In Situ Parameter Estimation of Synchronous Machines Using Genetic Algorithm Method

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Abstract. *The paper presents an in situ parameter estimation method to determine the equivalent circuit parameters of the Synchronous Machines. The parameters of synchronous generator, both cylindrical rotor and salient pole rotor, are estimated based on the circuit model. Genetic algorithm based parameter estimation technique is adopted, where only one set of in-situ measured load test data is used. Conventional methods viz., EMF, MMF, Potier triangle method uses rated voltage and rated current obtained from more than one operating condition to determine the parameters. However, Genetic Algorithm (GA) based method uses the working voltage and load current of a single operating point obtained from in-situ measured load test data, i.e. without isolation or disturbing the normal operating condition of the machine to estimate the parameters. The test results of the GA-based parameter estimation method are found to be closer to direct load test results and better than conventional methods.*

Keywords

Equivalent circuit model, genetic algorithm, parameter estimation, synchronous machines.

1. Introduction

The alternator, synchronous motor and synchronous converter belong to the classification of Synchronous Machines (SM). Alternators are widely used in the power generation; synchronous motor is used for power factor correction and various other applications. Determination of its parameters is useful in performance computations, power system load flow studies, power factor correction, and prediction of rise in winding temperature and health of alternator. In recent years, there is an interest in the modeling and estimation of SM parameters. The need for such parameter estimation arises because generator parameters and performance values computed from pre-determination methods tend to deviate substantially from design values and hence unreliable. The present paper addresses this problem using genetic algorithm method for parameter estimation of the synchronous machines. It could be applied to various power generation units for close monitoring of the machine performance.

This paper starts with the discussion of prior research in Section 2. and then the approach for solution showing the equivalent circuits of the synchronous machine considered are detailed in Section 3. Section 4. deals with the state-of-the-art and other conventional techniques to estimate parameters of both the cylindrical rotor and salient pole machines and Section 5. explains the parameter estimation using genetic algorithm technique, and finally, the results are discussed in Section 6.

2. Related Work and Prior Research

Several methodologies were applied to determine the impedance parameters of SM. Le and Wilson, [1], used a time-domain method for the identification of synchronous-machine equivalent-circuit parameters using on-line measurements obtained while the machine is operating under normal conditions and is perturbed by a small disturbance. The advantage of this method is that only linear optimization techniques are required to determine the machine parameters, and therefore convergence is guaranteed. Fairbairn and Harley, [2], estimate the electrical parameters online using an Extended Kalman Filter (EKF) but found the method is computationally intensive and noise sensitive for higher order models. Viarouge et al., [3], modeled and identifies Permanent Magnet SM parameters from Standstill Time Response Tests using a non-linear method on a small scaled SM and the results clearly show a good representation of the dynamic behavior of the machine over an extended frequency range. Touhami et.al, [4], proposed a novel method of parameter identification based on the frequency responses, where the SM is at standstill and supplied by voltage Pseudo-Random Binary Sequences (PRBS) and the parameters are estimated by auto regression. The estimation and tracking of SM parameters from time domain online disturbance measurements [5] (Longya Xu et al.) were based on a Novel Adaptive Algorithm using Artificial Neural Networks (ANN) Observers. Some of the researchers [6] (Pillutla et al.) had addressed the issue of estimating parameters instantaneously and processing data subsequently, where parameters are ultimately expressed as non-linear functions of operating conditions. Verbeeck J. et al., [7], used network synthesis techniques in determining the parameters of SM and came to a conclusion that only a limited number of parameters can be determined in a unique way from two-port information. Hatziargyriou N. D. et.al, [8], used constrained optimization techniques for parameter identification using real measurements under specific operating conditions. Bortini and Jardini, [9], used load rejection test data for determining the parameters. Karrari and Malik, [10], estimated the SM parameters from online measurements using the relations of the Heffron-Phillips parameters with the physical parameters. The studies carried out by M. A. Arjona and D. C. MacDonald, [11], describe reactance over the whole processing region of the machine, it presents saturation as a function of the air gap ampere–turns which shows that complicated relationship exists at leading power factors, making such relationship unseless. Sellschopp and Arjona., [12], determined the parameters using Standstill Frequency Response (SSFR) Tests. Huang et al., [13], used a novel line-to-line voltage perturbation technique for online measurement of SM parameters and showed that it is possible to obtain the full set of four complex small signal impedances of the synchronous machine d–q model over a wide frequency range. Underwood and Husain., [14], successfully used two recursive least square algorithm segments, a fast and slow one to estimate all four machine parameters. Arjona et al., [15], applied sine cardinal perturbations, for estimating the parameters of the electrical d-q axis equivalent circuits of a synchronous generator, the fundamental parameters of the SM are obtained using GA. Valverde and Heydt, [16], used non-linear parameter estimation for synchronous machines based on the unscented Kalman-filter, Zivanovic [17], proposed a parameter estimation algorithm based on multi-variate polynomial systems by reformulating least-squares estimation, Gatto et al., [18], proposed a novel online discrete time parameter estimation algorithm for surface mounted permanent magnet SM; Liu et al., [19], proposed a technique to estimate parameters under constant load torque; Cisneros-Gonzalez et al., [20], estimated parameters of a two-axis salient-pole SM based on standstill chirp test; Mukherjee et al., [21], proposed an economical method to estimate parameters based on a-b-c reference frame theory; Perez et al., [22], estimated parameters based on current decay test and particle swarm optimization; Liu et al., [23], proposed a position offset based parameter estimation for SM.

All the above mentioned involve computationally complex and tedious models. Alternatively, conventional methods for parameter estimation viz. both EMF and MMF methods uses rated voltage and rated current, which are obtained from two different operating conditions, to determine the parameters. They are said to be pessimistic and optimistic methods as the results deviate much from the actual results obtained from direct load tests results. Potier triangle method [24] is comparatively better than EMF and MMF method but still uses test data obtained from three different tests, viz. open circuit test, short circuit test and zero power factor test. Moreover, the machine parameters, particularly armature reactance (X_a), tends to vary due to change in load conditions, which are not reflected in conventional methods. This paper deals with the issue of parameter estimation of synchronous machines based on its equivalent circuit models and using its in-situ measured load test data. Genetic Algorithm (GA) has been used to estimate the parameters where the parameters could be estimated for different loading conditions by maximizing a simple objective function derived from the equivalent circuit model of the synchronous generator. The concepts and structure of GA is based on the book [25], the suggested method uses working voltage and load current measured in-situ from direct load test data to estimate the parameters, without interrupting the machine operation.

3. Approach for Solution

The simple equivalent circuit model of Cylindrical Rotor (CR) synchronous generator is shown in Fig. 1 whereas Fig. 2 shows its expanded form. Conventional pre-determination methods such as EMF method, MMF method, and D.C resistance test method are used to determine the equivalent circuit parameters such as armature resistance and synchronous reactance (X_s) and hence their performance, viz. regulation and efficiency. However, the Potier triangle method provides better information as it separates leakage reactance (X_l) and field excitation corresponding to armature reaction.

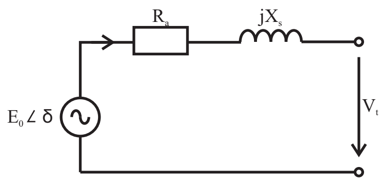

Fig. 1: Simple equivalent circuit model of SM.

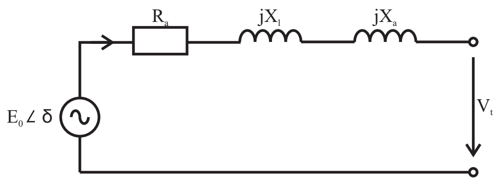

Fig. 2: Equivalent circuit of CR alternator.

In case of Salient-Pole (SP) machine synchronous reactance consist of the parameters namely X_{sd} and X_{sq}, as shown in Fig. 3, which could be measured using slip test. This paper considers exact equivalent circuit models for the CR machine and the SP machine as shown in Fig. 2 and Fig. 3 respectively.

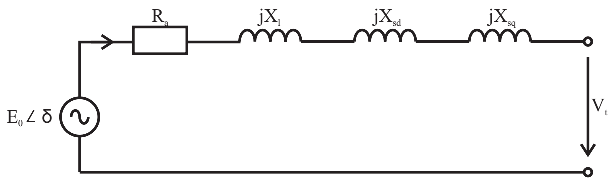

Fig. 3: Suggested equivalent circuit of SP alternator.

Estimation of the series branch parameters of the equivalent circuit such as R_a, X_l and X_a for cylindrical rotor and R_a, X_l, X_{sd} and X_{sq} for salient pole rotor in Fig. 2 and Fig. 3 respectively with good degree of accuracy is important as they have direct bearing on the performance of computation that is efficiency, voltage regulation, rise in winding temperature etc. However, the parameters determined from the conventional methods uses the test dat,a viz. open circuit test, short circuit test, zero power factor test, DC resistance test for CR machine and slip test for SP machine in which the test conditions vary widely from actual load condition of the machine.

Therefore it is clear that the parameters computed from these Pre-determination methods tend to vary with its actual values as operating conditions are different. Moreover, the machine is to be interrupted from its operating condition.

In the background of above facts, it would be desirable to determine the parameters and the performance of synchronous machines with the help of test data obtained at the actual load conditions. Further, it is also desirable to determine the parameters from just one shot of load test data, which will exactly reflect the actual operating conditions inside the machine.Therefore it is proposed to estimate all the parameters shown in Fig. 2 and Fig. 3 with only one set of test data, obtained from actual load conditions to get rid of too many tests conducted under different supply conditions. This paper uses the Genetic Algorithm (GA) which adopts a parallel search optimization technique that helps in obtaining the best fit of equivalent circuit parameters from its search space. The suggested methodology uses the in-situ measured signals from the load test and applies it on an appropriate objective function that is defined based on the equivalent circuit models shown in Fig. 2 and Fig. 3. Then the objective function is to be maximized to estimate the parameters using GA. The results of GA-based parameter estimation technique is compared with the results of one of the better conventional methods, viz. Potier triangle method and Slip test for the computation of the parameters of the CR and SP machines respectively. The suggested GA-based parameter estimation methodology maximizes an objective function that is derived from the equivalent circuit models. The objective functions used for parameter estimation are discussed in Section 4.

4. Parameter Estimation of SM using Potier Triangle Method and Slip Test

Many methods are available for determining the parameters of alternator (SM) and for pre-determination of regulation. They are EMF method, MMF method, Potier triangle method, ASA method. However the Potier triangle method is comparatively better than EMF and MMF method as it separates leakage reactance and armature reactance from the total synchronous reactance value. Therefore potier triangle method is considered for determination of synchronous impedance parameters R_a, X_l and X_a for Cylindrical Rotor (CR) type alternator. The slip test is considered for the determination of direct axis (X_{sd}) and quadrature axis (X_{sq}) synchronous reactance of Salient-Pole (SP) alternator.

4.1. Potier Method for CR Alternator

The Potier triangle method considers Armature reaction effect as the MMF drop and leakage reactance (X_l) as the EMF drop. It requires three tests namely, Open Circuit (OC) test, Short Circuit (SC) test and the Zero Power Factor (ZPF-lagging) test. Referring to Fig. 4, for the OC test, this method does not impose linearity. From OC test, Open Circuit Characteristic (OCC) curve is drawn. From SC test data and ZPF test data.

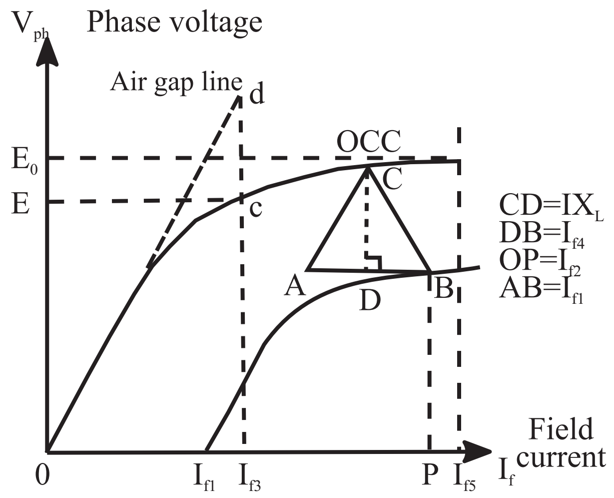

Fig. 4: Potier triangle method.

A ZPF characteristic is drawn as shown in Fig. 4, where in the ZPF test:

- Armature current is kept constant at the rated value I_a (rated).
- The pure inductive load is varied along with the excitation to rated load condition to obtain ZPF characteristics.
- Only two readings are enough to draw this ZPF characteristics. First is corresponding to short circuit conditions ($V_t = 0$; $I_a = I_a$ (rated)) and the second point is corresponding to full load conditions at Zero-Power Factor (ZPF) (V_t (rated) $=$ V_{OC}; $I_a = I_a$ (rated) at ZPF).

The Potier triangle is denoted by the triangle ABC as shown in the Fig. 4. In the Potier triangle method:

- The leakage reactance (X_l) is assumed to be constant, since the EMF drop I_aX_l is constant for the given armature current, which is normally kept at rated value.
- Since I_a is kept at the rated value, the armature reaction MMF is going to be constant.

From Fig. 4, the vertical distance CD gives the EMF drop due to leakage reactance I_aX_l and the horizontal distance BD gives MMF drop due to armature reaction. Since the EMF and MMF drops are going to be the same for all excitations, the triangle ABC can be moved along the OCC curve to fully trace the ZPF characteristics. Since the initial part of the OCC is almost linear the triangle ABC can be moved along OCC curve to locate the point C on OCC. Since the point C is located, the value (I_a(rated)$*X_l$) can be determined and so the value of X_l is determined. Since the point C is known as the Armature reaction drop, from this value K_{ar} is determined, which is the proportionality constant (MMF drop per unit armature current).

The vector equation for the synchronous machine in general is:

$$\vec{F_r} = \vec{F_f} + \vec{F_{ar}}. \tag{1}$$

Since armature reaction is demagnetizing, for ZPF (lagging) load vector equation becomes simple algebraic equation:

$$\vec{F_r} = \vec{F_f} - \vec{F_{ar}}. \tag{2}$$

F_r contributes for the induced voltage E_r. There is a need to find F_{ar} for a given armature current I_a i.e., the proportionality constant K_{ar} have to be determined. Assuming the resistance to be negligible then:

$$V_t = E_r - I_aX_l. \tag{3}$$

From Eq. (3), X_l value is to be determined. Using BD, the open circuit EMF is computed and hence regulation is determined. Although Potier triangle method method seems to be better than EMF and MMF method, it is not exact because of the following implicit assumptions made:

- R_a is assumed negligible.
- Power factor of the inductors used for conducting ZPF test would be different from zero.
- It is assumed that X_l as constant for all load conditions which may not be true. Point B corresponds to high excitation i.e. machine operates almost in the saturated region and hence high leakage inductance X_l. I_{fl} corresponds to less excitation i.e. operates in the linear region and less leakage. Less leakage for a given field current leads to lesser inductance and hence lesser value of X_l.
- The field current I_{f1} corresponds to less excitation i.e. machine operates in the linear region and less leakage, which leads to smaller value X_l.
- It is assumed X_a is constant. But under changes in load condition, the armature reaction also changes leading to change in armature reactance. This brings in the need to draw many Potier triangles for different load conditions.

4.2. Slip Test for SP Alternator

Determination of X_{sd} and X_{sq} of Salient-Pole (SP) Alternator; Cylindrical rotor theory is not applicable for salient pole alternators where Blondel's two-reaction theory is applied to determine the parameters. As per this theory, armature current I_a can be resolved into two components, i.e. I_d perpendicular to E_0 and I_q

along E_0. Armature reactance has two components namely d-axis armature reactance X_{ad} associated with I_d and q-axis armature reactanceX_{aq} linked with I_q, where:

$$X_{sd} = X_{ad} + X_l, \quad (4)$$

$$X_{sq} = X_{aq} + X_l. \quad (5)$$

For determining X_{sd} and X_{sq} slip test is to be conducted on the SP machine, and is calculated as follows:

$$X_{sd} = \frac{\frac{V_{\max}}{ph}}{I_{\min}}, \quad (6)$$

$$X_{sq} = \frac{\frac{V_{\max}}{ph}}{I_{\max}}. \quad (7)$$

From all the above methods the values of V_a, X_s, X_{sd}, and X_{sq} are obtained. Therefore, for cylindrical rotor machines the parameters X_l, X_a, R_a, are determined. Then for salient pole synchronous machine X_{sd}, X_{sq}, R_a are determined from pre-determination tests. Using the parameters obtained the open circuit voltage (E_0) is computed. Using the results obtained in both the CR and SP alternators the voltage regulation is computed as:

$$\%R = \frac{E_0 - V_t}{V_t}. \quad (8)$$

5. Suggested Methodology - Genetic Algorithm Based Parameter Estimation

Genetic Algorithm (GA) is a robust and global optimization technique applied further in the present parameter estimation problem. Although the fundamentals of GA could be obtained from Goldberg (1989), [25], a brief introduction to the design of GA structure and its application are presented here.

5.1. The GA Methodology and Structure

1) Problem Representation

Binary coded GA was reported to be giving considerable error in parameter estimation in view of the large difference in magnitude between different variables in a similar equivalent circuit structure of transformers, that is induction motors [26] (Pillay et al., 1998). To alleviate this problem the real coded GA [27] (Eshelman and Schaffer, 1992) is applied in the present work, where genetic processing is done variable by variable separately. Moreover, the parameters of the exact equivalent circuit model in Fig. 3 are floating point values. Therefore each individual parameter is represented as a vector of floating point numbers, with values within the corresponding variable's upper and lower bounds, as given by:

$$P_1, P_2, P_3, P_4, \ldots, P_n. \quad (9)$$

Similarly, every other individual variable is represented as a vector of real values within their own upper and lower bounds. The fitness of every individual is evaluated with the help of the objective function.

2) Initialization of the Population

GA requires the initialization of the population. The population size depends on the nature of the problem using a uniform random number distribution each one of the individuals is initialized within the chosen range of the variables.

3) Evaluation Function

GA searches for the optimal solution by maximizing a given fitness function. Therefore, an evaluation function, which provides a measure of the quality of the problem's solution, must be provided. In the presented problem, the objective function given by Eq. (21) is considered as the evaluation function. There are no constraints in this problem other than the bounds on the variables. Since GA maximizes the fitness function (ff), the minimization of the objective function (f_{obj}) is transformed into maximization of the fitness function:

$$\max(ff) = \frac{k}{f_{obj}}, \quad (10)$$

where k is a large constant.

4) Selection Strategy

The selection of parents to produce successive generations plays an important role in the GA. The goal is to allow the fittest individuals to be selected more often to reproduce and to achieve this tournament selection strategy is used. In tournament selection, n individuals are selected in random from the population and the best of the n is reproduced for the new population to participate in further genetic processing. This procedure is repeated until the mating pool is filled. In the present method tournaments are held between pairs of individuals, although larger tournaments can be used.

5) Crossover Operation

Crossover operation is a mixing operator that combines genetic material from selected parents. In the present case it is done variable by variable. Based on the theory of schemata the blend crossover operator (BLX-a) is employed in the present investigation. For the values of P_{ij} and P_{ik}, of the variable P_i of Eq. (9) in the parents j and k, this operator creates a new point uniformly at random from a range extending by an amount of $|P_{ij} - P_{ik}|$ on either side of the region bounded by two parents.

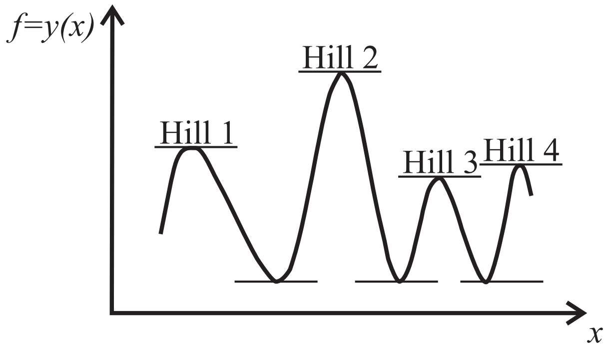

Fig. 5: Multimodal function.

6) Mutation Operation

Mutation acts as a background operator and is used to search the unexplored search space by randomly changing the values. The present work uses uniform mutation operation where a variable is selected from an individual randomly and set to a uniform random number between lower and upper limit.

7) Necessity for using GA

The results obtained from the predetermination methods confirm that the estimation of parameters of alternators are not straight forward. This is because the parameters, as said before, are highly non-linear, largely different in magnitude and hence their solution space is 'Multimodal' in nature. Therefore a powerful technique to provide global optimal solutions is preferable to address this problem. In the present problem, the function is multimodal. For example:

$$Z_s = \sqrt{R_a^2 + X_s^2}, \tag{11}$$

the synchronous impedance Z_s is dependant upon two variables n amely X_s and R_a. It can be easily seen that more than one value of X_s and R_a satisfies the above equation. Hence solution space is Multimodal. If the function is single-peak or unimodal, calculus based search methods is enough for estimation of the parameter. Since the function is Multimodal in nature we require a powerful optimization technique like GA Multimodal function is a function having a large number of local maxima and local minima.

The multiple-peak function (refer Fig. 5) causes a dilemma about which hill to climb. GA search algorithm starts looking at objective function values at every point in the space, one at a time. So GA looks at the values of the given objective function at every point in space and hence has a wider approach. In this way, GA finds safety in number. By maintaining a population of well-adopted sample points, the probability of reaching a false peak is reduced.

The GA-based parameter estimation method for both CR and SP synchronous machines is discussed in the following Subsection 5.2. and Subsection 5.3. respectively. Based on these methods, the parameters are estimated and their results are compared with the results obtained from conventional methods. GA-based parameter estimation for the CR machines and the SP machines are dealt independently.

5.2. Parameter Estimation for Cylindrical Rotor (CR) Machine using GA

A 5 KVA, 415 V, 50 Hz, I500 RPM, three-phase, Cylindrical Rotor (CR) alternator is considered as the first case study. The objective function for the GA-based parameter estimation for the CR generator is obtained as follows. The known values from the load test are:

$$E_0 = V_t - I \cdot Z_s, \tag{12}$$

where:

$$Z_s = \sqrt{R_a^2 + X_s^2}. \tag{13}$$

Let, E_0 in the Eq. (12) be called as E_{0-est1} and can be written as:

$$E_{0-est1} = V_t + I_a \cdot \sqrt{R_a^2 + X_s^2}, \tag{14}$$

$$P_{out} = V_t \cdot I_a \cdot \cos\phi, \tag{15}$$

$$P_{in} = \left(\frac{P_{out}}{3} + I_a^2 \cdot R_a\right) \tag{16}$$

In real synchronous machines of any size, the armature resistance $R_a << X_s$ and, therefore, the armature resistance can be ignored, which gives:

$$P_{in} = \frac{E_0 \cdot V_t}{X_s \cdot \sin\delta}, \tag{17}$$

where:

$$X_s = X_a + X_l. \tag{18}$$

From Eq. (16) and Eq. (17),

$$\frac{E_0 \cdot V_t}{X_s \cdot \sin\delta} = \left(\frac{P_{out}}{3} + I_a^2 \cdot R_a\right), \quad (19)$$

$$E_{0-est2} = \left(\frac{P_{out}}{3} + I_a^2 \cdot R_a\right) \cdot \frac{X_s}{V_t} \sin\delta, \quad (20)$$

$$f_{obj} = E_{0-est1} - E_{0-est2}, \quad (21)$$

$$\max(ff) = \frac{k}{f_{obj}}. \quad (22)$$

Equation (21) is the required objective function that needs to be minimized or in other words Eq. (22) is the fitness function that needs to be maximized for CR Alternator. Thus the GA uses only two equations, Eq. (14) and Eq. (20) and estimates *four unknown variables* namely X_a, X_l, δ, and R_a, with its parallel search technique in its search space.

The test results of Potier triangle method viz., OC, SC, ZPF and DC resistance tests of the CR synchronous generator are shown in Tab. 1, Tab. 2, Tab. 3 and Tab. 4. Table 5 provides the direct load test data that is used for the GA-based parameter estimation of CR alternator. The equivalent circuit parameters and performance computation results of both the conventional and GA-based methods are given in Tab. 6.

The GA method uses only one set of values available from the load test data, as given in the Tab. 5, to estimate the equivalent circuit parameters by applying them in the maximization of fitness function given in Eq. (22). In this method, 175 individuals participate in the tournament of every generation. At the end of 200 generations and when error tolerance is less than 1% of f_{obj} (i.e. difference between E_{0-est1} and E_{0-est2}) is reached, it is considered to be the solution. The probability of crossover P_c is set at 0.7 and the probability of mutation P_m at 0.001. Table 6 gives the parameters and performance computation estimated using GA and the results are compared with the conventional method and direct load test. From Tab. 6, it can be observed that the GA-based performance estimate is much closer to computed values from direct load test. Further, the estimated leakage reactance (X_l) using GA is found to be smaller than armature reactance (X_a), as against the one determined using Potier triangle method which provides over-optimistic and contrary results. This result is justified and correct as always the leakage reactance voltage drop is much less compared to armature reaction reactance voltage drop. Therefore the estimated parameters obtained from GA-based estimation are more appropriate with respect to the equivalent circuit model under consideration.

Tab. 1: Open circuit test data of CR alternator using 415 V, 50 Hz supply.

S. No.	Field current (I_f) in Amps	Phase Voltage (V_{ph}) in Volts
1	0.0	0.000
2	0.1	72.168
3	0.2	127.01
4	0.3	168.58
5	0.4	192.25
6	0.5	207.85

Tab. 2: Short circuit test data of CR alternator using 415 V, 50 Hz supply.

S. No.	Field current (I_f) in Amps	Short circuit current (I_{SC}) in Amps
1	0.05	0.5
2	0.10	1.4
3	0.15	2.2
4	0.20	2.9
5	0.25	3.6
6	0.30	4.0
7	0.35	4.6
8	0.40	5.2
9	0.45	6.9

Tab. 3: DC Test data for calculation of effective armature resistance of CR alternator.

S. No.	Voltage in Volts	Current in Amps	DC Resistance (R_{dc}) in Ohms
1	0.8	1.37	0.5839
2	1.2	1.99	0.6030
3	1.4	2.18	0.6422
4	1.8	2.80	0.6428
R_{dc}=0.6179 Ω			

Calculation of effective armature resistance:

$$R_a = R_{dc} \cdot 1.2 = 0.6179 \cdot 1.2 = 0.74148\ \Omega. \quad (23)$$

Tab. 4: ZPF Test data of CR alternator (refer to section 3.1 for Potier method).

S. No.	Voltage in Volts	Field current (I_{f2}) in Amps	Load current (I_L) in Amps
1	100	0.56	7

Tab. 5: Direct load test data of CR alternator.

S. No.	1
V_t (V)	376
I^a_a	6.9
W_1 (*4)[b]	320
W_1 (*8)[c]	310
W_1+W_2^d	3760
% R^e	10.37
Eff.[f]	97.26

Parameters in the Tab. 5:

- *a* - the load current is assumed to be approximately equal to armature current (I_a),

- b and c - are respectively multiplication factors of Watt-meters W_1 and W_2,
- d - the total wattmeter reading is equal to output power P_{out},
- e – percentage regulation of the machine,
- f - efficiency is calculated as $\frac{P_{out}}{P_{out} + I_a^2 \cdot R_a}$.

Tab. 6: GA-based estimated parameters of the CR alternator (four unknown variables) compared against conventional method and load test.

Parameters	Potier triangle method	GA based method	Direct load test
R_a	0.74148	0.7273	-
X_l	10.857	3.6362	-
X_a	5.218	9.390	-
δ	19.2	18.8	-
Regulation (%)	12.13	10.37	10.37
Efficiency[a] (%)	97.26	97.31	97.26

5.3. Parameter Estimation for Salient Pole (SP) Machine using GA

A 5 KVA, 415 V, 50 Hz, three-phase salient pole *alternator* is used for this case study. In case of the SP alternator, unlike the CR alternator, the equivalent circuit parameters, viz. direct and quadrature axis reactance needs to be measured using a rigorous test called slip test. The slip test data and the respective computed parameters X_{sq} and X_{sd} using Eq. (6) and Eq. (7) respectively and performance of SP synchronous machine are given in Tab. 7 and Tab. 8 respectively. The parameter estimation of the salient pole alternator is done by applying the in situ measured *full load* test parameters namely supply voltage, load current and output power. The present investigation uses unity power factor load.

Tab. 7: Slip test data for salient pole alternator.

$V_{\max}$ (V)	$V_{\min}$ (V)	$I_{\max}$ (A)	$I_{\min}$ (A)
80.5	80.3	5.4	4.5

Tab. 8: Calculated values of parameters and performance of SP alternator using pre-determination.

Parameters	Computed values
R_a	1.52
X_l	6.0
X_{ad}	NA[a]
X_{aq}	NA[a]
$X_{sd} = \frac{V_{\max}}{\sqrt{3} I_{ph}}$	10.32
$X_{sq} = \frac{V_{\min}}{\sqrt{3} I_{ph}}$	8.58
Δ	5.98
Regulation %	1.76
Efficiency %	98.45

a - NA - Not applicable because through slip test only the value of synchronous d and q - axis reactances are determined

From Two reaction theory the *phasor diagram* considered is given in Fig. 6 and Fig. 7.

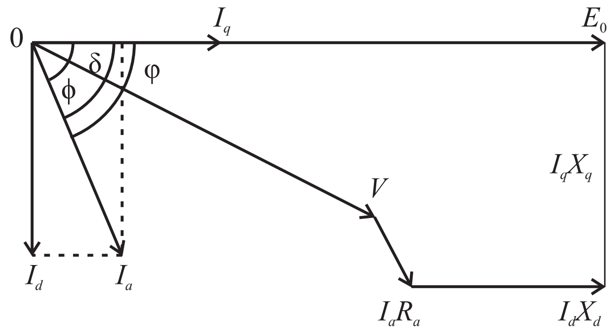

Fig. 6: Phasor diagram for salient pole alternator.

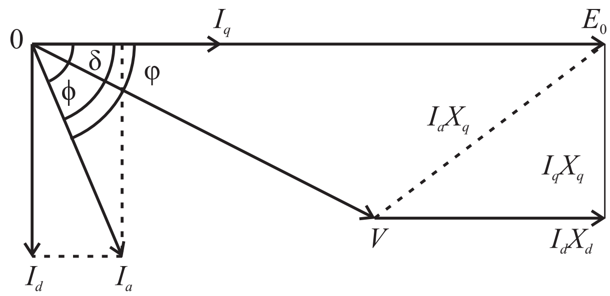

Fig. 7: Phasor diagram for salient pole alternator (neglecting R_a).

From the equivalent circuit:

$$E_{0-est1} = \sqrt{(V_t + I_a R_a)^2 + (I_d X_d + I_q R_q)^2}, \quad (24)$$

(since, $E_0 = V_t + I_a R_a + j\,(I_d R_d + I_q R_q)$),

$$P_{out} = Power - developed = V_t I_a \cos\phi, \quad (25)$$

$$I_a \cos\phi = \frac{P_{out}}{V_t}. \quad (26)$$

From Fig. 7,

$$I_a \cos\phi = I_q \cos\delta + I_d \sin\delta, \quad (27)$$

$$I_q X_{sq} = V_t \sin\delta, \quad (28)$$

$$I_d X_{sd} = E_0 - V_t \cos\delta, \quad (29)$$

$$I_d = I_a \sin\phi = I_a \sin(\phi + \delta), \quad (30)$$

$$I_q = I_a \cos\phi = I_a \cos(\phi + \delta), \quad (31)$$

From Eq. (27), Eq. (28) and Eq. (29),

$$I_a \cos\phi = \frac{V_t}{2} \sin 2\delta \cdot \left(\frac{X_{sd} - X_{sq}}{X_{sd} \cdot X_{sq}}\right) + \frac{E_0 \sin\delta}{X_{sd}}, \quad (32)$$

Eliminating $I_a \cos\phi$ in Eq. (32) using Eq. (26),

$$\frac{P_{out}}{V_t} = \frac{V_t}{2}\sin 2\delta \cdot \left(\frac{X_{sd} - X_{sq}}{X_{sd} \cdot X_{sq}}\right) + \frac{E_0 \sin\delta}{X_{sd}}, \quad (33)$$

Rearranging gives,

$$E_0 = \frac{(2P_{out} \cdot X_{sd} \cdot X_{sq})}{2V_t X_{sq} \sin\delta} \dots - \frac{\left(V_t^2 \left(X_{sd} - X_{sq}\right)\right) \cdot \sin 2\delta}{2V_t X_{sq} \sin\delta}, \quad (34)$$

$$E_{0-est2} = \frac{(2P_{out} \cdot X_{sd} \cdot X_{sq})}{2V_t X_{sq} \sin\delta} \dots - \frac{\left(V_t^2 \left(X_{sd} - X_{sq}\right)\right) \cdot \sin 2\delta}{2V_t X_{sq} \sin\delta}, \quad (35)$$

where:

$$X_{sd} = X_{ad} + X_l, \quad (36)$$

$$X_{sq} = X_{aq} + X_l, \quad (37)$$

$$f_{obj} = E_{0-est1} - E_{0-est2}, \quad (38)$$

$$\max(ff) = \frac{k}{f_{obj}}. \quad (39)$$

Equation (38) is the required objective function that needs to be minimized or in other words Eq. (39) is the fitness function that needs to be maximized for SP Alternator.

Thus GA uses only two equations, Eq. (24) and Eq. (35) and estimates *five unknown variables* namely X_{sd}, X_{sq}, δ, R_a, X_l. The GA method uses only one set of values available from the load test data (as given in the Tab. 9) to estimate the equivalent circuit parameters by applying them in the objective function. In this method, 150 individuals participate in the tournament of every generation. At the end of 150 generations and

Tab. 9: Load test data for SP alternator.

S. No.	1
V_t (V)	384
I_a^a	2.1
W_1 $(*4)^b$	80
W_1 $(*8)^c$	80
$W_1{+}W_2^d$	1280
% R^e	7.26
Eff.^{f}	98.45

Parameters in the Tab. 9:

- a - the load current is assumed to be approximately equal to armature current (I_a),
- b and c - are respectively multiplication factors of Watt-meters W_1 and W_2,
- d - the total wattmeter reading is equal to output power P_{out},
- e – percentage regulation of the machine,
- f - efficiency is calculated as $P_{out}/(P_{out}+ I_a^2 \cdot R_a)$.

when error tolerance is less than 1 % of F_{obj} (i.e. E_{0-est1} and E_{0-est2}) is reached, then it is considered to be the solution. The probability of crossover P_c is set at 0.7 and the probability of mutation P_m is at 0.001. The parameters estimated from GA is given in Tab. 10 and compared against the measured values. The values of X_{ad} and X_{aq} are obtained by fitting in the Eq. (36) and Eq. (37) respectively. The estimated parameters provide the performance results much closer to the actual load test data. But in the test results obtained from predetermination tests though the value of efficiency is found to be close, the regulation is not. Therefore in the SP machine also GA-based parameter estimation has provided better results.

Tab. 10: GA-based estimated parameters of the SP alternator (four unknown variables) compared against conventional method and load test.

Parameters	**Conventional method**	**GA-based method**	**Direct Load test**
R_a	1.52	1.2	-
X_l	6.00	5.7222	-
X_{ad}	4.32	10.0879	-
X_{aq}	2.58	7.1078	
X_{sd}	10.32	15.8104	
X_{sq}	8.58	12.83	
Δ	5.98	3.83	-
Regulation %	1.76	7.26	7.26
Efficiency %	98.45	98.77	98.45

6. Discussion of Results

In the proposed method, the initial values are generated by random number generation. The GA main program is run for 10 times with the set values for generation, population size, cross-over rate and mutation rate. Each time the results obtained were very close, as shown in Fig. 8. This shows the *repeatability* of the proposed method.

Also, it is observed that, the population of the individuals in the last generation is in exact closeness to the average values of the result obtained in the 10 test runs, as shown in Fig. 9.

It shows that the results obtained are converging. The Standard deviation is found to be close to zero. Genetic algorithm is effective compared to scores well against conventional methods as it employs a powerful searching technique and could choose the best set of the parameters to maximize the given objective functions. The GA-based method uses direct load test data

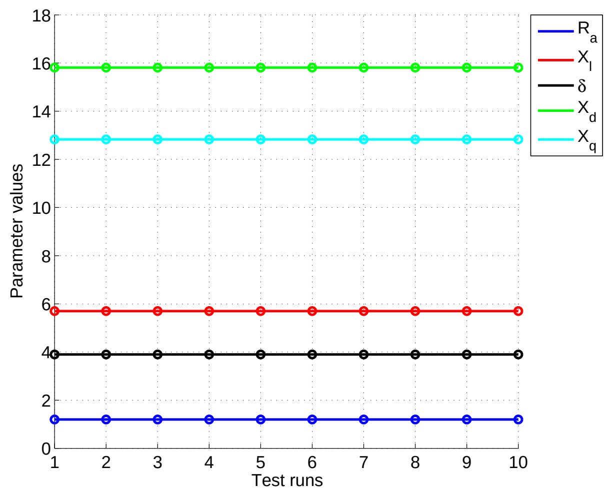

Fig. 8: Chart showing the repeatability aspect of the proposed GA method.

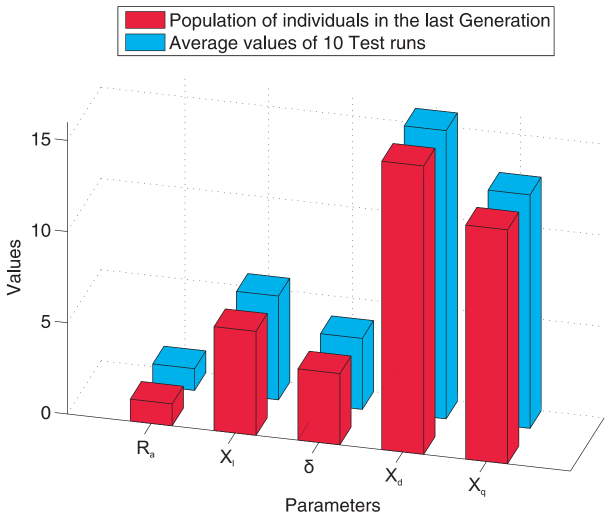

Fig. 9: Chart showing the convergence of the solution of the proposed GA method.

in comparison with the conventional methods which uses test data obtained from different operating conditions. Any change in circuit parameters due to change in load is inherently taken care of in GA-based parameter estimation, whereas this is not the case when the conventional methods are used. Despite the complexity of the parameters, due to the geometry of the windings, and their non-linear nature, GA performed well by providing global optimum solutions. The empiricism that is found in the separation of leakage reactance in conventional measurement method is eliminated in the GA-based method. The comparison of the results of the pre-determination methods and GA-based parameter estimation shows that some parameters are almost equal or closer in both cases, but some are totally deviating since the reactance parameters are highly non-linear due to complexity in windings. Further conventional methods like Potier triangle method follow empiricism in the separation of the leakage and armature reactance parameters. GA-based parameter estimation method uses just one measurement for the determination of all the parameters and eliminates all empiricism as found in conventional methods. Since the GA-based parameter estimation method uses in-situ measured test data at normal supply and load conditions, the sensitivity of change in temperature due to loading might be determined by estimating the change in resistance of the windings at different load conditions. Therefore besides the estimation of performance, the suggested method can also be applied to estimate the rise in temperature of the windings. This helps in deciding the maximum overload limit of alternators in its operating conditions.

7. Conclusion

Estimation of equivalent circuit parameters of both the cylindrical rotor and salient pole rotor alternators using the GA-based method is presented in this paper. The GA-based method was chosen, as its strength lies in the parallel nature of the search, and is better suited for the current problem as compared to other techniques such as immune algorithm and non-linear programming techniques. For multimodal functions, as considered in this paper, the GA is very much suitable. It was seen that one in-situ measurement of direct load test was adequate for the determination of all the parameters of interest, and all empiricism as found in pre-determination methods was eliminated For in-situ parameter estimation no isolation of the machine was required and the test was done on-site. The estimated parameters are compared with the results of conventional methods particularly the Potier triangle method and Slip test.

The suggested GA-based parameter estimation method is found to be versatile and superior to the conventional methods as the results obtained are in accordance to the theory and performance of the synchronous machines. A limitation of the proposed methodology exists in estimating reactance parameters, due to the windings complexity. A comparison with Particle Swarm Optimization (PSO) and other optimization techniques could be considered for research in the future .

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Appendix A Nomenclature

- R_e - Effective ac resistance (Ω),
- R_a - Armature resistance (Ω),
- X_s - Synchronous reactance (Ω),
- Z_s - Synchronous impedance (Ω),
- X_l - Leakage reactance (Ω),
- X_a - Armature reactance (Ω),

- X_{sd} - Synchronous direct-axis reactance (Ω),
- X_{sq} - Synchronous quadrature axis reactance (Ω),
- X_{ad} - Armature direct-axis reactance (Ω),
- X_{aq} - Armature quadrature-axis reactance (Ω),
- P_{in} - Input power per phase (W),
- P_{out} - Output power per phase (W),
- V_t - Terminal voltage (V),
- E_0 - Open circuit induced emf (V),
- δ - Load angle (radians),
- ϕ - Power factor angle (radians),
- I_l - Load current (Amps),
- I_f - Field current (Amps),
- I_a - Armature current (Amps),
- V_{ph} - Phase voltage (V).

Appendix B Alternator Parameters (CR and SP)

- $P_{in} = 5$ KVA,
- $V_{in} = 415$ V (three phase),
- $N = 1500$ RPM,
- $f = 50$ Hz.