_{C5}, I_{C7}, I_{C9}	-	Third, fifth, seventh and ninth order harmonics of the capacitive leakage current
I_R	-	Total resistive leakage current of MOSA in case-I of the system voltage
$I_{R\ Corrected}$	-	Peak magnitude of the corrected resistive leakage current (obtained from the proposed thumb-rule base technique)
I_{RVH}	-	Peak magnitude of the resistive current harmonics induced by the voltage distortion
$I_{RH(i)}$	-	Peak magnitude of H^{th} order harmonic component of the resistive leakage current acquired in case-I of the system voltage
$I_{RH(ii)}$	-	Peak magnitude of H^{th} order harmonic component of the resistive leakage current acquired in case-II of the system voltage
$I_{R(i)}$	-	Peak magnitude of the resistive leakage current extracted in case-I of the system voltage
$I_{R(ii)}$	-	Peak magnitude of the resistive leakage current extracted in case-II of the system voltage
I_{R3rd}	-	Resistive third harmonic current of MOSA
I_{R5th}	-	Resistive fifth harmonic current of MOSA
I_T	-	Total leakage current of MOSA in case-I of the system voltage

I_{TC}	-	Acquired total leakage current in the implementation of genetic algorithm
I_{TM}	-	Measured total leakage current in the implementation of genetic algorithm
I_{TVH}	-	Peak magnitude of the total current harmonics induced by the voltage distortion
$I_{T(i)}$	-	Peak magnitude of the total leakage current extracted in case-I of the system voltage
$I_{T(ii)}$	-	Peak magnitude of the total leakage current extracted in case-I of the system voltage
$I_{T'}$	-	Peak magnitude of the measured leakage current in case-II of the system voltage
N	-	Total number of samples
P	-	Total active power loss of the tested MOSA
R	-	Non-linear resistance of MOSA
S	-	Total apparent power loss of the tested MOSA
T_{max}	-	Recorded maximum temperature of MOSA
T_{min}	-	Recorded minimum temperature of MOSA
V_C	-	Initial voltage across MOSA with neglected I_R
V_{COV}	-	Continuous operating voltage of MOSA
V_{O-S}	-	Output voltage of the sensor
V_{P-N}	-	Phase to earth voltage across MOSA
V_{rated}	-	Rated voltage of MOSA
V_{rms}	-	Root mean square voltage
V_S	-	System voltage
V_{TOV}	-	Temporary over voltage
V_{10}	-	Residual or discharge voltage
V_{3rd}, V_{5th}, V_{7th}, V_{9th}	-	Third, fifth, seventh and ninth order harmonic components of the system voltage
W	-	Weight of the current sensor

Z	-	Equivalent impedance of MOSA
ω	-	Angular frequency
θ	-	Phase angle between I_T and I_R
φ	-	Phase angle between I_T and I_C
ε_0	-	Permittivity of the free space
ε_r	-	Relative permittivity of MOSA
$\% \Delta I_T$	-	Percentage change in the total leakage current
$\% \Delta I_R$	-	Percentage change in the resistive leakage current
$\% \Delta I_{RH}$	-	Percentage change in the resistive current's harmonics

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Metal Oxide Surge Arresters (MOSAs) act as overvoltage limiting devices to protect the transmission and distribution system from high voltage surges caused by severe lightning and switching operations [1, 2]. Any damage or malfunctioning in the arrester may disrupt the operation of other electrical equipment installed in the grid [3, 4]. Therefore, the arrester condition monitoring is vital to ensure the reliability of the power system [5, 6].

The most popular type of gapless MOSA contains zinc oxide elements due to its highly nonlinear voltage-current characteristic and faster conduction response for high voltage surges [7, 8]. As the non-linearity of zinc oxide is not ideal, in other words, its impedance cannot be designed to be infinite, it continuously draws leakage current when put in service at the standard operating voltage [9, 10]. Previous researchers have proposed numerous condition monitoring techniques of MOSA. By far, the leakage current based condition monitoring is the most widely employed technique to assess the ageing and degradation of MOSA [6, 11-15].

The leakage current of a gapless arrester can be acquired in two ways; offline and online measurements [16, 17]. The offline method requires the disconnection of the arrester from the grid, while the online technique monitors the leakage current of on-site arresters [18-20] without any grid supply disruption. Hence, to avoid the power disruption from the grid stations to the consumers when carrying out condition monitoring of MOSA, measuring the arrester's leakage current online is paramount [18, 21, 22].

The measured total arrester leakage current can be decomposed into the resistive and capacitive components [23, 24]. Clearly, the magnitude of the capacitive leakage current is linearly related to the applied voltage across the arrester terminals [25]. However, the resistive current has a non-linear relationship with the terminal voltage due to the non-linear zinc oxide characteristics [26-28]. More importantly, any deterioration in the non-linear properties of the MOSA is known to cause an increase in the resistive leakage current, particularly the odd harmonic components of the resistive current [29, 30]. In fact, the arrester resistive leakage current level is a known and reliable indicator of MOSA deterioration [5, 10, 19, 26-28, 31-33], provided it can be successfully extracted from the arrester total leakage current.

Several techniques and algorithms have been developed to extract the resistive component from the total leakage current. These techniques and algorithms can be divided into two categories; (i) system voltage-independent and (ii) system voltage-dependent categories [34, 35]. In the first category, the measurement of the system voltage is not required for successful implementation of the technique. On the contrary, the techniques in the system voltage dependent category (second category), the measurement of the system voltage is compulsory. Previously done research has shown that system voltage-independent techniques are easier to implement. On the contrary, system voltage-dependent techniques are rather difficult to execute because of the fact that recording system voltage profile using a high voltage probe is challenging for routine online MOSA condition monitoring. Examples of the system voltage-independent techniques (first category) are the Third Order Harmonic Analysis Method (TOHM) [17], Modified Shifted Current Method (MSCM) [36], Evolutionary Optimization Algorithm (EOA) [37], Orthogonal Vector Method (OVM) [38], and Circuit-based Analytical Method (CBM) [9]. While, the system voltage-dependent techniques (second category) include the Voltage-peak or Conventional Method (CM) [39], Capacitive Current Compensation Method (CCCM) [40], Field Probe Method (FPM) [41], Improved Capacitive Current Method (ICCM) [42], Improved Time Delay Method (ITDM) [43], Current Orthogonality Method (COM) [44], Least Square Method (LSM) [45], Multiple Linear Regression Method (MLRM) [46], and Genetic Algorithm (GA) [29].

It is noted that the system voltage-independent techniques are easier to implement due to the fact that the arrester terminal voltage measurement in an energised substation is quite challenging, especially during routine online measurements [47, 48]. Because of this difficulty, the arrester condition monitoring techniques based on the resistive leakage current from the first category are usually preferable. In particular, the modified shifted current method (MSCM) and the circuit-based analytical method (CBM), both of which do not require the arrester voltage to be measured, are the two most commonly employed resistive leakage current extraction techniques [34, 49]. Nevertheless, the resistive current computation accuracy provided by both techniques can still be further improved so that a better arrester condition assessment that what are currently offered can be made. Among the ideas for the improvement include the use of a suitably chosen hybrid or combined form of available techniques.

As previously mentioned, any deterioration of the non-linear properties of the metal oxide arrester is known to cause a corresponding increase in its resistive leakage current. The presence of harmonics in the system voltage may introduce errors in the resistive leakage current based condition monitoring technique of the metal oxide arrester. In a typical power system, harmonic components can be introduced into the system due to many causes such as from the load containing power electronics circuits. To maintain the arrester condition monitoring accuracy, the presence of such harmonics in the measured resistive leakage current must be eliminated or minimised. The authors in [32, 41, 42, 50-54] have studied and highlighted the effects and variations produced in the leakage current due to the system voltage harmonics. Several authors have introduced means to minimise the influence of voltage harmonics in the arrester condition monitoring techniques. Several of the reported elimination or minimisation techniques include CCCM [40], COM [44], and ITDM [43]. Unfortunately, most of these techniques seem to only suppress the harmonic components of the arrester capacitive leakage current [34] and are lack of any procedure to compensate for the variation in the arrester resistive leakage current due to the presence of harmonics in the supply voltage. Furthermore, these algorithms rely on the system voltage and the connection of the measurement system with the tested MOSA to extract its resistive leakage current. In addition, lengthy procedures are required to implement these techniques. An attempt to eliminate the effect of voltage harmonics in the resistive leakage current had been made using FPM and ICCM [41]. The commercially available leakage current measurement devices use the field probe method to minimize influence of voltage harmonics. However, the accuracy of the results is limited to only 20%. Another attempt at solving the problem is by using ICCM [42]. However, the execution of ICCM involves rather complex steps, and its accuracy is also questionable. Hence it can be said that the existing methods to compensate for the effect of system harmonics on the extracted resistive leakage current are either too complicated or not accurate enough. Therefore, it is desired to simplify the voltage harmonics elimination method as well to improve its elimination accuracy, in particular, using the techniques in the voltage independent category.

The sensitivity of leakage current increase to the deterioration of the non-linear properties is in fact more prevalent on the odd harmonic components of the resistive current. As previously noted, the measurement of odd harmonics of the resistive leakage current, especially the third harmonic component is a well-known metal oxide arrester condition monitoring technique. This is because the third harmonic resistive leakage current exhibits more sensitivity to ageing than that of the bulk resistive current [5, 22, 33, 55, 56]. Many researchers have proposed the resistive third harmonic current based condition monitoring techniques of MOSA such as leakage current method [33], flattop window algorithm [53], Prony analysis-Hilbert transform [32] and Fast Fourier transform method [50]. However, these techniques are less accurate in the presence of voltage harmonics. This is because the presence of odd harmonics in the system voltage increases the peak magnitude of the measured arrester resistive third harmonic current [27, 32, 33, 40, 42, 44, 50, 51, 53]. This increased magnitude of the third harmonic resistive current may result in a wrong assessment of the MOSA’s degradation status. For example, the presence of voltage harmonics has produced 10% and 39% errors in the extraction of the arrester resistive third harmonic current using the fast fourier transform and the leakage current method, respectively [33, 50]. Similarly, an error of 32-67% is introduced when neglecting the influence of voltage harmonics in the resistive third harmonic current, as reported in the flattop window-based of MOSA [53]. The prony analysis-Hilbert transformation method also reports an error of 40% in the resistive third harmonic current due to the presence of voltage harmonics [32]. Furthermore, the variation in odd harmonic components of the resistive leakage current produced by the voltage harmonics is still not studied. It can therefore be concluded that the resistive third harmonic current based condition assessment of MOSA is particularly and badly affected by the voltage harmonics. Hence a new ageing indicator is highly needed for the condition monitoring of MOSA, to avoid the inaccurate assessment in the presence of voltage harmonics.

1.2 Research Problem Statement

Previous studies have shown that MSCM and CBM are the most widely used system-voltage independent techniques for the extraction of resistive leakage current. However, the approximation of capacitive leakage current and the use of a constant phase angle between the total leakage current and its capacitive component make the MSCM algorithm rather inaccurate. On the other hand, the CBM algorithm is based on producing a peak magnitude of the resistive component of the leakage current only, without even generating its corresponding complete waveform. Based on these arguments, it is concluded that the existing voltage-independent techniques should be further improved to increase the accuracy of the resistive leakage current extraction. Therefore, it is essential to propose an improved algorithm to extract the arrester resistive leakage current with more straightforward steps and improved accuracy than the existing methods. The distortion in the system or source voltage affects the accuracy of metal oxide arrester resistive leakage current extraction algorithms. The existing techniques employed to compensate the influence of system harmonics in the resistive leakage current only suppress the capacitive leakage current harmonics. Furthermore, the need for the system voltage, lengthy measurement and computational procedures and low accuracy are the major drawbacks of the techniques employed to extract resistive leakage current in the presence of voltage harmonics. Therefore, it is required to propose some techniques to compensate for the effects of voltage harmonics in the resistive leakage current without the need for measuring the system voltage. Previous research has shown that the resistive leakage current's third harmonic component is considered the most reliable ageing indicator of MOSA. However, the condition monitoring of MOSA based on the resistive third harmonic current is particularly and severely affected by voltage harmonics. Therefore, it is highly needed to propose some alternative ageing indicators other than the resistive third harmonic current, which are less affected by the voltage harmonics.

1.3 Research Objectives

The objectives of the research are:

(a) To develop a modified shifted current method-circuit based analytical method (MSCM-CBM) hybrid technique with an improved measurement accuracy for the metal oxide arrester resistive leakage current extraction technique.

(b) To develop a thumb-rule based technique for compensating the effects of voltage harmonics in the extracted resistive leakage current of MOSA.

(c) To develop a condition monitoring technique using the resistive fifth harmonic leakage current as an ageing indicator of MOSA.

1.4 Research Scope

The scopes and limitations of this work are listed to define the intended boundary in which the research is conducted. These are mentioned below:

(a) Only the gapless polymeric housed 120 kV rated MOSAs were used for the experiments and validation of the proposed method, as they are most widely employed in the electrical grid.

(b) Only one current sensor, ALCL-40D, was clamped on the ground wire to measure the total leakage current of MOSA.

(c) The performance of the resistive fifth harmonic current as an ageing indicator is correlated with the surface temperature of MOSA in a laboratory environment.

1.5 Research Significance

The significance of this research is listed as:

In this research, a more straightforward and accurate method for extracting resistive leakage current of 120 kV rated MOSA has been proposed and verified experimentally. The implementation of this method is not dependent on the system voltage measurement. Also, the accuracy of results is not varied with the sensitivity of the leakage current measurement system.

Furthermore, a method has also been proposed to compensate for the influence of voltage harmonics in the measured resistive leakage current of MOSA. The proposed technique can be implemented by determining the total harmonic distortion of system voltage and leakage current of MOSA only. This technique also provides the waveform of the compensated resistive leakage current.

This research proposes the peak value of resistive fifth harmonic current as an ageing indicator of MOSA. The third harmonic component of the resistive leakage current varies more significantly with the voltage harmonics than the proposed index. However, the online condition monitoring of MOSA based on the proposed index proves to be more accurate than the resistive third harmonic current when the system voltage contains harmonics.

1.6 Contributions of Research

The following research contributions are listed:

(a) **MSCM-CBM hybrid algorithm for the extraction of resistive leakage current of MOSA**: Several systems voltage-independent algorithms have been proposed to extract the resistive leakage current, including MSCM and CBM. However, the performance of MSCM is affected by assuming the approximated magnitude of capacitive current and constant phase angle between the leakage current components at all levels of the source voltage. Likewise, CBM is not able to produce the resistive leakage current waveform. Furthermore, their results are erroneous in the presence of voltage harmonics. Therefore, this research proposes an algorithm based on the hybrid combination of MSCM and CBM to extract the resistive leakage current of online MOSAs and hence provides more straightforward computational steps. The MSCM-CBM hybrid method was developed and tested on Simulink software and then experimentally applied on 120kV rated MOSA. Results show that the resistive current extracted by the proposed hybrid method is 3.2 % more accurate than the modified shifted current method. Based on findings, it is concluded that the accuracy of resistive leakage current based condition monitoring of MOSA is improved by implementing the proposed technique. Simpler computational steps and voltage independence are the key features of the proposed hybrid algorithm.

(b) **A rule of thumb technique for voltage harmonic compensation:** Previous studies have shown that the resistive leakage current extraction techniques' accuracy decreases due to harmonic population in the system voltage. Some techniques have been proposed so far to consider the influence of voltage harmonics while extracting the peak magnitude of resistive leakage current, such as the CCCM, COM, and ITDM. But the measurement of system voltage, connection of hardware circuitry, lengthy and complex procedures are the major drawbacks of these techniques. In addition to this, the FPM is the most widely used technique for the compensation of harmonics. Corrective multipliers based on the applied and rated voltage ratio are used to compensate for the maximum magnitude of the resistive leakage current. But its results are less accurate to eliminate the variation in the resistive leakage current due to the voltage distortion. Therefore, the thumb rule technique has been proposed to eliminate the effects of voltage harmonics from the results of the hybrid method. The execution of the proposed technique is based on the measurement of THD of the system voltage and total leakage current only. This technique determines the magnitude of capacitive and resistive current harmonics induced by the voltage distortion. The performance of the proposed method is also validated by comparing its findings with the results of FPM. Based on the results, it is concluded that the proposed technique is at least 10.5 % more accurate than the existing compensation technique to correct the peak magnitude of resistive leakage current from the effects of the harmonics.

(c) **A resistive fifth harmonic current based condition monitoring of MOSA**: Literature review has shown that the resistive third harmonic current based condition monitoring of MOSA is affected due to the presence of harmonics in the system voltage. Many researchers have reported a significant error in the peak magnitude of the third harmonic current induced by the voltage distortion. Therefore, it is essential to determine the odd harmonic components of resistive leakage current as an ageing indicator of MOSA. This research proposes the peak magnitude of resistive fifth harmonic current as an ageing indicator of MOSA. Results have shown that the variation trend of I_{R5th} with the applied voltage and ageing of the arrester is similar to that of I_{R3rd}. The ageing classification of the tested MOSAs is verified experimentally by computing the % ratio of (I_{R3rd}/I_R) and (I_{R5th}/I_R) at the voltage levels from 70 to 120 kV. At the rated voltage level, the percentage ratio (I_{R3rd}/I_R) of all MOSA samples, namely, samples I to V, are determined to be 36.2, 40.6, 38.1, 39.2, and 35.0 %, respectively. On the other hand, the ratio (I_{R5th}/I_R) for samples-I to V at the rated voltage is 19.3, 21.2, 19.8, 20.5, and 17.3 %, respectively. The proposed ageing index is validated by determining the surface temperature and power loss parameters of 120kV rated tested MOSAs. Based on the results, it is concluded that the proposed resistive fifth harmonic current based condition monitoring of MOSA is more accurate than the existing technique in the presence of voltage harmonics.

1.7 Thesis Structure

This thesis is divided into a total of five chapters. Chapter 1 discusses the background of the research domain, problem statement to conduct the research, designed objectives to accomplish the work, scope, significance and achievements of the research.

Chapter 2 deliberates a comprehensive critical review on the techniques employed for the online condition monitoring of MOSA. Leakage current based condition monitoring of arresters is the most commonly used technique from the reviewed articles. However, previous studies have also revealed that the resistive component of total leakage current exhibits more sensitivity towards ageing and degradation of the arrester. Therefore, this research reviews the methodology, implementation, advantages and disadvantages of the available techniques used to extract resistive leakage current. It is also reviewed that the effect of voltage harmonics from the resistive leakage current and its harmonics is not considered in the available literature. These shortcomings of the existing techniques can be overcome by implementing a resistive current extraction method and compensating the effect of voltage's harmonics and it.

Chapter 3 presents the methodology to implement the proposed method to extract the resistive leakage current of MOSA without measuring the applied voltage. Furthermore, the procedure to implement the thumb-rule based technique is also discussed to compensate voltage's harmonics from the resistive leakage current. Moreover, the methodology to propose the resistive fifth harmonic current as a MOSA ageing indicator is also explained.

Chapter 4 is assigned to discuss the results of the proposed method to measure the resistive leakage current of 120 kV rated MOSA. First, the performance of the proposed method is validated by comparing the simulation and experimental results. Then, the proposed method results are also compared with the existing techniques to determine its accuracy. Furthermore, the findings of the thumb rule technique to compensate for the influence of voltage harmonics from the resistive current are also illustrated. Moreover, the variation of peak magnitude of the fifth harmonic component of resistive current with the voltage harmonics is also deliberated.

Chapter 5 concludes the thesis's significant findings and provides a future recommendation further to improve the accuracy of online condition monitoring of MOSA.

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