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Effect of silicon ratio and sheet thickness on energy efficiency of induction motor

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ABSTRACT

Electric machines consume a large portion of electricity in industry and daily life. To minimize energy consumption, it is necessary to increase the performance of electrical machines. There are three key factors influencing the energy efficiency of transformers and electric motors. Electrical steels, also known as silicon steel sheets, are widely used as core materials in electric motors, transformers, and generators. The silicon ratio of electrical steel has a crucial role in energy efficiency. In this study, a finite element model was used to observe the effect of silicon ratio and sheet thickness on motor efficiency. In the finite element model, M27, M36, and M43 core materials were employed in varying thicknesses (e.g., 0.36, 0.47, and 0.64). M43 silicon steel had the lowest electric motor efficiency, measuring 83.19%, whereas M27 silicon steel demonstrated the maximum efficiency, measuring 84.24%. An improvement in energy efficiency of 1.05% was found in the study's results. The results of the study indicated that motor efficiency could be increased by optimizing the thickness and silicon ratio of the silicon steel sheets.

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1. INTRODUCTION

Squirrel-cage induction motors (SCIM) are a type of motor commonly preferred in industry [1, 2]. SCIMs represent more than 90% of electric motors used in commercial applications [3]. Mechanical losses owing to friction in mechanical components, copper losses due to winding resistance, and iron losses because of core material are the three primary forms of losses in SCIMs [4]. Although mechanical and copper losses have been thoroughly studied, the phenomena of iron losses have not been fully understood [5]. Meanwhile, iron losses in the rotor and stator account for around 25% of SCIM losses [6]. Therefore, studies are carried out to reduce iron losses to a low level to improve the characteristic performance of SCIMs [7, 8]. Electrical steels are commonly utilized as core materials in electric motors, generators, and distribution transformers [9, 10]. Core materials characterized by low power losses and high magnetic permeability improve the performance of these machines [11]. Due to the advancements in chemistry, thermo-mechanics, and rolling process technologies, the last 20 years have contributed to research on reduced power losses [12]. Manufacturing low-iron-loss electrical steels has been a critical research issue for high-efficiency electrical machines and energy saving.

Non-grain oriented electrical steel (N-GOES) sheet is used in the stator and rotor core of induction motors. It is known that the magnetic properties of non-grain-oriented electrical steels are excellent for induction motors [13]. One of the most significant reasons for this is the presence of silicon (Si) in its chemical composition. Si plays a crucial role in ascending the electrical resistivity of electrical steel sheets. Although the increase in the ratio of silicon in silicon steel sheets improves some magnetic properties, this increase may negatively affect the magnetic saturation properties because silicon is a nonmagnetic material [14]. The production of electrical steels involves detailed processes, such as casting, rolling, and heat treatment, making research costly. Therefore, researching silicon steel is very costly. However, the finite element method (FEM) mitigates these disadvantages by providing a numerical approach that simplifies complex problems. FEM could reduce time and costs through simulation packages, allowing for quick design and electromagnetic analysis of rotary electrical machines [15, 16].

Some research has been conducted to study the effect of silicon ratio on the energy efficiency of induction motors [5, 17]. Morimoto [17] reported the core losses of soft magnetic composite and conventional lamination steel in induction motors.

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The effect of using soft composite material as the core material in the design of an asynchronous motor on iron losses was investigated. The core losses of the soft magnetic composite material were lower at frequencies higher than 104 Hz. Okamoto et al. [5] compared the core losses of a permanent magnet synchronous motor selecting an amorphous magnetic material instead of a non-oriented electrical steel stator core. They claimed that the amorphous material reduces the core losses compared to the electrical steel.

This study goals to investigate the energy-saving and energy-efficient effects of laminated sheets used in the rotor and stator parts of electric motors. Several silicon steel sheets were used for the finite element analysis of electric motors. The chemical compositions and physical characteristics of materials have been examined to have an impact on energy efficiency. The connection between losses and efficiency was researched. Simulations were performed with Ansys-RMxprt and Ansys-Maxwell software [1]. The study's novel approach is to assess the materials' magnetic, chemical, and physical features together and analyze how these properties impact losses.

2. MATERIALS AND METHODS

Various core materials with different properties were utilized to simulate induction motors in the stator and rotor parts. Finite element method was used in the analysis. In the chapter on material properties, material specific features were discussed. Modeling parameters of induction motors were involved in the finite element model.

2.1. Material Properties

In this paper, a 1.1 kW-2pole-3 phase squirrel cage induction motor was designed in the Ansys-RMxprt module. Non-grain-oriented electrical steels (M27, M36 and M43) with different silicon ratios were used for the rotor and stator part of the motor. It has been observed that electrical steel containing 6.5 % by weight silicon has good soft magnetic characteristics, including powerful electrical resistance, low magneto-crystalline anisotropy, low magnetostriction, and low magnetic saturation. However, steels with less than 3.5–4.0% silicon by weight are frequently utilized for industrial applications. Higher silicon content in electrical steels makes the material more brittle, which prevents the rolling process from manufacturing thinner sheets [18]. These silicon steel materials are frequently preferred by industrial motor manufacturers. The chemical compositions of silicon steels are given in Table 1.

Table 1. Chemical composition of non-oriented electrical steel sheet [19, 20].

Grade	*C max. (%)*	*Mn max. (%)*	*P max. (%)*	*S max. (%)*	*Si (%)*
M27	0.020	0.25	0.025	0.008	2.6-3.0
M36	0.025	0.25	0.025	0.008	2.2-2.8
M43	0.027	0.30	0.025	0.010	1.8-2.6

Three different sheet thicknesses were selected for each silicon steel (0.64 mm, 0.47 mm and 0.36 mm). Silicon steel grades and the thicknesses used in this study are demonstrated in Figure 1.

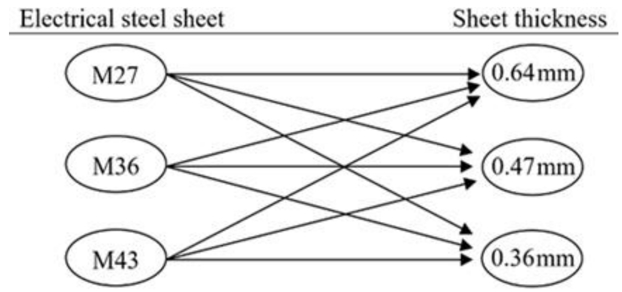


Fig. 1. Grades and thicknesses of silicon steel sheet.

2.2. Finite Element Model

ANSYS-Maxwell software was used to simulate core losses in the induction motor. Nine different models were created by using three different thicknesses for each silicon steel sheet. Simulations incorporating electric motor modelling have been performed at the full load. The analyses were performed three times in total. The results were obtained by calculating the average of these three analyses. In the FEM, the rotor windings of the induction motor were selected as a squirrel cage and made of cast copper. Specification of the induction motor is presented in Table 2 [20].

Table 2. Specification of induction motor [20].

Items	*Specification*
Phases number	3
Poles number	2
Rated output power (kW)	1.1
Rated voltage (V)	380
Rated speed (rpm)	2860
Operating temperature (°C)	75
Frequency (Hz)	50

The general electric motor assembly, rotor core, and stator core are shown in Figure 2(a, b and c). Induction motor models were created according to the methods used in the studies of Deshmukh et al [21]. Rotor core and stator core geometry designs of induction motors used in FEM were the same for all modelling. Geometric design values of stator and rotor parts are given in Table 3.

Table 3. The geometric design value of stator and rotor parts [20].

	Stator	*Rotor*
Outer diameter (mm)	140	77
Inner diameter (mm)	78	32
Length (mm)	250	250
Slots number	36	28
Stacking factor	0.95	0.95

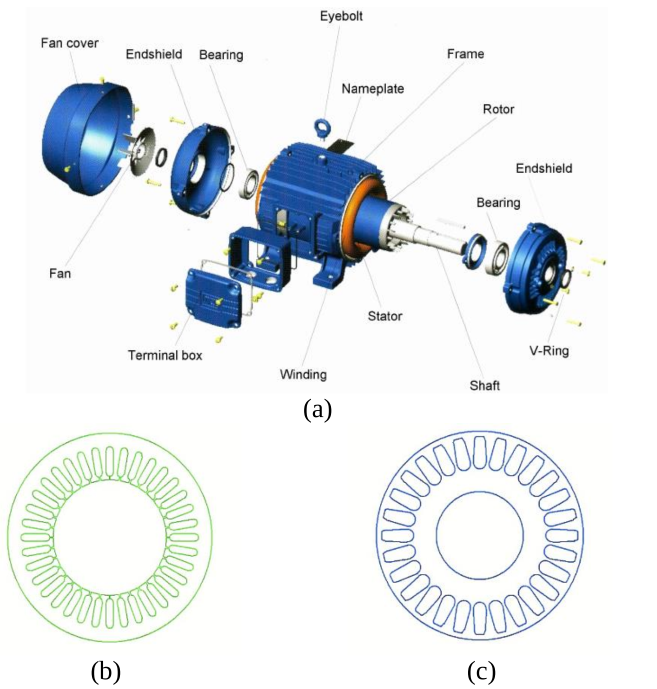


Fig. 2. (a) General electric motor assembly [22], (b) stator core, (c) rotor core.

Induction motor modeling was divided into mesh structures for finite element analysis as shown in Figure 3. Two mesh options were used as both length-based and surface approximation-based options for electromagnetic calculation.

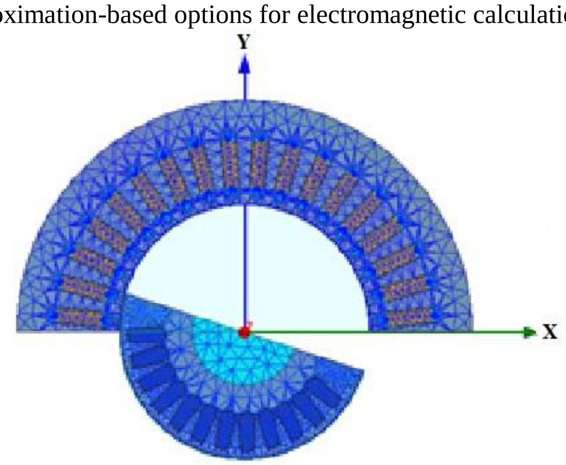


Fig. 3. Mesh structure of core materials [20].

Induction motor design was performed according to core losses and copper losses in the Ansys Maxwell program. Copper losses are calculated according to Equation (1) [4].

$$P_{cu} = R_{phase} * I^2 * M_{\Phi} \quad (1)$$

R_{phase} indicates the single-phase winding resistance, I indicate the current value in the winding and M_{Φ} indicates the phase number of the machine. Core losses are calculated by the sum of eddy current losses, hysteresis losses and other losses as shown in Equation (2) [23].

$$W_c = K_h f(B_m)^2 + K_e f(B_m)^2 + K_o(f B_m)^{1.5} \quad (2)$$

The coefficient K_h for hysteresis loss, K_e for eddy current loss and K_o for other losses were used calculation for core losses. The eddy current loss coefficient is calculated directly as Equation (3) [23];

$$K_e = \pi^2 \sigma \frac{d^2}{6} \quad (3)$$

Where σ was electrical conductivity and d was silicon steel sheet thickness.

3. RESULTS AND DISCUSSION

The correlation between magnetic flux density (B) and magnetic field strength (H), commonly referred to as the B-H curve for silicon steels, is depicted in Figure 4. The B-H curve consists of two distinct regions, with region A corresponding to low saturation and region B representing high saturation. As the magnetic materials moved through the high saturation region, the magnetic flux density shifted to a steady condition [24]. It has been reported that iron losses increase when the magnetic flux density exceeds the magnetic saturation limit [12, 23]. In the high saturation region, the material begins to act as an empty space and loses its magnetic properties.

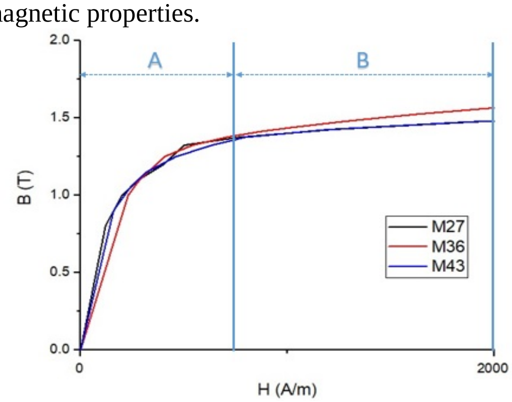


Fig. 4. B-H curve of magnetic cores.

Magnetic flux density distributions are shown in Figure 5. The core materials preferred in the modelling were suitable for the *B-H* characteristic. Magnetic saturation was not reached except for some small parts near the slots by either of the three materials. Figure 5(a, b and c) [20] is given to demonstrate electric motors performing in the low saturation zone.

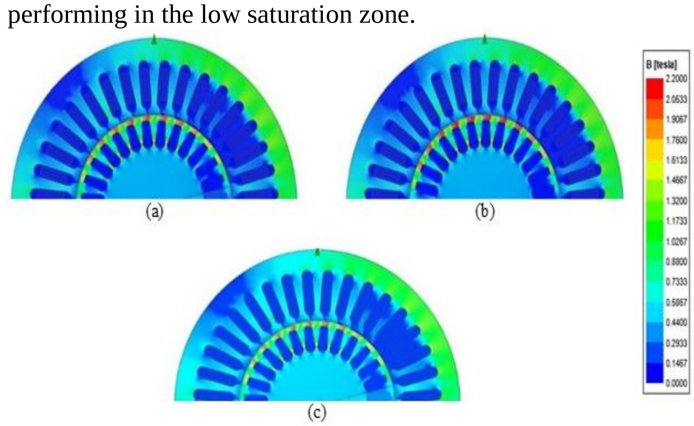
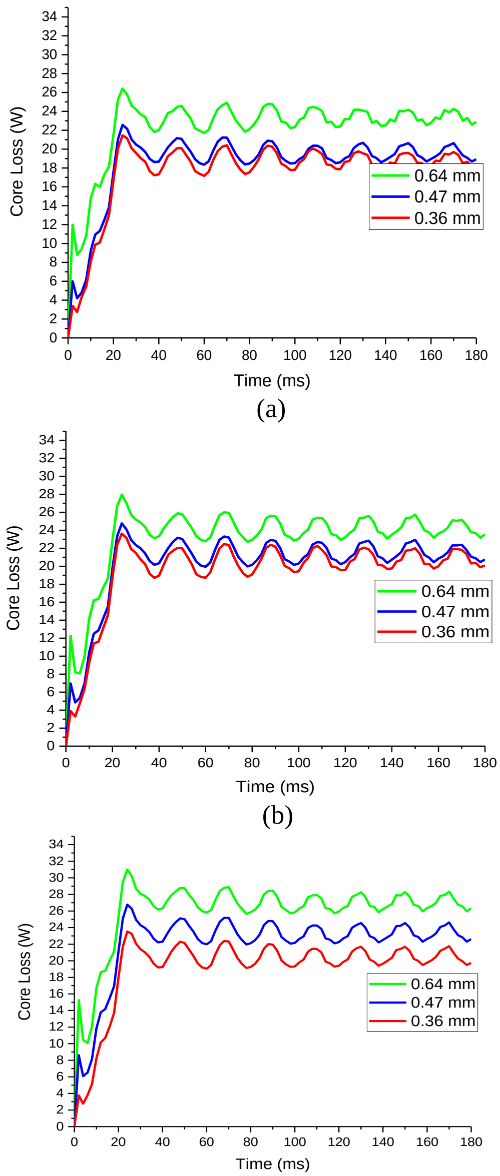


Fig. 5. Magnetic flux density distributions of (a) M27, (b) M36 and (c) M43 electrical steel sheets [20].

Core losses on the electrical motors are indicated in Figure 6(a-c). The simulation results showed that the M27 core electric motor with the highest silicon content had a lower iron loss compared to other cores of the same thickness. When the silicon content of electrical steel is increased, core losses in the stator and rotor parts decrease. Core losses are one of the undesirable losses, and have an efficiency-reducing feature on the electric motor [25]. According to the simulations, reducing core losses is provided to improve induction motor efficiency. The lowest core losses for all thicknesses were found in M27 electrical steel. Therefore, the simulation results revealed that the induction motor modelled with M27 core material had the highest performance according to the core losses. Moreover, the performance of electric motor simulations was found to improve as the thickness of the steel used decreased. Lower core loss was observed in the M36 core material due to its high silicon ratio content as compared to the M43 core material.



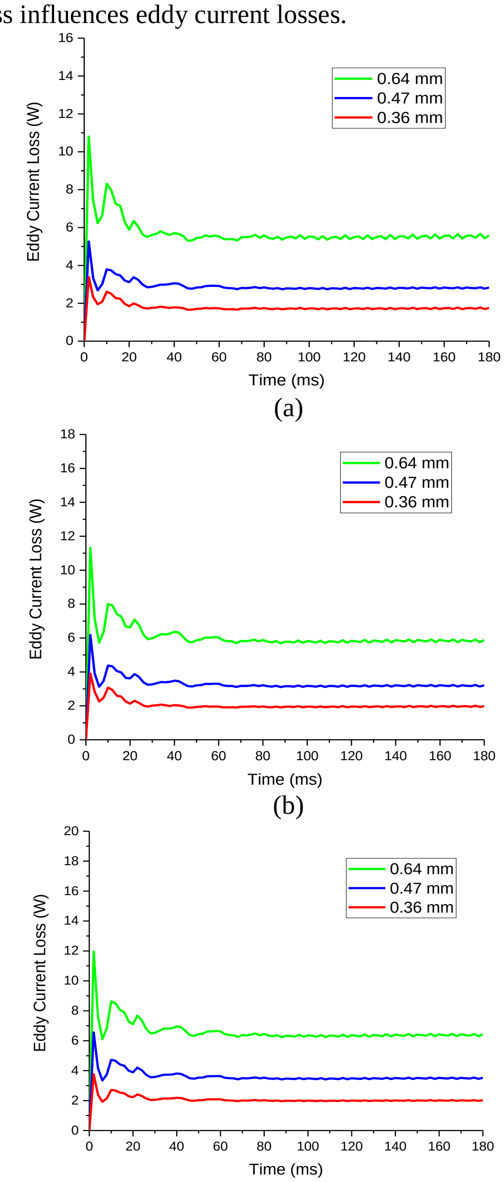
(a)

(b)

(c)

Fig. 6. Core loss results of electrical steel sheets of different thicknesses, (a) M27, (b) M36, (c) M43 slicon steels.

The eddy current losses versus time graphs were demonstrated for all materials and thicknesses in Figure 7(a-c). Eddy's current losses changed less after 20 ms, and the change in losses was steady at 180 ms. Eddy currents could be reduced by decreasing the thickness of the lamination sheet. Eddy current losses were minimized by using thinned electrical steel sheets in all three materials. There was a proportional relationship between the thickness of the electrical steels and eddy current losses. Eddy current losses were reduced by decreasing the thickness of the electric motor core. The modelling results revealed that there was no relationship between sheet thickness and hysteresis losses. It was thought that hysteresis losses might be related to the magnetic properties of the alloying elements and also the grain orientation of the material. Eddy current losses were the least in electrical steels with a thickness of 0.36 mm. In electric motor simulations, 0.36 mm thick M27 electrical steel reached the lowest eddy current losses. The results show that, like the silicon ratio, sheet thickness influences eddy current losses.



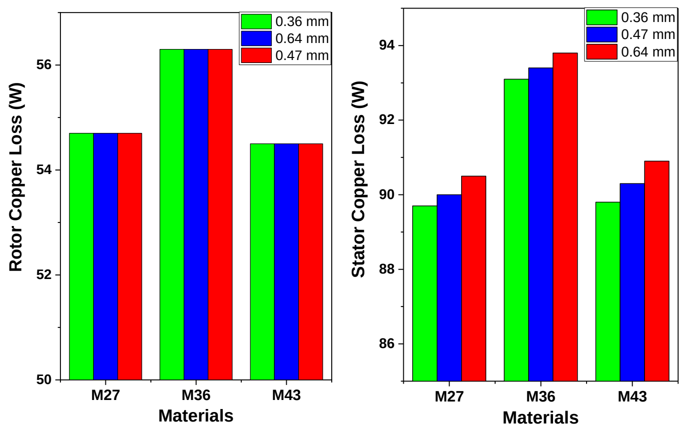
(a)

(b)

(c)

Fig. 7. Eddy current loss results of electrical steel sheets of different thicknesses, (a) M27, (b) M36, (c) M43 silicon steels.

Another important parameter was counted as copper losses to influence the efficiency of induction motor. Copper losses in electrical machines are the losses that occur in the magnetic flux in the windings of the machine [26]. Figure 8(a, b) is given to show the copper losses from the electrical motors due to different sheet materials and thicknesses. It was obtained that magnetic core thickness has no significant effect on copper losses. Another outcome from Figure 8(b) was found that the copper losses from the stator were bigger than the copper losses from the rotor. This result about the copper losses was found to be similar to the literature. It can be said briefly that the reason for this is that the design of the stator in electric motors causes more resistance [27, 28].



(a) (b)

Fig. 8. Copper loss results of electric motors depend on sheet materials and thickness for (a) Rotor and (b) Stator.

Higher copper losses were observed from the electric motors using an M36 steel sheet in both the rotor and stator. Accordingly, it was observed that copper losses were very similar to each other in electric motors where M27 and M43 electrical steels were used. The stator and rotor currents were required for the electric motor model using M36 electrical steel to reach 1.1 kW power are 2.60 A and 2.23 A, respectively. The higher phase current of M36 electrical steel than others increased the copper losses as illustrated in Table 4.

Table 4. Phase currents from the electric motors depend on different materials and thicknesses.

Materials	*Thickness (mm)*	*Stator Phase Current (A)*	*Rotor Phase Currents (A)*
M27	0.64	2.56	2.19
	0.47	2.55	2.19
	0.36	2.55	2.19
M36	0.64	2.59	2.23
	0.47	2.60	2.23
	0.36	2.60	2.23
M43	0.64	2.56	2.19
	0.47	2.55	2.19
	0.36	2.55	2.18

Figure 9 is given to show the energy performance improvements depending on the core thickness for M27, M36 and M43 steel sheets. Minimum efficiency was found as 83.19 % from the electric motor which used 0.64 mm M43 electrical steel sheet. The maximum was detected as 84.24 % using a 0.36 mm M27 electrical steel sheet in the rotor and stator. It was observed that the decrease in core thickness causes an ascend in efficiency in all materials. As the thickness changed in the three materials, the difference in efficiency remained approximately the same between different core materials. It was noticed that the thickness change has the same effect for all three materials. The reduction in eddy current losses as thickness decreases is assumed to be the reason for this performance improvement in thickness decrease. To increase the energy efficiency of induction motors, it is necessary to minimize power losses. Reducing iron losses is a good way to increase energy efficiency. However, there is indecision between core losses and the efficiency of M36 and M43 electrical steels. Although an increase in silicon ratio appeared to minimize core losses, the efficiency of M36 electrical steel was lower than that of M43 electrical steel. Because M36 electrical steel phase currents were higher than other electrical steels. The increased copper losses were caused by the high current in the rotor and stator copper conductors. According to the IEC 60034-30-1 standard, IE1 is defined as standard efficiency, IE2 as high efficiency, IE3 as very high efficiency, and IE4 as super very high-efficiency motors. The modelling results were evaluated based on the IEC 60034-30-1 standard. All of the models are in the very high efficiency class [29].

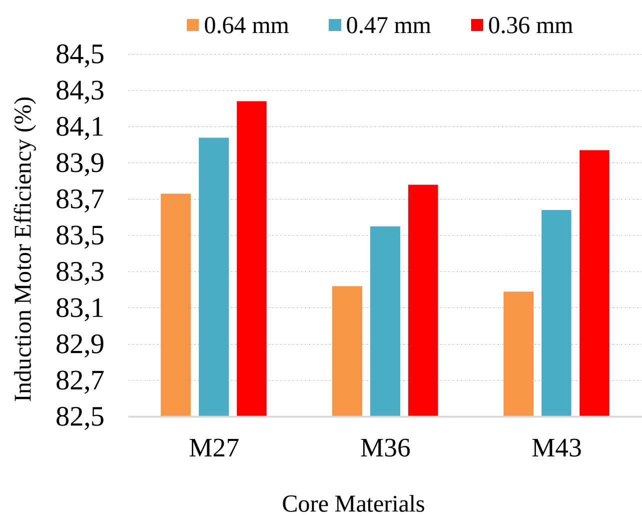


Fig. 9. Effects of the thickness of rotor and stator cores on induction motor efficiency.

Table 5 shows the calculated annual consumption of the modelled electric motors. It is seen that the motor with the lowest efficiency of 83.19% may have an annual expense of 1519.5 dollars depending on the billing in Turkey, while the annual bill of the electric motor with the highest efficiency of 84.24% is calculated as 1500.5 dollars. Although the difference of 19 dollars is not very significant for a single electric motor, it is thought that it may be more significant in businesses using dozens of electric motors.

Table 5. Payback period and energy savings of a highly efficient motor at 100% load.

Grades	*Thickness*	*Power*	*Efficiency*	*Energy Saving*	*Annual Bill*
-	*mm*	*kW*	*%*	*kWh*	*US$/year*
M27	0.64	1.1	83.73	11508.419	1509.7
	0.47		84.04	11465.968	1504.1
	0.36		84.24	11438.746	1500.5
M36	0.64	1.1	83.22	11578.947	1518.9
	0.47		83.55	11533.213	1512.9
	0.36		83.78	11501.551	1508.8
M43	0.64	1.1	83.19	11583.122	1519.5
	0.47		83.64	11520.803	1511.3
	0.36		83.97	11475.526	1505.3

4. CONCLUSION

In this study, a 1.1 kW, 2-pole, 3-phase squirrel cage induction motor was designed using the Ansys-RMxprt module. The simulation involves a finite element analysis of electrical steel combinations with variable silicon ratios and sheet thicknesses. The following conclusions were drawn in this research;

- Copper and core losses have been shown to have a significant impact on electric motor performance.
- The increment in electric motor efficiency was achieved by reducing eddy current losses.
- The reduction of eddy current and hysteresis of the induction motor was possible by using the different silicon ratios.
- The use of sheet metal with low thickness has increased the efficiency of the induction motor by reducing the eddy losses.
- The simulation showed that eddy losses could be estimated faster using the finite element method by changing the sheet thickness of the rotor and stator parts.
- Increasing the efficiency of electrical motors will not only contribute to the environment in terms of energy efficiency, which is of increasing importance, but will also provide significant economic benefits to companies that use dozens of electric motors.

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