Comparison of different methods for efficiency determination acc.to IEC for specific induction motor

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***Abstract* - As energy efficiency is becoming more and more important, it was no surprise that IEC introduced new standards with mandatory efficiency classes for the biggest electric power consumers, electric motors. More precisely, induction motors which are estimated to use more than 60% of worldwide electric energy. IEC 60034-30-1:2014 defines efficiency classes IE1, IE2, IE3 and IE4 (where IE4 is highest rating i.e. biggest energy savings) for induction motors rated for sinusoidal voltage. Measurement methods required equipment accuracy and data analysis are described in 60034-2-1. Edition 2.0 of this standard came into force in June 2014 and replaced edition 1.0. from year 2007. Before this standard, the valid standard was IEC 60034-2:1996. The main issues are: efficiency classes became mandatory from year 2009 and not just voluntary as before, an agenda to unify class standards all over the world under these new IEC standards has been put forth and measurement methods are standardized worldwide. In this paper, one induction motor will be tested according to the newest standard and analyzed to check how different methods of loss calculation affect efficiency. Loss calculation will be determined acc. to IEC 60034-2, IEC 60034-2-1 (direct and indirect method).**

Keywords – induction motor; efficiency; losses; IEC; additional losses

I. INTRODUCTION

In this article will be displayed and compared different efficiencies obtained from the single tested induction motor. Measured data are the same, only difference is in analysis of this data acc.to IEC standards and methods.

Main difference in methods are direct efficiency determination or indirect efficiency determination. Direct efficiency determination is method by which the determination of efficiency is made by directly measuring the input power and output power.

Indirect efficiency measurement is method by which the determination of efficiency is made by measuring the input power or the output power and determining the total losses. Those losses are added to the output power, thus giving the input power, or subtracted from the input power, thus giving the output power [7].

For motors, electrical power is input power and mechanical power is output power. The respective loss components are, iron losses, windage and friction losses, stator and rotor winding losses, additional load losses. All of them will be determined as stated in IEC 60034-2-1.

II. MANDATORY LEGISLATIVES

A. *Efficiency classes*

This article will compare efficiencies obtained from the single tested induction motor. Measured data are the same, only difference is in analysis of this data acc.to IEC standards and methods.

Induction (asynchronous) motors, as energy using products, must comply to new ecological standards and legislation (ErP directive - ErP = Energy related Products and EU directive EC 640/2009) for efficiency of induction motors that have become national law in all EU countries [9]. This guidelines and demands are based on IEC standard 60034-30-1 that defines four efficiency classes (IE1 – IE4) for 50 and 60 Hz on line operation motors. Class IE1 is lowest i.e. most energy consumption while IE4 is highest class. New efficiency classes have been defined in IEC 60034-30-1 for induction motors where IE stands for International Efficiency:

- IE1 (Standard Efficiency)
- IE2 (High Efficiency)
- IE3 (Premium Efficiency)
- IE4 (Super Premium Efficiency)
- IE5 – yet to be fully defined

The efficiency classes should be determined accordant to IEC 60034-2-1 where there are measurement equipment and procedure described in detail. The changes became effective:

- from 16. July 2011: the specified minimum efficiency class for induction motors must be IE2
- from 01. January 2015: the specified minimum efficiency class for induction motors must be IE3 for power ratings from 7.5 kW to 375 kW or alternatively, an IE2 motor plus frequency converter
- from 01. January 2017: the specified minimum efficiency IE3 must be achieved for power ratings from 0.75 kW up to 375 kW or alternatively, an IE2 motor plus frequency converter.

B. *Scope*

Energy classes are specified for single speed electric motors that are rated according to IEC 60034-1 or IEC 60079-0, are rated for operation on a sinusoidal voltage supply and:

- have a rated power P_n from 0,12 kW to 1000 kW
- have a rated voltage U_n above 50 V up to 1 kV
- have 2, 4, 6 or 8 poles
- are capable of continuous operation at their rated power with a temperature rise within the specified insulation temperature class
- are marked with any ambient temperature within the range of -20 °C to + 60 °C
- are marked with an altitude up to 4000 m above sea level

Standard IEC 60034-30-1 establishes a set of limit efficiency values based on frequency, number of poles and motor power [6]. Excluded are:

- single speed motors with 10 or more poles or multi speed motors
- motors with mechanical commutators (such as DC motors)
- motors completely integrated into a machine
- motors with integrated frequency converters when the motor cannot be tested separately from the converter
- brake motors when the brake is an integral part of the inner motor construction
- submersible motors specifically designed to operate wholly immersed in a liquid
- smoke extraction motors with a temperature class above 400 °C

The current regulation EC 640/2009 will be replaced from July 2021 by Regulation on electric motor and variable speed drives EU 2019/1781 that will expand demands and widen the scope of electric motor regulated [10].

TABLE I. TESTED MOTOR DATA

3 PHASE MOTOR	TYPE: 100L - 4
400 V	TRIANGLE
50 HZ	1455 RPM
4,65 A	COS Φ = 0.81
2,2 KW	IE2 – 84,3 %
3 PHASE MOTOR	TYPE: 100L - 4

TABLE II. LOADING AND MEASUREMENT EQUIPMENT

Load motor	400V, 50 Hz, 11kW
Torque transducers	TM 310/011
Torque and speed display	Model 3411, Magtrol
Digital microhroohmeter	UT 320A
Data acquisition	NI USB 6212
3 phase transformer	Metrel, 0 - 470V

III. DESCRIPTION OF EQUIPMENT

A. *Demands acc. to IEC on equipment*

Digital instruments must be used whenever possible. The measuring instruments for electric quantities shall have the equivalent of an accuracy class of 0,2 in case of a direct test and 0,5 in case of an indirect test.

The instrument used to measure the torque shall have a minimum class of 0,2. The speed measurement should be accurate within 0,1 revolution per minute.

B. *Equipment*

- Data of used equipment for measurement are represented in Table I.
- Tested motor data are represented in Table II.
- Testing station with tested motor, load motor and torque transducer is displayed in Figure 1

IV. TEST PROCEDURE AND DATA ANALYSIS

A. *Efficiency calculation*

The electric motor efficiency (η) is defined as the ratio between output power (P_2) and input power (P_1).

$$\eta = \frac{P_2}{P_1} = \frac{P_1 - P_T}{P_1} \qquad (1)$$

Regarding indirect measurement method in IEC 60034-2-1 standard, the mechanical output power is not directly

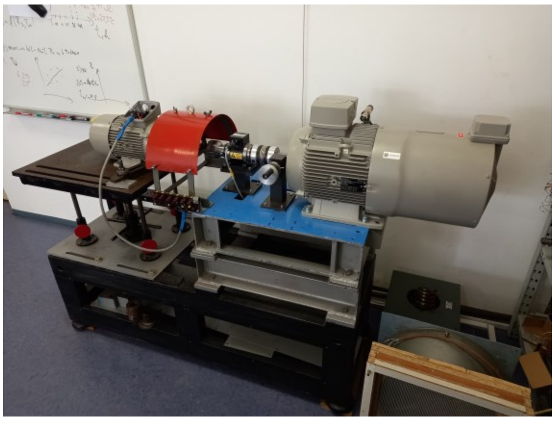

Figure 1. Testing station

measured, but it is calculated subtracting total motor losses (P_T) from the input power (P_1).

Total losses are calculated as the sum of constant losses (P_c), the load losses in stator ($P_{s,\theta}$) and rotor ($P_{r,\theta}$) corrected to a reference coolant temperature of θ = 25 °C and additional load losses (P_{LL}):

$$P_T = P_c + P_{s,\theta} + P_{r,\theta} + P_{LL} \qquad (2)$$

In this paper additional load losses will be calculated on the following manner:

- Determined as 0.5% of input power [8]
- Determined from assigned value [7]
- Determined from residual losses [7]

First method is used in IEC 60034-2, and the last two are introduced in IEC 60034-2-1 where determination from residual losses is preferred low uncertainty method. Tests below are described in an order they were performed.

B. Rated load test

The machine was loaded by suitable means (load motor) with rated output power and operated until thermal equilibrium is achieved (rate of change 1 K or less per half hour). Following quantities are recorded: input power (P_1), torque (T), current (I), voltage (U), operating speed (n), voltage frequency (f), stator resistance (R), temperature of ambient i.e. cooling air (θ_c) and winding temperature at rated load determined from resistance change (θ_w).

Stator winding losses are calculated as:

$$P_{s,\theta} = 1{,}5 \cdot I^2 \cdot R \cdot k_\theta \qquad (3)$$

where current (I) and stator resistance (R) are line to line values and the correction factor (k_θ) is for stator winding resistance to a standard reference temperature of 25 °C . Correction factor for stator winding resistance (k_θ) is calculated as:

$$k_\theta = \frac{235+\theta_w+25-\theta_c}{235+\theta_w} \qquad (4)$$

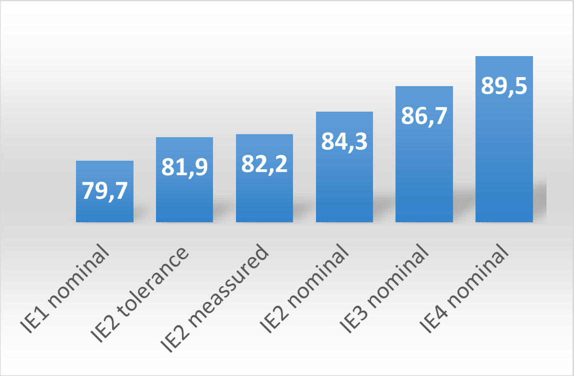

Figure 2. Relevant IE efficiencies values for 2,2 kW, 50Hz, 2,2kW motor [6]

Slip correction factor (s_θ) is calculated as:

$$s_\theta = s \cdot k_\theta \qquad (5)$$

Rotor winding losses are calculated as:

$$P_{r,\theta} = (P_1 - P_{s,\theta} - P_{fe}) \cdot s_\theta \qquad (6)$$

where are used measured values for iron losses (P_{fe}) and stator winding losses ($P_{s,\theta}$) subtracted from electrical input power (P_1) and multiplied with the slip corrected to a reference coolant temperature of 25 °C (s_θ).

C. Load curve test

The test is carried out immediately after the load test with the motor at operating temperature. Six load points are recorded: 140 %, 120 %, 100 %, 80 %, 60 %, 40 % of rated load. For each load point, recorded data are: voltage (U), current (I), input power (P_1), operating speed (n), frequency (f), torque (T).

From this test, additional load losses (P_{LL}) are determined. Firstly, residual load losses (P_{Lr}) shall be determined for each load point by subtracting from the input power (P_1): the output power (P_2), the uncorrected stator winding losses at the resistance of the test (P_s), the uncorrected rotor winding (P_r), the iron losses (P_{fe}) and the windage and friction losses (P_{fw}):

$$P_{Lr} = P_1 - P_2 - P_s - P_r - P_{fe} - P_{fw} \qquad (7)$$

After smoothing of residual loss data versus the square torque by using the linear regression analysis, the validity of the test is checked by the correlation coefficient for linear regression. If obtained correlation coefficient is strictly higher than 0.95, the additional load losses (P_{LL}) can be calculated as:

$$P_{LL} = A \cdot T^2 \qquad (8)$$

Where A is the regression line slope of the residual data and T is the machine torque.

TABLE III. CALCULATED EFFICIENCIES

Direct method		
Total losses = 471 W	**η = 82,4 %**	
Indirect method		
IEC 60034-2-1 with stray losses determined from residual losses	Total losses = 475,6 W	η = 82,2 %
IEC 60034-2-1 with stray losses determined from assigned value	Total losses = 490,9 W	η = 81,6 %
IEC 60034-2 with stray losses determined as 0,5% of input power	Total losses = 495,3 W	η = 81,5 %

TABLE IV. COMPARISON BETWEEN THE LOSS CONTRIBUTION COMPUTED BY DIFFERENT STANDARDS IN RATED LOAD

INDIRECT METHOD					
STATOR JOULE LOSSES (W)		ROTOR JOULE LOSSES (W)		IRON LOSSES (W)	
60034-2-1	60034-2	60034-2-1	60034-2	60034-2-1	60034-2
216,6	241,9	74,6	81,2	111,5	130,6

STRAY LOAD LOSSES (W)			FRICTION AND WINDAGE LOSSES (W)	
60034-2-1 FROM RESIDUAL LOSSES	60034-2-1 FROM ASSIGNED VALUE	60034-2 AS 0,5 % OF INPUT POWER		
46,9	62,2	13,4	26	28,2

Assigned value for additional losses introduced in IEC 60034-2-1 can be calculated for 1 kW < P_2 < 10 000 kW as:

$$P_{LL} = P_1 \cdot \left[0{,}025 - 0{,}005 log_{10}\left(\frac{P_2}{1\ kW}\right)\right] \qquad (9)$$

D. No load test

The no load test is carried out on a hot machine immediately after the load curve test. In the standard [1] is suggested to make this test in eight voltage points descending from 110% of rated voltage down to 30% of rated voltage. For this paper were recorded twelve points from 120% down to 10% with decrement of 10%. At each of the voltage values must be recorded: voltage (U_0), current (I_0), power (P_0). Determine the stator resistance (R_0) immediately before and after the no load test. The interpolated winding resistance of each voltage point shall be calculated by interpolating the resistances before and after the test linearly with the electrical power (P_0). From this test are obtained constant losses, subtracting the no load stator winding losses (P_{s0}) from the no load input power (P_0):

$$P_c = P_0 - P_{s0} = P_{fw} + P_{fe} \qquad (10)$$

and also is determined summation of friction and windage losses (P_{fw}) and the iron losses (P_{fe}).

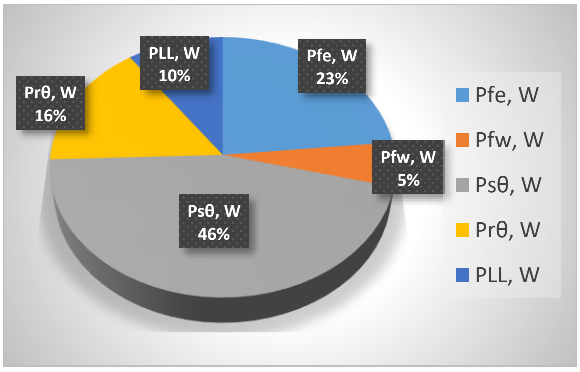

Figure 3. Distribution of losses on tested motor

Where stator losses (Ps) is calculated as:

$$P_s = 1{,}5 \cdot I_0^2 \cdot R_{ll,0} \qquad (11)$$

with $R_{ll,0}$ being the interpolated winding resistance at each voltage point.

For friction and windage losses, from the four or more consecutive no load loss points between approximately 60% and 30 % of voltage, curve of constant losses (P_c) must be developed against the voltage squared (U_0^2). Then, a line must be extrapolated to zero voltage. Interception of line at zero voltage is considered the friction and windage losses (P_{fw}).

For the iron losses, from the values of voltage between approximately 90% and 110% of rated voltage, curve of iron losses (P_{fe}) must be developed against voltage at each point (U_0) where:

$$P_{fe} = P_c - P_{fw} \qquad (12)$$

To determine the iron losses at full load the inner voltage U_i that takes the resistive voltage drop in the primary winding into account is calculated by:

$$U_i = \sqrt{\left(U - \frac{\sqrt{3}}{2} \cdot I \cdot R \cdot cos\varphi\right)^2 + \left(\frac{\sqrt{3}}{2} \cdot I \cdot R \cdot sin\varphi\right)^2} \qquad (13)$$

where voltage (U), current (I), resistance (R) and power factor (cos φ) are from the rated load test.

The iron losses at full load must be interpolated from the iron losses over voltage U_0 curve at the voltage U_i [1].

All relevant efficiencies classes data for type of tested motor are represented in Figure 2.

V. RESULTS AND DISCUSSION

Distribution of losses on measured motor is displayed in Figure 3 from where is evident that dominant losses are the one in stator winding. Calculated losses regarding different standards are displayed in table IV. Measured efficiency is represented in the table III where are comparable values obtained with direct and indirect method according to IEC

60034-2 and IEC 60034-2-1. Additional load losses are calculated in three methods as mentioned above. For motor of rated power 2,2 kW, 4 poles, rated voltage 400V and rated frequency 50 Hz nominal efficiency required to meet efficiency class IE2 acc.to IEC 60034-30-1 is 84,3 %. Tolerated value acc. to IEC 60034-1 is 81,9 %. The tested motor has efficiency in tolerance for IE2 class according to direct method and indirect method with additional losses determined from residual losses which is obligatory way of testing for motor of this size and power. All of efficiencies are represented in table III.

VI. CONCLUSION

In this paper are described different methods of efficiency determination from a single tested motor. Also the measurement methods are generally described with special acknowledgment in differences between standards IEC 60034-2 and IEC 60034-2-1. Three methods for additional loss calculation are described and calculated. Results are showing that the most comparable values from indirect method with direct method, are the ones with addition losses determined from residual losses. This is also stipulated in the standard as preferable method with low uncertainty. It has to be emphasized that efficiency values from motor manufacturers are only comparable if the same measuring methods are used.

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