Parameters evaluation for steady state induction machines using genetic algorithm

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In this paper the use of genetic algorithm as an optimization technique is implemented for calculating the values of steady state induction machines parameters. The problem is stated as minimizing an objective function comprising the difference between calculated and measured steady state characteristics at different slips. The objective function used requires the measurement of electrical quantities only. This technique is applied to both single-phase and three-phase induction motors.

يتعرض هذا البحث لاستخدام الخوارزم الوراثي كطريقة من طرق إيجاد الحل الأمثل لبارامترات الآلات التأثيرية في الحالة المستقرة. وقد تم صياغة المشكلة فى صورة إيجاد القيمة الصغرى لدالة الهدف التى تشتمل على قياسات وحسابات كهربية فقط عند قيم مختلفة من قيم معامل الانزلاق. وقد تم تطبيق الطريقة بنجاح على آلة تأثيرية أحادية الوجه وكذلك على آلة تأثيرية ثلاثية الوجه ذات قفص سنجابي. وقد تم عمل مقارنة معملية لخواص الأداء والتي تشتمل على قياسات لكل من التيار الكهربي المغذى للآلة وعلى قدره الدخل لها. وقد أظهرت الطريقة كفاءة عالية في إيجاد البارامترات الممثلة للآلة في الحالة المستقرة وذلك عند مقارنة الحسابات المستنتجة من البارامترات المحسوبة بالطريقة المقترحة بالقياسات المعملية.

Keywords: Induction machines, Parameters evaluation, Genetic algorithm.

1. Introduction

Accurate estimation of an induction machine parameters is of great importance, specially for the simulation of induction motor drive. This specialty arises from the fact that any simulation technique is tested via experimental work for the validity of this simulation. Therefore, a great attention should be given for the estimation of the machine parameters. Many techniques have been adopted for this purpose [1-9].

In previous papers [1,2] authors pointed out the necessity for a more detailed representation of rotor winding in order to take into account the deep-bar effect in the evaluation of motor characteristics over the full range of rotor slip. An equivalent circuit with two rotor loops is suitably used for representing double-cage and deep-bar motors. In [1,2] the machine parameters are obtained knowing a locked-rotor impedance test plus a load test.

Andria et al. [3] presented a method for identifying the parameters of a new model of induction motor used for deep-bar machines. The method depends on knowing three locked rotor tests, two of which are at rated current and two different frequency, and the third is at rated frequency and maximum input current. Also, no-load and load tests are required.

Rogers et al. [4] developed a technique by which a motor model may be calculated from a knowledge of standard specification data. This includes normal operating conditions at full-load, the starting performance (starting current and starting torque), and breakdown torque.

Willis et al. [5] conducted standstill frequency response tests. This test consists of a series of low power measurements, with the motor at rest and disconnected from the normal power supply, to determine the impedance of the machine at various frequencies. Then standard Bode techniques are used to estimate a transfer function that will approximate its frequency response. The electrical parameters are then calculated from this approximate transfer function. The results obtained showed some agreement with the manufacturer's performance curves.

In reference [6] parameters estimation for induction machines is based on sensitivity analysis. In [7] the parameters estimation is formulated as a nonlinear least-squares minimization problem, and a recursive algorithm is proposed to solve the minimization problem stated. In both [6,7] the modeling is based on steady-state equations obtained from the normal equivalent circuit. They require the calculation of too many derivatives for the continuous updating of the estimated parameter vector. The techniques described in [6, 7] are somewhat complicated and require a great attention for the initial estimation of the induction machine parameters.

In references [8,9] a single rotor cage machine was considered for investigation. The machine characterization is addressed using dynamic model equations. In [8] the error between the measured output of the real system, and the model's output are then calculated. A weighted sum of the errors is computed after completion of the simulation interval. This weighted sum of errors is used to drive an optimization algorithm to adjust the parameters of the model. The optimization technique used is somewhat complicated. A direct optimization method is used first to determine the real minimum. Thereafter a gradient method with step halving was used to zoom in on the minimum. In [9] the technique described gives only R_s , L_s , L_r/R_r , and M^2/L_r and not R_s , L_s R_r , L_r , and M. The least-squares algorithm for optimization is used to minimize the residual error.

In this paper, the estimation of the parameters of single-phase and three-phase induction machines with two rotor loops is performed using equations obtained from the induction machine steady-state equivalent circuit. The problem is stated as minimizing an objective function comprising the differences between calculated and measured steady-state stator phase current and input power at different slips. Genetic algorithm technique is applied for the optimization process.

2. Machine models

2.1. Single-phase induction machine model

The steady-state operation of the single-phase induction machine can be conducted using the double-revolving field equivalent circuit shown in Fig.(1). The equations of the stator current I , and the input power P can be written as :

$$I = \frac{V}{\sqrt{R_{eq}^2 + X_{eq}^2}}, \tag{1}$$

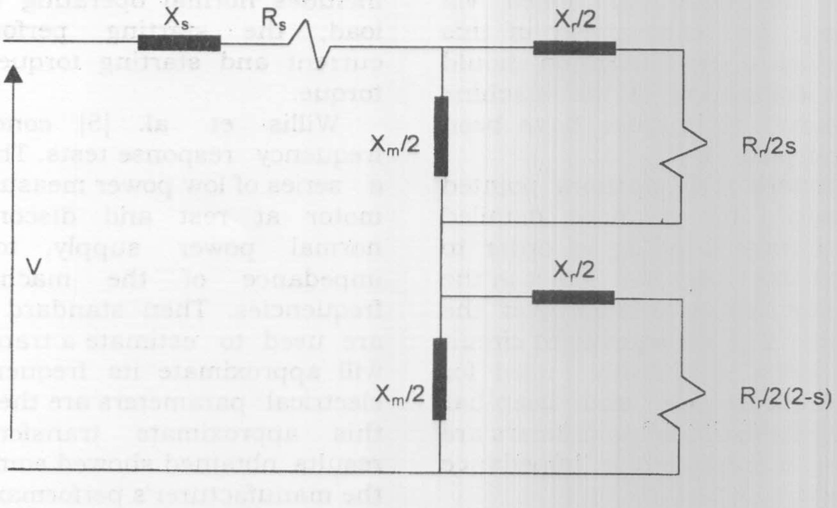


Fig. 1. Equivalent circuit for single-phase induction motor at steady-state.

$$P=\frac{V^2 R_{eq}}{R_{eq}^2+X_{eq}^2}, \qquad (2)$$

where :

$$R_{eq}=R_s+0.5R_1+0.5R_2, \qquad (3)$$

$$X_{eq}=X_s+0.5X_1+0.5X_2, \qquad (4)$$

$$R_1=\frac{X_m^2(R_r/s)}{(R_r/s)^2+(X_m+X_r)^2}, \qquad (5)$$

$$R_2=\frac{X_m^2(R_r/2-s)}{(R_r/2-s)^2+(X_m+X_r)^2}, \qquad (6)$$

$$X_1=\frac{X_m[(R_r/s)^2+X_r(X_m+X_r)]}{(R_r/s)^2+(X_m+X_r)^2}, \qquad (7)$$

$$X_2=\frac{X_m[(R_r/2-s)^2+X_r(X_m+X_r)]}{(R_r/2-s)^2+(X_m+X_r)^2} \qquad (8)$$

2.2. Three-phase induction machine model

The exact equivalent circuit for a three-phase two-loop rotor induction motor is shown in Fig.2. The resistance R_m is omitted and the core loss is lumped with the windage and friction losses. The equations of the stator phase current I, and the input three-phase power P can be written as :

$$I=\frac{V}{\sqrt{R_{eq}^2+X_{eq}^2}}, \qquad (9)$$

$$P=\frac{3V^2 R_{eq}}{R_{eq}^2+X_{eq}^2}, \qquad (10)$$

where :

$$R_{eq}=R_s+\frac{(R_r/s)X_m^2}{(R_r/s)^2+(X_m+X_{rio}+X_r)^2}, \qquad (11)$$

$$X_{eq}=X_s+\frac{X_m[(R_r/s)^2+(X_r+X_{rio})(X_m+X_{rio}+X_r)]}{(R_r/s)^2+(X_m+X_{rio}+X_r)^2}, \qquad (12)$$

$$R_r=\frac{R_{ri}R_{ro}(R_{ri}+R_{ro})+(R_{ri}X_{ro}^2+R_{ro}X_{ri}^2)s^2}{(R_{ri}+R_{ro})^2+(X_{ri}+X_{ro})^2 s^2}, \qquad (13)$$

and

$$X_r=\frac{X_{ri}X_{ro}(X_{ri}+X_{ro})s^2+R_{ri}^2X_{ro}+R_{ro}^2X_{ri}}{(R_{ri}+R_{ro})^2+(X_{ri}+X_{ro})^2 s^2}. \qquad (14)$$

3. Optimization problem formulation

The objective function used for the optimization problem is suggested in [7], and is adopted in this paper. Mathematically, the problem is stated as :

Minimize

$$F(U) = F_1(U) + F_2(U), \qquad (15)$$

where :

$$F_1(U) = \frac{1}{N}\left[\sum_{i=1}^{N}(I_{measurted}-I_{calculated})^2\right], \text{ and}$$

$$F_2(U) = \frac{1}{N}\left[\sum_{i=1}^{N}(P_{measured}-P_{calculated})^2\right].$$

N is the length of experimental data vector ;
U is the parameter vector , and is given by :

<u>for single-phase induction motor</u>
$U = [\,R_s \quad R_r \quad X_s \quad X_r \quad X_m\,]^t$

<u>for three-phase two-loop rotor induction motor</u>
$U = [\,R_s \quad R_{ri} \quad R_{ro} \quad X_s \quad X_{ri} \quad X_{ro} \quad X_{rio} \quad X_m\,]^t$

<u>for three-phase one loop rotor induction motor</u>
$U = [\,R_s \quad R_r \quad X_s \quad X_r \quad X_m\,]^t$

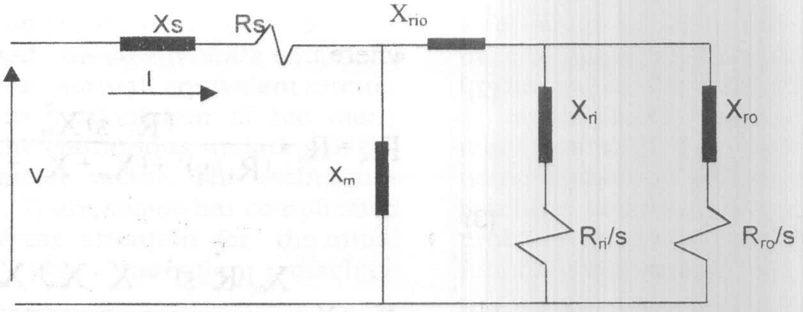


Fig.2. Equivalent circuit for three-phase rotor loops inclusion motor at steady –state.

$I_{measured}$ and $P_{measured}$ are experimental data of the stator phase current and input power , in p.u. values respectively. $I_{calculated}$ and $P_{calculated}$ are both functions of slip and vector U and are in p.u. values. For single-phase machine they are obtained using eqns. (1) to (8), while for three-phase machine they are obtained using eqns. (9)-(14),

Subject to

$$U^{min} \le U \le U^{max}, \qquad (16)$$

where U^{min} and U^{max} are the parameter vector minimum and maximum values respectively.

4. Genetic algorithm (Ga)

The genetic algorithm is a search procedure, which mimics the way biological evolution work. The mathematical basis for Ga is given in [10]. The main advantages of Ga are:

1-The Ga uses a set of population points which are randomly chosen. Therefore, the Ga explores several areas of the search space, and, therefore, reduces the probability of striking false maxima or minima.

2-The Ga does not require continuous derivatives calculations because transition rules are probabilistic and not deterministic. Each member of the population is evaluated to find its merit or fitness. Fitness is a single numerical value that indicates how well a member solves the original problem. The relative fitness of the best population push the Ga towards the optimal solution. As the Ga moves from one generation to the other, its objective is to produce better solutions to the original problem.

Three basic operators are utilized with Ga's solution technique. These operators are : the reproduction operator, the crossover operator, and the mutation operator.

1. The reproduction operator . This operator chooses individuals from the current generation for mating to produce a new generation . Selection is based on the fitness for each individual. This operator makes highly fit individuals most likely the ones to produce the new generation. The selection parameter determines the number of individuals which are chosen for mating. Several selection techniques are used for this purpose, among them tournament, proportional, ranking, etc. [10]. Elitism is an important operation used within the mating procedure. It forces the best individual of the current population to be member of the next generation. The reproduction process continues until the number of new individuals is equal to the original population size.
2. The crossover operator. This operator allows the exchange of information among individuals in the population and causes the characteristics of the best individuals to be recombined to reproduce the new generation.
3. The mutation operator. This operator ensures needed diversity. It is used to randomly change the value of one individual , or to change the value of an individual that does not satisfy the limits

imposed by the problem. This operator is considered as a correction tool to remedy individuals produced by crossover if it produces an invisible individual.

Ga has been used for solving too many problems. This includes: power industry applications [11], control applications [12-13], distribution systems [14], machine design [15], and many others.

5. Parameters evaluation using genetic algorithm

GA is used for the parameters evaluation of single-phase and three-phase induction motors. The solution is obtained as follows:

1- Classical tests (no-load test, blocked rotor test, and dc test) are performed to find an initial guess for the parameter vector U_o.

2- Knowing U_o find the values for U^{min} and U^{max} as follows :

$$U^{min} = 0.6\ U_o$$

$$U^{max} = 1.4\ U_o$$

3- Randomly find value for an individual U satisfying equation (16).

4- Evaluate the fitness function given by eq. (15) for this individual for the N points representing different machine measured phase input current $I_{measured}$ and total input power $P_{measured}$ at different slips. For single-phase induction motor $I_{calculated}$ and $P_{calculated}$ are obtained from equations (1) to (8), while for three-phase induction motor eq. (9) to (14) are used for this calculation.

5- Repeat steps (3) to (4) until initial population is completely created, then go to step (6).

6- Calculate the average fitness function, which is the sum of all partial fitness function values divided by the population size.

7- Perform crossover operation for reproduction to form next generation.

8- Evaluate the fitness function as in step (4).

9- Repeat steps (7) to (8) until the new population is completely produced, then go to step (10).

10- Calculate the average fitness function as given in step (6).

11-Repeat steps (7) to (10) until the average fitness function converges.

12-Print final value for parameter vector U_F .

6. Simulation and experimental results

A computer program written in Pascal language was prepared for the digital simulation of the problem described . As mentioned previously, both single-phase and three-phase induction motors are examined.

In the simulation study, the number of experimental data points was taken 15 (N=15).The Ga parameters used are: maximum number of generations = 50; population size = 500; crossover and mutation probabilities = 1.0 , and 0.0 respectively.

6.1 *Single-phase induction motor*

The single-phase machine used has the following data:

0.9 kw, 220 V , 8.5 A , 50 Hz , 4 – Poles , P.F. = 0.74 ,1435 rpm

The parameter vector U_O in Ohms obtained from classical tests is as follows:

$$U_O = [\,2.8 \quad 2.26 \quad 2.74 \quad 2.74 \quad 60.78]^t$$

The estimated value for parameter vector U_F in Ohms obtained using the GA described is as follows:

$$U_F = [\,3.53 \quad 1.76 \quad 2.98 \quad 2.41 \quad 74.89\,]^t$$

The base quantities used for the current and power calculations are: r.m.s phase voltage V_{base} = 220 V, and r.m.s phase current I_{base} = 8.5A. fig. 3. shows the experimental (measured), and estimated stator current and input power using U_F and U_O . Maximum deviations of 7.72% and 19.01% were encountered for stator current and input power respectively from measured values when using U_O , while these deviations were 3.17% and 2.75% respectively when using U_F. The fitness function $F_1\,(U_O) = 8.008\text{x}10^{-3}$,

$F_2(U_O)=10.718\text{x}10^{-3}$, and $F(U_O) = 18.726\text{x}10^{-3}$ when using U_O. The fitness function $F_1(U_F) = 1.379\text{x}10^{-3}$, $F_2(U_F) = 1.388\text{x}10^{-3}$, and $F(U_F) = 2.767\text{x}10^{-3}$ when using U_F.

The Torque/Slip characteristics for this machine calculated using parameter vectors U_O and U_F are shown in Fig. 4.

6.2. Three-phase induction motor

The three-phase machine available has a single-cage rotor. It is of class A according to NEMA classification. It has the following data:

2.2 kw, 380/660 V Δ / Y, 5.2 / 3.0 A, 50 Hz, 4-Poles, P.F. = 0.82, and 1415 rpm.

The parameter vector U_O in Ohms obtained from classical tests is as follows:

$U_O = [\ 11.32 \quad 7.5 \quad 8.89 \quad 8.89 \quad 181.57\ ]^t$

Equations (9)-(12) will be used, for this investigation, instead of Eqs. (9-14) used for the two rotor loops case.

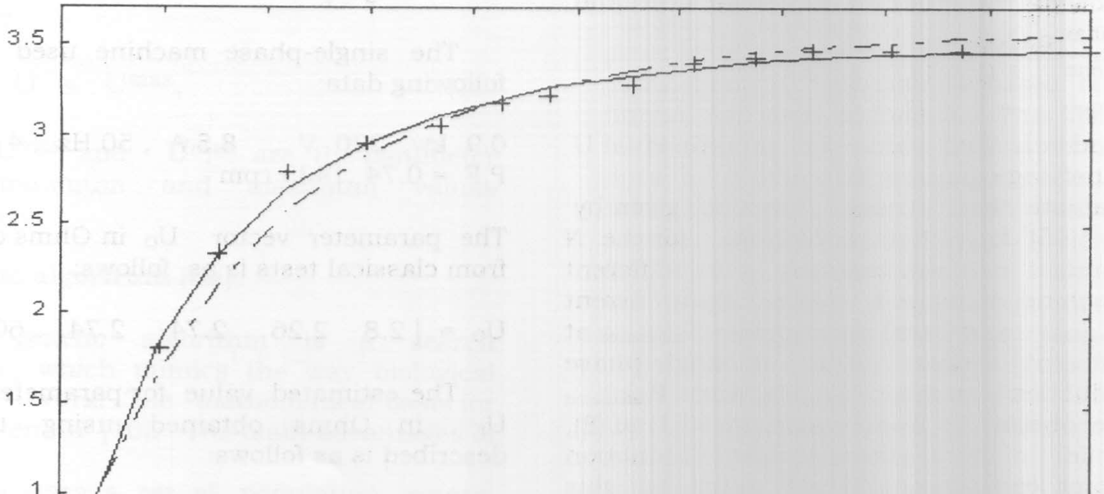


Fig. 3 – a. Experimental and calculated stator current.
+ : Experimental measurements —: Calculated values using U_F -.-.-: Calculated values using U_O

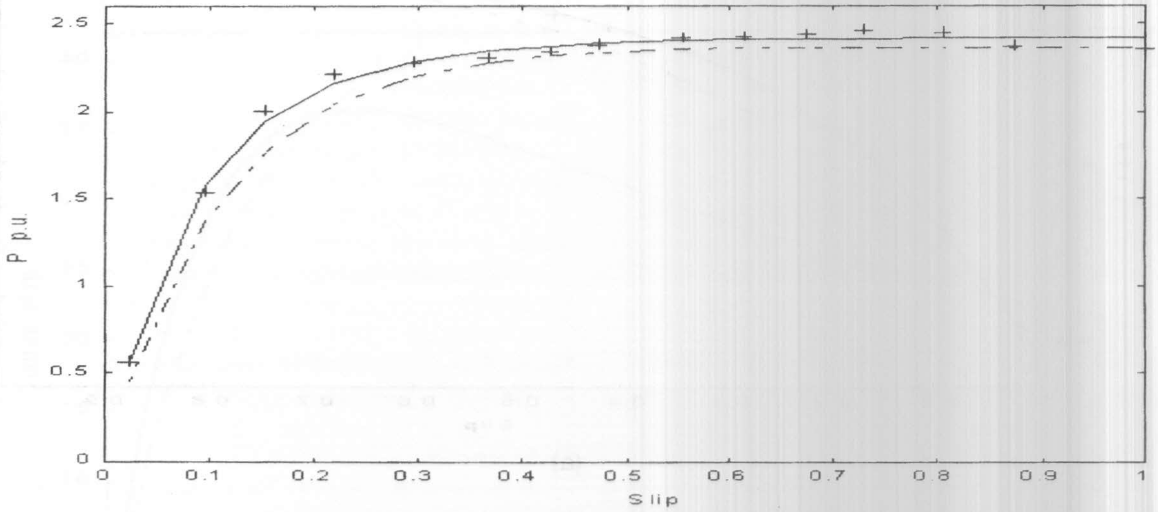


Fig. 3- b. Experimental and calculated input power
+ : Experimental measurements —: Calculated values using U_F -.-.-: Calculated values using U_O

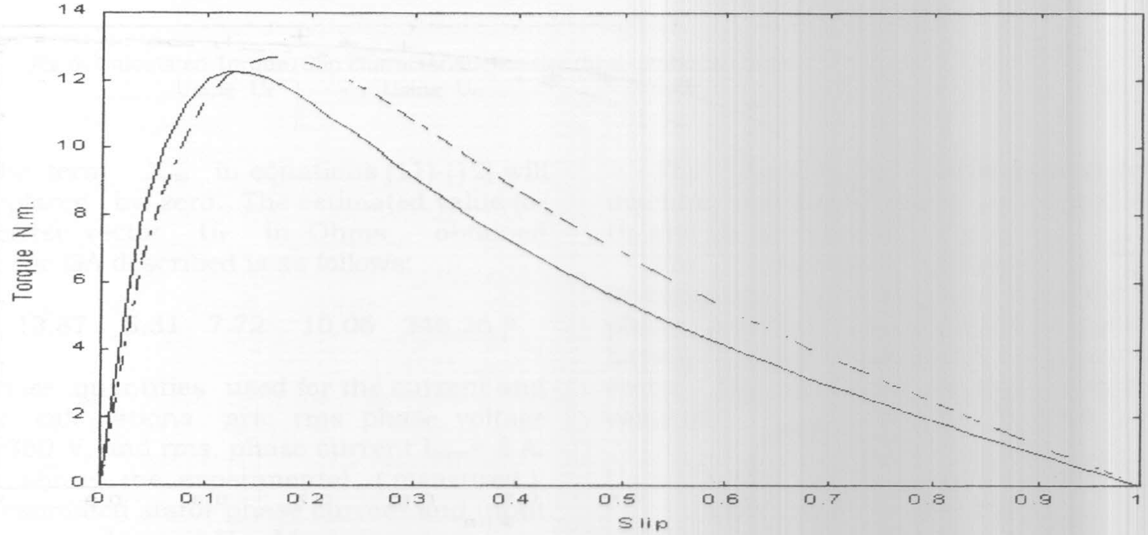
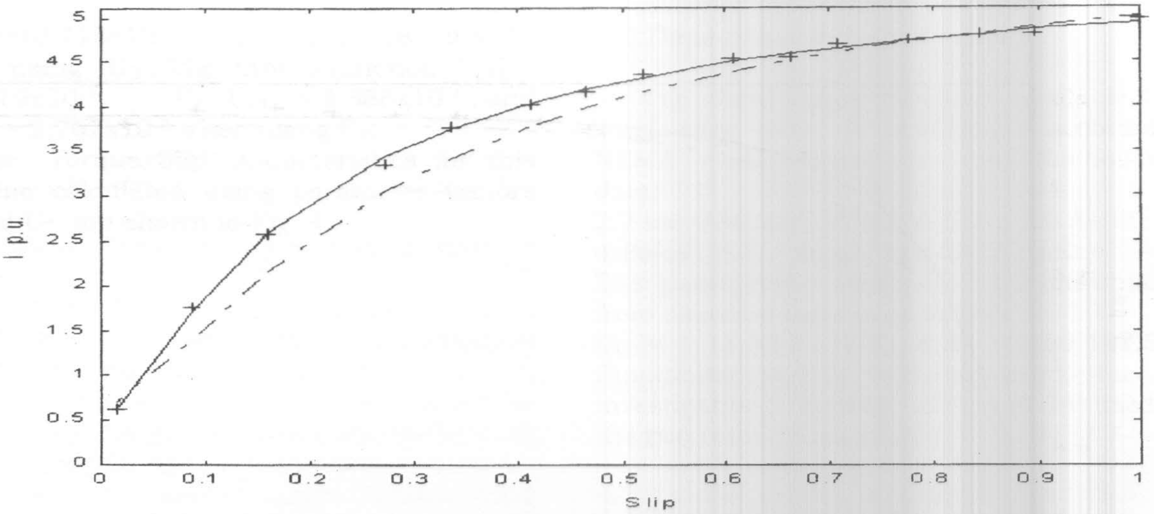
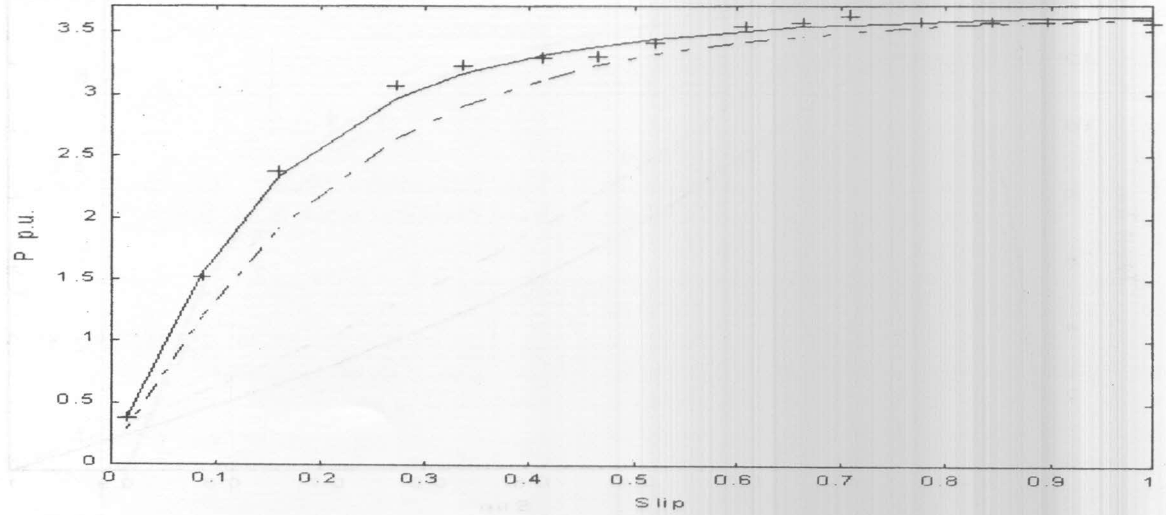


Fig. 4. Calculated torque/slip characteristic for the single-phase machine .
____: Using U_F -.-.- : Using U_O



(a)



(b)

Fig. 5. (a) Experimental and calculated stator phase current
(b) Experimental and calculated total input power
+: Experimental measurements —:Calculated values using U_F -.-.-: Calculated values using U_O

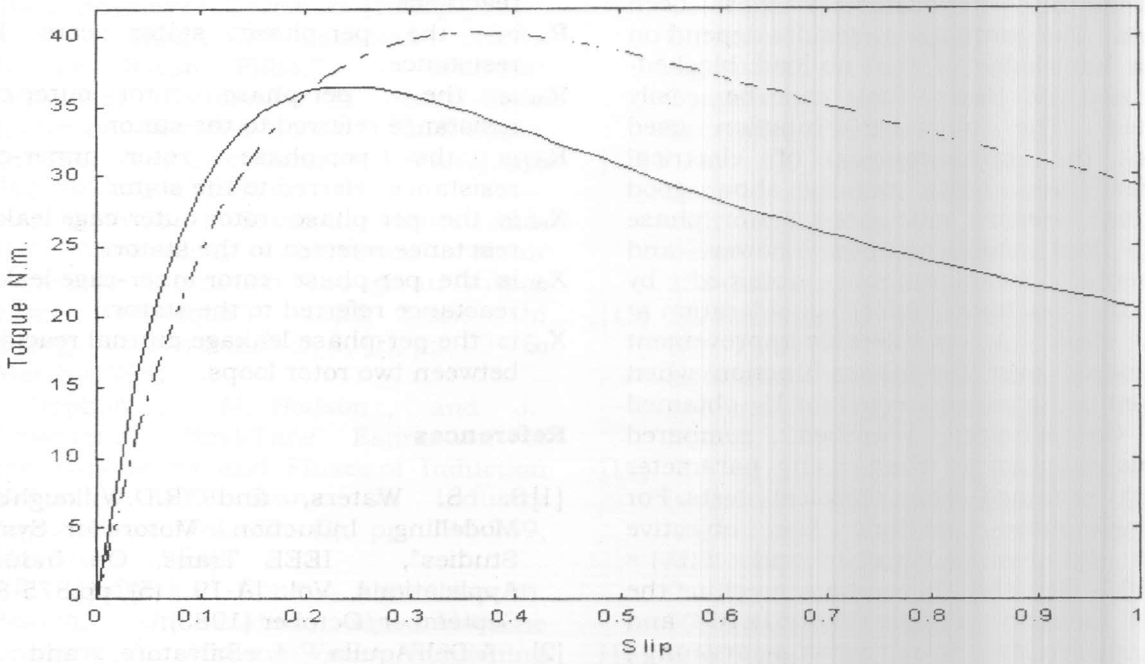


Fig.6. Calculated Torque/Slip characteristic for the three-phase machine.
____ : Using U_F -.-.- Using U_O

The term X_{rio} in equations (11)-(12) will be replaced by zero. The estimated value for parameter vector U_F in Ohms obtained using the GA described is as follows:

U_F = [13.87 5.31 7.72 10.06 246.26]^t

The base quantities used for the current and power calculations are: rms phase voltage V_{base}=380 V, and rms. phase current I_{base}= 3 A. Fig.5. shows the experimental (measured), and estimated stator phase current and input power using U_F and U_O. Maximum deviations of 20.32% and 24.33% were encountered for stator phase current and input power respectively from measured values when using U_O, while these deviations were 3.08% and 3.34% respectively when using U_F. The fitness function F_1 (U_O) = 44.113x10^{-3} , F_2 (U_O) = 44.948x10^{-3} , and F (U_O) = 89.061x10^{-3} when using U_O . The fitness function F_1 (U_F) = 1.541x10^{-3} , F_2 (U_F) = 2.595x10^{-3} , and F(U_F) = 4.136x10^{-3} when using U_F .

The Torque/Slip characteristics for this machine calculated using parameter vectors U_O and U_F are shown in Fig. 6.

For comparison purpose, a further investigation is carried out over the three-phase machine. The machine is considered having a two loops rotor . The parameter vector U_F in Ohms, in this case, has the value of:

U_F = [13.85 10.24 11.07 7.37 13.88
13.65 3.56 249.62] ^{t}

Maximum deviations of 3.06% and 3.33% were encountered for stator phase current and input power respectively from measured values. The fitness function F_1 (U_F) = 1.558x10^{-3}, F_2 (U_F) = 2.582x10^{-3} and F(U_F) = 4.140x10^{-3}. It is clear that these results are compatible with those obtained having treated the machine as a single-cage rotor.

7. Conclusions

The implementation of Ga technique to the evaluation of single-phase and three-phase induction motor parameters has been presented. The simulation results depend on previous knowledge of the no-load, blocked-rotor, and dc tests that can be easily conducted. The objective function used requires the measurement of electrical quantities only. The results show good correlation between calculated stator phase current and total input power and experimental measurements obtained by loading the machine under consideration at different slips. A considerable improvement was achieved over the fitness function when calculated using parameter vector U_F obtained using Ga technique described , compared with this calculation when using parameter vector U_O obtained from classical tests. For the single-phase machine the objective function $F(U_O) = 18.726x10^{-3}$ and $F(U_F) = 2.767x10^{-3}$. For the three-phase machine the objective function $F(U_O) = 89.061x10^{-3}$ and $F(U_F) = 4.136x10^{-3}$. It is worth mentioning , here, that the parameter vector U_F obtained for the machine has a different significance from that given by parameter vector U_O . The parameter vector U_F represents the machine more accurately and cannot be obtained from classical tests.

The Ga does not require continuous derivatives calculations because transition rules are probabilistic and not deterministic. GA only needs to evaluate an objective function to guide its search. Therefore, there is no need for derivatives or other auxiliary knowledge. It requires neither deep mathematical knowledge nor great computer programming skill.

List of symbols

R_s is the per-phase stator winding resistance.
R_r is the per-phase rotor circuit resistance referred to the stator.
L_s is the per-phase stator leakage inductance.
L_r is the per-phase rotor leakage inductance.
M is the per-phase stator magnetizing inductance.
X_s is the per-phase stator leakage reactance.
X_r is the per-phase rotor leakage reactance referred to the stator.
X_m is the per-phase stator magnetizing reactance.
R_m is the per-phase stator core loss resistance.
R_{ro} is the per-phase rotor outer-cage resistance referred to the stator.
R_{ri} is the per-phase rotor inner-cage resistance referred to the stator.
X_{ro} is the per-phase rotor outer-cage leakage reactance referred to the stator.
X_{ri} is the per-phase rotor inner-cage leakage reactance referred to the stator.
X_{rio} is the per-phase leakage mutual reactance between two rotor loops.

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