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 efficiency estimation procedures are studied obviously in this paper and compare with the genetic algorithm procedures.

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
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 \( P_m \) 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:

\[
P_n = P_{0\theta} \frac{I_1^2}{I_2} \tag{1}
\]

\[
r_\theta = 0.018r_1 \frac{1-s_s}{s_\theta} \tag{2}
\]

where:
- \( P_n, P_{0\theta} \) stray load loss in any load and full load respectively
- \( I_1, I_{0\theta} \) rotor current in any load and full load respectively
- \( s_s \) full-load motor slip

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

\[
\bar{Y}_2 = \frac{1}{s \left(r_\theta + r_c + jx_\phi \right)} \tag{3}
\]

\[
\bar{Y}_n = \frac{1}{s r_n} \tag{4}
\]

\[
\bar{Y} = \frac{1}{r_n + jx_1} \tag{5}
\]

where:
- \( s, x_2 \) stator and rotor leakage reactances respectively
- \( x_n \) core loss equivalent resistance
- \( \bar{Y}_s, \bar{Y}_n \) Stator and rotor branch admittances respectively

\[
\bar{Y}_2, \bar{Y}_n \quad \text{magnetizing branch admittance}
\]

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

\[
I_{1\text{out}} = \frac{\bar{Y}_2 \bar{Y}_n}{\bar{Y}_2 + \bar{Y}_n + \bar{P}_s} \tag{6}
\]

\[
I_{2\text{out}} = \frac{\bar{Y}_2 \bar{Y}_n}{\bar{Y}_2 + \bar{Y}_n + \bar{P}_n} \tag{7}
\]

\[
I_{\text{out}} = \frac{\bar{Y}_2 \bar{Y}_n}{\bar{Y}_2 + \bar{Y}_n} \tag{8}
\]

\[
P_{\text{out}} = \frac{3}{s} \left( r_1 I_1^2 + \frac{r_c + r_n}{s} I_1 I_m^* \right) \tag{9}
\]

\[
P_{\text{out}} = \frac{3}{s} \left( r_n I_2^2 \right) \tag{10}
\]

\[
\eta = \frac{100 \frac{P_{\text{out}}}{P_n}}{P_{\text{out}}} \tag{11}
\]

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:

\[
f_1 = 100 \frac{I_{1\text{out}} - I_1}{I_1} \tag{12}
\]

\[
f_2 = 100 \frac{P_{\text{out}} - P_n}{P_n} \tag{13}
\]

\[
f_1 = 100 \frac{PF_{\text{out}} - PF_n}{PF_n} \tag{14}
\]

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

\[
f_{fit} = \frac{1}{f'_1 + f'_2 + f'_3} \tag{15}
\]

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:

\[
f_4 = 100 \frac{P_{\text{out}} - P_{\text{out1}}}{P_{\text{out}}} \tag{16}
\]
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.

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

<table>
<thead>
<tr>
<th>LoadPs</th>
<th>3 M</th>
<th>3.5 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>220/380 V</td>
<td>14/8.4 A</td>
<td></td>
</tr>
<tr>
<td>PF=0.8</td>
<td>Design class B</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>LoadPs</th>
<th>13.19</th>
<th>26.21</th>
<th>39.05</th>
<th>51.7</th>
<th>64.18</th>
<th>76.47</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1 (A)</td>
<td>3.22</td>
<td>3.76</td>
<td>4.2</td>
<td>4.88</td>
<td>5.7</td>
<td>6.57</td>
<td>8.4</td>
</tr>
<tr>
<td>n1 (rpm)</td>
<td>1480</td>
<td>1470</td>
<td>1460</td>
<td>1450</td>
<td>1440</td>
<td>1430</td>
<td>1420</td>
</tr>
<tr>
<td>V1 (V)</td>
<td>380</td>
<td>380</td>
<td>380</td>
<td>380</td>
<td>380</td>
<td>380</td>
<td>380</td>
</tr>
<tr>
<td>P1 (W)</td>
<td>680</td>
<td>1240</td>
<td>1750</td>
<td>2250</td>
<td>2740</td>
<td>3290</td>
<td>4423</td>
</tr>
<tr>
<td>Pout (W)</td>
<td>494.95</td>
<td>923.63</td>
<td>1367</td>
<td>1822.1</td>
<td>2261.9</td>
<td>2695.49</td>
<td>3500</td>
</tr>
<tr>
<td>δ%</td>
<td>68.375</td>
<td>74.486</td>
<td>78.114</td>
<td>80.983</td>
<td>82.553</td>
<td>81.931</td>
<td>79.132</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Load (%)</th>
<th>16.95</th>
<th>30.57</th>
<th>45.23</th>
<th>59.9</th>
<th>74.35</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (A)</td>
<td>3.58</td>
<td>4.42</td>
<td>5.52</td>
<td>6.86</td>
<td>8.32</td>
<td>11.5</td>
</tr>
<tr>
<td>(n_r) (rpm)</td>
<td>1460</td>
<td>1450</td>
<td>1440</td>
<td>1430</td>
<td>1420</td>
<td>1410</td>
</tr>
<tr>
<td>(V_1) (V)</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>220</td>
</tr>
<tr>
<td>(P_{in}) (W)</td>
<td>800</td>
<td>1280</td>
<td>1790</td>
<td>2340</td>
<td>2920</td>
<td>3944</td>
</tr>
<tr>
<td>(P_{out}) (W)</td>
<td>508.67</td>
<td>917.35</td>
<td>1357.17</td>
<td>1797</td>
<td>2230.53</td>
<td>3000</td>
</tr>
<tr>
<td>(\eta)</td>
<td>63.58</td>
<td>71.67</td>
<td>75.82</td>
<td>76.79</td>
<td>76.39</td>
<td>76.06</td>
</tr>
<tr>
<td>(\eta)-error</td>
<td>-8.95</td>
<td>-3.09</td>
<td>-0.15</td>
<td>0.25</td>
<td>-0.34</td>
<td>-0.29</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Load (%)</th>
<th>16.95</th>
<th>30.57</th>
<th>45.23</th>
<th>59.9</th>
<th>74.35</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta)</td>
<td>72.53</td>
<td>74.76</td>
<td>75.97</td>
<td>76.54</td>
<td>76.73</td>
<td>76.35</td>
</tr>
<tr>
<td>(\eta)-error</td>
<td>-8.95</td>
<td>-3.09</td>
<td>-0.15</td>
<td>0.25</td>
<td>-0.34</td>
<td>-0.29</td>
</tr>
</tbody>
</table>

Average error = 2.8649

**Table 9:** Estimated efficiency in the second method, for the second motor

<table>
<thead>
<tr>
<th>Load (%)</th>
<th>16.95</th>
<th>30.57</th>
<th>45.23</th>
<th>59.9</th>
<th>74.35</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta)</td>
<td>68.63</td>
<td>74.54</td>
<td>75.81</td>
<td>76.43</td>
<td>76.66</td>
<td>76.3</td>
</tr>
<tr>
<td>(\eta)-error</td>
<td>-5.05</td>
<td>-2.87</td>
<td>0.01</td>
<td>0.36</td>
<td>-0.27</td>
<td>-0.24</td>
</tr>
</tbody>
</table>

Average error = 2.18

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

<table>
<thead>
<tr>
<th>Load (%)</th>
<th>16.95</th>
<th>30.57</th>
<th>45.23</th>
<th>59.9</th>
<th>74.35</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta)</td>
<td>67.50</td>
<td>73.17</td>
<td>75.74</td>
<td>76.19</td>
<td>76.27</td>
<td>75.80</td>
</tr>
<tr>
<td>(\eta)-error</td>
<td>-3.92</td>
<td>-1.5</td>
<td>0.08</td>
<td>0.60</td>
<td>0.12</td>
<td>0.26</td>
</tr>
</tbody>
</table>

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.

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

6. CONCLUSIONS

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7. REFERENCES


