Towards Energy Efficiency at Induction Motors-Technical and Economic Aspects

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***Abstract* – Induction motors account for forty percents of the world's electricity consumption and for almost seventy percents of total electricity consumption in industry. Therefore, several technical aspects of the construction of induction asynchronous motors—specifically motor length, diameter, and the number of conductors in the stator slots—are analysed, and the impact of each parameter on motor efficiency is examined individually Furthermore, the effect of replacing aluminium rotor bars with copper bars on motor efficiency is examined. The effect of efficiency increasing on electricity savings in correlation to motor operating hours is presented. In addition, a comparative analysis is conducted between the asynchronous motor model exhibiting the highest efficiency and a synchronous line-start motor constructed with identical design parameters. Adequate conclusions on usage of energy efficient motors instead of motors with lower efficiency and their impact on electricity savings are derived.**

***Keywords* – Energy efficiency, induction motor, electricity savings, motor design parameters.**

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1. Introduction

Electric motors are among the largest consumers of electrical energy. For instance, their consumption of electricity is double compared to lighting.

Forty to forty three percents of electricity consumption worldwide is accounted to electrical motors and 6046 Mt emission of CO_2. By 2030, electricity consumption by electric motors is projected to reach 13,360 TWh per year, with associated CO_2 emissions expected to rise to 8,570 Mt annually [1]. If different sectors are investigated, the electricity consumption by electrical motors is as follows: In industry, the electricity consumption is 4.488 TWh annually, and the motor drives account for 69 % of this electricity consumption. In the commercial sector, electricity consumption is 1412 TWh annually, and motor drives account for 39 % of electricity consumption in this sector. In the residential sector, with electricity consumption of 948 TWh annually, motor drives consumption is 22 %. In transport and agriculture, the electricity consumption is 260 TWh annually and electric drive electricity consumption is 39 %.

These figures suggest that the greatest potential for energy savings lies within the industrial sector. The largest portion of the electrical motors are the motors below 0.75 kW , used in households and commercial sectors. They are integrated into compressors, fans, hard-discs and many other domestic appliances. On the other hand, the largest portion of electricity consumption is accounted for by middle power motors. In this category there are motors between 0.75 kW and 375 kW. Most of them are asynchronous squirrel cage motors which are still the biggest portion of all the electric motors. In the same time they are the biggest obstacle in adopting certain energy policies as they are known for their low efficiency originating from their principle of operating and technical limits in their construction (relatively low power factor, higher stator currents compared to other types of motors, bigger copper losses, construction difficulties to achieve small air gap i.e. higher power factor and consequently lower stator current, and copper losses i.e. higher efficiency factor).

Generally, motors with lower power ratings have lower efficiency compared to the same type of motors with higher power rating. In the EU the regulation IEC 60034-30-1 is in force according to which all motors are classified into four major categories: IE1-standard efficiency, IE2-high efficiency, IE3–premium efficiency and IE4-super premium efficiency [2].

For example, 4-pole, 2.2 kW asynchronous motor at 50 Hz has IE2 efficiency class with 84.3% efficiency, IE3 efficiency class with 86.7% efficiency and IE4 efficiency class with 89.5 % efficiency [3]. Under current EU regulations, all electric motors in operation within the European Union are required to meet designated efficiency classes. The IE3 efficiency class is mandatory for all three-phase motors with power ratings between 0.75 kW and 1000 kW. Furthermore, as of July 2023, compliance with the IE4 efficiency class is required for motors rated between 75 kW and 200 kW [3]. These strict efficiency requirements impose many design challenges on the producers as increased efficiency of the asynchronous motors is correlated to the increased production costs. Various strategies may be employed to improve the operational efficiency of asynchronous motors. The cross-section of the wire of the stator winding can be increased, i.e. number of turns of the stator winding decreases resulting in asynchronous motor with higher efficiency which can be implemented in electrical vehicles for wide range of operating speed as it is stated in [4]. Modification can be done in the iron core for example by adding slits in the middle of the stator and rotor teeth that resulted in increased efficiency [5], [6]. Efficiency can be improved by implementing various control techniques when motors operate as a part of variable speed drives enabling motors to operate with the highest efficiency for a given load torque [7], [8], [9]. Replacement of aluminum cage with copper in the rotor of the asynchronous motor can significantly improve efficiency, especially for motors with smaller power ratings [10]. In [11] is presented the analysis of impact of winding type on motor efficiency. Three types of stator windings are included in the analysis: concentric single-layer winding, concentric double layer winding and fractional concentric winding. The achieved results show very little difference in efficiency and copper mass in favor of fractional concentric winding [11]. Although with smaller power rating single-phase motors have piqued researchers' interest in terms of efficiency increasing. Authors in [12] have demonstrated that the required efficiency levels for single-phase asynchronous motors can be achieved by increasing the motor's axial length, optimizing the design of the rotor bar slot, and carefully selecting the auxiliary-to-main winding turns ratio in conjunction with the rating of the capacitor used.

Motor efficiency is highly dependent on accurate calculation of losses, specifically the losses that are difficult to measure or calculate accurately, such as stray losses, which are differently treated in different standards [13], [14], [15]. According to [13], variations in the treatment of stray losses result in differing efficiency values for the same tested motor. Specifically, IEEE Std. 112 derives stray losses indirectly from testing, GOST 25941-83 assumes a fixed value of 0.5% of the rated power, while JEC-37 disregards stray losses entirely, leading to the highest reported efficiency among the analyzed motors. Stray losses primarily arise from leakage fluxes induced by load currents; consequently, various design and manufacturing factors can significantly influence their magnitude [13]. Reference [16] provides an analysis of how various rewinding practices affect motor efficiency, with particular emphasis on the resulting efficiency reductions and associated losses. The increased efficiency of the asynchronous motor can be achieved by modification of several design parameters: larger cross-section of copper wire in stator winding, larger motor core i.e. increased length of the motor and diameter of the stator. All these issues together with the replacement of rotor aluminum bars with the copper ones are addressed in this paper and separately the impact of each of the above-mentioned design parameters on motor efficiency is analyzed for 2.2 kW, 4-pole, asynchronous squirrel cage motor. For finding the most optimal motor design with highest efficiency, the optimetric analysis is run where three parameters: the number of conductors per slot, motor length and outer stator diameter are varied in predefined boundaries resulting in 770 combinations out of these varied parameters, i.e. 770 different motor models. The model with the highest efficiency which satisfies IE3 efficiency class is chosen as the best solution, referred to as model M1. The accuracy of the designed model is validated through comparison with a 2.2 kW, 4-pole motor of IE3 efficiency class, manufactured by Rade Koncar (type H5AZ 100LA-4). The second model is developed from model M1 by substituting the rotor's aluminum winding with copper. All the other design parameters remain unchanged. This model is referred to as model M2. Despite the replacement of rotor aluminum winding with the copper winding, the model M2 did not achieved IE4 efficiency class. The comparative analysis of parameters and operating characteristics of M1, M2 and H5AZ 100LA-4 are presented. The effects of each varied parameter on motor efficiency are systematically analyzed, enabling comprehensive conclusions about the extent to which motor length, stator diameter, and the number of conductors per stator slot influence overall efficiency.

The IE4 class is achieved with line-start synchronous motor derived from the model M1 by adding the permanent magnets in the rotor. The annual energy savings are calculated when IE4 class motor, 2.2 kW, is used instead of IE3 class. Based on incremental cost of the motor (IE4 class instead of IE3 class) the annual electricity bill savings and the payback period for buying the super-premium efficiency motor IE4 class is estimated. The aim of this paper is to provide a comprehensive analysis of the design measures that provide increased efficiency at asynchronous motor along with overview of the material consumption that have implications on the production cost and finally to make a comparison of the asynchronous motor of IE3 class and line-start synchronous motor as a possible alternative for replacement of asynchronous squirrel cage motor by pointing out the advantages and drawbacks of this replacement. The analysis presented could be useful for motor designers as often they face numerous design challenges regarding efficiency and the production costs. Often the motor optimal design is the trade-off between quality and quantity of the in-built materials and their cost. Nevertheless, the presented analysis may also provide useful guidelines for industry engineers in achieving the higher efficiency of the electrical drives, along with significant operational costs savings.

2. Optometric Analysis and Deriving the IE3 Efficiency Class Asynchronous Motor

Ansys program and its software modules RMxprt and Otimetrics are used to model the asynchronous squirrel cage motor by inputting the motor geometry and materials. The motor cross-section is presented on Figure 1.

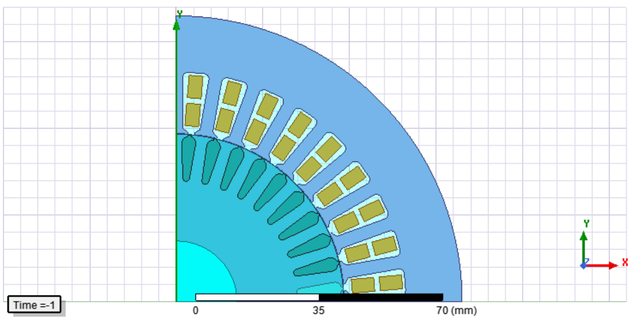


Figure 1. Motor cross-section

Three design parameters are selected to be varied within predefined boundaries: number of conductors per stator slot CPS, motor length-ML and outer stator diameter-OSD. The ranges of variations of the parameters are presented in Table 1.

Table 1. Ranges of variations of parameters

Parameter	Range	Step
CPS (/)	75-85	1
ML (mm)	100-109	1
OSD (mm)	166-172	1

These variations of parameters and their combinations resulted in 770 various motor models. The model with highest efficiency (87.6 %) is selected for further analysis (M1). The rotor aluminum winding of squirrel cage type in model M1 has been replaced with copper winding thus the second motor model M2 is obtained, without changing any other parameter of M1. Finally, the obtained models M1 and M2 are compared with IE3 class 2.2 kW, 4-pole, induction squirrel cage motor, produced by Rade Končar company from Croatia, type H5AZ 100L-4 [17]. Table 2 presents the key parameters and operating characteristics of all three motors.

Table 2. Operating characteristics of various models of asynchronous motor

Parameter/ Characteristic	M1 (IE3)	M2	H5AZ 100LA-4 (IE3)
Output power [kW]	2.2	2.2	2.2
Rated speed [rpm]	1460	1474	1445
Rated torque [Nm]	14.4	14.2	14.5
Current [A]	4.4	4.32	4.8
Power factor [/]	0.860	0.862	0.76
Efficiency full load [%]	87.6	88.4	86.7
Efficiency 75 % load [%]	87.5	87.9	86.3
Efficiency 50 % load [%]	85.3	85.7	86
Locked-rotor torque ratio [/]	3.1	2.5	3.5
Locked-rotor current ratio [A]	9.3	10	7.1
Break-down torque ratio [/]	4.2	4.2	3.8
CPS [/]	81	81	/
Air gap length [mm]	0.3	0.3	/
Motor length [mm]	109	109	/
Stator outer diameter [mm]	172	172	/
Slot fill factor [%]	69	69	/
Stator copper losses [W]	141	139	/
Rotor winding losses [W]	60	38.7	/
Iron core losses [W]	47.5	47.5	/
Frictional & windage losses [W]	24	24	/
Stray losses [W]	39.6	39.6	/
Copper weight [kg]	3.3	5.5	/
Aluminium weight in rotor [kg]	0.66	/	/
Core steel weight [kg]	13.3	13.3	/
Net weight without housing [kg]	17.3	18.8	
Total weight [kg]	/	/	25

The line-start synchronous motor can be easily designed by modifying the asynchronous squirrel cage motor by adding flux barriers inside the rotor and inserting the permanent magnets inside them. One such modification is presented in Figure 2. In recent years, the significance of synchronous motors has grown considerably due to their inherent capability to consistently attain higher efficiency classes compared to other motor types, making them increasingly favorable for energy-efficient industrial applications. Line-start synchronous motors have drawn attention as this type of synchronous motor does not need an inverter for starting, once that is plugged into the power supply. This is due to the presence of permanent magnets inside the flux barriers that pull the motor into synchronism and the rotor cage winding that provide the starting torque like in the asynchronous squirrel cage motor. Once the motor achieves synchronization with the power supply network, the rotor current is effectively reduced to zero. Consequently, during rated load operation, the rotor winding experiences no electrical losses, which contributes to the overall higher efficiency of synchronous motors compared to asynchronous counterparts.

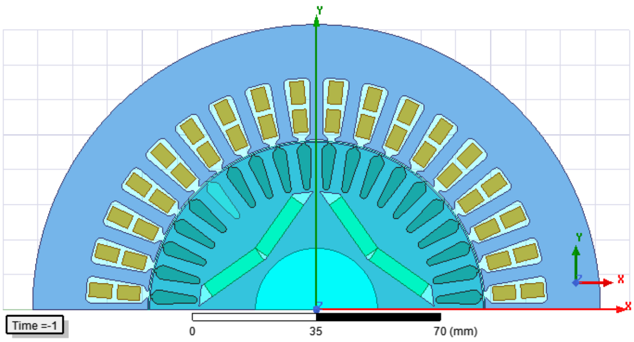


Figure 2. Cross-section of line-start synchronous motor

The line-start synchronous motor model is developed from the asynchronous motor by incorporating flux barriers and embedding permanent magnets within them. All motor dimensions remain unchanged except for the rotor outer diameter that is decreased, i.e. air gap length is increased to achieve better overloading capacity i.e. maximum output power.

However, it should be noted that at the line-start synchronous motor the same or even better performance characteristics like efficiency is obtained with the smaller motor dimensions i.e. with smaller outer stator diameter and axial length than in the asynchronous motor. Furthermore, the rotor winding is made of aluminum in line-start synchronous motor.

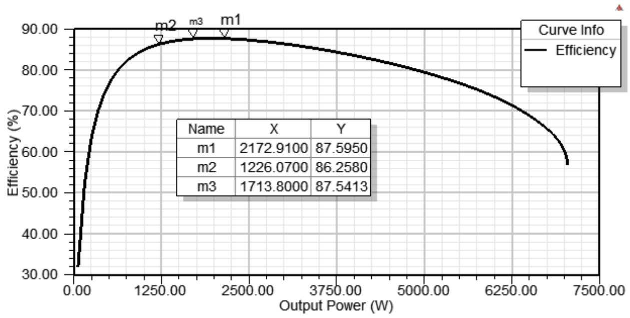
This motor model will be referred to as model LSSM. The operating characteristics of model LSSM at rated load are presented in Table 3.

Table 3. Operating characteristics of line-start synchronous motor IE4 class

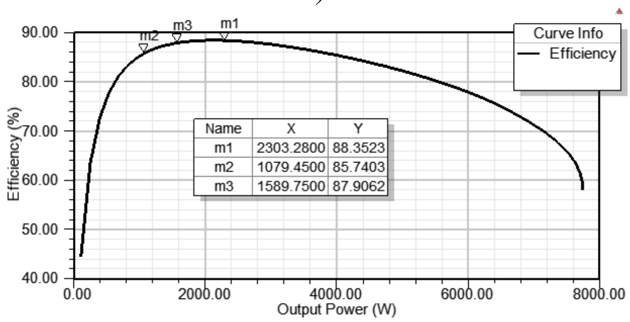
Parameter/ Characteristic	LSSM (IE4)
Output power [kW]	2.2
Rated speed [rpm]	1500
Rated torque [Nm]	14
Torque angle [°]	63.6
Current [A]	3.6
Power factor [/]	0.99
Efficiency full load [%]	94.4
Max. output power [W]	5073
CPS [/]	81
Air gap length [mm]	0.7
Motor length [mm]	109
Stator outer diameter [mm]	172
Slot fill factor [%]	69
Stator copper losses [W]	82.5
Iron core losses [W]	26
Frictional losses [W]	22
Copper weight [kg]	3.3
Aluminium weight [kg]	0.66
Core steel weight [kg]	12.5
Magnet weight [kg]	0.68
Total net weight [kg]	17.14

3. Steady-state Behaviour and Numerical Model Development

The most typical operating characteristics of analysed motors like efficiency, torque and power factor are presented in this section. The presented characteristics are aimed to support data, given in Table 1 and Table 2. The steady-state efficiency characteristics of models M1, M2, and LSSM are presented in Figure 3. In Figure 3 the efficiency is presented for some operating points (50 %, 75 % and 100% of the full load) for models M1 and M2, and for the model SLSM the rated efficiency can be read out for the torque angle, given in Table 3.



a)



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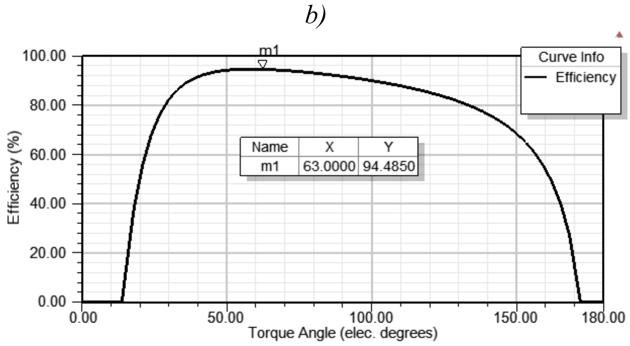


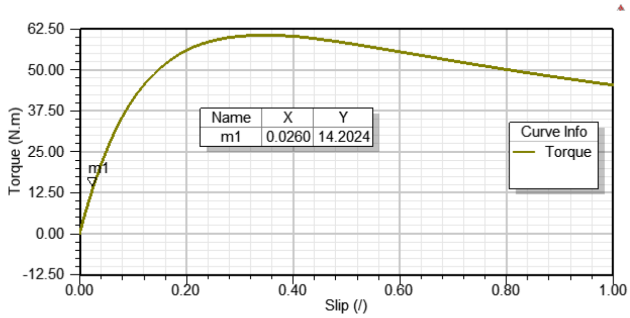
c)

Figure 3. Efficiency characteristics under steady-state operating conditions a) Efficiency of model M1 b) Efficiency of model M2 c) Efficiency of model LSSM

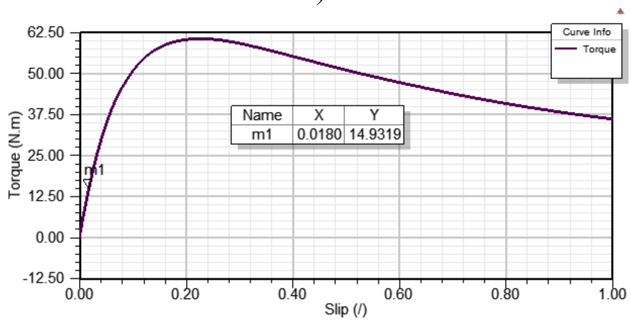
In Figure 4 the characteristic of torque for various operating slips is presented. The rated torque is read for the rated slip defined by rated speed 1460 rpm (Table 1) for model M1 and for the model M2 from the rated speed 1474 rpm (Table 1). The rated slip is found from:

$$s = \frac{n_1 - n_n}{n_1} \cdot 100 \ \ (\%) \tag{1}$$

n_1 is the synchronous speed 1500 rpm and n_n is the rated speed.



a)



b)

Figure 4. Torque characteristics under steady-state operating conditions a) Torque versus slip for model M1 b) Torque versus slip for model M2

For M3 model the characteristics of air-gap power P_{ag} is presented in Figure 5. The output torque, for the given torque angle, with satisfactory accuracy can be found from:

$$T_2 = \frac{P_{ag}}{n_1} \tag{2}$$

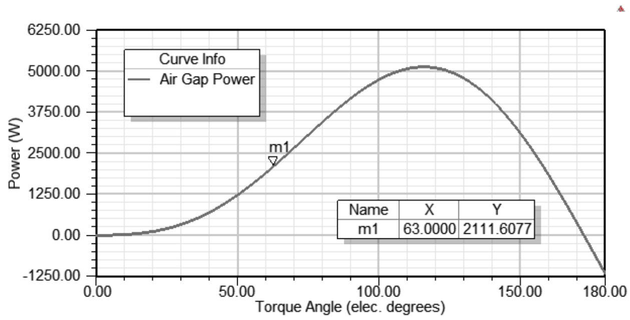


Figure 5. Steady-state characteristics of air-gap power of model LSSM

Figures 6a and 6b present the power factor as a function of output power for models M1 and M2, respectively. In Figure 6 c) the power factor for various torque angles of LSSM is presented.

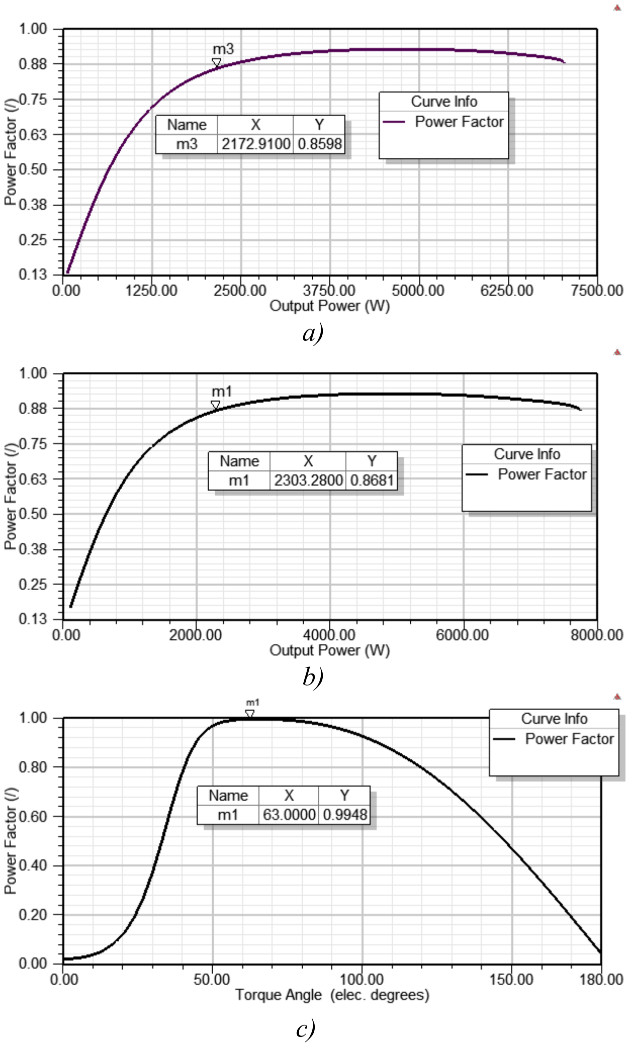


Figure 6. Steady-state characteristics of power factor a) Power factor versus output power for model M1b) Power factor versus output power for model M2 c) Power factor versus output power for model LSSM

The accurate design of motor models should be validated through the calculation of magnetic flux density distribution within the motor cross-sections. The Finite Element Method (FEM) is employed to compute the magnetic flux density in all motor models. Figure 7 illustrates the magnetic flux density distribution for models M1, M2, and the line-start synchronous motor (LSSM). Analysis of the magnetic flux density distribution within the motor cross-section enables designers to identify regions of the magnetic core susceptible to saturation, which can result in increased losses, motor overheating, and reduced efficiency.

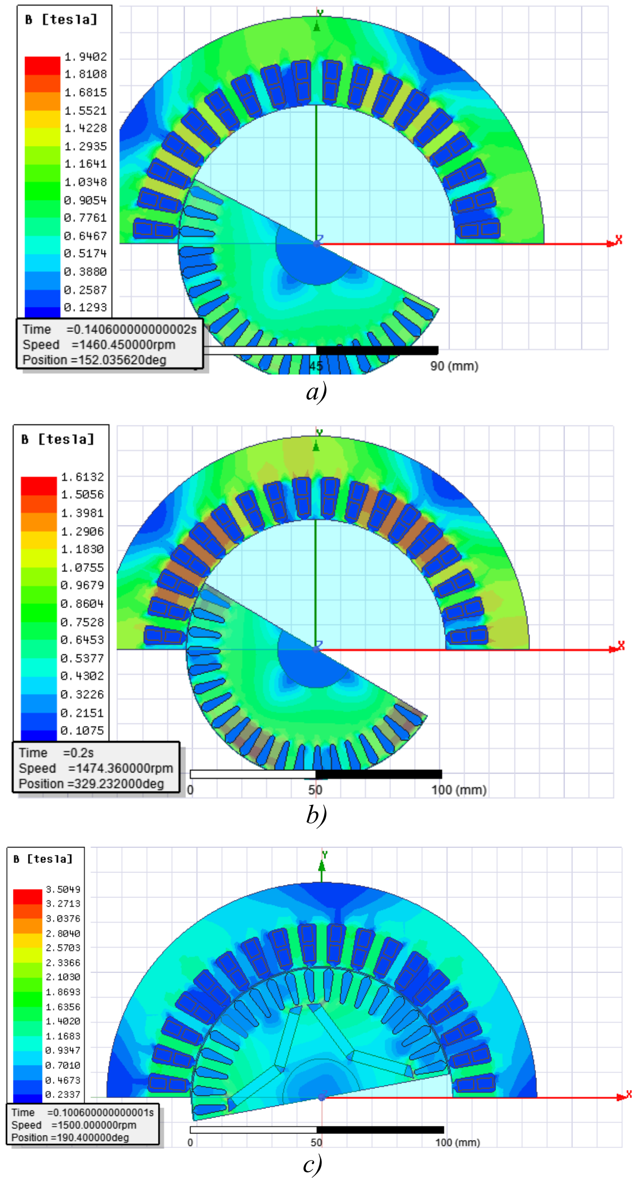


Figure 7. Flux density distribution at motor models a) Fux density distribution in model M1 b) Fux density distribution in model M2 c) Fux density distribution in model LSSM

4. Discussion of the Optimization Results

The materials, electrical and mechanical design are the factors that affect motor efficiency. According to [18] active material and stator and rotor geometry have the most decisive impact on motor efficiency. Some energy savings are possible by proper installation and operation of the motors. From an electrical design perspective, several key recommendations should be considered to enhance the efficiency of an asynchronous motor.

Notable design improvements include increasing the cross-sectional area of the copper windings to reduce resistance and copper losses; enlarging the motor's axial length and diameter to optimize the magnetic flux density distribution, reduce core saturation, and minimize iron losses; substituting aluminum with copper in the rotor winding to improve reliability, efficiency, and operational lifespan; and decreasing the air gap to enhance both efficiency and power factor by reducing the magnetizing current requirement. However, the proper design of the machine air gap is subject to manufacturing limitations on one hand, and on the other hand too small air gap decreases the overloading capability of the motor.

The use of high-quality steel laminations with low core losses further enhances motor efficiency. There are several recommendations regarding proper operation of the asynchronous motors that can contribute to better utilization of electrical energy. The asynchronous motor should be properly sized regarding the application, i.e. the usage of oversized motors for the small loads is decreasing the drive efficiency rapidly. This is also the case with the models M1 and M2 and according to the given efficiency for 50 % load in Table 2, the efficiency drops from 87.6 % to 85.3 % for model M1, and from 88.4% to 85.7% for model M2. Motor that is not working with the full load has the decreasing power factor which leads to increasing consumption of the reactive power and higher electricity bills. The motors which have been rewind have decreased efficiency by 3-4 %. Finding the optimal motor design can be a challenging task as there are lot of design and operational requirements that should be satisfied simultaneously along with the savings in the production costs.

Therefore, it is important to determine the right design parameters that satisfy certain objectives like in this case, motor efficiency. Three parameters are chosen to be analyzed by optimetric analysis: number of conductors per stator slot (CPS), the machine length (ML) and outer stator diameter (OSD) i.e. finding the best combination of these three parameters that results with the highest efficiency is the goal of the optimetric analysis, done by the aid of software module optimetrics in Ansys program. The impact of variation of each of these three parameters on motor efficiency and power factor is analyzed for model M1. Model M2 is derived from model M1 by replacing the aluminum in rotor winding with cooper; therefore, for this model no optometric analysis is necessary as the results obtained for model M1 are used. In Fig. 8 the impact of parameter CPS on efficiency of M1 is presented.

In Figure 8 the analysis is done when only CPS is the varied parameter, and the remaining two parameters (ML and OSD) are kept constant, and their values are equal to the appropriate values given in Table 2.

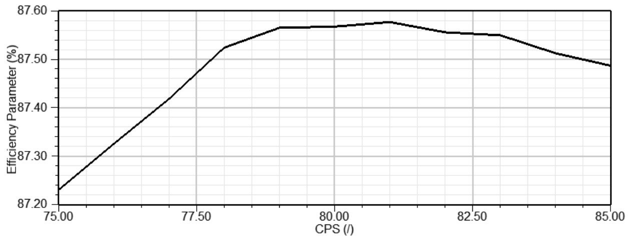


Figure 8. Impact of CPS on efficiency for M1

The increasing of number of conductors increases the stator resistance but decrease the stator current. Therefore, models with 81 and 85 conductors per slot have almost negligible difference, concerning efficiency, in favour to the model with 81 CPS. On the other hand, the model with 75 CPS has lower resistance but higher stator current which increase the copper losses. Apart from copper losses in the stator winding, the models with different number of conductors per slot have different speed, i.e. slip which affects the losses in the rotor winding. The difference in stator currents has impact on flux density distribution and core losses which again affect the motor overall efficiency. Therefore, by the aid of computer calculations the best value of each design parameter can be found with respect to the objective characteristic, in this case efficiency, but simultaneously the other important operating characteristics can be calculated and analysed. In Figure 9 the impact of motor length to the efficiency is presented. The same method is applied as in the earlier case; the motor length is varied, while the remaining two parameters CPS and OSD are kept constant and equal to the values, given in Table 2. Following the presented results in Figure 9 the increase of motor length increases the efficiency. The drawback is the increased quantity of material, bigger motor dimensions and increased production cost.

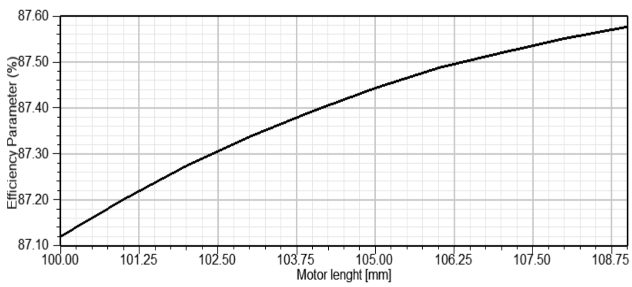


Figure 9. Impact of ML on efficiency for M1

Similar discussion is valid for Figure 10 where the impact of outer stator diameter to efficiency is presented. Here, parameters CPS and ML are kept constant and equal to the adequate values given in Table 2. Only parameter OSD is varied.

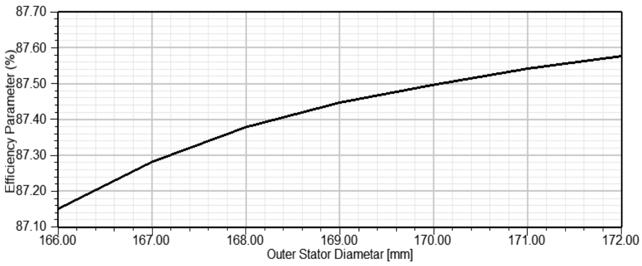


Figure 10. Impact of OSD on efficiency for M1

The increase of the outer stator diameter increases efficiency. The increase of stator diameter has positive impact on flux density distribution and prevents the core saturation. The drawback is the increased material consumption and production costs. The above discussed design modifications allow IE3 efficiency class to be achieved for the asynchronous motor.

Besides efficiency, the results presented in Table 2 point out that also the other important operating parameters like overloading capacity of the motor i.e break-down torque ratio and power factor are satisfactory and even outperform the model H5AZ 100LA-4. The drawback of model M1 is the high starting current, i.e. locked-rotor current ratio. The starting torque i.e. locked-rotor torque ratio is 3.1 and follows the locked-rotor torque ratio of H5AZ 100LA-4. The comparison of software model M1 to catalogue data of Končar motor of IE3 class, H5AZ 100LA-4 (Table 2) shows satisfactory agreement and verifies the accuracy of derived model M1 and the results and conclusions originating from the M1 model. Further step in improvement of motor design was to replace the aluminium in the squirrel cage rotor winding with copper. This design modification effectively and significantly improves the efficiency from 87.6% to 88.4 %. The increase of efficiency is due to decreased losses in the rotor winding which in case of the copper rotor winding should be 40 % to 50 % less than in case of the aluminium winding. The decreased losses, lowers the operating temperature of the motor. This suggests that copper rotor motors will have less maintenance and longer lifetime. The other aspect of this modification is the starting torque and current. The starting torque is decreased but it is still satisfactory as it more than double than the rated torque. It can be expected that replacement of aluminium with copper in rotor winding will lead to decreased starting torque. The other drawback of this modification is the high starting current, ten times the rated current.

With higher power ratings the starting currents are becoming more critical, and the motor might require new design of the laminated steel sheets. Although the rotor aluminium winding is replaced with copper winding, for 2.2 kW motor, the IE4 class was not achieved. The next modification includes new stator laminations with flux barriers where permanent magnets are placed. This new model is the line-start synchronous motor, which does not need power converter for starting; it can be started directly with network power supply as the squirrel cage winding provides the necessary starting torque. The synchronous motors easily achieve the high efficiency classes. Several factors contribute to this: there are no rotor losses since the rotor rotates synchronously with the magnetic field, resulting in no induced current in the rotor windings; the power factor is very high, approaching unity, which reduces the line current; additionally, both copper and core losses are minimized.

The derived model LSSM has achieved the IE4 efficiency class due to previously described operating characteristics originating from the motor construction and principle of operation. The model LSSM is derived for the same output power and with the same dimensions as the asynchronous motor to obtain comparable results. The drawbacks of this model are production complexity i.e. more complex cutting of the rotor laminations and cost of extra material, in this case the permanent magnets. The design of all motor models is validated by analysing the magnetic flux density distribution using the Finite Element Method, which enables precise calculation of flux density within the models' cross-sections. From the result, presented in Figure 7, it can be concluded the models are well designed in terms of core saturation. This guarantees that no hot spots will occur during motor operation originating from core saturation and increased core losses. The models presented in this paper prove that small modifications in motor design can significantly improve its efficiency and overall operating performance. Yet, the design process is complex, involving various parameters that can have different impact of the final output characteristics of the motor. Even more, finding the right combination of several parameters, without specialized software, can be a tremendous task.

Therefore, the presented optimetric analysis with three parameters that are varied within certain limits, selected, and defined, on the base of designer's experience, allows obtaining numerous models quickly and accurately out of which the best model can be chosen for the selected operating characteristic. For each model, all parameters and operating characteristics are calculated providing the broader perspective of analysed problem as often improvement of one operating parameter can deteriorates the other.

5. Economic Analysis

Improvements in the efficiency of motors can be achieved mainly through the design modifications, namely better filling of stator slots with copper i.e. using more copper wires, larger cross-section of copper wire, larger motor dimensions, usage of high-quality steel lamination etc. Most of these measures demand higher initial costs for the motor production due to increased quantity and quality of the in-built materials. The various analyses have been conducted on cost-effectiveness of replacement of old motors, often with low efficiency, with the new motors with premium efficiency or super-premium efficiency in terms of electricity savings versus purchasing costs of the motors [19]. Another aspect is the environmental impact as the electricity production, necessary for driving the electrical motors, often is associated with increased CO_2 emission, especially in case of coal fired power plants. Therefore, replacing standard motors with high-efficiency motors can significantly reduce the carbon footprint, as indicated in [20], [21], [22]. Annual energy saving can be calculated according to [23]:

$$AES = P\,x\,L\,x\,hr\left[\frac{1}{\eta_{std}} - \frac{1}{\eta_{hem}}\right] \quad (3)$$

Where P is the motor rated power (kW), AES is the annual energy savings (kWh), L is the load factor (percentage of the full load), *hr* is the operating hours, η_{std} is the standard efficiency class of the motor (%) and η_{hem} (%) is the efficiency of high efficient motor. Annual bill savings associated with the energy savings can be calculated from:

$$Savings = AES\,x\,C \quad (4)$$

C is the average energy cost (EUR/kWh). The payback period is calculated from:

$$\text{Simple payback period} = \frac{Icremental \quad cost}{Annual\,EUR\,savings} \quad (5)$$

Incremental costs of the motors for IE3 and IE4 class are calculated on the base of the approximate prices given in [23] and [24]. The above-described method is implemented in calculating the payback period for two scenarios: the motor M1 is replaced by M2 and the motor M1 is replaced by LSSM. The replacement is calculated for efficiency at full load and for 2920 operating hours and 4020 operating hours. The average price of electricity is considered to be 0.22 EUR/kWh and the incremental costs for replacing the M1 with M2 is 50 EUR and for replacement of M1 with LSSM is 300 EUR.

Based on the data presented above, the results for annual savings and the payback period are summarized in Table 4.

Table 4. Payback period for replacement of M1 with M2 and LSSM

Replacement	2920 operating hours		
	Energy savings (kWh/year)	Bill savings (EUR/year)	Payback period (years)
M1 with M2	64	14	3.5
M1 with LSSM	518	114	2.6
	4020 operating hours		
M1 with M2	88	19	2.6
M1 with LSSM	713	156	1.9

Replacing the model M1, which in this analysis is the motor with the lowest efficiency, with more efficient models M2 and LSSM according to the results presented in Table 3, provides the cost-effective solution especially if the motor has more operating hours. Even more, the replacement of M1 with LSSM, which has the highest efficiency, despite the higher initial cost, provides the faster payback of the investment. Certain precautions should be taken as the motors with higher efficiency have increased speed which places the increase of the load upon the motor [23]. Therefore, when replacing a standard squirrel cage motor with a high-efficiency variant, it is essential to select a motor with equal or lower rated speed. This ensures that the anticipated energy savings from improved efficiency are not offset by increased energy consumption, which could otherwise negate the intended benefits.

6. Conclusion

Energy efficiency is of paramount importance in the modern society which is demanding more energy in terms of the limited resources. Electric motors account for a significant share of global electricity consumption, making them one of the largest consumers of electrical energy. Therefore, their energy efficient design can significantly change the global energy landscape. In this paper is presented the technical and economic analysis for modelling more efficient motors, based on large number of variation of the design parameters such us number of conductors per stator slot, motor length and outer stator diameter that significantly impact the motor efficiency and contribute to achieving IE3 class of efficiency for asynchronous squirrel cage motor of 2.2 kW. Each varied parameter is individually analysed to assess its influence on motor efficiency.

The usage of software tools allows the numerous motor models to be calculated relatively fast and out of them the best solution to be selected in terms of the predefined output parameter. Furthermore, it was presented model of the motor with copper instead of aluminium bars in rotor winding with considerably improved efficiency versus relatively low production costs and short payback period. Finally, the motor of IE3 class was replaced with line-start synchronous motor of IE4 class of premium efficiency. Despite the higher initial investment, the line-start synchronous motor of IE4 class, for smaller power applications, is the cost-effective solution due to the higher efficiencies and short pay-back period, especially for longer operating hours. However, every replacement should be carefully done, as the asynchronous motors with higher efficiencies have higher speeds for the same loading and can place larger loads upon the motor, resulting in increased energy consumption that will nullify the positive effect of increased efficiency. The presented analysis can serve to electrical engineers in the industrial facilities as guidelines for achieving more energy efficient production lines.

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