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Application of the Hurricane Optimization Algorithm to Estimate Parameters in Single-Phase Transformers Considering Voltage and Current Measures

Brandon Cortés-Caicedo [1], Oscar Danilo Montoya [2,3,*] and Andrés Arias-Londoño [4]

[1] Departamento de Mecatrónica y Electromecánica, Facultad de Ingeniería, Instituto Tecnológico Metropolitano, Medellín 050036, Colombia; brandoncortes326234@correo.itm.edu.co
[2] Grupo de Compatibilidad e Interferencia Electromagnética, Facultad de Ingeniería, Universidad Distrital Francisco José de Caldas, Bogotá 110231, Colombia
[3] Laboratorio Inteligente de Energía, Facultad de Ingeniería, Universidad Tecnológica de Bolívar, Cartagena 131001, Colombia
[4] Facultad de Ingeniería, Campus Robledo, Institución Universitaria Pascual Bravo, Medellín 050036, Colombia; andres.arias366@pascualbravo.edu.co
* Correspondence: odmontoyag@udistrital.edu.co

Abstract: In this research paper, a combinatorial optimization approach is proposed for parameter estimation in single-phase transformers considering voltage and current measurements at the transformer terminals. This problem is represented through a nonlinear programming model (NLP), whose objective is to minimize the root mean square error between the measured voltage and current values and the calculated values from the equivalent model of the single-phase transformer. These values of voltage and current can be determined by applying Kirchhoff's Laws to the model T of the transformer, where its parameters, series resistance and reactance as well as the magnetization resistance and reactance, i.e., R_1, R_2', X_1, X_2', R_c y X_m, are provided by the Hurricane Optimization Algorithm (HOA). The numerical results in the 4 kVA, 10 kVA and 15 kVA single-phase test transformers demonstrate the applicability of the proposed method since it allows the reduction of the average error between the measured and calculated electrical variables by 1000% compared to the methods reported in the specialized literature. This ensures that the parameters estimated by the proposed methodology, in each test transformer, are close to the real value with an accuracy error of less than 6%. Additionally, the computation times required by the algorithm to find the optimal solution are less than 1 second, which makes the proposed HOA robust, reliable, and efficient. All simulations were performed in the MATLAB programming environment.

Keywords: hurricane optimization algorithm; parametric estimation; single-phase transformers; minimization of mean square error; nonlinear programming model; voltage; current measures

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1. Introduction

1.1. General Context

In the last years the power energy has become into an essential right for the humankind, due to its use and contribution in the technological and social development [1,2]. In order to meet the demand in the consumption points (i.e., end users), it has been implemented a complex of elements in charge of generate, transform, transport, distribute and commercialize the power energy [3]. One of the most important devices in this process chain, and more general in the electrical sector, are the transformers. These devices are responsible to interconnect the generation points with the transmission networks, at the same time are in charge to interconnect the transmission and subtransmission networks with the end users, which can be residential, industrial or commercial type [4]. This can be reached by raising the voltage level (high, medium and low voltage) at each stage [5].

For this reason, the transformers play an important role to guarantee the power supply in the power systems. One of the most researched aspects in power and distribution systems is the power losses quantity, as this represents an index of the efficiency and the operative status of the network, particularly in the area of distribution systems, as the total power losses can range within 6% to 18% [6]. The transformers have the major participation, with 60% of total power losses due to low level of loads that can be presented in the network [4]. For a proper analysis at any power system with transformers, a precise model should be considered, that allows to know the parameters of the equivalent circuit of the transformer, as these can provide its characterization and behavior within the network [7]. Furthermore, this is not an easy task as the factory parameters of the transformer can vary, with respect to its nominal values, along its useful life due to winding isolating and dielectric paper deterioration [8–10].

1.2. Motivation

Under this context, one of the classic methods to determine the transformer parameters are the short and open circuit tests, however, these are laboratory tests that can only be done on transformers that are not connected to the system [11]. This means, if we want to estimate the transformer parameters under operation, it is necessary to disconnect it from the load point and move it to the point of the laboratory [12]. This practice is not recommended and brings negative consequences for the reliability indices given that there are multiple users in the distribution systems [6]. Besides, from the economic point of view, it is not suitable due to the large number of transformers presented in a power distribution system [6]. In the Colombian context, within 2010 and 2018, there were installed 581,592 new transformers [13]. Therefore, in this research document it is proposed the parameters estimation of single phase transformers connected along the distribution networks by using voltage and current measurements at its terminals. The principal advantage of this methodology is that allows to determine the single phase transformer parameters without interrupting its operation. To address this problem, it is proposed an objective function that minimizes the average square error within the values of current and voltage measured in the transformer terminals and the values computed from the electrical model. Likewise, it is proposed a metaheuristic algorithm that solves the non-linear programming model (NLP) that represents this problem. This mathematical model is developed from the application of the Kirchhoff laws in the equivalent model of the single phase transformer [14].

1.3. Review of the State of the Art

In the specialized literature, it is possible to find different optimization options, based on metaheuristic algorithms, that fulfill the problem of parameters estimation in single phase transformers. This is the case of [15], where a technique based on evolutionary programming is proposed to estimate the parameters of a single-phase transformer without the requirement of any experimental measurement, minimizing the quadratic error between the voltage and current values of the nameplate data and the calculated values. For this purpose, the authors of this paper employ two metaheuristic techniques as a comparison methodology: particle swarm optimization and genetic algorithm. The proposed methodology is implemented in three test transformers where the effectiveness and robustness of the techniques used are demonstrated. However, the authors of this paper do not perform a statistical analysis to determine the repeatability of the metaheuristic algorithms used, as well as an analysis of the computational time taken by each methodology to obtain a solution. This problem is also presented by the authors of [14], where they solve the problem of parameter estimation in single-phase transformers, minimizing the quadratic error between the nominal values of nameplate data and calculated values, using two metaheuristic optimization techniques as a comparison methodology: the imperialistic competitive algorithm and the gravitational search algorithm.

In [16], a methodology based on the particle swarm optimization algorithm is proposed to solve the problem of optimal parameter estimation in single-phase transformers. In this paper they use as objective function the minimization of the quadratic error of the following parameters: nominal voltages and currents, no-load currents and the impedance percentage. The results obtained by the developed methodology are validated in two single-phase test transformers where the efficiency of the particle swarm algorithm to solve this problem is demonstrated. However, this work has not included comparison methodologies, statistical analysis to determine the repeatability and robustness of the metaheuristic technique used, and analysis of the computational time. In [17], the problem of parameter estimation in single-phase transformers using current and voltage values under a known load condition is solved. The objective of this document is to minimize the error between the actual transformer parameter values and the estimated values from the proposed methodology. The artificial bee colony algorithm is used for this purpose, where the results obtained are validated by proposing different test scenarios. However, other algorithms reported in the specialized literature are not used as a comparison methodology, as well as a time and statistical analysis is not performed to determine the robustness, efficiency and repeatability of the proposed methodology. In [7], a chaotic optimization algorithm is proposed to solve the problem of parameter estimation in single-phase transformers by minimizing the quadratic error between the measured and estimated transformer variables (i.e., voltage, current and power variables). The results obtained for the test transformers under different test scenarios are validated by comparing them with the results obtained by different optimization algorithms proposed in the specialized literature that have solved this problem. However, the authors of this paper did not perform a statistical and computational time analysis to determine the robustness and repeatability of the proposed methodology.

In [18], the Coyote optimization algorithm is proposed to estimate parameters in single-phase and three-phase transformers using data provided by the manufacturer. The proposed methodology seeks to minimize the error between the real and estimated parameters. The results obtained for the different test transformers are compared with two metaheuristic techniques known in the specialized literature where the efficiency and capacity of the developed algorithm to solve the proposed problem is demonstrated. However, the authors neither do not analyze computational times, nor perform a statistical analysis to determine the repeatability of the methodology used. The authors of [19], propose a methodology for the estimation of parameters in single-phase transformers based on the application of jellyfish search optimizer algorithm. This is achieved by using current and voltage values at a given load condition. The objective function worked in this paper seeks to minimize the difference between the actual data and the estimated parameter values. The numerical results obtained for the test transformer used in this research are compared with the particle swarm optimization algorithm, with which the convergence of the algorithm is also compared. In addition, a statistical analysis is performed to verify the repeatability and robustness of the developed methodology; however, an analysis of the computational time that the algorithm takes to reach an optimal solution is needed. In [20], a nonlinear programming model is proposed to solve the parametric estimation problem in single-phase transformers from the point of view of metaheuristic optimization considering only voltage and current measurements of the transformer terminals. The main objective of the authors is to minimize the mean square error between the measured and calculated voltage and current variables. The nonlinear programming model is solved by implementing the black hole optimization algorithm. The results obtained for the different test transformers show the efficiency of the proposed methodology when compared to other methods reported in the specialized literature. In addition, the authors of this paper perform a statistical and computational time analysis where the repeatability and robustness of the proposed algorithm is evidenced. Finally, a computational experiment is proposed where the parameters obtained by the proposed methodology and the real parameters are compared. The input power for each test transformer is calculated, confirming that the parameters found in this paper replicate the behavior of the real transformer. In [13], the sine cosine optimization algorithm for parametric estimation in single-phase transformers considering voltage and current measurements is proposed. For this purpose, a non-linear programming model is conformed, which is formulated by applying Kirfchoff's laws to the equivalent model of the transformer. The results obtained for the different test transformers are validated by comparison with the specialized GAMS software. However, comparison methodologies based on metaheuristic algorithms are needed, as well as a statistical and computational time analysis to determine the repeatability and robustness of the proposed algorithm. Nevertheless, it is shown that the parameters found adequately represent the behavior of the real transformer by calculating the input power and efficiency with the actual and calculated parameters. Finally, the authors of [21] address the problem of parameter estimation in single-phase transformers by applying the crow search algorithm. To achieve this, they formulate a nonlinear programming model with which they seek to minimize the mean square error between the measured and calculated voltage and current values. The numerical results of the test transformers used, demonstrate the efficiency of the proposed methodology when compared with the MATLAB fmincon tool. Similarly, strategies based on metaheuristic algorithms and commercial software are used as comparison methodologies to demonstrate the efficiency of the algorithm used. However, a computational and statistical time analysis is needed to determine the repeatability and robustness of the methodology used. On the other hand, a complementary analysis is performed where it is shown that the parameters determined by the optimization algorithm used replicate the behavior of the real transformer.

As it was observed in the above review of the state of the art the main characteristic of the optimization methodologies described before, is their combinatorial nature in the continuous domain, which have the ability to find good quality solutions (i.e., feasible solutions) with the least possible computational effort, being easy to implement in multiple programming languages [22]. In addition, it can also be identified that: (i) all methodologies described in the state of the art employ as a performance indicator the minimization of the mean square error; and (ii) the hurricane optimization algorithm has not been previously applied to this problem. Therefore, this paper proposes the use of the Hurricane Optimization Algorithm (HOA) for the estimation of parameters in single-phase transformers from the measured voltage and current values, performing the evaluation of an objective function based on the minimization of the mean square error between the measured and calculated values.

1.4. Scope and Main Contributions

Due to the importance of transformers in the electrical power system, especially for distribution systems, to guarantee the supply of electrical energy to end users (i.e., commercial, residential and industrial users), the need arises to propose new solution methodologies that allow to find its parameters with reliable and excellent quality results. Therefore, this paper proposes a new methodology to solve the problem of parameter estimation in single-phase transformers. Based on the above review of the state of the art of the parameters estimation in single phase transformers the main contributions of this paper are listed as follows:

- HOA application to the problem of single phase parameters estimation from measurements of voltage and current at the terminals, given a load condition.
- The possibility to approach to a global optimal solution of the problem under study, when the current reports of the specialized literature are significantly improved for the 4 kVA, 10 kVA and 15 kVA single phase transformers.
- The parameters found for each test transformer accurately replicate the behavior of real transformers when calculating voltage regulation and efficiency under load variations at the output terminals.

Note that the importance of this research lies with updating the electrical information for the utilities regarding their distribution networks for planning and operation purposes, since updated information regarding all their electrical devices, mainly lines and transformers, can help with accurate simulations that also provide information on revised maintenance plans and possibilities to attend (i.e., connect) new users in the current grids, and the required actions to deal supply electrical energy to these users.

1.5. Document Setting

The rest of this document is organized as follows: Section 2 presents the mathematical formulation of the parameters estimation problem in single phase transformers considering voltage and current measurements given a condition load; Section 3 shows the implementation of the HOA, with its main features, to solve optimization problems; Section 4 describes the main characteristics of the test 4 kVA, 10 kVA and 15 kVA single phase transformers; Section 5 reveals the results obtained for the transformers parameters estimation with a complete analysis and discussions; finally, in Section 6 are exposed the conclusions and future works obtained from the development of this research article.

2. Mathematical Formulation

Generally, the transformer parameters estimation is performed in a experimental manner through the short and open circuit tests [15]. Furthermore, in this document the transformer parameters are estimated from current and voltage readings at terminals. For which, it is proposed to minimize the average square error between the voltage and current values measured at terminals of the transformer and the corresponding values that are calculated from the transformer model shown in Figure 1 to solve the mathematical equations. That said, the objective function to minimize is defined in (1) [6].

$$\min z = \frac{1}{2}\left(\left(\frac{I_1 - |i_1|}{I_1}\right)^2 + \left(\frac{I_2' - |i_2'|}{I_2'}\right)^2 + \left(\frac{V_2' - |v_2'|}{V_2'}\right)^2\right) \tag{1}$$

where z is the mean squared error to be minimized. I_1 is the current measured at the primary winding. I_2' is the current measured at the secondary winding referred to the primary winding. V_2' is the voltage measured at the secondary winding referred to the primary winding. i_1 is the current calculated at the primary winding. i_2' is the current calculated at the secondary winding referred to the primary winding. v_2' is the voltage calculated at the secondary winding referred to the primary winding.

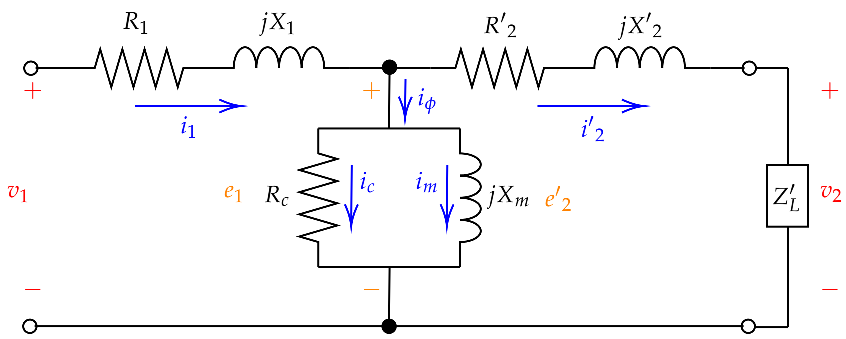

Figure 1. Transformer equivalent circuit referred to the primary side.

In Figure 1 R_1 and R_2' are the resistances of the primary and secondary windings referred to the primary winding, respectively. X_1 and X_2' are the dispersion reactances of the primary and secondary windings referred to the primary side, respectively. R_c is the equivalent resistance that presents the transformer when computing the core losses. X_m corresponds to the magnetization reactance. Z_L' represents the impedance associated with the load connected with the secondary side of the transformer referred to the primary side. v_1 is the voltage at the primary side. e_1 and e_2' correspond to the voltage drop in the magnetization branch from the primary and secondary side referred to the primary, respectively. Finally, i_ϕ is the excitation current of the transformer, i_c is the current of core losses and i_m is the magnetization current.

Likewise, in Figure 1 it is shown the equivalent circuit of a two-winding single phase transformer referred to the primary side. This model is known as the model T, as the magnetization branch is between the series branches [7]. Notice that this model of transformer is chosen as presents a better electrical approximation in regards with the stationary state.

Applying the first and second Kirchhoff laws to the model shown in Figure 1 we obtain the Equations presented in (2) to (7), which can be found at [18]:

$$i_1 = i_\phi + i_2' \tag{2}$$

$$i_\phi = e_2'\left(\frac{1}{R_c} + \frac{1}{jX_m}\right) \Leftrightarrow i_\phi = e_2'\left(\frac{jR_cX_m}{R_c + jX_m}\right) \Leftrightarrow i_\phi = e_2'Z_0 \tag{3}$$

$$v_2' = i_2'Z_L' \tag{4}$$

$$e_2' = i_2'(R_2' + jX_2') + v_2' \Leftrightarrow e_2' = i_2'Z_2' + v_2' \tag{5}$$

$$e_2' = e_1 \tag{6}$$

$$v_1 = i_1(R_1 + jX_1) + e_1 \Leftrightarrow v_1 = i_1Z_1 + e_1 \tag{7}$$

It is important to mention that v_1 is considered as an input value, which implies that it is a constant for the problem of parameters estimation in single phase transformers [6]. Now, to be able to compute the value of the objective function shown in (1), the challenge is to obtain an expression for the value i_1, i_2' and v_2' in function of the decision parameters of the problem, i.e., $R_1, R_2', R_c, X_1, X_2'$ and X_m, which will be determined by using the proposed optimization algorithm.

For this, (4) and (5) are replaced in (3), reaching the expression shown in (8) [20]:

$$i_\phi = i_2'\left(\frac{Z_2' + Z_L'}{Z_0}\right) \tag{8}$$

Replacing (8) in (2) and solving for i_2', we can obtain the expression in (9).

$$i_2' = i_1\left(\frac{Z_0}{Z_2' + Z_L' + Z_0}\right) \tag{9}$$

Replacing (4)–(6) and (9) in (7) and solving for i_1, the expression in (10) is obtained.

$$i_1 = \frac{v_1}{\left(Z_1 + \frac{Z_0(Z_2'+Z_L')}{Z_0+Z_2'+Z_L'}\right)} \Leftrightarrow i_1 = \frac{v_1}{Z} \tag{10}$$

Finally, replacing (10) in (9), it is obtained the expression in (11).

$$i_2' = \frac{v_1}{Z}\left(\frac{Z_0}{Z_2' + Z_L' + Z_0}\right) \tag{11}$$

From the mathematical development the Equations (10), (11) and (4) are obtained, which allow to compute i_1, i_2' and v_2', respectively.

By the other side, the problem of optimal estimation of parameters in single phase transformers has a set of constraints related with their operative limitations (see Equations (4), (10) and (11), and upper and lower boundaries of the decision variables presented in the type box constraints shown from (12) to (17).

$$R_1^{\min} \leq R_1 \leq R_1^{\max} \tag{12}$$

$$R_2'^{\min} \leq R_2' \leq R_2'^{\max} \tag{13}$$

$$R_c^{\min} \leq R_c \leq R_c^{\max} \tag{14}$$

$$X_1^{\min} \leq X_1 \leq X_1^{\max} \tag{15}$$

$$X_2'^{\min} \leq X_2' \leq X_2'^{\max} \tag{16}$$

$$X_m^{\min} \leq X_m \leq X_m^{\max} \tag{17}$$

Remark 1. *The optimization model for the parameters estimation in single phase transformers is composed by the objective function (1) and the set of constraints shown in (10), (11) and (4), together with the type box constraints (12)–(17). Notice that this model is non-linear non-convex due to the multiplication and divisions when computing values of voltage and current. As per above mentioned, the solution of this model can generate multiple local optimal solutions [20], being necessary the implementation of metaheuristic techniques, which are efficient when solving non-linear optimization models [23].*

3. Methodology Proposed: Hurricane Optimization Algorithm

To solve the problem of optimal parameters estimation in single phase transformers, modeled in the above section, the parameters to be determined are R_1, R_2', R_c, X_1, X_2' and X_m. In order to minimize the average square error between the voltage and current values measured and computed at transformer terminals, it is proposed the application of the Hurricane Optimization Algorithm (HOA) [24]. HOA is an optimization metaheuristic technique based on the observation of the hurricanes nature and how the wind moves through the surrounding atmosphere during this phenomena [24].

HOA is an algorithm that works due to interaction of the natural forces of a hurricane and the wind parcels found there, making them to move towards the different zones of the hurricane [25]. This is achieved by the mathematical model of the phenomena through some simple rules that allow the exploration of the solution space in electrical engineering problems [25–27]. One of the main features of this algorithm is that it is an optimization technique based on population, that is, the population of candidate solutions is randomly generated. For this case the wind parcels are the population individuals. In general, the largest part of the wind tends to enter in the central zone of the hurricane. This zone is characterized of having the lowest pressure, where the hurricane eye is located, which, for this case, represents the best possible solution [24].

3.1. Initial Population

HOA works with an initial population composed by wind parcels randomly distributed in the hurricane, this allows the algorithm to start with its exploration and exploitation process in the solution space [27]. The initial population of wind parcels takes the structure shown in (18):

$$P^t = \begin{bmatrix} p_{11}^t & p_{12}^t & \cdots & p_{1N_v}^t \\ p_{21}^t & p_{22}^t & \cdots & p_{2N_v}^t \\ \vdots & \vdots & \ddots & \vdots \\ p_{N_i 1}^t & p_{N_i 2}^t & \cdots & p_{N_i, N_v}^t \end{bmatrix} \tag{18}$$

where P^t is the wind parcels population in the iteration t, when $t = 0$ the initial population of individuals is obtained. N_i represents the number of wind parcels (individuals) and N_v is the number of variables or the dimension of the solution space, in other words, the number of parameters of a single phase transformer, i.e., six in this study case.

To create the initial population of individuals it is used (19), which will generate a matrix of random numbers, within the upper and lower limits, that contains possible solutions of the problem under study.

$$P^0 = y^{\min} ones(N_i, N_v) + (y^{\max} - y^{\min}) rand(N_i, N_v) \tag{19}$$

where $ones(N_i, N_v) \in \mathbb{R}^{N_i \times N_v}$ represents an all-ones matrix. $rand(N_i, N_v) \in \mathbb{R}^{N_i \times N_v}$ represents an all-random numbers matrix within 0 and 1 generated from a normal distribution.

Finally, $y^{\min} \in \mathbb{R}^{dim \times 1}$ y $y^{\max} \in \mathbb{R}^{N_v \times 1}$ are vectors that represent the upper and lower limits of the solution space, as shown as follows:

$$y^{\min} = \begin{bmatrix} R_1^{\min} \\ R_2'^{\min} \\ R_c^{\min} \\ X_1^{\min} \\ X_2'^{\min} \\ X_m^{\min} \end{bmatrix}, y^{\max} = \begin{bmatrix} R_1^{\max} \\ R_2'^{\max} \\ R_c^{\max} \\ X_1^{\max} \\ X_2'^{\max} \\ X_m^{\max} \end{bmatrix}.$$

Finally, to determine the hurricane eye each individual of the wind parcels population is evaluated in the objective function shown in (1) and the best solution is selected as the hurricane eye [24].

3.2. Wind Parcels Movement

Owing to the interaction of the wind parcels with natural forces of the hurricane, these will displaced from their initial point to a different point of the solution space. The movement of the wind parcels is characterized by keeping a constant angular velocity, i.e., w, and by displacing around the hurricane eye, with the goal of locating at zones with less atmospheric pressure [27]. This movement can be represented mathematically in two different ways due to rotation provided by the hurricane winds, as shown in (20) and (21) [25].

$$P_i^{t+1} = \begin{cases} r_i^t \sin(\varphi_i^0 + \varphi_i^t) + P_{HE}^t & r_1 < 0.5 \\ r_i^t \cos(\varphi_i^0 + \varphi_i^t) + P_{HE}^t & r_1 \geq 0.5 \end{cases} \tag{20}$$

$$r_i^t = R_0 \exp(r_2 \varphi_i^t) \tag{21}$$

where P_i^{t+1} is the new position of the wind parcel i when the evolution criteria of the algorithm is applied, being $i = 1, 2, \ldots, N_i$. The parameter r_1 is a random variable between 0 and 1, which guarantees the equity of commutations between the sine and cosine trigonometric functions indicated in (20). φ_i^0 is the initial angular coordinate of a wind parcel i, which takes random values between 0 and 2π. P_{HE}^t represents the hurricane eye in the iteration t. r_i^t and φ_i^t are radial and angular coordinates in polar representation, respectively. In (21) when $t = 0$, φ_i^t is an all-zeros vector, for which r_i^t will take the value of R_0. Being R_0 the radius of the hurricane eye, which takes the value of 1×10^{-5}, according to [24]. Finally, r_2 is a random number between 0 and 1.

As the wind parcel P_i^{t+1} needs velocity to start moving and keep under movement, it is considered a rate of change in the angular displacement (angular velocity) summed to its angular coordinate φ_i^t, as shown in (22) [28].

$$\varphi_i^{t+1} = \begin{cases} \varphi_i^t + w & r_i^t \leq R_{\max} \\ \varphi_i^t + w\left(\frac{R_{\max}}{r_i^t}\right)^{r_3} & r_i^t > R_{\max} \end{cases} \tag{22}$$

where w is the angular velocity, which is assumed constant with a value of $\frac{\pi}{10}$ and $R_{\max}$ is the radius where the maximum wind velocity is found, which is taken as 0.2, in accordance with [24]. Finally, r_3 is a random value between 0 and 1.

3.3. Hurricane Eye Updating

To make the solutions feasible, the new positions of the wind parcels caused by the interaction of the hurricane forces, have to be within the limits of the solution space. In this sense, the upper and lower limits are verified at each individual contained in the set of new positions P^{t+1}, as shown in (23) [28].

$$P_i^{t+1} = \begin{cases} P_i^{t+1} & y^{\min} \leq P_i^{t+1} \leq y^{\max} \\ y^{\min} + rand(y^{\max} - y^{\min}) & \text{otherwise} \end{cases} \tag{23}$$

where *rand* provides random numbers with normal distribution between 0 and 1. Once the upper and lower limits of the individuals are verified, and adjusted those that were not feasible, the objective function shown in (1) is evaluated. Any individual of the set of candidate solutions P^{t+1} can be selected as the new hurricane eye if, and only if, the value of its objective function is better than the current hurricane eye P^t_{HE}. This update is defined with (24) [24].

$$P^{t+1}_{HE} = \begin{cases} P^{t+1}_i & \text{If } F(P^{t+1}_i) < F(P^t_{HE}) \\ P^t_{HE} & \text{otherwise} \end{cases} \tag{24}$$

where $F(\cdot)$ represents the objective function to minimize.

In the Algorithm 1 it is presented a summary of the HOA implementation to solve the parameters estimation problem in single phase transformers considering voltage and current readings [29].

Algorithm 1: Hurricane Optimization Algorithm to solve optimization problems.

Define parameters N_i, t_{max}, N_v, $y^{\min}$, $y^{\max}$, w, R_0, $R_{\max}$;
Create the initial population via (19);
Randomly generate values between 0 and 2π for the initial angular coordinate of the wind parcels;
Let $t = 0$;
Compute the objective function of the Equation (1) for each individual;
Choose the best solution and define it as the hurricane eye (HE);
for $t \leq t_{max}$ **do**
    Determine the wind parcels from Equations (20) and (21);
    Determine the new angular coordinate from Equation (22);
    Verify the feasibility of the individuals of the new population from Equation (23);
    Evaluate the fitness function of the individuals of the new population;
    if $F(P^{t+1}_i) < F(P^t_{HE})$ **then**
        Replace the hurricane eye
    else
        Keep the best solution currently obtained as P^{t+1}_{HE};
Result: The best solution is found for P^t_{HE} and its objective function is $F(P^t_{HE})$

4. Single-Phase Test Transformers

In this section it is presented the main features of the test single phase transformers used to validate the optimization methodology proposed for the parameters estimation. The three test single phase transformers considered have 4 kVA, 10 kVA and 15 kVA of nominal power, respectively.

4.1. 4 kVA Test Transformer

This is a single phase 4 kVA transformer that operates at a frequency of 50 Hz with a 250/125 V of voltage ratio. In Table 1 are shown the voltage and current measurements for this transformer [15]. In the same manner, in Table 2 are presented the values for the open and short circuit tests of the transformer parameters given by the manufacturer [15]. Finally, the load impedance, which was used to do the transformer measurements, was assumed purely resistive with a value of 15.6250 Ω [15].

Table 1. Measured voltage and currents for the 4 kVA test transformer.

Parameter	Value	Units
V_1	250.0000	V
V_2'	235.5967	V
I_1	15.2825	A
I_2'	15.0782	A

Table 2. Short-circuit and open-circuit test values for the 4 kVA test transformer.

Parameter	$y^{\min}$ (Ω)	Value(Ω)	$y^{\max}$ (Ω)
R_1	0.32	0.4	0.48
R_2'	0.32	0.4	0.48
X_1	0.16	0.2	0.24
X_2'	1.6	2	2.4
R_c	1200	1500	1800
X_m	600	750	900

4.2. 10 kVA Test Transformer

This is a 10 kVA single phase transformer that operates at a frequency of 50 Hz with a voltage ratio of 500/125 V. In Table 3 it can be observed the voltage and current readings corresponding to this transformer [15]. In addition, in Table 4 it is presented the values for the open and short circuit tests of this transformer given by the manufacturer [15]. Finally, the load impedance, which was used to do the transformer measurements, has a purely resistive value of 25 Ω [20].

Table 3. Measured voltage and currents for the 10 kVA test transformer.

Parameter	Value	Units
V_1	500.0000	V
V_2'	451.8047	V
I_1	18.8877	A
I_2'	18.0722	A

Table 4. Short-circuit and open-circuit test values for the 10 kVA test transformer.

Parameter	$y^{\min}$ (Ω)	Value (Ω)	$y^{\max}$ (Ω)
R_1	0.72	0.9	1.08
R_2'	1.28	1.6	1.92
X_1	0.752	0.94	1.128
X_2'	0.352	0.44	0.528
R_c	560	700	840
X_m	200	250	300

4.3. 15 kVA Test Transformer

This is a 15 kVA single phase transformer that operates at a nominal frequency of 50 Hz with a voltage ratio of 2400/240 V. In Table 5 it can be observed the voltage and current readings corresponding to this transformer [15]. Likewise, in Table 6 it is presented the values for the open and short circuit tests of this transformer given by the manufacturer [15]. Finally, the load impedance, which was used to do the transformer measurements, has a purely resistive value of 384 Ω [20].

Table 5. Measured voltage and currents for the 15 kVA test transformer.

Parameter	Value	Units
V_1	2400.0000	V
V_2'	2371.4165	V
I_1	6.2053	A
I_2'	6.1756	A

Table 6. Short-circuit and open-circuit test values for the 15 kVA test transformer.

Parameter	$y^{\min}$ (Ω)	Value (Ω)	$y^{\max}$ (Ω)
R_1	1.96	2.45	2.94
R_2'	1.6	2	2.4
X_1	2.512	3.14	3.768
X_2'	1.7835	2.2294	2.6753
R_c	84,000	105,000	126,000
X_m	7285	9106	10,927

Remark 2. *It is assumed that during the useful lifetime of the three transformers, i.e., 4 kVA, 10 kVA and 15 kVA, their parameters have a maximum variation of* $\pm$ *20%, which corresponds to the upper and lower limits taken for the decision variables, shown in Table 2, Table 4 and Table 6, respectively.*

5. Numerical Results and Discussions

This section contains the numerical validation of the methodology performed to solve the problem of parameters estimation in the test 4 kVA, 10 kVA and 15 kVA single phase transformers, considering a given load impedance. In this sense, to demonstrate the efficiency of the proposed algorithm, the HOA is compared with different optimization methodologies reported in the specialized literature, which include: particle swarm optimization (PSO) [15], genetic algorithm (GA) [15], imperialist competitive algorithm (ICA) [14], gravitational search algorithm (GSA) [14] and the black hole optimization algorithm (BHO) [20]. Besides, for the HOA developed in this work, 10 individuals are used in all the computational simulations, 1000 iterations and 100 consecutive evaluations, this latter with the objective of finding the best value, the average value and the worst value of the objective function. Likewise, the standard deviation is determined of the 100 solutions found and the average time taken by the algorithm to determine the parameters of the transformers under study.

The optimization model proposed in (1) to (17) has been implemented and solved in MATLAB version 2019b using own scripts in a personal laptop of MD Ryzen 7 3700U (AMD, Santa Clara, CA, USA), 2.3 GHz, 16 GB RAM with Windows 10 Home Single Language of 64-bits.

5.1. Results in the 4 kVA Test Transformer

The numerical results shown in Table 7 specify the following: the solution given by the proposed optimization algorithm finds the lowest average error respect to the real 4 kVA test single phase transformer parameters with an additional improvement of 0.7267% respect to the GSA, 4.8367% respect to the ICA, 5.8821% respect to the BHO, 9.9557% respect to the GA and finally, 18.7767% respect to the PSO. Notice that this error is due to the errors individually introduced for each parameter determined by the methodology proposed respect to the real value. However, the parameters found by the HOA tend to be the real parameters of the 4 kVA transformer if compared with the methodologies developed in the specialized literature.

Likewise, in Table 8 it is analyzed the performance of the HOA when computing the error between values of voltage and current measured at 4 kVA transformer terminals and the values obtained with the model T. The numerical results show the following: the solution given by the HOA is more accurate if compared with the different methodologies proposed in the specialized literature, obtaining an average error of 7.3860×10^{-7} %, overcoming the HBO with an average error of 8.1894×10^{-4}%, which implies that the methodology proposed is 1000 times better than the best methodology reported so far.

Table 7. Numerical results in the 4 kVA test transformer regarding estimated parameters.

Method	R_1 (Ω)	X_1 (Ω)	R_2' (Ω)	X_2' (Ω)	R_c (Ω)	X_m (Ω)	Average Error (%)
Actual	0.4	0.2	0.4	2	1500	750	-
PSO	0.5870	0.2554	0.2090	1.6020	1476	738	-
PSO error (%)	46.7500	27.700	47.7500	19.9000	1.6000	1.6000	24.2180
GA	0.5980	0.2260	0.3360	1.9570	1410	707	-
GA error (%)	49.5000	13.0000	16.0000	2.1500	6.0000	5.7330	15.3970
ICA	0.4300	0.2020	0.3940	2.5000	1200	700	-
ICA error (%)	7.5000	1.0000	1.5000	25.0000	20.0000	6.6670	10.2780
GSA	0.4250	0.2030	0.4150	2.3990	1426	750.3000	-
GSA error (%)	6.2500	1.5000	3.7500	19.9500	4.9330	0.6270	6.1680
BHO	0.4512	0.2492	0.3780	1.7016	1478.7763	684.8906	-
BHO error (%)	12.8199	24.6172	5.4908	14.9163	1.4149	8.6812	11.3234
HOA	0.4254	0.2017	0.3468	2.1945	1532.9038	748.2237	-
HOA error (%)	6.3607	0.8479	13.2822	9.7267	2.1936	0.2368	5.4413

Table 8. Numerical results in the 4 kVA test transformer regarding calculated and measured voltage and current variables.

Method	I_1 (A)	I_2' (A)	V_2' (V)	Average Error (%)
Actual	15.2825	15.0782	235.5967	-
PSO	15.3153	15.1172	236.2065	-
PSO error (%)	0.2148	0.2588	0.2588	0.2442
GA	15.1714	14.9574	233.7093	-
GA error (%)	0.7266	0.8011	0.8011	0.7763
ICA	15.2449	14.9881	234.1894	-
ICA error (%)	0.2457	0.5974	0.5974	0.4802
GSA	15.2088	14.9894	234.2087	-
GSA error (%)	0.4824	0.5891	0.5891	0.5535
BHO	15.2826	15.0783	235.5985	-
BHO error (%)	9.3413×10^{-4}	7.6134×10^{-4}	7.6134×10^{-4}	8.1894×10^{-4}
HOA	15.2825	15.0782	235.5967	-
HOA error (%)	2.9376×10^{-7}	9.6102×10^{-7}	9.6102×10^{-7}	7.3860×10^{-7}

To validate the effectiveness and robustness of the HOA and solve the proposed problem in this research document, it was performed 100 consecutive evaluations of the methodology proposed in the 4 kVA test system. The best solution found was 9.6672×10^{-17}, the average value was 1.4847×10^{-7}, and the worst value was 1.4847×10^{-7}, with an standard deviation of 2.6181×10^{-7} and an average processing time of 0.67 s, greatly improving the results obtained by the BHO in [20].

5.2. Results in the 10 kVA Test Transformer

The numerical results shown in Table 9 show the following: the solution given by the proposed optimization algorithm finds the lowest average error respect to the real parameters of the 10 kVA single phase transformer with an additional improvement of 0.4100% respect to the GSA, 0.8561% respect to the ICA, 5.4759% respect to the BHO, 6.4020% respect to the GA and finally, 14.7822% respect to the PSO. As happened with the case above, the parameters found with the HOA tend to be the same values of the real parameters of the 10 kVA transformer if compared with the methodologies developed in the specialized literature.

Table 9. Numerical results in the 10 kVA test transformer regarding estimated parameters.

Method	R_1 (Ω)	X_1 (Ω)	R_2' (Ω)	X_2' (Ω)	R_c (Ω)	X_m (Ω)	Average Error (%)
Actual	0.9	0.94	1.6	0.44	700	250	-
PSO	0.8110	0.8608	1.6780	0.7540	713	314.2000	-
PSO error (%)	9.8889	8.4255	4.8750	71.3636	1.8571	25.6800	20.3484
GA	1.0250	0.8000	1.5070	0.4930	651.5000	204.4000	-
GA error (%)	13.8889	14.8936	5.8125	12.0455	6.9286	18.2400	11.9682
ICA	0.8000	0.8000	1.5000	0.4259	692.48	255	-
ICA error (%)	11.1111	14.8936	6.2500	3.2045	1.0743	2.0000	6.4223
GSA	0.8001	0.8119	1.5004	0.4236	695.5400	251.3500	-
GSA error (%)	11.1000	13.6277	6.2250	3.7273	0.6371	0.5400	5.9762
BHO	0.9430	1.0340	1.5350	0.6240	698.6760	263.5120	-
BHO error (%)	4.7778	10.0000	4.0625	41.8182	0.1891	5.4048	11.0421
HOA	0.8056	0.8723	1.7075	0.4718	702.7584	253.3966	-
HOA error (%)	10.4912	7.2038	6.7171	7.2326	0.3941	1.3586	5.5662

Moreover, in Table 10 it is analyzed the performance of the HOA developed when computing the error between the voltage and current measured at the 10 kVA test transformer terminals and the values computed from the model T. The numerical results show that: the solution provided by the HOA is more accurate if compared with the other methodologies proposed by the specialized literature, obtaining an average error of 4.4252×10^{-7} overcoming the HBO with an average error of 0.0033%, which implies that the methodology proposed is 10000 times better than the methodology reported so far.

Table 10. Numerical results in the 10 kVA test transformer regarding calculated and measured voltage and current variables.

Method	I_1 (A)	I_2' (A)	V_2' (V)	Average Error (%)
Actual	18.8877	18.0722	451.8047	-
PSO	18.8719	18.0906	452.2639	-
PSO error (%)	0.0836	0.1016	0.1016	0.0956
GA	18.9683	18.0472	451.1802	-
GA error (%)	0.4264	0.1382	0.1382	0.2343
ICA	19.0427	18.2217	455.5431	-
ICA error (%)	0.8208	0.8274	0.8274	0.8252
GSA	19.0405	18.2196	455.4897	-
GSA error (%)	0.8089	0.8156	0.8156	0.8134
BHO	18.8883	18.0728	451.8202	-
BHO error (%)	0.0032	0.0034	0.0034	0.0033
HOA	18.8877	18.0722	451.8047	-
HOA error (%)	4.4461×10^{-7}	4.4148×10^{-7}	4.4148×10^{-7}	4.4252×10^{-7}

To validate the effectiveness and robustness of the HOA and solve the proposed problem in this research document, it was performed 100 consecutive evaluations of the methodology proposed in the 10 kVA test system. The best solution found was 2.9374×10^{-17}, the average value was 9.5375×10^{-7}, and the worst value was 8.6619×10^{-6}, with an standard deviation of 1.5561×10^{-6} and an average processing time of 0.66 s, greatly improving the results obtained by the BHO in [20].

5.3. Results in the 15 kVA Test Transformer

The numerical results in Table 11 show the following: the solution provided by the proposed optimization algorithm finds the lowest average error respect to the real parameters of the 15 kVA single phase transformer with an additional improvement of 0.3714% respect to GSA, 3.7788% respect to BHO, 4.9433% respect to ICA, 5.8538% respect to GA and finally, 7.0963% respect to PSO. As happened with previous case, the parameters found with the HOA tend to be the same values of the real parameters of the 15 kVA transformer if compared with the methodologies developed in the specialized literature.

Table 11. Numerical results in the 15 kVA test transformer regarding estimated parameters.

Method	R_1 (Ω)	X_1 (Ω)	R'_2 (Ω)	X'_2 (Ω)	R_c (Ω)	X_m (Ω)	Average Error (%)
Actual	2.45	3.14	2	2.2294	105000	9106	-
PSO	2.2500	4.0820	2.2000	1.8526	99517	9009	-
PSO error(%)	8.1633	30.0000	10.0000	16.9014	5.2219	1.0652	11.8920
GA	2.7600	3.4140	1.6800	1.8460	97001	8951	-
GA error (%)	12.6531	8.7261	16.0000	17.1975	7.6181	1.7022	10.6495
ICA	2.0000	3.0000	1.8000	2.0000	120000	9200	-
ICA error (%)	18.3673	4.4586	10.0000	10.2898	14.2857	1.0323	9.7390
GSA	2.0000	3.1100	1.8100	2.2600	104281	9094.87	-
GSA error (%)	18.3673	0.9554	9.5000	1.3726	0.6848	0.1222	5.1671
BHO	2.4268	3.9150	1.9807	2.6700	10,3891.2660	9473.4020	-
BHO error (%)	0.9469	24.6815	0.9650	19.7632	1.0559	4.0347	8.5745
HOA	2.4725	2.6797	1.9971	2.3891	10,7640.4347	8798.7411	-
HOA error (%)	0.9197	14.6601	0.1436	7.1617	2.5147	3.3742	4.7957

Moreover, in Table 12 it is analyzed the performance of the HOA developed when computing the error between the voltage and current measured at the 15 kVA test transformer terminals and the values computed from the model T. The numerical results show that: the solution provided by the HOA is more accurate if compared with the other methodologies proposed by the specialized literature, obtaining an average error of 3.4822×10^{-8} overcoming the HBO with an average error of 1.5204×10^{-5} %, which implies that the methodology proposed is 1000 times better than the methodology reported so far.

To validate the effectiveness and robustness of the HOA and solve the proposed problem in this research document, it was performed 100 consecutive evaluations of the methodology proposed in the 15 kVA test system. The best solution found was 1.8318×10^{-19}, the average value was 2.0747×10^{-10}, and the worst value was 3.6490×10^{-9}, with an standard deviation of 2.0748×10^{-10} and an average processing time of 0.67 s, greatly improving the results obtained by the BHO in [20].

The results previously obtained in the 4 kVA, 10 kVA and 15 kVA single phase transformers, demonstrate the superiority of the methodology proposed to obtain the solution of the problem under study respect with the best value of the objective function, average error respect with the measured values and the computational processing time if compared with the methodologies exposed in the specialized literature. This confirms the repeatability properties of the HOA to solve the problem posed in this research work, as if executed multiple times for the test transformers under study, the developed method will generate the best average outcome or at least a very close value.

Table 12. Numerical results in the 15 kVA test transformer regarding calculated and measured voltage and current variables.

Method	I_1 (A)	I_2' (A)	V_2' (V)	Average Error (%)
Actual	6.2053	6.1756	2371.4165	-
PSO	6.2056	6.1748	2371.1131	-
PSO error (%)	0.0057	0.0128	0.0128	0.0104
GA	6.2070	6.1755	2371.3903	-
GA error (%)	0.0278	0.0011	0.0011	0.0100
ICA	6.2128	6.1861	2375.4788	-
ICA error (%)	0.1207	0.1713	0.1713	0.1545
GSA	6.2157	6.1858	2375.3439	-
GSA error (%)	0.1685	0.1656	0.1656	0.1666
BHO	6.2053	6.1756	2371.4169	-
BHO error (%)	1.5501×10^{-5}	1.5055×10^{-5}	1.5055×10^{-5}	1.5204×10^{-5}
HOA	6.2053	6.1756	2371.4165	-
HOA error (%)	3.0677×10^{-8}	3.6895×10^{-8}	3.6895×10^{-8}	3.4822×10^{-8}

5.4. Complementary Analysis and Discussion

This section shows the effectiveness of the electric parameters estimation in single phase transformers, modeled with the model T, using a metaheuristic optimization technique such as the HOA. To demonstrate that the errors found by the methodology proposed for the single phase transformers are negligible when compared with the real values (see Tables 7, 9 and 11), it is computed the voltage regulation and the efficiency of each test transformer, when there is a variation of the resistive load connected at secondary terminals of the transformers from 50% to 150% of their nominal value.

Voltage regulation (VR) for a single phase transformer referred to the primary side, as shown in model T in Figure 1, is computed as depicted in (25), which can be found at [30]:

$$VR_{\%} = 100 \cdot \frac{|v_1| - |v_2'|}{|v_2'|} \tag{25}$$

The efficiency (η) of a single phase transformer is computed as shown in (26), which can be found at [30]:

$$\eta_{\%} = 100 \cdot \frac{P_{out}}{P_{in}} = 100 \cdot \frac{\text{real}(v_2' i_2'^{*})}{\text{real}(v_1 i_1^{*})} \tag{26}$$

where P_{in} and P_{out} represent the active power at primary and secondary sides terminals of the transformer, respectively. In Figure 2, Figure 3 and Figure 4, it is shown a comparison between the voltage regulation and efficiency, for the test single phase transformers of 4 kVA, 10 kVA and 15 kVA, respectively, with the parameters determined by the HOA proposed and the real parameters of the transformer.

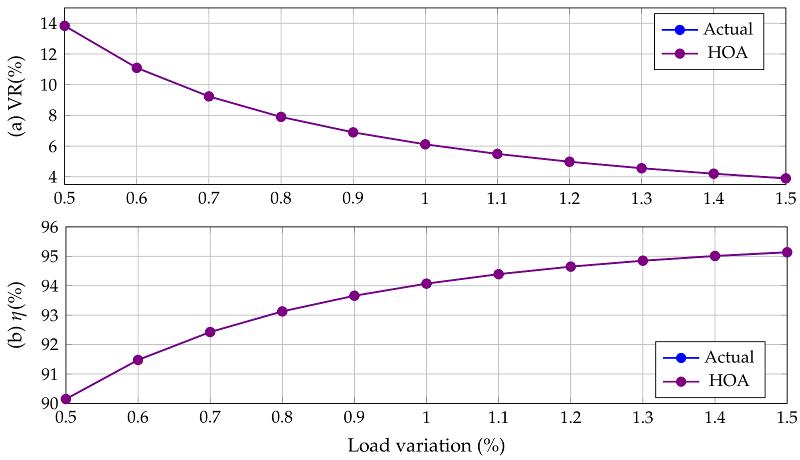

Figure 2. Behavior of the 4 kVA test transformer with load variations: (**a**) Voltage regulation and (**b**) Efficiency.

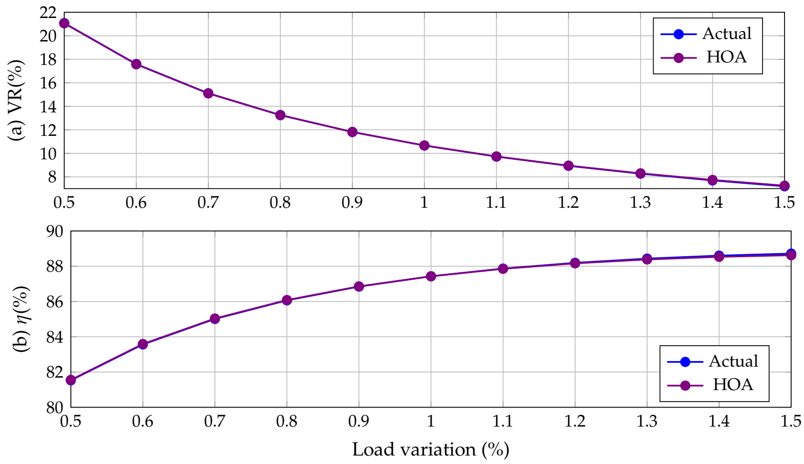

Figure 3. Behavior of the 10 kVA test transformer with load variations: (**a**) Voltage regulation and (**b**) Efficiency.

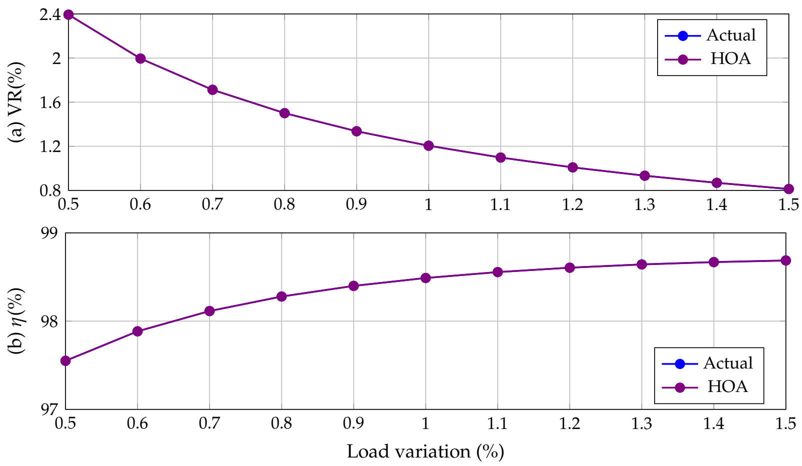

Figure 4. Behavior of the 15 kVA test transformer with load variations: (**a**) Voltage regulation and (**b**) Efficiency.

From the figures previously shown it can be concluded the following:

✓ Installing a load impedance of 50% of the nominal value in the secondary side of the test transformers implies different values of voltage regulation, being these of

13.8498%, 21.0785% and 2.3925%, for the 4 kVA, 10 kVA and 15 kVA transformers, respectively. This behavior in the voltage regulation is explained as follows: if the terminals voltage at the primary side is kept and the load impedance is reduced, the current absorbed by the transformer is increased, making higher the voltage drop in the series branch, with a decrease in the voltage at secondary side of the transformer. This causes high percentages of voltage regulation.

✓ Likewise, the efficiency of the transformer when the load impedance is 50% of the nominal value, presents the following values: 90.1236%, 81.5310% and 97.5516%, for the 4 kVA, 10 kVA and 15 kVA transformers respectively. This is due to the absorption of the current, as the windings of the transformer dissipate a larger power, making higher the input power. This causes low percentages of transformer efficiency.

✓ As the load impedance is increased the voltage regulation is decreased, reaching its minimum value when the load impedance presents a value of 150% respect to its nominal value being these 3.8812%, 7.2295% and 0.8170%, for the 4 kVA, 10 kVA and 15 kVA transformers, respectively. Notice that, if the voltage at the primary side terminals is constant, and as the power consumed at the secondary side is increased, the current drawn by the transformer is reduced, causing a reduction of the voltage drop in the series branch of the transformer and consequently, a lower voltage value at the secondary side terminals of the transformer and, low voltage regulation percentages.

✓ By the other side, as the load impedance is increased, the efficiency is also increased, reaching its maximum value when the load impedance presents a value of 150% respect to its nominal value, being these of 95.1625%, 88.6610% and 98.6793%, for the 4 kVA, 10 kVA and 15 kVA, respectively.

✓ Finally, from Figures 2–4, it can be observed that the voltage regulation and efficiency behavior are the same for the parameters estimated by the HOA proposed and the real parameters of the 4 kVA, 10 kVA and 15 kVA transformers. Besides, it is determined that the maximum error between the data acquired for voltage regulation is 0.2939% for a load condition of 150% in the 4 kVA transformer, 0.2951% for a load condition of 150% in the 10 kVA transformer and 0.4153% for a load condition of 150% in the 15 kVA transformer. The maximum error in the results obtained for efficiency is 0.0223% for a load condition of 50% in the 4 kVA transformer, 0.0399% for a load condition of 150% in the 10 kVA transformer and 0.0067% for a load condition of 150% in the 15 kVA transformer. This confirms that, from the circuit and mathematical point of view (i.e., voltage, current and power computed), the developed HOA is a suitable method to solve the problem of parameters estimation in single phase transformers with errors less than 1×10^{-5}%.

6. Conclusions and Future Works

The problem of the parametric estimation in single-phase transformers was addressed in this research through the application of the hurricane optimization algorithm. The mathematical formulation of the studied problem was based on the minimization of the mean square error between the measured and calculated electrical variables (i.e., input/output voltages and currents), which was subject to Kirchhoff's laws applied to the equivalent electrical circuit of single-phase transformers represented with the T-model. Numerical results showed that the objective function found for all the three transformers analyzed was less than 1×10^{-16}, which implies that the HOA algorithm ensures a high-quality solution with the low computational effort since the average processing times were less than 700 ms. The main characteristic of the obtained solutions is that these are different from the literature reports; however, with respect to the objective function value, these are near to the global optimum, and these confirm that the studied problem has multiple high-quality solutions becoming the proposed HOA as the reference method in the current literature to solve the problem of parametric estimation in single-phase transformers.

In regards with the average error found, when comparing each of the transformer parameters, obtained by the different optimization methodologies, with the real values, the HOA took the first place overcoming the GSA, ICA and the BHO. In the same manner, this method presents high accuracy when it is compared with the values of voltage and current measured and computed at terminals of test single phase transformers, with average errors less than 1×10^{-7}%, which is better than the results obtained so far with the different metaheuristic techniques exposed in the specialized literature, that were used with comparison purposes in this research work.

Numerical results in the studied test transformers showed that utility companies can update its electrical diagrams for simulations and planning purposes by considering only current and voltage measures in terminals of the transformer without interfering with the continuity of the electrical service (i.e., quality indexes). In addition, the information on the parameters of the transformers will help to identify incipient faults on these devices such as isolation deterioration, unusual temperature increments, as well as, measure the global efficiency performance of the transformer.

For future works, it is possible to examine and potentially address the following: (i) solve the problem under study with new high numerical performance metaheuristic methods such as the vortex search algorithm, salp swarm optimization algorithm, or black widow algorithm, among others; (ii) formulate the problem of single phase transformer parameters estimation when more than one measurement of voltage, current and input/output power is used; (iii) extend the current approach to the parameters estimation of three phase transformers considering the Y and Δ winding connections.

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