Induction Motor Efficiency Estimation using Genetic Algorithm

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Abstract- Due to the high percentage of induction motors in industrial market, there exist a large opportunity for energy savings. Replacement of working induction motors with more efficient ones can be an important resource for energy savings. A calculation of energy savings and payback periods, as a result of such a replacement, based on nameplate motor efficiency or manufacture's data can lead to large errors [1]. Efficiency of induction motors (IMs) can be extracted using some procedures that use the no-load test results. In the cases that we must estimate the efficiency on-line, some of these procedures can't be efficient. In some cases the efficiency estimates using the rating values of the motor, but these procedures can have errors due to the different working condition of the motor. In this paper the efficiency of an IM estimated by using the genetic algorithm. The results are compared with the measured values of the torque and power. The results show smaller errors for this procedure compared with the conventional classical procedures, hence the cost of the equipments is reduced and on-line estimation of the efficiency can be made.

Key words- genetic algorithm, induction motor, efficiency

1. INTRODUCTION

IMs due to their better and optimum characteristics and cost are the greatest driving loads in the electrical distribution systems. Over the 50% of the electrical loads in the industrial countries are IMs [2], so optimization of the energy consumption of the IMs can optimized the whole of the electrical energy consumption. The replacement of working induction motors with more efficient ones can be an important resource of energy savings. A calculation of energy savings, as a result of such a replacement, based on nameplate motor efficiency or manufacturer's data can be lead to large errors [1]. For this purpose the efficiency of IMs must be estimated correctly hence on-line. Some of the efficiency estimation procedures are studied obviously in this paper and compare with the genetic algorithm procedures.

2. EFFICIENCY ESTIMATION PROCEDURES

A report [3] surveyed over thirty methods for evaluating the efficiency of induction motors. Basically all of the efficiency estimation methods can be divided to six groups as follows:

2.1) Measurement of the output torque of an IM is the direct way of efficiency measurement. Using a dynamometer for torque measurement isn't a good and errorless method [4]. Torque measurement applying the torque sensors, can be very accurate but a very expensive and simplex method.

2.2) Efficiency estimation using calculated air-gap torque, using the measured input current and voltage, and applying the integral equations, average air-gap torque and power can be calculated. Then subtracting the friction, windage and stray-load losses, output power and efficiency are calculated. Due to the need for no-load test or values of the core and mechanical losses in this method, this procedure can't be implemented easily in the industrial environments. Of course there are numerous variations and modifications to simplify the no load test and reduce the number of measurements under load to just one load point [5].

2.3) In the method of efficiency estimation using slip values for efficiency calculation, a linear modulation made between slip and output power of the motor. Calculating of the output power of the motor in the different slips, can be applied in the efficiency calculation in each slip. This method is the simplest one, but has the minimum accuracy. Many studies show that the average error of this method is about 15-20 percent.

2.4) Efficiency estimation using motor current method uses the motor input current with respect to the motor rated values or direct current measurements, for the efficiency estimation and is very perfect than the slip based method. But the variation of the motor current versus its output power isn't linear, so the efficiency estimation can't be applicable for a wide range of the motor loads.

2.5) Efficiency estimation using losses separation method is designed for the direct losses measurement of the motor, so can be made the best results except than the direct output torque measurement method. In IEEE 112 [4] this method is known as **E** method. Due to the requirements of this method to reverse rotation of the motor for calculation of the stray-load losses, this method isn't applicable in an efficient region of the load.

2.6) In the method of efficiency estimation using equivalent circuit of the motor, when the on-line tests or the tests that must be made in the other values of the motor loads, can't be possible, equivalent circuit of the motor can be held in the efficiency estimation. In this method the equivalent circuit parameters of the motor are calculated using the DC, locked-rotor and no-load tests or any impedance tests of the motor. This method isn't capable of efficiency estimation in a wide range of the motor load [4].

3. INTRODUCTION TO GENETIC ALGORITHM

Emergent computational paradigms that have their philosophical basis in physical processes such as natural evolution and laws of thermo-dynamics use random sampling as a tool to guide a highly exploitative search process [6].

Genetic algorithm is one of the optimization methods that inspired from the natural genetics. Genetic algorithm is a directed random search technique that is widely applied in optimization problems. This is especially useful for complex optimization problems where the number of parameters is large and the analytical global solutions are difficult to obtain [7]. Due to GA's capability of finding the global optimum in the wide range of the functions, it has very applications in the optimization problems. In this method using random but intelligent search in a predefined area, the parameters of the proposed function lead to their optimum values. This method is a conventional procedure for non-linear equations solution. In the Genetic algorithm the search of the optimal solution is basically performed proceeding from one group (population) of possible points in the search space to another, according to procedures that resemble those of natural selection and genetics and

designed such as to steer the search towards better solutions. While evolving through its generational steps, the algorithm examines and evaluates several solution points in the search space, before converging to the best solution [8]. The standard Genetic algorithm process is as follows [7]:

> **begin**
>> $\tau \rightarrow 0$ // τ: number of iteration
>> initialize $P(\tau)$ //$P(\tau)$: population for iteration τ
>> evaluate $f(P(\tau))$ // $f(P(\tau))$:fitness function
> **while** (not termination condition) **do**
> **begin**
>> $\tau \rightarrow \tau + 1$
>> select 2 parents $p1$ and $p2$ from $P(\tau. 1)$
>> perform genetic operations (crossover and mutation)
>> reproduce a new $P(\tau)$
>> evaluate $f(P(\tau))$
> **end**
> **end**

In this method each chromosome is one of the problem variables and represents one of the points in the answer area, and contains some of genes. This algorithm differs with some of the other methods because of:
- This method works using the code of each variable, instead of the own variables.
- This method search from a wide range of variables.
- Differentiation is not used in this method.
- This method used the random transient functions, instead of the definite functions.

In the genetic algorithm coding of a plan is taken from the chromosome space, that's limited to a set of transferred parameters including the real figures in the length of a string. Coded parameters is showing using genes in the chromosome. Binary coding is the best of them. In this way parameters is showing as a string of zeros and ones. After the coding of the parameters and definition of their limitations, genetic operators such as selection operator, crossing operator and jumping operator, are applied and finally the results are returned as decimal figures.

4. INDUCTION MOTOR EFFICIENCY ESTIMATION USING GENETIC ALGORITHM

In this section main considerations of losses separation methods, equivalent circuit and genetic algorithm are composed, for analysis of the non-linear algebraic equation. Measurements are similar to the losses separation method approximately, unless the no-load test. In the first stage, after the motor turning out, the stator winding resistance (r_1), stator line voltage (V_1), stator input current (I_1), input power of the motor (P_{in}) and motor speed, for different values of the load are measured and so the input power factor of the motor is calculated. The stray load loss of the motor and its equivalent resistance, are calculated using the equations as follows:

$$P_{st} = P_{stfl} \frac{I_2^2}{I_{2fl}^2} \tag{1}$$

$$r_{st} = 0.018 r_2 \frac{1 - s_{fl}}{s_{fl}} \tag{2}$$

where:

P_{st}, P_{stfl}	stray load loss in any load and full load respectively
I_2, I_{2fl}	rotor current in any load and full load respectively
s_{fl}	full-load motor slip

Stator and rotor winding resistances are modified in each temperature. Using the modified values of stator and rotor

(r_{1c}, r_{2c}), the admittance of each branch of the equivalent circuit is calculated using the following equations:

$$\overline{Y}_2 = \frac{1}{\frac{r_{2c}}{s} + r_{st} + jx_2} \tag{3}$$

$$\overline{Y}_m = -\frac{j}{x_m} + \frac{1}{r_m} \tag{4}$$

$$\overline{Y}_1 = \frac{1}{r_{1c} + jx_1} \tag{5}$$

where:

x_1, x_2	stator and rotor leakage reactances respectively
x_m	magnetizing reactance
r_m	core loss equivalent resistance
$\overline{Y}_1$, $\overline{Y}_2$	Stator and rotor branch admittances respectively
$\overline{Y}_m$	magnetizing branch admittance

The stator, rotor and magnetizing currents (I_1, I_2 and I_m), output, input powers (P_{out} and P_{in}) and efficiency (η) of the motor can be calculated using the following equations:

$$I_{2est.} = \left| \frac{\overline{V}_1 \overline{Y}_1 \overline{Y}_2}{\overline{Y}_1 + \overline{Y}_2 + \overline{Y}_m} \right| \tag{6}$$

$$I_{1est.} = \left| I_2 \right| \left| \frac{\overline{V}_1 \overline{Y}_1 (\overline{Y}_2 + \overline{Y}_m)}{\overline{Y}_1 + \overline{Y}_2 + \overline{Y}_m} \right| \tag{7}$$

$$I_{mest.} = \left| \frac{\overline{V}_1 \overline{Y}_{12}}{r_m (\overline{Y}_1 + \overline{Y}_2 + \overline{Y}_m)} \right| \tag{8}$$

$$P_{inest.} = 3[r_{1c} I_1^2 + (\frac{r_{2c}}{s} + r_{st}) I_2^2 + r_m I_m^2] \tag{9}$$

$$P_{outest.} = 3 \frac{1-s}{s} r_{2c} I_2^2 \tag{10}$$

$$\eta = 100 \frac{P_{outest.}}{P_{inest.}} \tag{11}$$

The *est.* subscripts refer to the estimated values of each variable.

The object of the genetic algorithm is minimizing the error between the measured and calculated parameters. Two sets of the input parameters can be used in the calculation process as follows:
1. input power, stator current and power factor
2. output power, stator current, power factor and full-load output power

Three error functions can be exists using the first set of the parameters as follows:

$$f_1 = 100 \frac{I_{1est.} - I_1}{I_1} \tag{12}$$

$$f_2 = 100 \frac{P_{inest.} - P_{in}}{P_{in}} \tag{13}$$

$$f_3 = 100 \frac{pf_{est.} - pf}{pf} \tag{14}$$

The fitting function is the equation number (15) that must be minimized.

$$ff_2 = \frac{1}{f_1^2 + f_2^2 + f_3^2} \tag{15}$$

Except the three above mentioned error functions, another error and fitting functions is used in the efficiency estimation using second set of the parameters as follows:

$$f_4 = 100 \frac{P_{out} - P_{outest.}}{P_{out}} \tag{16}$$

$$ff_3 = \frac{1}{f_1^2 + f_2^2 + f_3^2 + f_4^2} \qquad (17)$$

In this way using the genetic algorithm, the equivalent circuit parameters of the motor estimates and the motor efficiency calculated.

In this paper, efficiency of an induction motor estimates in three conditions. In the first condition only the rated values of the motor is used as the input parameters of the algorithm. In the second condition measured input values of the motor in different loads, and finally in the third condition measured full-load output power of the motor is used as the input parameters of the algorithm. In all the conditions efficiency of the motor is estimated and compared with its real value. Fig. 1 shows the flowchart of the third method of efficiency estimation; the flowcharts of two other methods are approximately the same as this method.
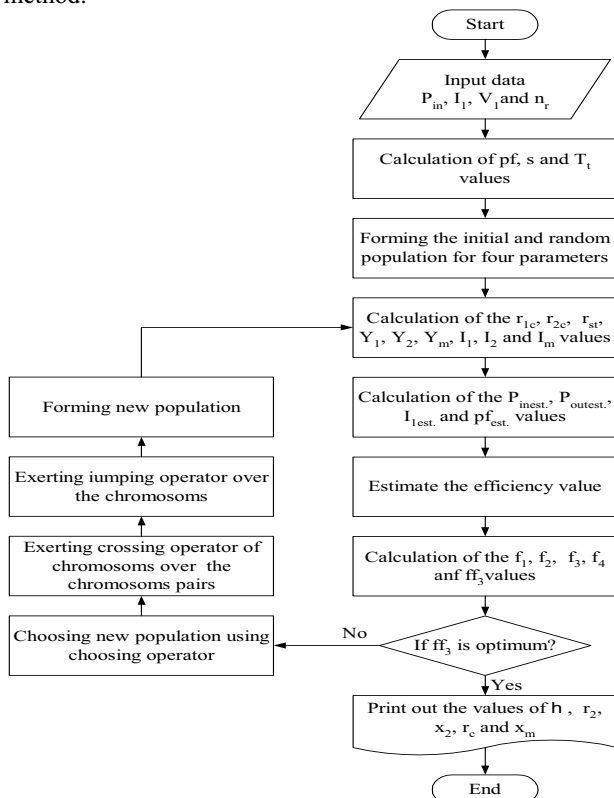

Fig. 1. Flowchart of the efficiency estimation using third method

5. ILLUSTRATIVE EXAMPLES

First example- Table 1 shows the first test motor nominal values. In the table 2, no-load, locked-rotor and loading test results of the motor are shown.

Table 1. Nominal values of the first test motor

DL2050	3~M	3.5 kW
220/380 V	D/Y	14/8.4 A
Pf=0.8	Design class B	50 Hz

Table 2. Test results of the first motor in the 7 load points

Load%	13.19	26.21	39.05	51.7	64.18	76.47	100
I_1 (A)	3.22	3.7	4.2	4.88	5.7	6.57	8.4
n_r (rpm)	1480	1470	1460	1450	1440	1430	1420
V_1 (V)	380	380	380	380	380	380	380
P_{in} (W)	680	1240	1750	2250	2740	3290	4423
P_{out} (W)	494.95	923.63	1367	1822.1	2261.9	2695.49	3500
η%	68.375	74.486	78.114	80.983	82.553	81.93	79.132

Using the three above mentioned conditions, the efficiency of the motor in any load is estimated and the error of each method is calculated. Tables 3-5 show the results. In

Fig.3, the estimated efficiency versus the motor load curves are shown.

Table 3. Estimated efficiency in the first method, for the first motor

Load%	13.19	26.21	39.05	51.7	64.18	76.47	100
η%	78.212	81.697	82.87	82.998	82.597	81.911	80.957
η-error	-9.837	-7.211	-4.756	-2.015	-0.044	-0.019	-1.825
Average error=5.004							

Table 4. Estimated efficiency in the second method, for the first motor

Load%	13.19	26.21	39.05	51.7	64.18	76.47	100
η%	70.523	76.18	78.868	80.105	80.562	80.578	81.117
η-error	-2.148	-1.694	-0.754	0.878	1.991	1.352	-1.985
Average error=1.824							

Table 5. Estimated efficiency in the third method, for the first motor

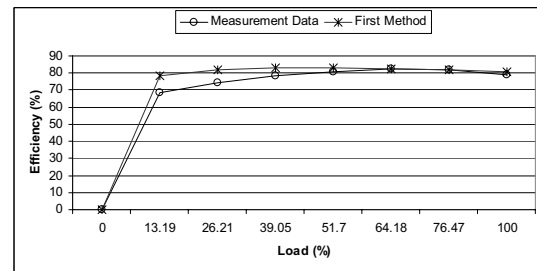| Load%	13.19	26.21	39.05	51.7	64.18	76.47	100
η%	69.082	75.002	77.873	79.238	79.782	79.866	79.443
η-error	-0.707	-0.516	0.241	1.745	2.771	2.064	-0.311
Average error=1.495							

Fig. 2. Measured[o] and estimated[*] efficiency versus load in the first method, for the first motor
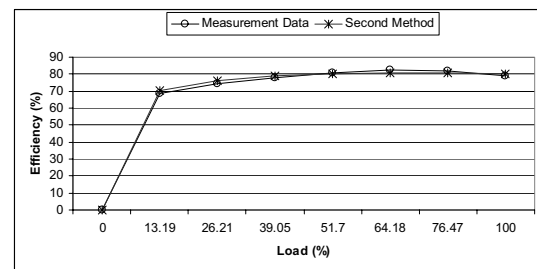

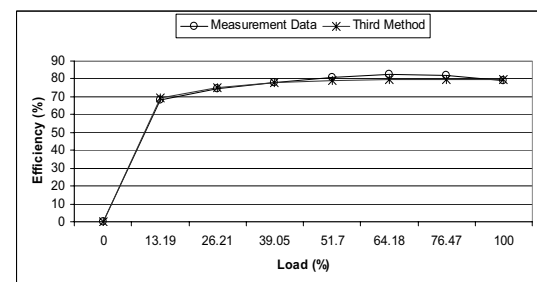Fig. 3. Measured[o] and estimated[*] efficiency versus load in the second method, for the first motor

Fig. 4. Measured[o] and estimated[*] efficiency versus load in the third method, for the first motor
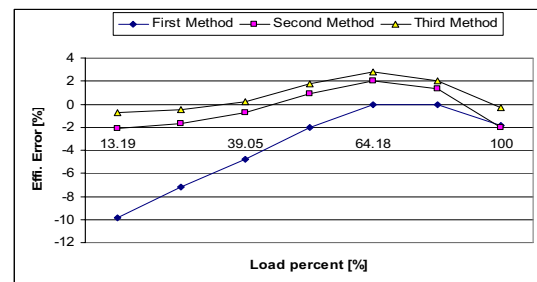

Fig. 5. Estimated efficiency values versus load for three methods, in the first motor

Second example- Table 6 shows the second test motor nominal values. In the table 7, no-load, locked-rotor and loading test results of the motor are shown.

Table 6. Nominal values of the second test motor

DL2051	3~M	3 kW
220 V	Y /Y	11.5 A
Pf=0.9	Design class A	50 Hz

Table 7. Test results of the second motor in the 6 load points

Load%	16.19	30.57	45.23	59.9	74.35	100
I_1 (A)	3.58	4.42	5.52	6.86	8.32	11.5
n_r (rpm)	1460	1450	1440	1430	1420	1410
V_1 (V)	220	220	220	220	220	220
P_{in} (W)	800	1280	1790	2340	2920	3944
P_{out} (W)	508.67	917.35	1357.17	1797	2230.53	3000
η%	63.58	71.67	75.82	76.79	76.39	76.06

Using the three above mentioned conditions, the efficiency of the motor in any load is estimated and the error of each method is calculated. Tables 8-10 show the results. In Figs. 6-9 the estimated efficiency versus the motor load curves are shown.

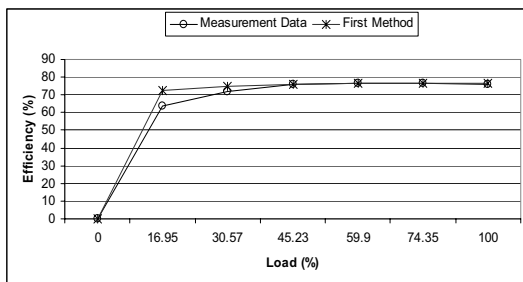Table 8.Estimated efficiency in the first method, for the second motor

Load%	16.95	30.57	45.23	59.9	74.35	100
η%	72.53	74.76	75.97	76.54	76.73	76.35
η-error	-8.95	-3.09	-0.15	0.25	-0.34	-0.29
Average error=2.8649						

Table 9.Estimated efficiency in the second method, for the second motor

Load%	16.95	30.57	45.23	59.9	74.35	100
η%	68.63	74.54	75.81	76.43	76.66	76.3
η-error	-5.05	-2.87	0.01	0.36	-0.27	-0.24
Average error=2.18						

Table 10.Estimated efficiency in the third method, for the second motor

Load%	16.95	30.57	45.23	59.9	74.35	100
η%	67.50	73.17	75.74	76.19	76.27	75.80
η-error	-3.92	-1.5	0.08	0.60	0.12	0.26
Average error=1.6						

Fig. 6. Measured° and estimated* efficiency versus load in the first method, for the second motor
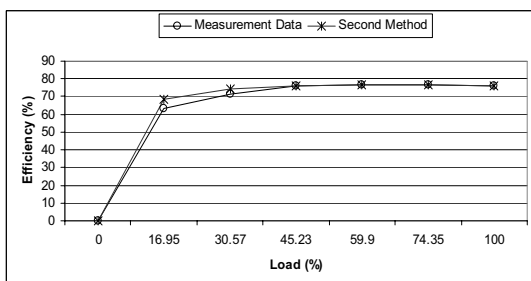
Fig. 7. Measured° and estimated* efficiency versus load in the second method, for the second motor

6. CONCLUSIONS

algorithm is one of the optimization methods that can be applied for efficiency estimation of an induction motor. Using this algorithm in three different methods,
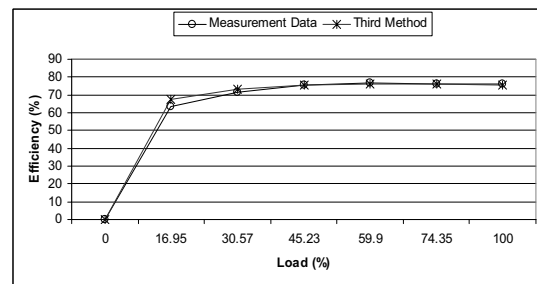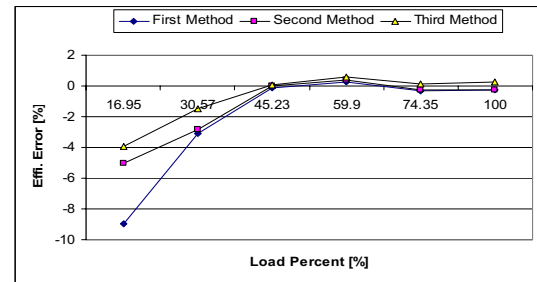

Fig. 8. Measured° and estimated* efficiency versus load in the third method, for the second motor

Fig. 9. Estimated efficiency values versus load for three methods, in the second motor

efficiency of an induction motor is estimated. Following comparisons can be made about these three methods:

1. In the first method only the rated values of the motor is needed, but the estimated efficiency isn't accurate. This method can be used only for giving an approximate value of the efficiency.

2. In the second method only the electrical input parameters of the motor is used, hence the accuracy of this method is better than that of the first method. This method can be used as an efficient and accurate method of motor efficiency estimation.

3. In the third method the error is the lowest one, but due to the use of the mechanical output parameters of the motor, this method can't be used in working condition of the motor.

7. REFERENCES

[1] K. F. Cheek, P. Pillay, "Impact of Energy Efficient Motors in the Petrochemical Industry on Entergy's Demand side Management Program", Electric Power Systems Research 42, Vol. 1, 1997, pp. 11-15.

[2] P. Pillay, V. Levin, P. Otaduy, J. Kueck, "In-situ Induction Motor Efficiency Determination Using the Genetic Algorithm", IEEE trans. On Energy Conversion, Vol. 13, No. 4, Dec. 1998, pp. 326-333.

[3] J. D. Kueck, J. R. Gray, R. C. Driver, J. S. Hsu, "Assessment of Available Methods for evaluating In-Service Motor Efficiency", Report on National Laboratory ORNL-TM-13237 managed by Lockheed Martin Energy Research Corporation, 1996.

[4] IEEE Power Engineering Society, IEEE Standard Test Procedure for Poly phase Induction Motors and Generators, IEEE Std. 112-1991, Dec. 5, 1991

[5] J. C. Hirzel, "Efficiency Measurement and Evaluation of Existing Motors", IEEE Conf. Paper PCI-83-25, Petroleum and Chemical Industry Conference, 1983.

[6] H.K. Ozturka, O.E. Canyurta, A. Hepbaslib, Z. Utluc "Three Different Genetic Algorithm Approaches to the Estimation of Residential Energy Input/Output Values", Elsevier, Building and Environment 39, 2004, pp. 807–816.

[7] H.K. Lam, S.H. Ling, F.H.F. Leung, P.K.S. Tam "Function Estimation using a Neural-Fuzzy Network and an Improved Genetic Algorithm", Elsevier, International Journal of Approximate Reasoning 36, 2004, pp. 243–260.

[8]   Marzio Marseguerra, Enrico Zio, Luca Podollini "Model Parameter
       Estimation and Sensitivity by Genetic Algorithms", Elsevier, Annals
       of Nuclear Energy 30, 2003, pp. 1437–1456.