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Identification of Equivalent Circuit of Transformer Insulation Parameters Assisted by Constrained GA&PSO Algorithms

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Abstract – **Power transformer is a very valuable device of electrical transmission and distribution networks. The life of a power transformer mainly depends on the insulation system conditions. A non-destructive method used for monitoring this system is the Recovery Voltage Measurement (RVM), which allows estimating the polarization spectrum. Mathematical models of this spectrum are used to better understand the physical insulation properties in response to moisture and aging. These models are often used to identify the equivalent circuit of the insulation system. The parameters estimation of this circuit can be performed in different stages of the life of the transformer by RVM measured results. In this paper, the authors present two constrained optimization methods based on the heuristic algorithms GA and PSO to solve the parameter estimation problem. The performances of the two different approaches are compared.**

I. INTRODUCTION

Power transformer represents an indispensable and expensive component of electrical power transmission, distribution network and large industrial plants. Although important progress in the design of these electrical devices has been made in recent years, the insulation system is their weakest component. Because it is essential the power transformers function properly for many years, oil/cellulose composite has been used as the main insulation for more than a century. The electrical properties of this insulation system during transformer operation are subjected to different types of stresses (electrical, mechanical, thermal and environmental) in several parts of the structure, which leads to degradation process of insulation, increasing the risk of failure. The experts in the domain believe that the life of a transformer essentially depends on the lifetime of paper insulation. Its aging process becomes faster at higher operating temperatures, especially when the moisture is present. The accumulation of water in the insulation paper and in the oil represents one of the most severe problems in the power transformers. The water, in fact, weakens the insulation properties of the oil and increases the speed of the depolymerisation of the cellulose molecules, reducing the breakdown voltage of the insulation system. So water is considered a very important indicator of the degradation level of the power transformer insulation system. Although nowadays a lot of transformers around the world are very close to the end of their design life, it is not a good economical choice to replace them with new ones because of their age. For this reason, the reliability and the maintenance of power transformers to manage their life have gained a big interest in the last years. Researchers over the last decades have proposed several appropriate tools to diagnose power equipment insulation non-destructively. In fact, there is no direct way to determine the moisture content in the solid insulation, being necessary to open the transformer. The intrusive technique, like the degree of polarization (DP) paper analysis, is a method to evaluate the paper degradation, but it is expensive and time consuming. The well-established nonintrusive methods are the return voltage measurements (RVM), polarization current (PCM) measurement and frequency dielectric spectroscopy (FDS) [1-3]. Although PCM is a simple method, the measured current due the polarization varies significantly and often it is comparable to background noise [4]. The FDS is a noise robustness method, but the aging status and moisture content indication obtained by measurements are several influenced by several factors [5]. RVM [6-7] is a time response method, it is less noise-sensitive and is simple to set up on-site. This method is based on the determination of the polarization time constant of the spectrum of the dielectric dissipation factor. The polarization process in the dielectric can be modelled by an equivalent circuit, which represents an infinite number of dipole arrangements. This circuit can be used to derive a set of equations, which can be correlated with the RV curves obtained by the measured data. Therefore, the parameters of the equivalent circuit can be identified by some parameter identification techniques. In this paper, these parameters of the circuit that represent the polarization process have been obtained from the power transformer RVM measurements by using two different heuristic algorithms with constraints: genetic algorithm (GA) and particle swarm optimization method (PSO). The performances of the two-optimization techniques have been compared in terms of time-consuming and convergence velocity.

II. THE RECOVERY VOLTAGE METHOD

The recovery voltage method (RVM) is an offline non-destructive diagnostic technique that allows investigating the polarisation process of dielectric in the time domain. In particular, the polarisation process can be described as a process of energy storage and can only exist in the presence of an external electric field. This one produces two leakage currents in the dielectric: conduction current and polarization current [8]. The polarization current depends on the dipoles that have the tendency to align in the direction of the field. When this one is removed, the dipoles, which are randomly distributed inside the dielectric, relax and return to the original condition [9]. This phenomenon can be modelled by using several resistance/capacitors (R-C) pairs with different time constant, which represent the dipoles [10]. Different levels of moisture in the insulation can change this polarization process significantly because of the polarization of water molecules. For this reason, the RV measurements in the power transformer can also offer information about the quantity of water absorbed by the insulation. Increasing the moisture level makes the polarisation process faster and stronger. The setup of the RV test is shown in figure 1.

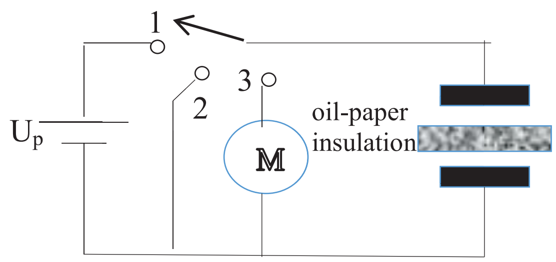

Fig. 1 RV measurement set-up

The RVM test consists of the implementation of many polarization and depolarization cycles in order to obtain an oil-paper insulation polarization spectrum. Each cycle is accomplished in the following three phases, which are cyclically repeated:

1. When the switch is in position 1 a dc voltage constant U_p is applied to the dielectric terminals for a time t_c, and the polarization process starts. Each region of the dielectric affected by the moisture (R-C pairs) has a different polarization time.
2. The switch is turned in position 2 after the time t_c: the voltage source is disconnected and both terminals of the dielectric are short-circuited during a time t_d and the depolarization process starts.
3. The switch is turned in position 3 after the time t_d: a high-impedance voltmeter is connected to the dielectric terminals and the recovery voltage is measured.

These three steps are repeated for different values of the time tc. During the depolarization process each capacitor discharges differently. The charge distribution inside the dielectric reaches a new equilibrium condition when the switch is turned to position 3. Therefore, the voltage measured by the meter reaches a maximum value Um before to go to zero. This voltage peak, the tm corresponding this maximum and the initial slope of the curve S represent the RV parameters. The polarization spectrum is defined as the curves obtained by plotting the value of Um, tm and S obtained from each measurement versus charging time tc, The dominant time constant of this curve is directly related to the moisture inside the dielectric. Therefore, if the condition of insulation system changes for aging or for other factors, the waveform of return voltage will change too. Figure 2 shows the principle of the return voltage measurement. .

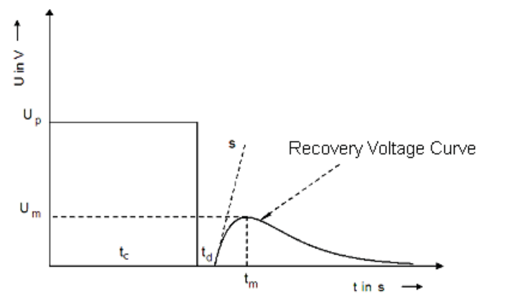

Fig. 2. Principle of return voltage measurement.

A. Insulation Model for Dielectric Response

Several researchers have proposed many equivalent circuits to model the transformer oil-paper insulation over the last few years to understand the dielectric response. A simplified equivalent circuit used to describe the insulation system's polarization behavior is shown in figure 3. This model is known as the extended Debye (ED) model [10], which is based on a simple series connection of the resistor and capacitor RC. In particular, the different pairs Ri-Ci of the circuit represent the various dipole groups randomly distributed in the dielectric. The response time of each group after the application of an electric field may differ from one to another. These processes can be modeled by a parallel arrangement of branches, each containing a series connection of resistor and capacitor. Apart from the polarization current, conduction current flows in the insulation for the presence of an electric field. RG represents the electrical resistance of the dielectric to this conduction current. CG represents the geometric capacitance of the dielectric. Moreover, during the service time the behaviour of the insulation system changes and this affects the polarization process. For this reason, the values of the electrical components of the ED model should be updated during the life cycle of the transformer. In this paper, the polarization process was modelled using a single RC branch with variable elements.

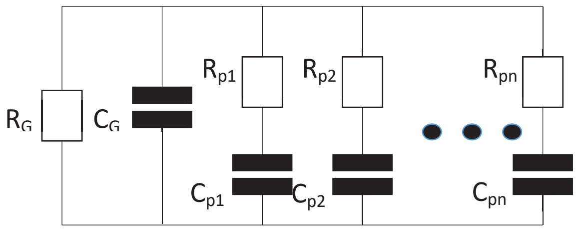

Fig. 3 Extended Debye model

B. Mathematical Description of the Recovery Voltage Method

When the switch of figure 1 is in the position 1, with all capacitors initially discharged, a dc voltage Up is applied and after tc seconds the n-th capacitor Cpn is charged to a voltage Vcpn with final value:

$$V_{C_{pn}}(t_c) = U_p\left(1 - \exp\left[\frac{-t_c}{R_{pn}C_{pn}}\right]\right) \qquad (1)$$

When the switch is turned in position 2 the dielectric is short-circuited and after t_d seconds the remaining voltage in C_{pn} is:

$$V_{C_{pn}}(t_c, t_d) = V_{C_{pn}}(t_c)\exp\left[\frac{-t_d}{R_{pn}C_{pn}}\right] \qquad (2)$$

The ratio between t_c and t_d is normally fixed and equal to 2 ($t_d = t_c/2$). When the short-circuit is removed and the voltmeter is connected (switch in position 3), then the recovery voltage across M (figure 1) is the result of all remaining voltages in all capacitors. The capacitor C_G discharge very quickly under normal conditions and then its contribution to recovery voltage is not important. The return voltage contribution V_{ri} due to the capacitor C_i in time domain can be obtained by computing the inverse Laplace transform of the transfer functiolenn $V_{ri}(s)/V_{ci}(s)$ [11] from the equation of equivat circuit. In this work, we assume that a single polarization branch represents the insulation (only one R_PC_p branch).

$$\frac{V_r(s)}{V_{C_p}(s)} = k\frac{s}{(s+p_1)(s+p_2)} \qquad (3)$$

$$k = \frac{C_pR_G}{R_GC_GC_pR_p} = \frac{\tau_{GP}}{\tau_G \cdot \tau_P} \qquad (4)$$

In (5) the poles of the transfer function (3) are reported:

$$p_{1,2} = \frac{-(\tau_G+\tau_P+\tau_{GP})}{2\tau_G\tau_P} \pm \frac{\sqrt{(\tau_G+\tau_P+\tau_{GP})^2 - 4\tau_G\tau_P}}{2\tau_G\tau_P} \qquad (5)$$

Noting that $(\tau_G + \tau_P + \tau_{GP})^2 > 4\tau_G\tau_P$ for all τ_G, τ_P, $\tau_{GP} \in R^+$, the term inside the square-root is always positive and then the imaginary part of poles p1 and p2 are zero and the real part is negative. Therefore the recovery voltage in the time domain is:

$$V_r(t, t_c) = kV_{C_P}(t_c)(A_1\exp(tp_1) + A_2\exp(tp_2)) \qquad (6)$$

$$A_1 = \frac{1}{p_1 - p_2} \qquad A_2 = \frac{1}{p_2 - p_1} \qquad (7)$$

The voltage response of the circuit starts at zero and ends at zero and its peak is at a time equal to tpeak. This time can be computed differentiating with respect to t the equation (6) and set equal to zero:

$$t_{peak} = \frac{\ln(p_2/p_1)}{p_1 - p_2} \qquad (8)$$

It can be observed that if the values of poles p1 and p2 are close, the recovery voltage takes more time to die out. Therefore, the voltage polarization spectrum is obtained by plotting Vrmax, versus different values of tc. Vrmax is computed by equation (5) with t=tpeak.

III. GA AND PSO OPTIMIZED IDENTIFICATION METHODS OF INSULATION POLARIZATION PARAMETERS

Since insulation system of a power transformer is characterized of different polarization process with widely varying response time, in this work the authors propose to use a set of RVM measured data with different charge time tc to estimate the polarization parameters of the equivalent circuit. Because of this circuit is described by a group of nonlinear equations with exponential functions, the solving problem is transformed into a constrained optimization problem. In this paper, the authors use two heuristic algorithms to solve the parameter estimation problem: Genetic algorithm (GA) and Particle Swarm Optimization method (PSO). The GA algorithm (GA) was developed by Goldberg, in 1989, and it is a stochastic global search method based on the principle of natural selection [12]. The individuals of the population (chromosomes) are potential solutions to the optimization problem and each step they are randomly selected to be parents and to produce the children for the next generation. A new generation from the current population is created by the following rules: the selection picks out a pair of individuals (parents) according to their fitness values; the crossover combines two parents who will contribute to the population of the next generation; the mutation applies random changes in individual parents which create children. The GA algorithm continues to produce a new population until it reaches the desired point. The Particle Swarm Optimization (PSO) method is a heuristic algorithm introduced by Kennedy and Eberhart in 1995 [13]. It is inspired by the sociological behaviour of swarms of birds or a flock of fishes, where a number of simple entities called particles potential solution of the problem and, flying in a multidimensional space of solutions, it tries to reach the best position. Two vectors define the position of the ith particle in the D-dimensional search space: the position vector and the speed vector. Each particle searches the solution according to its own flying experience and to the experience of the other particles. In the searching process are used the cognitive and social parameters, which depend on the personal particle experience and on the swarm social experience. The values chosen for all these parameters define the performance of the PSO algorithm. In this paper, the insulation polarization parameters are obtained by using two different heuristic algorithms in order to compare their optimization performances. This result can be reached by defining an objective function (fitness function), minimized by GA and PSO, which is a function of the polarization parameters RP and CP of the equivalent circuit (Figure 3 with only one branch RC).

A. RVM Parameters Identification algorithm

The identification algorithm of polarization parameters, proposed by authors, is an iterative procedure based on a set of recorded RVM measured data of a three-phase power transformer. These measurements are the voltage Vrmax and the time tpeak obtained for different values of the charge time tc . The identification process is performed by a comparison of these measured results and the RVM calculated data obtained from the equations (4)-(7). It can be noted that these equations depend on the polarization parameters RP and CP. These parameters, which are used to determine the polarization spectrum of the insulation system, are the variables used in the optimization procedure. Polarization elements are calculated for each charging time tc, and the inputs of the procedure are the measured parameters Vrmaxm, tpeakm, tc, RG and CG. The optimized RP and CP's optimized values are identified by a fitness function, which is defined for minimizing the error between the measured data and calculated data. The weighting fitness function is the following:

$$F = w1|Vrmx_m - Vrmx_c| + w2|tpk_m - tpk_c| \qquad (9)$$

where F=F(RP,CP) and V_{rmxc} and t_{pkc} are the calculated data. The optimization procedure is done complying with the constraints $(\tau_G + \tau_P + \tau_{GP})^2 > 4\tau_G\tau_P$ and τ_G, τ_P,$\tau_{GP} \geq 0$ to the have imaginary part of poles p1 and p2 equal to zero and the real part negative (see section II). The flowchart of the algorithm proposed is shown in Fig. 4. The two heuristic algorithms GA and PSO perform the minimization of the fitness function.

IV. ANALYSIS OF RESULTS

The optimization method, proposed in this paper, has been implemented with the help of GA and PSO codes written in Matlab libraries. After the method has been successfully tested, it was used to identify the RP and CP parameters from the RVM measurements performed on the power transformer 6.3/35kV, 8MVA, YNd5, RG=590MΩ and CG=13178 pF obtained from [14]. This transformer has been tested on site using the RVM5461 instrument and the results are shown in Table I. On the LV windings have been applied a constant voltage of 2000 V and the HV windings have been short-circuited and grounded.

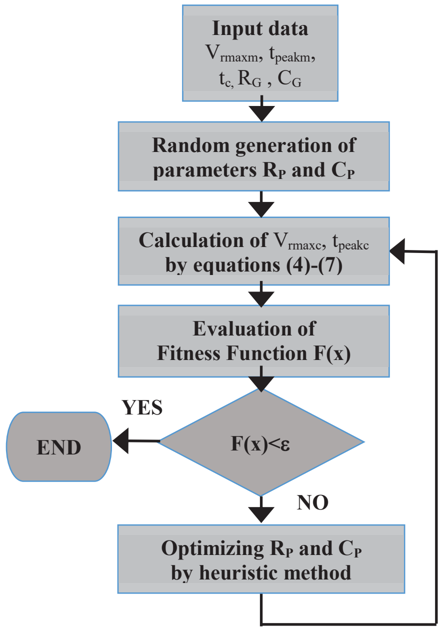

Fig. 4 Flowchart of the polarization parameters identification algorithm

Table 1. RVM measurements - 8MW Power Transformer.

t_c	V_{rmax} (V)	t_{peak} (s)
0.02	12.4	0.695
0.05	27.2	0.995
0.1	49.8	1.200
0.2	90.6	1.300
0.5	187	1.490
1	288	1.680
2	362	2.100
5	343	3.590
10	278	8.000
20	230	17.50
50	200	28

Table 2. Optimized Polarization Parameters R_p and C_p

t_c (s)	R_{PGA} (Ω)	C_{PGA} (Ω)	R_{PPSO} (Ω)	C_{PPSO} (Ω)
0.02	1.9087e+08	5.1252e-10	1.9394e+08	5.6062e-10
0.05	1.9330e+08	8.8103e-10	1.9303e+08	8.7680e-10
0.1	1.7438e+08	1.2385e-09	1.7438e+08	1.2384e-09
0.2	1.3094e+08	1.8620e-09	1.3176e+08	1.8666e-09
0.5	1.0044e+08	4.3428e-09	7.1892e+07	4.6093e-09
1	5.1235e+07	1.0399e-08	4.2887e+07	1.1441e-08
2	5.0002e+07	1.9259e-08	3.8783e+07	2.2806e-08
5	6.4973e+07	2.9633e-08	6.5166e+07	2.9566e-08
10	2.5737e+08	1.5951e-08	2.3040e+08	1.7171e-08
20	8.9409e+08	1.0456e-08	8.8923e+08	1.0485e-08
50	1.4736e+09	1.3092e-08	1.4835e+09	1.3040e-08

The optimized procedure assisted by GA and PSO has been performed for each charge time tc, which changes in the range [0.02sec–50sec]. The population of polarization elements is created randomly with a uniform distribution from a predefined range. The genetic algorithm has been used with a population of 300 individuals with 100 generations, crossover rate of 80% and migration interval of 10 individuals. The initial population of particles used in PSO is 300 and the number of iterations is 150. The identification parameters results obtained applying the two heuristic algorithms are shown in Table II. In order to compare the performances of the two methods implemented for the polarization parameters identification, the convergence-speed and the time-consuming have been considered. The convergence curves of fitness for the two heuristic algorithms are shown in figure 5. The convergence-speed of GA is higher than PSO because the best fitness value is reached with a minor number of iterations (5 generations GA and 25 iterations PSO). Moreover, figure 6 shows the comparison of the best objective function values between the GA and PSO optimization procedures. It can be noted that the PSO method is characterized by fitness values lower than GA. Therefore, the PSO success for finding the best solution for the tested method is better than GA procedure. This result is confirmed by figure 7 and figure 8, which show the comparison of the measured and the calculated RVM data from the optimized equivalent circuit by GA and PSO algorithms. The figures show a good fitting in terms of V_{rmax} and t_{peak} through the charge time range for both heuristic algorithms. Although the GA and PSO performances are the same for the voltage polarization curve V_{rmax}, the fitting between measured and calculated data for the polarization curve t_{peak} by PSO is worse than GA. The percentage error (deviation) for each calculated result regarding each corresponding measured value has been computed for comparing the performances of the two algorithms. The deviation formula is the following:

$$\text{Deviation} = \frac{\text{calculated} - \text{measured}}{\text{measured}} \, (\%) \qquad (10)$$

Figure 9 and figure 10 show the deviation of V_{rmax} and t_{peak} calculated by the polarization parameters optimized by GA and PSO. The deviation of t_{peak} offered by the PSO method is always lower than GA method for each charge time t_c. Moreover, the authors have demonstrated that the performance of the PSO approach is better than GA in terms of time-consuming.

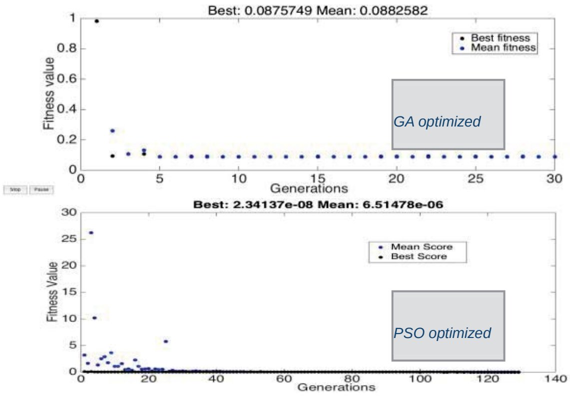

Fig. 5 PSO and GA convergence

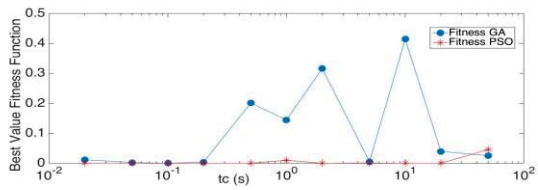

Fig.6 GA and PSO Best Fitness value

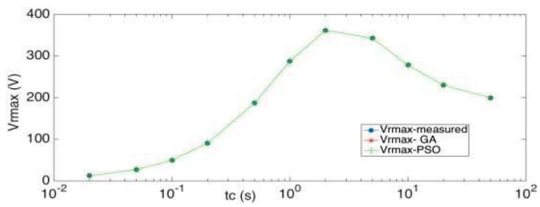

Fig.7 Comparison of calculated V_{rmaxc} by PSO and GA identification parameters and measured V_{rmaxm}.

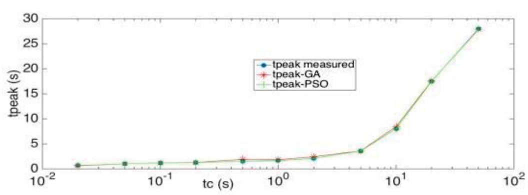

Fig.8 Comparison of calculated t_{peakc} by PSO and GA Identification parameters and measured t_{peakm}.

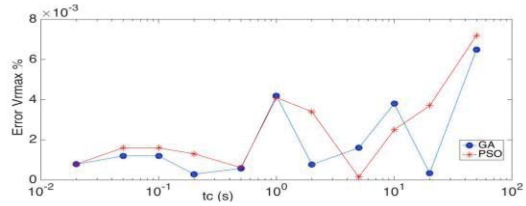

Fig.9 GA and PSO V_{rmax} percentage error

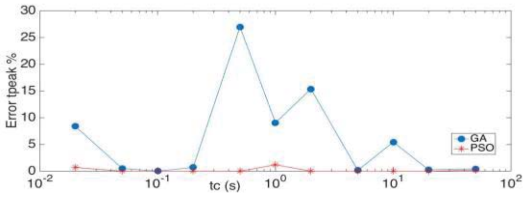

Fig.10 GA and PSO t_{peak} percentage error.

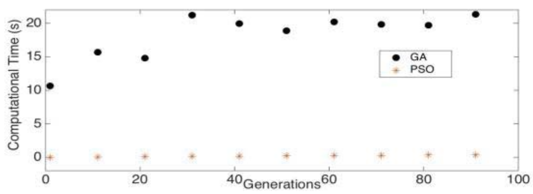

Fig.11 PSO and GA computational time

The time-consuming depends on the computational cost of the algorithm. In figure 11, the two methods have been evaluated for the same input data (t_c, V_{rmaxm}, t_{peakm}) and considering several generations/iterations. GA algorithm has a computational time of around 20 seconds and PSO around 0.2 seconds. This result has been confirmed for every input data.

V. CONCLUSION

The RVM method allows estimating the polarization spectrum of the insulation system of a power transformer. This spectrum gives information about the degradation level of the dielectric caused by aging and/or presence of moisture. An equivalent electric circuit composed with several polarizations branches R-C has been used to model the polarization process. In this paper the authors have been implemented a constrained optimized procedure based on GA and PSO heuristic algorithms for solving parameters estimation of the equivalent circuit. The proposed procedure is based on RVM measured experiments implemented on a specific power transformer located in hydropower plants. The GA and PSO succeeded in finding the best solutions for the tested methods. Therefore, the RVM curves have been calculated from the estimated circuit. A comparison of the calculated data and the measured results has been performed for the both GA and PSO algorithms. The results show that the proposed model is effective and feasible. GA convergence-speed is always higher than PSO. Moreover, the percentage error and the time-consuming of PSO are always lower than GA.

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