On-line Monitoring of Metal-oxide Surge Arresters using Improved Equivalent Model with Evolutionary Optimisation Algorithm

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***Abstract*—A resistive-current extraction algorithm to assist with on-line monitoring of surge arresters is proposed in this paper. The algorithm is based on the improved equivalent model for surge arresters and combines evolutionary optimisation with the base-frequency approximating method. A genetic algorithm is used to obtain the optimal capacitance such that the phase shift between the base-components of the branch voltage and current is minimised thereby yielding a good approximation of the resistive current. In this paper, the algorithm is implemented and tested using Matlab/Simulink. Results indicate that the proposed algorithm is able to efficiently and accurately obtain the resistive component of the leakage current, using the improved equivalent model, under both ideal and distorted supply conditions.**

***Index Terms*—surge arresters; resistive current extraction; evolutionary optimisation; genetic algorithm.**

I. INTRODUCTION

Metal oxide surge arresters (MOSAs) play an efficient role in lightning and switching transients protection of electronic components, data circuits as well as of electric power system equipment [1], [2]. Recent advancements documented in the field of MOSA technology have highlighted the need for effective on-line condition monitoring (whilst MOSA is under operation) and diagnostic techniques, in the context of early detection methods of electrical degradation, which has been proven to be inherent to the MOSA's life [3]- [6]. Leakage current measurement is the most commonly applied condition assessment of MOSA-based surge arresters [7]- [9]. This form of degradation characterisation requires extraction of the resistive component from the measured leakage current, and therefore mainly relies on the basic insulation description or RC model of the MOSA [10], as well as on the reportedly adopted resistive current extraction principles or methodologies [10], [11]. An alternative leakage current extraction technique that is based on the improved equivalent model of MOSA has also been presented in recent years [12]. This paper presents a modified extraction algorithm based on the improved equivalent model. The presented algorithm uses evolutionary computation, in the form of Genetic Algorithm (GA), to both accurately and efficiently approximate the resistive component of the leakage current.

II. BACKGROUND

A. Basic Description of MOSA Models and Current Extraction Principles

At normal operating voltage and temperature MOSAs behave like insulating materials [13]. Therefore, the resistance-capacitance (RC) parallel circuit mode (shown in Fig. 1) such as attributed to insulators [10], has been adopted as the basic description of the zinc-oxide grains and the inter-granular boundaries which constitute the internal configuration of MOSA units. This therefore justifies the resistive and capacitive components as fundamental constituents of the leakage current. In order to determine the actual condition of MOSA, the resistive component is generally extracted on the basis of two fundamental principles: the phase shift and the current compensation methods [14], [15]. However, the implementation of both these principles has been hampered with several weaknesses and deficiencies.

B. Improved Equivalent Model

In order to improve on the deficiencies resulting from the basic model the improved equivalent model (shown in Fig. 2), which assumes a series RC branch in parallel with a capacitive branch, has been proposed [12]. Resistive current extraction is rather based on iterative techniques which are concluded on the basis of phase comparison. In this study, the resistive current extraction technique based on the improved equivalent model of MOSA is enhanced with the aid of evolutionary optimisation.

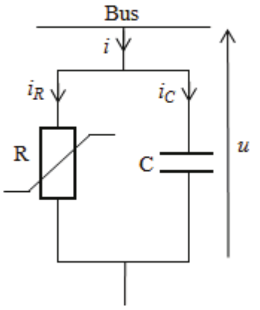

Fig. 1: Simplified equivalent model of MOSA.

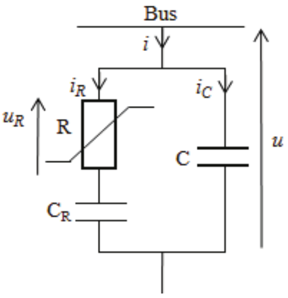

Fig. 2: Improved equivalent model of MOSA.

The algorithm for extracting the resistive component of leakage current is modified for the purpose of improving the efficiency and accuracy, and thus making it more suitable for online application - as well as to enable monitoring of the MOSA under harmonic distortion conditions.

III. METHODOLOGY

A. Modification of Extraction Algorithm

The current extraction algorithm is based on the improved model as shown in Fig. 2. This improved model essentially assumes an additional capacitive element in series to the resistive branch of the simplified model. This series capacitance accounts for the typical phase shift between the bus voltage $u(t)$ and current $i_R(t)$. The phase shift found in practice indicates that there is deficiency in the simplified equivalent model which requires the introduction of a series capacitance. Extraction of the resistive current is now more complex and requires solving for two unknown capacitances. The resistive current and voltage is firstly derived, using the improved equivalent model.

$$\begin{aligned} i_R(t) &= i(t) - i_C(t) \\ &= i(t) - C\frac{du(t)}{dt} \end{aligned} \tag{1}$$

$$\begin{aligned} u_R(t) &= u(t) - \frac{1}{C_R}\int i_R(t)dt \\ &= u(t) - \frac{1}{C_R}\int \Big(i(t) - C\frac{du(t)}{dt}\Big)dt \\ &= \Big(1+\frac{C}{C_R}\Big)u(t) - \frac{1}{C_R}\int i(t)dt \end{aligned} \tag{2}$$

Using (1) and (2), the peak values of the resistive current and resistive voltage - which are in phase - are determined by (3) and (4) at the instant t_m,

$$\frac{di_R(t)}{dt}\Big|_{t=t_m} = \Big[\frac{di(t)}{dt} - C\frac{d^2u(t)}{dt^2}\Big]\Big|_{t=t_m} \tag{3}$$

$$\frac{du_R(t)}{dt}\Big|_{t=t_m} = \Big[\Big(1+\frac{C}{C_R}\Big)\frac{du(t)}{dt} - \frac{i(t)}{C_R}\Big]\Big|_{t=t_m} \tag{4}$$

The sampled leakage current and line voltage may be expressed as Fourier series which are given in (5) and (6). The respective coefficients are given in (7) to (10) where T is the period of the angular base frequency ω and k is integer number of the frequency component.

$$i(t) = \sum_{k=0}^{\infty}\Big(p_k\cos(k\omega t) + q_k\sin(k\omega t)\Big) \tag{5}$$

$$u(t) = \sum_{k=0}^{\infty}\Big(a_k\cos(k\omega t) + b_k\sin(k\omega t)\Big) \tag{6}$$

$$p_k = \frac{2}{T}\int_0^T i(t)\cos(k\omega t)dt \tag{7}$$

$$q_k = \frac{2}{T}\int_0^T i(t)\sin(k\omega t)dt \tag{8}$$

$$a_k = \frac{2}{T}\int_0^T u(t)\cos(k\omega t)dt \tag{9}$$

$$b_k = \frac{2}{T}\int_0^T u(t)\sin(k\omega t)dt \tag{10}$$

In order to obtain a direct relationship between C and C_R, the expressions for the voltage and current, given in (5) and (6), are substituted into (3) and (4) and an in-phase relationship of the base frequency ($k = 1$) components is assumed.

$$C_R = \frac{p_1^2 + q_1^2 + 2\omega C(a_1q_1 - b_1p_1) + \omega^2C^2(a_1^2 + b_1^2)}{\Big[(b_1p_1 - a_1q_1) - \omega C(a_1^2 + b_1^2)\Big]} \tag{11}$$

Using the base frequency ($k = 1$), an initial value for the parallel capacitance is calculated by (12).

$$C^{(0)} = \frac{b_1p_1 - a_1q_1}{\omega(a_1^2 + b_1^2)} \tag{12}$$

In the initially presented extraction algorithm [12], the following steps were proposed:

- Assume an initial value for C using (12) and then calculate C_R using (11).
- Determine the resistive current and voltage $i_R(t)$ and $u_R(t)$.
- Based on the in-phase criteria between these parameters adjust C and repeat until a valid approximation is obtained.

The proposed algorithm follows the aforementioned basic steps in extracting the resistive current modifications, however the following novel modifications are made to ensure more efficient and accurate convergence to a solution.

- Fourier fitting function is employed to determine coefficients as given in (7) to (10).
- The approximation of an initial value for the parallel capacitance C is only used as an upper bound in the optimisation algorithm.
- Adjustment of C is carried out automatically and stochastically using evolutionary optimisation in the form of a GA.

- A quantitative assessment of the in-phase relationship is carried out within the fitness function (of the GA) by calculating the phase difference between the signals via the FFT. This method is used rather than the previously proposed cross-correlation technique.

B. Objective Function and Constraints

The presented extraction algorithm essentially approaches the problem as an optimisation problem and therefore an object/cost function is required. This enables a fitness function to be constructed and the GA to be applied. In this case, the phase shift between the resistive branch voltage and current is minimised. Essentially, the GA solves for the branch capacitance until the criteria given by (13) is met. The upper bound of the capacitance is determined by (12) and lower bound as is taken as zero. Hence, the solution space is constrained and adjustment of the capacitance is carried out stochastically by the GA.

$$min\left|angle\left(\mathcal{F}[u_R(t)]\right) - angle\left(\mathcal{F}[i_R(t)]\right)\right| \tag{13}$$

C. Genetic Algorithm

The modified extraction algorithm presented here utilises evolutionary optimisation in the form of a genetic algorithm. GA is the most popular type of evolutionary computation technique used to solve both constrained and unconstrained optimisation problems via the principle of natural selection [16]. Essentially, the GA stochastically assigns fitness to solutions within the solution space (search space) [17]. In this case, the solution space is constrained by the upper bound as determined by (12), where the series capacitance $C_R = \infty$, and the lower bound is zero. The proposed algorithm finds the most suitable solution to satisfy the objective function given by (13). It should be highlighted that this extraction algorithm is essentially solving for two inter-related capacitances that meet the minimum phase-shift criteria and that the solution space is likely to have multiple feasible solutions. Hence, GA is preferred to simple manual decrements of the parallel capacitance as presented in [12] which may result in an inaccurate solution and require iterations through entire solution space before finding a suitable result. Furthermore, the genetic algorithm enables rapid and efficient convergence to an accurate solution thereby making the proposed extraction algorithm more suitable for on-line application.

D. Overview

The overall steps involved in the presented modified extraction algorithm, using the improved equivalent model, are given in Fig. 3. Main iterations are executed automatically by the GA which essentially searches for the parallel capacitance C that provides the minimum shift between the base frequency components of $i_R(t)$ and $u_R(t)$.

IV. MODEL TESTING AND VERIFICATION

A. Simulation Model

The extraction algorithm was tested and verified using a simulation model constructed in Matlab/Simulink. A Simulink model was created to mimic the improved equivalent model given in Fig. 2. A non-linear resistor block was used together with capacitances to model the MOSA. The characteristics of the resistive component are governed by (12) with the descriptions and values of the parameters used in the simulation model given in Table I (rms values are given where applicable). The V-I characteristic used in the test case was selected based on a typical MOSA (with a single column assumed in the model). Although model parameters were selected arbitrarily, the characteristics are based on typical values that would be experienced in a practice.

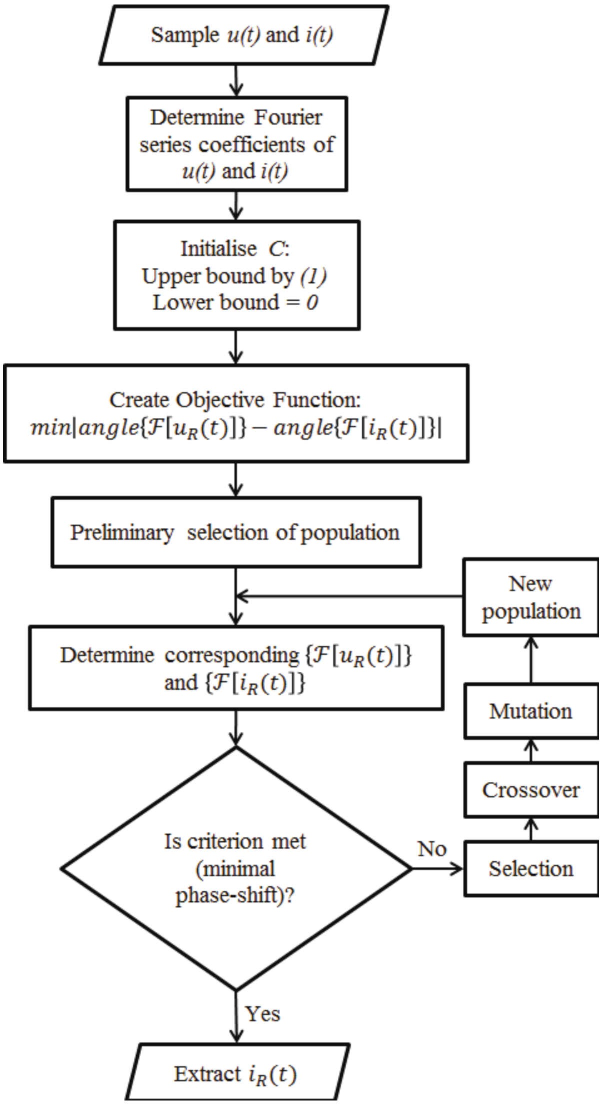

Fig. 3: Modified current extraction algorithm based on the improved equivalent MOSA model.

$$\frac{I}{I_0} = A\left(\frac{V}{V_0}\right)^{\alpha} \tag{14}$$

It should be noted that these values were selected for the purpose of testing the algorithm and will vary according to

TABLE I: Test model parameters

Parameter	Description	Value
V_0	Protection Voltage	$495\ kV$
V	Source Voltage	$230\ kV$
i	Leakage Current	$100\ \mu A$
I_0	Reference Current	$0.5\ kA$
α	Non-linearity Constant	21
V_0	Protection Voltage	$495\ kV$
A	Varistor Constant (dependent on material type)	1
C	Branch Capacitor	$100\ pF$
C_R	Series Capacitor	$40\ pF$

the application as well as the actual MOSA being monitored. The only inputs required by the extraction algorithm are the sampled $i(t)$ and $u(t)$. In this test model, the sampling frequency is 25 kHz with 50000 samples recorded at a power frequency of 50 Hz.

B. Results

The main objective of the extraction algorithm is to determine the current in the resistive branch of the MOSA model. Therefore, this is the main focus of the results. Two test cases are used to verify the algorithm i.e. one with an ideal bus voltage (pure sinewave) and the other with a distorted voltage source. In each case, actual currents were measured in branch on the model to compare the results obtained from the algorithm. Fig. 4 shows the resistive branch currents which were obtained by the extraction algorithm and the actual current as measured in the branch.

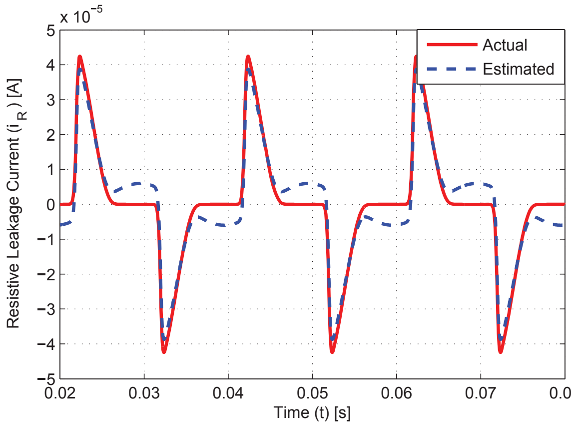

Fig. 4: Comparison of actual and estimated (extraction algorithm) resistive branch leakage current.

Fig. 5 gives similar results obtained for the case of harmonic distortion in the source. The harmonic distortion is carried out by adding a 3^{rd} harmonic and 5^{rd} harmonic at 10% and 5% of the magnitude of the fundamental frequency component, respectively. The voltage for the ideal source case is shown together with the resistive branch leakage current in Fig. 6. The previously described typical phase shift between the voltage and resistive branch current can be seen in this figure. This phase shift is due to the effect of the series capacitor in the improved equivalent model. Fig. 7 shows the performance of the GA in the form of the best and mean fitness values. The GA converges to a solution after approximately 650 iterations of the fitness function and 8 generations. The overall extraction algorithm yields an error of 0.7% and 2% (for each case) in estimating $i_R(t)$.

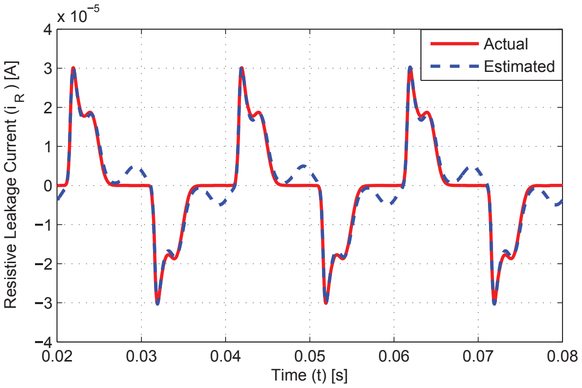

Fig. 5: Comparison of actual and estimated resistive branch leakage current with distorted source (addition of 3^{rd} and 5^{rd} harmonics).

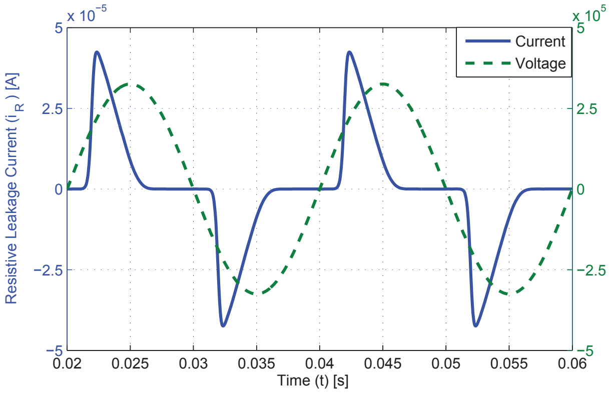

Fig. 6: Resistive branch leakage current $i_R(t)$ and voltage $u(t)$ obtained from simulation model.

V. CONCLUSION

An evolutionary optimisation algorithm is proposed in this study in order to improve the accuracy and efficiency of resistive component extraction technique in MOSA's leakage current. The improved equivalent model of MOSA is used on the basis of this application. In this study, it was observed that the extraction technique based on evolutionary algorithm (GA), such as demonstrated in case of a sinewave-type bus system voltage being applied across MOSA, provides better estimation of the resistive current than other proposed computational methods. Additionally, the algorithm does improve the computational stage of condition monitoring of MOSA, which should fundamentally be preceded by physical measurement of both the bus voltage and leakage current. The next step

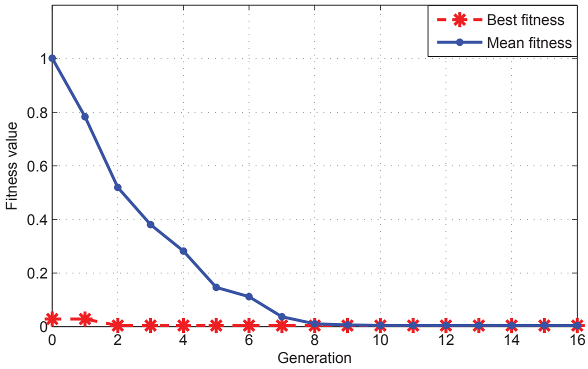

Fig. 7: GA Fitness values (minimised phase-shift) through iterations extraction algorithm.

of this research will be to validate the proposed resistive-current extraction algorithm using experimental measurements on MOSAs and test the on-line performance thereof.

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