CURRENT STUDY CONCERNED INDUCTION MOTOR EFFICIENCY AND ITS EXPERIMENTAL DETERMINATION

ABSTRACT A definition and kinds of efficiency determination methods, models of power flow and selected efficiency determination methods by standards: Japanese JEC, American IEEE 112, International IEC 60034-2 and the latest IEC 61972 and proposition of the newest methods prepared by the author are presented in this work. There are presented distributions of losses in induction squirrel-cage motor applied in particular methods, too. In this work are characterized efficiency determination methods, underlining the differences among them. There are compared the values of efficiency from different methods for the same motor and features of particular methods and presented current world tendency in progress of efficiency determination methods in induction squirrel-cage motors.

1. INTRODUCTION

Experimental efficiency determination is constantly current because of appearing both new induction motor type and new efficiency determination methods.

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Some propositions of efficiency determination methods are proposed by different institutions and countries. Then it is worth considering real losses distribution and power flow diagrams to evaluate their accordance with physical phenomena which occur in induction motor.

2. DEFINITION OF EFFICIENCY

Efficiency in electrical machines are defined as ratio of output power $P_{out}$ to input power $P_{in}$:

$$\eta = \frac{P_{out}}{P_{in}} \quad (1)$$

Because output power is equal input power minus losses $P_t$ occured in electrical machine

$$P_{out} = P_{in} - P_t \quad (2)$$

so it is possible to express efficiency as

$$\eta = \frac{P_{in} - P_t}{P_{in}} = 1 - \frac{P_t}{P_{in}} \quad (3)$$

$$\eta = \frac{P_{out}}{P_{out} + P_t} = 1 - \frac{P_t}{P_{out} + P_t} \quad (4)$$

These formulas are valid for both motors and generators. It results from them that efficiency can be determined if it is known output and input power or losses and output or input power. Because in motors is more conveniently to measure input power (measurement of electrical quantities) efficiency is usually determined by (3). Instead in generators is more conveniently to measure output power therefore generators efficiency is usually determined by (4).
3. KINDS OF EFFICIENCY DETERMINATION METHODS

There are two kinds of efficiency determination methods. The first one are direct methods e. g. input-output method (1). The second one create methods which using losses ((3) and (4)) and they are named indirect methods.

4. LOSS COMPONENTS IN SQUIRREL-CAGE INDUCTION MOTOR

Both in publication and standards are used different power flow models to determine squirrel-cage induction motor efficiency. Usually are distinguished five components of losses as follows

- stator winding losses determined on the basis of currents and resistance values;
- core losses determined from no-load test;
- rotor winding losses determined on the basis of internal power and slip;
- mechanical losses determined from no-load test;
- stray load losses which are the difference between input power and the four components above.

In table 1 is presented a distribution of loss components in five 4-poles motors of different size. On fig.1 are shown participation (percentage) of different loss components in total losses determined by method B standard IEEE 112. It can be noticed that percentage participation of stator and rotor winding losses decreases if motor size increases. Inverse tendency concerns stray load losses, which participation in total losses increases if motor size increases.

On fig. 2 is presented an example of percentage participation of different loss components in total losses determined by method B standard IEEE 112 [4] for motor 160 L-4. Stray load losses take proportionally big part in this motor (20 %). Winding losses comprise 58 % and core losses 20 %. Mechanical losses are proportionally small (3 %).
TABLE 1
Loss components determined by method B standard IEEE 112 [4] in five 4-poles motors

<table>
<thead>
<tr>
<th>Motor type</th>
<th>90 L-4</th>
<th>112 M-4</th>
<th>160 L-4</th>
<th>225 S-4</th>
<th>280 M-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (P_N) [kW]</td>
<td>1.5</td>
<td>4</td>
<td>15</td>
<td>37</td>
<td>90</td>
</tr>
<tr>
<td>2 (P_{in}) [W]</td>
<td>1777.9</td>
<td>4528.1</td>
<td>16772.9</td>
<td>40499.0</td>
<td>96316.1</td>
</tr>
<tr>
<td>3 (P_{Fe}) [W]</td>
<td>60.1</td>
<td>117.6</td>
<td>348.8</td>
<td>860.7</td>
<td>935.2</td>
</tr>
<tr>
<td>4 (P_m) [W]</td>
<td>12.0</td>
<td>51.3</td>
<td>58.2</td>
<td>348.0</td>
<td>1284.8</td>
</tr>
<tr>
<td>5 (P_{ws}) [W]</td>
<td>121.5</td>
<td>197.2</td>
<td>593.3</td>
<td>1139.8</td>
<td>1863.3</td>
</tr>
<tr>
<td>6 (P_{wr}) [W]</td>
<td>68.1</td>
<td>114.8</td>
<td>429.8</td>
<td>583.2</td>
<td>989.2</td>
</tr>
<tr>
<td>7 (P_{ul}) [W]</td>
<td>15.9</td>
<td>47.3</td>
<td>343.1</td>
<td>580.6</td>
<td>1237.7</td>
</tr>
<tr>
<td>8 (P_t) [W]</td>
<td>277.6</td>
<td>528.2</td>
<td>1773.2</td>
<td>3512.3</td>
<td>6310.2</td>
</tr>
</tbody>
</table>

where:

- \(P_N\) – motor rated power;
- \(P_{in}\) – input power;
- \(P_{Fe}\) – core losses determined from no-load test;
- \(P_m\) – mechanical losses determined from no-load test;
- \(P_{ws}\) – stator winding losses;
- \(P_{wr}\) – rotor winding losses;
- \(P_{ul}\) – stray load losses;
- \(P_t\) – total losses.

Subscript \(s\) – stator, \(r\) – rotor.

Fig. 1. Percentage participation of different loss components in total losses determined by method B standard IEEE 112 [4]
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Taking into consideration different power flow models, which are more or less in accord with a real distribution of losses in motor, results from reasons as follows:

- need to compile efficiency determination methods, which are possible to use even in bad equipped laboratory;
- method simplicity;
- rejecting of models, in which a determination of loss components is difficult because of obtaining different results of losses from different methods.

The consequence of using loss determination method not agreed with a real loss distribution is obtaining conventional efficiency value it means different from real efficiency value.

In the next subparagraphs are presented miscellaneous power flow models used in standards and propositions of new ones.

![Figure 2](image-url)

**Fig. 2.** Example of percentage participation of different loss components in total losses determined by method B standard IEEE 112 [4] for motor 160 L-4

### 4.1. Power flow model without considering of stray load losses

On the fig. 3 is presented power flow model without considering of stray load losses, which is applied in Japanese standard JEC. Omitting this component of losses increases efficiency up to 3 pt. %.
Fig. 3. Power flow diagram without considering of stray load losses in squirrel-cage induction motor at rated load (motor 160 L-4 rated power 15 kW, \(2p = 4, \eta = 91.51\%\) (JEC)). Widths of streams are proportional to respective powers

This diagram corresponds with the equation system as follows

\[
P_{in} = P_{ws} + P_{Fe} + P_i \quad (3.1a)
\]

\[
P_i = P_{wr} + P_m + P_{out} \quad (3.1b)
\]

\[
P_m = P_{mbe} + P_{mv} \quad (3.1c)
\]

where:

\(P_{in}\) – input power;

\(P_{ws}\) – stator winding losses;

\(P_{Fe}\) – core losses determined from no-load test;
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\[ P_l \] – internal power;
\[ P_{wr} \] – rotor winding losses;
\[ P_m \] – mechanical losses determined from no-load test;
\[ P_{out} \] – output power;
\[ P_{mbe} \] – friction losses;
\[ P_{mv} \] – windage losses.

Additional subscript \( s \) – stator, \( r \) – rotor.

4.2. Power flow model with considering of stray load losses

On the fig. 4 is presented power flow model with considering of stray load losses, which is applied in several standards: IEC 60034-2, IEEE 112 (CSA C390, NEMA MG-1), IEC 61972 [3,4,5,6,7] for motor 160 L-4.

This diagram corresponds with the equation system as follows

\[
P_{in} = P_{ws} + P_{Fe} + P_{l} \tag{3.2a}
\]

\[
P_{l} = P_{wr} + P_{al} + P_{m} + P_{out} \tag{3.2b}
\]

\[
P_{m} = P_{mbe} + P_{mv} \tag{3.2c}
\]

where:
\[ P_{al} \] – stray load losses.

In presented diagram of power flow is assumed that core losses \( P_{Fe} \) determined from no-load test are located in stator although it is not truth because a part of them stray no-load losses \( P_{al} \) are located in rotor. Stray load losses \( P_{al} \) instead may have different percentage distribution between stator and rotor but location only in rotor is not correct, too.

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Fig. 4. Power flow diagram in squirrel-cage induction motor at rated load (motor 160 L-4 rated power 15 kW, \(2p = 4\), \(\eta = 89.43\%\) (IEEE 112-method B)). Widths of streams are proportional to respective powers.

4.3. Proposition of new power flow model with considering of loss flow approximate to real

On the fig. 5 is presented a new power flow diagram in induction motor with considering of core losses partition to fundamental and stray no-load losses and stray load losses partition between stator and rotor.

This diagram corresponds with the equation system as follows

\[
P_{\text{in}} = P_{ws} + P_{Fe} + P_{als} + P_i
\]

(3.3a)
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\[ P_i = P_{wr} + P_{a0} + P_{alr} + P_m + P_{out} \]  
\[ P_m = P_{mbe} + P_{mv} \]

where:
- \( P_{Feq} \) – fundamental core losses;
- \( P_{alis} \) – stator stray load losses;
- \( P_{a0} \) – stray no-load losses;
- \( P_{alr} \) – stator stray load losses.

\[ P_{in}=16735 \text{ W} \]

\[ P_{ws}=593 \text{ W} \]
\[ P_{Feq}=194 \text{ W} \]
\[ P_{alis}=172 \text{ W} \]
\[ P_{wr}=427 \text{ W} \]
\[ P_{a0}=119 \text{ W} \]
\[ P_{alr}=172 \text{ W} \]
\[ P_{im}=15058 \text{ W} \]
\[ P_m=58 \text{ W} \]

\[ P_{out}=15000 \text{ W} \]

Fig. 5. Proposition of new power flow diagram in squirrel-cage induction motor at rated load (motor 160 L-4 rated power 15 kW, \( 2p = 4 \), \( \eta = 89.63 \% \) (method Prop. 1)). Widths of streams are proportional to respective powers.
5. EFFICIENCY DETERMINATION METHODS

There are several standards which concern efficiency determination or include efficiency determination method. The most important are

- JEC [3],
- IEC 60034-2:2000 [3],
- IEC 61972:2002 [7].

Efficiency determination methods in these standards may be divided into three groups: direct, indirect and mixed. **Direct** determination consists in direct measurement of output and input power. **Indirect** determination consists in measurement of machine losses and input power (3) or output power (4). **Indirect** efficiency determination may be carried out by methods as follows

- segregation of losses method and their summation,
- total losses (one value e. g. from calorimetric method).

5.1. JEC standard

In this Japanese standard, which is based on power flow diagram on fig. 3, stray load losses are omitted and stator winding losses are conventional (determined for conventional stator resistance in reference temperature depended on class of insulation systems) [2].

5.2. IEC 60034-2 standard

There are several method in this standard, but recommended is segregation of losses method which is based on power flow diagram on fig. 4. Stray load losses are equal 0,5 % of input (motors) or rated (generators) power. Stator winding losses are conventional (determined for conventional stator resistance in reference temperature depended on class of insulation systems). So both loss components are conventional.

5.3. IEEE 112 standard

This standard includes five basic method: **A, B, C, E, F** and two modification of method E and F: **E1** and **F1**.
Method B is indirect method and is based on power flow diagram on fig. 4. Output power is measured but not taken directly to determining efficiency only to stray loss determination. So stray load losses are determined from measurements. Stator winding losses are determined for real temperature.

5.4. IEC 61972 standard

Method 1 in this standard is similar to method B. There is difference between these methods in core losses. In B method they are invariable. In method 1 these losses are depended on load.

5.5. Proposition 1 of new efficiency determination method

Proposition 1 of new efficiency determination method is based on power flow diagram on fig. 5. The differences between this proposition and method 1 of IEC 61972 are as follows

- core losses $P_{Fe}$ are divided into fundamental losses $P_{Fe,p}$ located in stator and stray no-load losses $P_{a0}$ located in rotor. Partition of core losses $P_{Fe}$ into the two components can be assumed as $P_{Fe,p}/P_{Fe} = 0.6$ and $P_{a0}/P_{Fe} = 0.4$ (on the basis of my research).
- stray load losses $P_{al}$ are divided into stator and rotor in ratio 1:1. From references [8] it results that partition of these losses between stator $P_{als}$ and rotor $P_{alr}$ depends on construction, materials and technology of motor e. g. in motor with 28 rotor slots $P_{als}/P_{alr} = 20\% / 80\%$, and in motor with 44 rotor slots $P_{als}/P_{alr} = 65\% / 35\%$. From calculation by [9] for motor 160 L-4 with 28 rotor slots $P_{als}/P_{alr} = 60\% / 40\%$. Under these facts is decided that taking $P_{als}/P_{alr} = 50\% / 50\%$ will be average value.

The other points of algorithm are the same as in method 1 of IEC 61972.

5.6. Proposition 2 of new efficiency determination method

Proposition 2 of new efficiency determination method similarly as proposition 1 is based on power flow diagram on fig. 5. The differences between this proposition 2 and proposition 1 are as follows
in core losses under load is taken into consideration not only the voltage drop on stator resistance but on stator reactance, too [1].

- Mechanical losses are calculated for slip under load by formula [1]

\[
P_{ms} = P_m (1-s)^2
\]

or when friction losses \(P_{mbe}\) and windage losses \(P_{mv}\) are known by

\[
P_{ms} = P_{mbe}(1-s) + P_{mv} (1-s)^3
\]

The other points of algorithm are the same as in proposition 1 and method 1 of IEC 61972.

5.7. Efficiency determination results by different methods

In table 2 are presented efficiency determination results for 160 L-4 motor determined by methods described in chapter 5. The highest value gives Japanese standard (91,51 %), then segregation of losses method by IEC 60034-2 (91,06 %), proposition 2 (89,85 %), proposition 1 (89,63 %), method 1 by IEC 61972 (89,62 %) and the lowest by method B IEEE 112 (89,43 %).

**TABLE 2**

Losses and efficiency of 160 L-4 motor determined by different methods

<table>
<thead>
<tr>
<th>Norma</th>
<th>JEC</th>
<th>IEC 60034-2 m. 9.1</th>
<th>IEEE 112 m. B</th>
<th>IEC 61972 m. 1</th>
<th>Prop. 1</th>
<th>Prop. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(\eta) [%]</td>
<td>91,51</td>
<td>91,06</td>
<td>89,43</td>
<td>89,62</td>
<td>89,63</td>
</tr>
<tr>
<td>2</td>
<td>(P_m) [W]</td>
<td>16391,0</td>
<td>16473,4</td>
<td>16773,2</td>
<td>16736,5</td>
<td>16735,1</td>
</tr>
<tr>
<td>3</td>
<td>(P_{Fe}) [W]</td>
<td>348,8</td>
<td>348,8</td>
<td>348,8</td>
<td>313,0</td>
<td>(313,0)</td>
</tr>
<tr>
<td>3a</td>
<td>(P_{Fe}p) [W]</td>
<td>194,1</td>
<td>171,1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>(P_{ab}) [W]</td>
<td>171,6</td>
<td>171,6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>(P_m) [W]</td>
<td>58,2</td>
<td>58,2</td>
<td>58,2</td>
<td>58,2</td>
<td>58,2</td>
</tr>
<tr>
<td>5</td>
<td>(P_{sw}) [W]</td>
<td>554,2</td>
<td>554,2</td>
<td>593,3</td>
<td>593,3</td>
<td>593,3</td>
</tr>
<tr>
<td>6</td>
<td>(P_{sw}) [W]</td>
<td>429,8</td>
<td>429,8</td>
<td>429,8</td>
<td>429,8</td>
<td>427,5</td>
</tr>
<tr>
<td>6a</td>
<td>(P_{ab}) [W]</td>
<td>118,9</td>
<td>104,8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>(P_{el}) [W]</td>
<td>0,0</td>
<td>82,4</td>
<td>343,1</td>
<td>343,1</td>
<td></td>
</tr>
<tr>
<td>7b</td>
<td>(P_{el}) [W]</td>
<td>171,5</td>
<td>171,5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>(P_{t}) [W]</td>
<td>1391,0</td>
<td>1473,4</td>
<td>1773,2</td>
<td>1737,4</td>
<td>1735,1</td>
</tr>
<tr>
<td>9</td>
<td>Model Fig. no.</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6. CONCLUSION

On the basis [10, 11] and chapter 5, in table 3 are presented the features of considered method. It results from this table that all features has only proposition 2. The segregation of losses method (IEC 60034-2) has not got any of these features.

Development of efficiency determination method in squirrel-cage motors is connected with high efficiency motors. There is visible tendency to efficiency determination more and more near the real value. But there are some proposition which dismisses us from this purpose e. g. eh-star method for stray load losses determination.

TABLE. 3
Features of different methods

<table>
<thead>
<tr>
<th></th>
<th>IEC 60034-2 m. 9.1</th>
<th>IEEE 112 m. B</th>
<th>IEC 61972 m. 1</th>
<th>Prop. 1</th>
<th>Prop. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Winding losses in real temperature</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>2</td>
<td>Voltage drop on stator resistance under load</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>3</td>
<td>Voltage drop on stator resistance and reactance under load</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>4</td>
<td>Core losses divided into fundamental and stray no-load</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>5</td>
<td>Stray load losses from measurements (regression analysis)</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>6</td>
<td>Partition of stray load losses between stator and rotor</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>7</td>
<td>Correction of mechanical losses under load</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
</tbody>
</table>

LITERATURE


AKTUALNE STUDIUM DOTYCZĄCE SPRAWNOŚCI SILNIKÓW INDUKCYJNYCH I EKSPERYMENTALNEGO JEJ WYZNACZANIA

Konrad DąBAŁA

ABSTRACT W pracy przedstawiono definicję i rodzaje metod wyznaczania sprawności, modele przepływu mocy oraz wybrane metody wyznaczania sprawności według norm: japońskiej JEC, amerykańskiej IEEE 112, międzynarodowych IEC 60034-2 i najnowszej IEC 61972 a także propozycje nowych metod opracowanych przez autora pracy. Przedstawiono także rozkłady strat w silniku indukcyjnym klatkowym stosowane w poszczególnych metodach. Scharakteryzowano metody wyznaczania sprawności, kładąc nacisk na uwypuklenie różnic między nimi. Porównano wartości sprawności otrzymane poszczególnymi metodami dla tego samego silnika. Porównano cechy poszczególnych metod oraz podano aktualne tendencje światowe w rozwoju metod wyznaczania sprawności w silnikach indukcyjnych klatkowych.