

A Case Study of Determining Energy Efficiency in Squirrel Cage Induction Motor According to IEC 60034-2-1:2014 Standard

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Abstract. Efficiency and sustainability are the most important and focused issues today. Industrial systems are the main working field to reduce energy consumption because of its share in the total amount of energy. According to TSI (Turkey Statistical Institute) data, industry sector in Turkey consumed 47.1% of total electrical energy in 2013. Electric motor-based systems are the important type of electrical loads in the industry. In the European Union, these systems are estimated to account for about 70% of all industrial electricity consumption. Since 1998, the motor producers and the standard organizations are trying to classify electrical motors by efficiency with standard methods. Nowadays, in EU and the other relevant countries, the IEC standard methods are used to determine the efficiency class of the induction motors. The latest standard was published in December 2014 with the code IEC 60034-2-1. In this study, an IE3 class 22 kW 4 poles induction motor was tested and the efficiency value was calculated by using IEC 60034-2-1 standard method. And the results were evaluated according to eco-design requirements for electric motors (EU 640/2009). The study covers all tests and calculation steps clearly in this paper.

Key words

Energy efficiency, Electric motors, Squirrel cage induction motor, IEC 60034-2-1 standard, Efficiency classes IE.

1. Introduction

The first formation about efficiency in electric motors was founded in 1998 by CEMEP (European Committee of Manufacturers of Electrical Machines and Power Electronics). The Committee's main issue was to protect consumers and prevent unfair competition in the electric motor production sector. As part of the voluntary agreement between CEMEP and the European Commission, three efficiency classes were defined for the power range of 1.1 kW to 90 kW [1].

- EFF3 = Motors with a low efficiency level
- EFF2 = Motors with an improved efficiency level
- EFF1 = Motors with a high efficiency level

This voluntary agreement has expired and then IEC standard was established in 2008 as an IEC 60034-30:2008 and renewed in 2014 as an IEC 60034-30-1:2014 [2]. The standard defines the efficiency classes for low voltage three-phase motors with a power range from 0.12 kW to 1,000 kW. The code of “IE” stands for “International Efficiency” and is combined with a number:

- IE1 = Standard efficiency
- IE2 = High efficiency
- IE3 = Premium efficiency
- IE4 = Super Premium efficiency
- IE5 = Envisaged for a future edition of the standard

The classifying standard covers the 2, 4, 6 or 8 poles motors that have a rated voltage U_N above 50 V up to 1 kV and are capable of continuous operation at their rated power with a temperature rise within the specified insulation temperature class. These motors ambient temperature is within the range of $-20\text{ }^{\circ}\text{C}$ to $+60\text{ }^{\circ}\text{C}$ and marked with an altitude up to 4,000 m above sea level [3].

The measuring method is also updated with the development of the other standards like classifying standard. The method was established IEC 60034-2-2 and updated in 2007 as IEC 60034-2-1 and the last changes was applied in 2014. The classifying standards IEC 60034-30-1 mentions that efficiency and losses should be verified in according to IEC 60034-2-1 standard with the ideal method of the specific motor type as given in IEC 60034-2-1:2014 [2, 3].

A study was published by Renier in 1999 about Comparison of IEEE 112-1996, IEC 34-2 - IEC 34-2A and JEC standards for determining efficiency of three phase induction motors [4]. A previous study was published by Cao in 2009. It describes a comparative study of induction motor testing standards IEEE 112 and the old version of IEC 60034-2-1:2007. Six induction motors were tested following two standards and the

results are compared with regard to their instrumental accuracy and test techniques [5]. There are some papers describe a set of experiments and discusses their results for determining the efficiency of the induction motors [6,7].

In this study, an IE3 class 22 kW, 4 poles induction motor was tested and the efficiency was calculated by using IEC 60034-2-1:2014 standard method. The standard contains differences between the previous one such as test order. The study covers all new tests and calculation steps very clearly in this paper. The standard IEC 60034-2-1:2014 version “*method 2-1-1B Summation of losses, additional load losses according to the method of residual loss*” was used to determine the efficiency of the sample motor and IEC 60034-30-1 was used the match the efficiency class and the results were evaluated according to EU directive eco-design requirements for electric motors (EU 640/2009) [8, 9].

2. The Motor Test Laboratory

The test laboratory is located in Turkish Standards Institute Campus in Turkey / Kocaeli. The laboratory is commissioned in March 2015 and also accredited from TURKAK (Turkish Accreditation Agency). TURKAK is a full member of EA (European Cooperation for Accreditation), IAF (International Accreditation Forum), and ILAC (International Laboratory Accreditation Cooperation) [10].

3. The Motor Test Sequences

The standard covers all rotating electrical machines and defines three different ideal procedures with low uncertainty within the given range of application. The method 2-1-1B is “*summation of separate losses, additional load loss determined by the method of residual loss*” to be applied for all three-phase motors with rated output power up to 2 MW [8].

Table 1. The motor parameters under test.

3-Phase Squirrel Cage Induction Motor			
Rated Power	22 kW	Rated rpm	1475
Rated Voltage	380 V	Rated Torque	Nm
Rated Freq.	50 Hz.	Rated Current	42 A
Duty Type	S1 Cont.	Isolation	IP-55, F

According to sample properties which are given in Table 1 the method 2-1-1B was used to determine the efficiency. This method determines the efficiency by the summation of separate losses; which are named iron loss, windage and friction losses, stator and rotor copper losses, additional load losses. The test method gives an obligation to trace a path about the tests. These tests are interconnected to each other and the test personnel should follow the instructions. The initial conditions to start the test protocol for instance room temperature should be equal or very similar to normal operating conditions. The tests starts with cold winding resistance measurement and in every independent test, the winding resistance should be measured at the beginning and at the end of the tests. The test sequences with the order are cold resistance, S1 - rated load test, LC - load curve test, NL - no-load test.

A. Cold Resistance Test

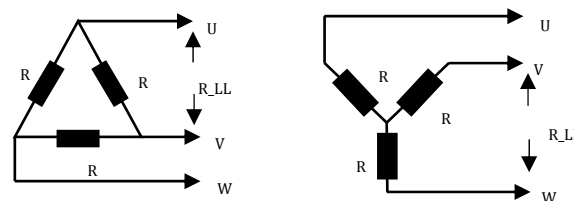


Fig. 1 Line to line resistance according to the connection types.

Winding resistance R_{LL} that was shown in Fig. 1 is the ohmic value that is determined by measuring the line-to-line arithmetic average resistance of the stator when the sample adapted the initial conditions of the test room. Before the test, the room temperature and the winding temperature should be written. The cold resistance is important to all calculations because of the related equations and temperature rise of the windings. Cold resistance measurement results of the motor are given in Table 2.

Table 2. Cold resistance test results.

$R_{LL} \Omega$	Ambient °C	Winding °C
0,20347	25.5	25.5

B. Rated Load Test (S1 Test)

The test was performed according to clause 6.1.3.2.1. The motor should be loaded by suitable means with rated output power and operated until thermal equilibrium is achieved. When the thermal equilibrium is achieved, the winding temperature rate of change 1 K or less per half hour. This temperature rise up test simulates the motor normal operating conditions at rated load. As a result of this test the winding temperature and winding resistance takes the rated operating value. During the test, $P_1, P_2, T, I, U, n, F, \cos\phi$ values should be recorded. The standard EN 60034-1 describes three different temperature measurement method; resistance method, embedded temperature detector (ETD) method, thermometer method. The resistance method is the better and useful one. But to detect the thermal equilibrium position a thermocouple is probably the best device to use, and thermocouple is to be located as closely as possible to the stator windings as possible. By the way, when the temperature rate of change 1 K or less per half hour, the test will be stop and the resistance will be measured [11].

The P_1, P_2 are refers to the input and output power (W), T is the torque value (Nm), I is the current during the S1 test (A), U is supply voltage (V), n is the operating speed (rpm), F is the supply frequency (Hz), $\cos\phi$ is the power factor. The test's main idea is measuring the winding temperature θ_w and to calculate the temperature correction factor k_θ . The winding resistance values were recorded during the test, shall be referred to a standard reference temperature of 25 °C. The correction factor is used to adjust the winding resistance to a standard reference coolant temperature. The measured winding temperature should be determined by the resistance change method that explained in 8.6.2.3.3 of IEC 60034-1.

$$k = 235 \text{ (Cu)} \quad \theta_w = \frac{R_{s1}}{R_{LL}}(k + \theta_1) - k \quad (1)$$

$$k_\theta = \frac{235 + \theta_w + 25 - \theta_c}{235 + \theta_w} \quad (2)$$

The R_{s1} is the measured resistance value after the rated load test that given in Table 3. The resistance should be read in 30s time interval when the test is finished. The θ_1 is the measured coolant temperature when the S1 test was finished. The winding temperature θ_w is calculated from eqn. (1) and correction factor k_θ is calculated from eqn. (2). The value θ_c is the ambient temperature after the S1 test.

Table 3. S1 Test results

$R_{s1} \Omega$	$\theta_c ^\circ\text{C}$	$\theta_1 ^\circ\text{C}$	$\theta_w ^\circ\text{C}$	k_θ
0.25967	25.5	31.7	98.6	0.9798

C. Load Curve Test (LC Test)

This test is interconnected to the rated load test. Test should be carried out immediately after the rated load test with the motor at operating temperature. Load curve depends on six load points: approximately 125%, 115%, 100%, 75%, 50% and 25% of rated load. Each load point should be achieved as quickly as possible to minimize temperature variations in the motor during testing. The LC test results are given in Table 4. During the test $R_{LC1}, R_{LC2}, P_1, P_2, T, I, U, n, F, \cos\phi$ values should be recorded. R_{LC1}, R_{LC2} are the resistance values that are measured before and after the LC test.

Table 4. LC Test results.

Loading rate kW		125%	115%	100%
		27.5	25.3	22.1
U	V	380	380	380
I	A	52.5	48.1	41.8
Cosφ		0.88	0.88	0.87
n	rpm	1466	1469	1474
F	Hz	50.0	50.0	50.0
T	Nm	179.2	164.5	143.1
P2	kW	27.5	25.3	22.1
P1	kW	30.3	27.7	24.0
Loading rate kW		75%	50%	25%
		16.5	11.0	5.5
U	V	380	380	380
I	A	31.7	22.7	15.4
Cosφ		0.85	0.79	0.60
n	rpm	1481	1488	1494
F	Hz	50.0	50.0	50.0
T	Nm	106.6	70.7	35.2
P2	kW	16.5	11.0	5.5
P1	kW	17.8	11.9	6.1
Resistance	R_{LC1}	0.25547	R_{LC2}	0.25300

D. No Load Test (NL Test)

Different from the former version of standard, the no-load test should be carried out on a warm motor immediately after the load curve test on eight values of voltage. Test Laboratories should be available for decoupling the motor from the loading system in seconds. Because in some cases the coupling equipment would be jammed to the rotor of the sample motor due to the temperature rise up. So the

easy connect couplings will help.

The values at approximately 110%, 100%, 95%, 90%, 60%, 50%, 40% and 30% of rated voltage basically no load test results which are given in Table 5 were used to calculate the constant losses (iron and windage and friction losses). Test was performed as quickly as possible with the readings taken in descending order of voltage and values of $R_{NL1}, R_{NL2}, P_1, I, U, F, \cos\phi$ were recorded during the test. R_{NL1}, R_{NL2} are the resistance values measured before and after the NL test.

Table 5. NL Test results.

Voltage Ratio	110%	100%	95%	90%
U (V)	418	380	361	342
I (A)	14.2	12.0	11.1	10.3
Cosφ	0.06	0.06	0.07	0.07
F (Hz)	50.0	50.0	50.0	50.0
P1 (kW)	0.59	0.49	0.45	0.42
Voltage Ratio	60%	50%	40%	30%
U (V)	228	190	152	114
I (A)	6.3	5.2	4.2	3.2
Cosφ	0.09	0.11	0.14	0.19
F (Hz)	50.0	50.0	50.0	50.0
P1 (kW)	0.23	0.19	0.15	0.12
Resistance	R_{NL1}	0.24633	R_{NL2}	0.24400

4. The Efficiency Calculations

A. Constant Losses

The constant losses calculations depend on no-load test outputs and the methodology explained in clause 6.1.3.2.5. Subtracting the no-load winding losses P_s (W) (according to the eqn. (3)) from the no-load input power P_0 (W) gives the constant losses P_c (W) explained in eqn. (4), that are the sum of the friction, windage P_{fw} (W) and iron losses P_{fe} (W). Determined the constant losses for each value of voltage are recorded.

$$P_s = 1.5 * I_0^2 * R \quad (3)$$

$$P_c = P_0 - P_s = P_{fw} + P_{fe} \quad (4)$$

The I_0 is the recorded current value at each voltage ratio from the no-load test. The R is the winding resistance value of each voltage point should be calculated by interpolating the resistances before and after the test linearly with the electrical power P_0 . The interpolation curve shown in Fig.2 and the results are given in Table 6.

In order to separate the constant losses, standard offers two different calculation methods depend on the different voltage levels. The first four point; 110%, 100%, 95% and 90% of rated voltage are used for the determination of iron losses and the last four point 60%, 50%, 40% and 30% of rated voltage are used for the determination of windage and friction losses.

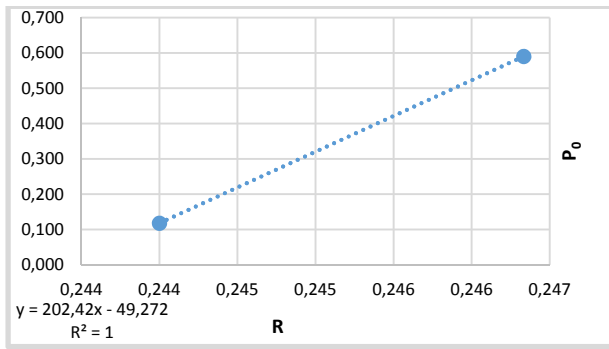


Fig. 2 Interpolation curve between R & P₀.

Table 6. Constant losses calculation results

NL	110%	100%	95%	90%
R Ω	0,24633	0,24585	0,24565	0,24547
Ps W	74.53	52.76	45.15	38.90
Pc W	515.64	440.08	406.31	376.57
NL	60%	50%	40%	30%
R Ω	0,24458	0,24436	0,24416	0,24400
Ps W	14.50	9.88	6.45	3.64
Pc W	220.43	180.22	144.18	114.21

The method describes a curve shown in Fig. 3 of constant losses P_c against the squared voltage points U_0^2 between 60% of voltage and 30%.

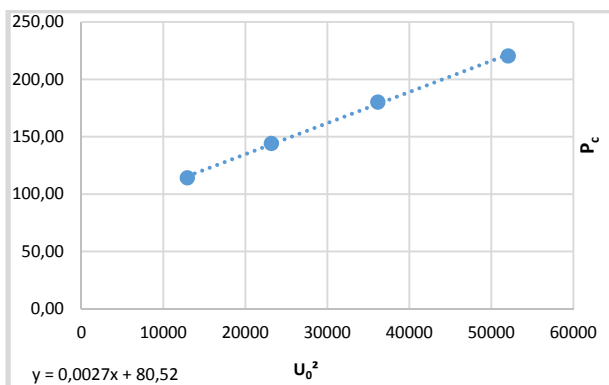


Fig. 3 Curve between U_0^2 & P_c .

In order to find the friction and windage losses P_{fw0} at approximately synchronous speed, line extrapolated to zero voltage and determined the intercept at zero voltage. By using the last four point of nominal voltage, standard trying to minimize the iron losses effect on the constant losses. And taking zero voltage response of curve is an acceptance of method.

$$P_{fw0} = 80.52 \text{ W}$$

The standard describes another curve to find the iron losses P_{fe} by using values of voltage between 90% and 110% of rated voltage against to U_0 . To determine the P_{fe} the eqn. (5) is used and the results are given in Table 7.

$$P_{fe} = P_c - P_{fw} \quad (5)$$

Table 7. Iron losses results

	110%	100%	95%	90%
(U) ²	175078	144613	130425	117297
P _{fe} W	515.64	440.08	406.31	376.57
P _{fe} W	435.12	359.56	325.79	296.05

To determine the iron losses at full load, the standard describes a new voltage value for motor from eqn. (6). Voltage values corresponding to the U_i value in the curve which is shown in Fig. 4 is give the iron losses. This new voltage value corresponds to the normal operating condition at rated situation of the motor. By using this voltage value, iron losses should be able to estimate more accurate.

$$U_i = \sqrt{\left(U - \frac{\sqrt{3}}{2} * I * R * \cos \varphi\right)^2 + \left(\frac{\sqrt{3}}{2} * I * R * \sin \varphi\right)^2} \quad (6)$$

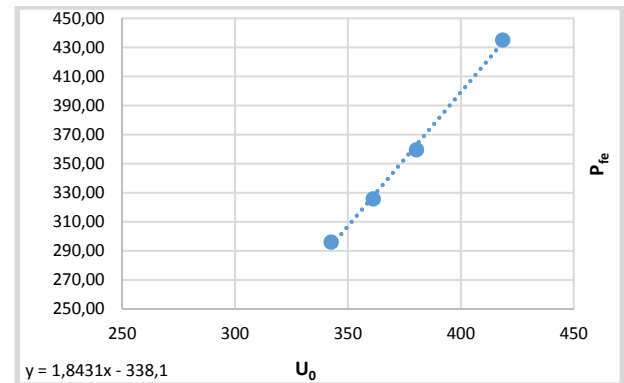


Fig. 4 Curve between U_0 & P_{fe} .

The values $R, I, U, \cos \varphi$ in eqn. (6) come from the rated load test results. By the way the resistive voltage drop in the primary winding should be calculated into account.

$$P_{fe} = 347.71 \text{ W}$$

B. Variable Losses

The calculations depend on load curve test outputs and the methodology is explained in clause 6.1.3.2.2 and 6.1.3.2.3. To calculate resistance values for each load point, the R_{LC1} and R_{LC2} values were used. For 125%, 115%, 100% load points, R_{LC1} should be used which was measured resistance value before the load curve test. For other resistance values in between 0% and 100% load points the linear interpolation curve fitting operation was performed. The resistance against loading ratio curve is given in Fig.5.

$$s = \frac{n_s - n}{n_s} \quad (7)$$

$$s_\theta = s * k_\theta \quad (8)$$

$$P_{s\theta} = P_s * k_\theta \quad (9)$$

$$P_r = (P_1 - P_s - P_{fe}) * s \quad (10)$$

$$P_{r\theta} = (P_1 - P_{s\theta} - P_{fe}) * s_\theta \quad (11)$$

$$P_{1\theta} = P_1 - (P_s - P_{s\theta} + P_r - P_{r\theta}) \quad (12)$$

For calculating the variable losses the eqns. (2), (3), (7), (8), (9) should be used. The P_r (W) means rotor losses and s_θ is the corrected slope. For each loss the correction

factor should be considered. The corrected rotor winding losses are determined using the corrected value of the stator winding losses that indicated in eqns. (10) and (11). With the corrected stator and rotor winding losses, the corrected input power is calculated from eqn. (12). The calculation results of variable losses are given in Table 8. All corrections supplies the homogeneous results between the test laboratories.

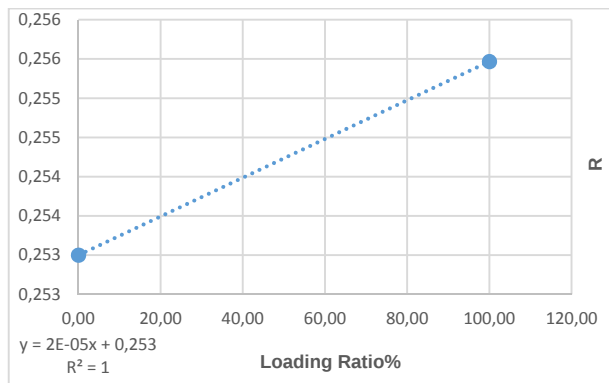


Fig. 5 Curve between load points & R.

Table 8. Variable losses calculation results

Load Points		125%	115%	100%	75%	50%	25%
s		0.023	0.021	0.017	0.012	0.008	0.004
s_0		0.022	0.020	0.017	0.012	0.008	0.004
R	Ω	0.255	0.255	0.255	0.255	0.254	0.254
P_s	W	1055.0	885.8	670.5	384.2	197.3	60.1
P_{s0}	W	1033.8	868.0	657.0	376.5	193.3	58.9
P_{fe}	W	351.4	351.4	351.4	351.4	351.4	351.4
P_r	W	656.9	544.2	400.3	211.9	89.8	22.0
Pr_0	W	644.2	533.6	392.5	207.7	88.1	21.5
Pl_0	kW	30.3	27.7	24.0	17.8	11.9	6.1

C. Residual Losses

The calculations depend on all test outputs without multiplying correction factor and the methodology is explained in clause 6.1.3.2.6. The residual loss is an estimate of the undetermined loss, so the correction factor should be not considered to get more accurate results. The residual losses should be determined for each load point from eqn. (14) by subtracting from the input power: the output power that given in eqn. (12), the uncorrected stator winding losses at the resistance of the test, the iron losses, the windage and friction losses, and the uncorrected rotor winding losses corresponding to the determined value of slip that given in eqn. (13).

$$P_2 = 2 * \pi * T * \left(\frac{n}{60}\right) \quad (12)$$

$$P_{fw} = P_{fw0} * (1 - s)^{2.5} \quad (13)$$

$$P_{Lr} = P_1 - P_2 - P_s - P_r - P_{fe} - P_{fw} \quad (14)$$

The residual loss data should be smoothed by using the linear regression analysis based on expressing the losses as a function of the square of the load torque according to the relationship that given in eqn. (15- 16). So the Fig. 6 shows the smoothing of the residual loss data.

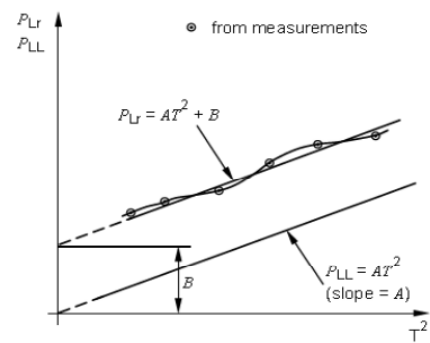


Fig. 6 Smoothing of the residual loss data.

$$P_{Lr} = A * X + B \text{ When } X = T^2 \quad (15)$$

$$P_{LL} = A * T^2 \quad (16)$$

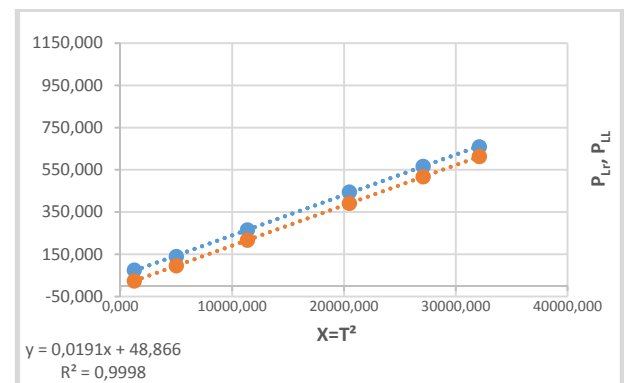


Fig. 7 Residual losses.

Table 9. Residual losses calculation results

Load Points		125%	115%	100%
P_1	kW	30.3	27.7	24.0
P_2	kW	27.5	25.3	22.1
P_s	W	1055.0	885.8	670.5
P_r	W	656.9	544.2	400.3
P_{fe}	W	351.42	351.42	351.42
P_{fw}	W	76.02	76.45	77.06
P_{Lr}	W	658.9	566.7	444.9
T^2		32104.0	27075.1	20474.5
P_{LL}	W	613.1	517.1	391.0
Load Points		75%	50%	25%
P_1	kW	17.8	11.9	6.1
P_2	kW	16.5	11.0	5.5
P_s	W	384.2	197.3	60.1
P_r	W	211.9	89.8	22.0
P_{fe}	W	351.42	351.42	351.42
P_{fw}	W	78.05	78.93	79.74
P_{Lr}	W	265.4	139.3	75.1
T^2		11358.8	4996.6	1235.9
P_{LL}	W	216.9	95.4	23.6

The correlation coefficient R^2 should be calculated for the regression analysis and in this case $R^2 = 0.99$. When the correlation coefficient is less than 0.95, the worst points should be deleted and the regression should be repeated. If correlation coefficient is less than 0.95, the test was unsatisfactory and errors in the instrumentation or test readings, or both, are indicated. The source of the error should be investigated and corrected, and the test

should be repeated. In case of sufficient test data, a correlation coefficient of 0.98 or better is possible. In this study residual losses calculation results are given in Table 9 and the correlation coefficient is shown in Residual losses Fig. 7.

D. Determining Efficiency

The calculation methodology is explained in clause 6.1.3.3. The total losses given in eqn. (18) should be taken as the sum of the adjusted iron losses, the corrected friction and windage losses that given in eqn. (17), the load losses and the additional load losses.

$$P_{fw} = P_{fw0} * (1 - s_{\theta})^{2.5} \quad (17)$$

$$P_T = P_{fe} + P_{fw} + P_{s\theta} + P_{r\theta} + P_{LL} \quad (18)$$

$$\eta = \frac{P_{1,\theta} - P_T}{P_{1,\theta}} \quad (19)$$

Table 10. Efficiency calculation results

Load Points		125%	115%	100%
P _{fw}	W	74.6	75.0	75.6
P _T	W	2718.6	2346.6	1869.1
EFF		91.0%	91.5%	92.2%
Load Points		75%	50%	25%
P _{fw}	W	76.5	77.4	78.2
P _T	W	1230.6	807.2	535.2
EFF		93.1%	93.2%	91.2%

The efficiency was calculated according to eqn. (19) and the results are given in Table 10 for each loading points. To evaluate the results, the EC 640/2009 directive was used. IE3 labeled 22 kW 4-pole induction motor efficiency value should be 93.0% according to the Table-2 from directive and the standard IEC 60034-30-1. The directive contains the verification procedure in clause ANNEX III. According to procedure the nominal motor efficiency (η) and the losses ($1-\eta$) should not vary from the values set out in directive Table-2 by more than 15 % on power range 0.75-150 kW [3, 8].

$$\frac{(1-\eta)*15}{100} = \frac{(1-0.922)*15}{100} = 0.0117 \quad (20)$$

$$92.2 \geq 0.9300 - 0.0117 = 0.9183 \quad (21)$$

Result of the eqn. (20-21), the efficiency value 92.2% that determined from study is in range of possible smallest value of IE3 according to EC 640/2009.

5. Conclusion

The energy efficiency is the most important issue for induction motors in industrial use. Hence, the standardization is gaining importance. The standard method should be used to get the same results in everywhere in the world.

In this paper, the IEC 60034-2-1:2014 standard method 2-1-1B is used for to determine the efficiency level for an IE3 labeled 22 kW 4 pole squirrel cage induction motor. The test results are evaluated according to EC 640/2009 directive. The importance of efficiency determination

takes part for market control in EU. In EU the mandatory applications started since June 16, 2011 with and obligation that specified minimum efficiency IE2 for induction motors. From January 2015 minimum efficiency IE3 should be maintained for power ratings from 7.5 kW to 375 kW or efficiency IE2 and plus frequency inverter should be supplied. And in January 1, 2017 the lower limit is going to be 0.75 kW for induction motors [9].

Different from former version of the standard, the new version well defines S1, LC, NL test steps and test order clearly and serves an obligation for resistance measurement before and after test. Standard's thermal equilibrium represents the motor's rated operating conditions in S1 test. The winding resistance in warm condition is important for calculating the correlation factor also comes from the S1 test. The tests are interconnected the LC test should start after the S1 warm resistance measurement. The variable losses calculated from the LC test results. The last test NL is used for calculating constant losses. Consequently, the new standard method and the EC regulations are relevant and integrate each other.

Acknowledgement

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