INTERNATIONAL SCIENTIFIC AND VOCATIONAL JOURNAL (ISVOS JOURNAL)

Vol.: 6 Issue: 1 Date: 28.06.2022 Received: 13.06.2022 Accepted: 28.06.2022 Final Version: 28.06.2022

ISVOS Journal, 2022, 6(1): 32-40 - https://doi.org/10.47897/bilmes.1129634

Transforming of Conventional Type Squirrel Cage Induction Motor to Permanent Magnet Synchronous Motor for Improving Efficiency on Industrial Applications

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Abstract

The increasing of world population, forced human beings to produce clean energy, more creative solutions have been developed to use the energy with most efficient way. Researches on this topic still working today. Nowadays, new electrical machines are invented and the currently used ones are being continue to be improved. In industry, if a survey is made according to use of electric motors, it will be seen that, induction motors used in industry average eighty percent. When viewed from the efficiency and energy quality of the interconnected system, increasing efficiency of induction motors will provide advantages for the production, transmission, distribution systems and the network. On the other hand, Permanent Magnet Synchronous Motors (PMSMs) have not windings on rotor core and much more efficient than induction motors. In this way PMSMs will save the company from spending unnecessary energy. For this reason, in this study, an industrial conventional type squirrel cage induction motor (SCIM) has been converted into a permanent magnet synchronous motor (PMSM) for improve the overall efficiency. For improving the efficiency in design and production, induction motor's stator core will not change. Only squirrel cage rotor core of induction motor will change with PMSM in rotor design production stage. As a result of this conversion, various electromechanical parameters have changed and improved. Electromechanical modification process has been provide better energy density and power density for this motor. As a result of the research, the cost of modification process will be amortized in usage. In this way, conventional type induction motor (IM) that dominates the vast majority of the industry is converted into PMSM, it is seen that energy efficiency and energy quality will increase.

Keywords: "Squirrel cage induction motor, permanent magnet synchronous motor, energy efficiency, energy quality, industrial design."

1. Introduction

Compared to SCIMs and PMSMs in terms of efficiency, energy and power density, PMSMs have higher energy and power density than SCIMs. *Considering the energy efficiency in the industry, in order to increase energy quality and efficiency, SCIMs use in industry need to be modified or to produce more efficient motors without changing the production line.* In addition, it is predicted be an important advantage not to change the production line too much and to decrease costs. According to these predictions, a modification process can be made to increase the efficiency of SCIMs used in the industry.

Actually, the most important question should be this. *How to make a physical modification for the production of SCIM?* Regarding the physical modification, the first problem that comes to mind for the motor manufacturer is the process of renewing or reprocessing sheet cutting molds, in which the stator and rotor cores of the motor are produced. Siliceous sheets can be pressed and shaped by the press molds according to the desired slot-pole combination. Depending on the desired motor power and speed, the physical parameters such as the diameter of the stator and rotor, the number of stator slots, the number of rotor slots etc. also change. Every physical change means the change of motor core press production molds and this change is one of the most costly processes for the motor manufacturer.

If the two motor types used in the industry, PMSM works with higher efficiency than SCIM. Owing to this feature, SCIM can be converted to PMSM and the stator core and/or winding set can remain the same. In order not to change the production bands already used for SCIM production, the topology of the motor stator core sheets and stator windings produced must remain the

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same. In fact, at this stage, the slot-pole combination of the motor does not change. For example, if the motor is 2-pole or 4-pole, the distributed windings are placed in the slots in the same way and according to the number of poles on the motor, the position of the magnet poles to be placed on the rotor core is determined. Furthermore, it is not necessary to produce the short circuit bars in the rotor core of conventional type SCIM and thus, the cost of aluminum casting to the rotor core is eliminated. The only process that needs to be done at this stage is the circular cutting of the rotor sheets and the placement of magnet poles after the rotor core is packaged. Main fact for this implementation that, applying the best practical and simple way to increase the motor torque, output power and efficiency.

Looking at the literature, there are various studies for SCIMs to improve efficiency.

W.Fei,P.C.K.Luk, J.Ma, J.X.Shen and G.Yang wrote an article named “A High-Performance Line-Start Permanent Magnet Synchronous Motor Amended From a Small Industrial Three-Phase Induction Motor”. In this article, induction motor named IMY90S-4 has small dimensions and this IM has been amended to line start permanent magnet synchronous motor (LSPMSM). LSPMSM has been developed to have high efficiency in steady state and synchronous speed. It is designed with a FEM program that performs 2D analysis. The prototype has been made and the design results were compared with the experimental results. As a result, LSPMSM has proven to have higher efficiency and power factor than IMY90S-4 IM. [1]

E.Mese, M.Ayaz, M.Tezcan, K.Yilmaz and E.Ozdemir wrote an article named “A Permanent Magnet Synchronous Machine with Motor and Generator Functionalities in Single Stator Core”. In this article, the design and analysis of a PMSM with a single stator core, double winding, operating in motor and generator modes were made. This machine was made with FEM and experimental method. Furthermore, comparison was made between the distributed winding and the concentrated winding. The concentrated winding was preferred. Thus, magnetic and electrical isolation was provided. [2]

T.Sebastian wrote an article named “Temperature Effects on Torque Production and Efficiency of PM Motors Using NdFeB Magnets”. In this article, NdFeB magnets motors have been studied on the change of torque and efficiency according to temperature. As a result, high efficiency motor has a positive slope but the low efficiency motor has a negative slope in the torque-temperature curve. [3]

Won-Ho Kim, Ki-Chan Kim, Seung-Joo Kim, Dong-Woo Kang, Sung-Chul Go, Hyung-Woo Lee, Yon-Do Chun and Ju Lee wrote an article named “A Study on the Optimal Rotor Design of LSPM Considering the Starting Torque and Efficiency”. In this article, an optimal rotor design has been made to adjust the starting torque and efficiency of line start permanent magnet motor. In design, equivalent circuit and permanent magnets are designed with FEM program. Taguchi method and weight function were used to evaluate the production tolerance. The characteristics of the optimal model were compared to a conventional IM with the same nominal power. [4]

N.F.Ershad, M.Mirsalim and A.D.Aliabad wrote an article named “Line-start permanent magnet motors: proper design for pole-changingstarting method”. In this article, proper design has been made for pole-changing starting method of LSPMSM. In the steady state, to make the power factor and starting torque as perfect as possible, the stator windings were adjusted and optimum rotor resistance was calculated. In design, a 2D analysis FEM program was used and a prototype was created. The results of the tests performed on the prototype were the same as the simulation results. As a result, pole-changing starting method proved to increase the starting torque. [5]

Andrew M.Knight and Catherine I.McClay wrote an article named “The Design of H0000igh-Efficiency Line-Start Motors”. In this article, it has been studied on the design of highly efficient and line start motors. In the design, FEM program that used Eddy current analysis was used. As a result of the simulation, PMSM has proven to be up to 50% reduction in losses compared to IM in steady state and full load. [6]

A.D.Aliabad, M.Mirsalim and N.F.Ershad wrote an article named “Line-Start Permanent-Magnet Motors: Significant Improvements in Starting Torque, Synchronization, and Steady-State Performance”. In this article, important improvements in starting torque, synchronization and steady-state performance of LSPMSM were explained. Motors design, a FEM program that used 2D analysis was used. Based on the simulation results, stronger permanent magnets were used in the newly designed motor. In the new design, it has been observed that efficiency and output power capacity of motor has increased significantly compared to the before motor. [7]

M.A. Rahman and A.M.Osheiba wrote an article named “Performance of Large Line-Start Permanent Magnet Synchronous Motors”. In this article, the performance of 25 HP line start PMSM has been examined. SmCoS and NdBFe were compared as permanent magnets and the motor using NdBFe, high power factor and over 94% efficiency has been achieved. [8].

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Qinfen Lu, Xiaoyan Huang, Yunyue Ye and Youtong Fang wrote an article named "Experiment and analysis of high power line-start PM motor". This article focused on the design and prototyping of a high power line-start permanent magnet motor (LSPM) for industrial "fans, pumps and compressors. Compared with design, LSPM had higher efficiency, power factor and high overload ability. However, it can not start take into account current limitation, 1000A. As a result, the method of placing PMs in the rotor was found to be unsuitable for low voltage start high power LSPM. [10]

Kazumi Kurihara and M. Azizur Rahman wrote an article named "High-Efficiency Line-Start Interior Permanent-Magnet Synchronous Motors". In this article, design of a high-efficiency, small, new interior permanent-magnet (IPM) motor using NdBFe magnets was made. A prototype was made and time-stepped FEM was used to estimate dynamic and transient performance of prototype. As a result of the study, successful design simulation and experimental results were obtained. The maximum load inertia suitable to the rotor-bar depth explained on simulation results. [11]

Dan Stoia, Mihai Cernat, Adisa A. Jimoh and Dan V. Nicolae wrote an article named "Analytical Design and Analysis of Line-Start Permanent Magnet Synchronous Motors". In this article, an analytical design method for LSPMSM, according to synchronous steady state and asynchronous starting parameters was given. In this way, it is possible to calculate all synchronous and asynchronous starting parameters. [12]

Amin Mahmoudi, Solmaz Kahourzade, Nasrudin Abd Rahim, Wooi Ping Hew and Mohammad Nasir Uddin wrote an article named "Design, Analysis, and Prototyping of a Novel-Structured Solid-Rotor-Ringed Line-Start Axial-Flux Permanent-Magnet Motor". In this article, design, analysis and prototyping of a new structured line-start solid-rotor based axial-flux permanent-magnet (AFPM) motor capable of auto starting with solid-rotor rings was given. The design of motor was tested in simulation using FEA software Vector Field Opera 14.0. In prototype, 1 HP LSAFPM synchronous motor was fabricated and has been used to test performance in real time. [13]

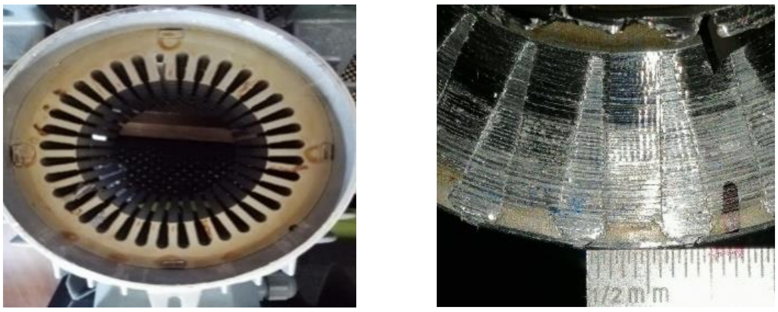
Gang Cui, Lifei Liu, Shan Li, Pingxi Yang, Fan Yang, Lin Chen and Jiwei Dong wrote an article named "Optimization Design of High Efficiency Variable Frequency Induction Motor Based on Finite Element Analysis". In this article, an example of a 55 kW variable frequency induction motor was analyzed. The effect of stator slot type, rotor slot type, winding type on motor loss was given. The prototype was made and the test results shown design was right. [14]

2. Electromagnetic Modelling of Squirrel Cage Induction Motor

SCIM, that planned for modify, physical dimensions were measured in laboratory. Analytical method and finite element analysis (FEM) were used to determine the performance of the SCIM using measured dimensions, nameplate and catalog information. In this study, physical dimensions of the SCIM what shown in Figure 1. stator and rotor core dimensions, stator and rotor diameters, stator and rotor slot dimensions were measured and also electrical parameters (nameplate information shown in Table 1.) were saved for use in the analytical method and design of the SCIM.

Table 1. Nameplate data of modified SCIM.

Number of Phases	3
Frequency	50 Hz
Connection Type	Star
Line to line RMS Voltage	380 V
Output Power	1100 W
Power Factor (PF)	0.77
Speed	1415 rpm
Pole (p)	4
Efficiency (η)	81.4%



(a) **(b)**

Figure 1. Stator (a) and rotor (b) slot overviews.

2.1. Modeling of Conventional Induction Motor by Basic Analytical Method

To increase efficiency, SCIM has to be modeled analytically with general design formulas. In the apparent power formula of SCIM, K_w, winding factor, $\overline{B}$, average flux density in air gap, ac, ampere-conductor per m periphery, D, stator inner diameter, L, length of core, n, revolutions per second. Thus, average apparent power value can be calculated [15].

$$S = 1.11\, K_w\, \Pi^2\, \overline{B}\, ac\, D^2 L\, n\, 10^{-3}\, kVA \tag{1}$$

To calculate the flux per pole (2), $\overline{B}$, average flux density in air gap, Y, pole pitch, L, length of core are used.

$$\phi_m = \overline{B} Y L \tag{2}$$

To find the number of turns per phase (3), E_{ph}, phase voltage, K_w, winding factor, f, frequency, $\emptyset_m$, flux per pole are used.

$$N_{ph} = \frac{E_{ph}}{4.44 K_w f \phi_m} \tag{3}$$

As a result of measurement of physical dimensions and calculations with analytical method, electrical and physical parameters of 1.1 kW SCIM have been obtained. (Table 2.)

Table 2. Electrical and physical parameters of modified SCIM.

Input Power (S)	1.755 kVA
Reference Speed (n)	1500 rpm
Winding Factor (K_w)	0.95
Revolutions per Second (n)	25 rps
Average Flux Density in Air-Gap ($\overline{B}$)	0.45 Wb/m^2
Ampere-Conductor per m Periphery (ac)	25000 At/m
Length of Core (L)	95 mm
Stator Inner Diameter (D)	79.6 mm
Flux per Pole ($\emptyset_m$)	2.675 mWb
Number of Turns per Pole (N_{ph})	410
Conductors per Slot	69

2.2. Dynamic Analysis and Modeling of Induction Motor with Finite Element Analysis

Measurements of SCIM in the laboratory and calculations were made using analytical method. For SCIM desgin a program that works with finite element analysis which is a numerical method was used.

If the operation of the program is explained simply; All electrical or mechanical parts are modeled in 3D into small pyramids and obtained by meshing. The number of meshes determines the resolution.

For the design of the stator of SCIM, outer diameter is 130 mm, inner diameter is 79.6 mm and length is 95 mm. The stator has 36 slots and conventional steel lamination was chosen for the material of the stator. For the stator core, 250 pieces of laminations were used and the stacking factor was determined as 0.95.

For stator slot structure design, the measured stator slot size parameters were transferred to FEM program.

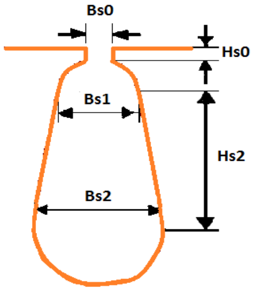


Figure 2. Slot structure of stator core.

Table 3. Stator slot parameters of SCIM.

Stator Slot Dimensions	***Value***
Hs0	0.5 mm
Hs2	7 mm
Bs0	1.5 mm
Bs1	3 mm
Bs2	5 mm

For stator winding design, single layer, single core cable with 62 conductors per slot was used. To find the most efficient value of the number of conductors per slot, the optimetric part of FEM program that makes the step solution is used (the optimetric analysis shown in Figure 3.) and according to this analysis, 62 windings were used instead of 69 windings.

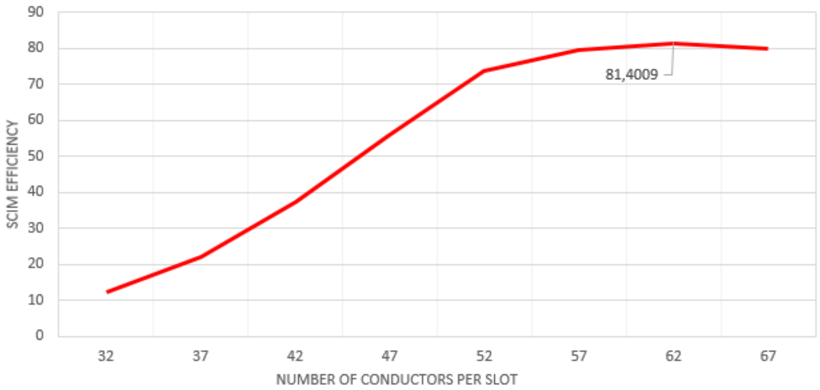


Figure 3. Variation of the efficiency SCIM by the number of conductors per slot.

For rotor core design of SCIM, outer diameter is 78.6 mm, inner diameter is 30 mm and length is 95 mm. The rotor has 28 slots and steel_1008 was chosen as material as in the same stator.

For rotor slot structure design, the measured stator slot size parameters were transferred to FEM program.

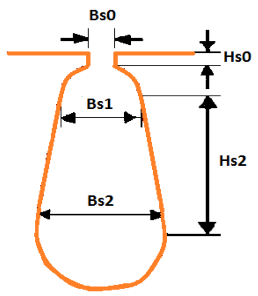


Figure 4. Slot structure of rotor.

Table 4. Rotor slot parameters of SCIM.

Rotor Slot Dimensions	***Value***
Hs0	0.5 mm
Hs2	7 mm
Bs0	1.5 mm
Bs1	5 mm
Bs2	3 mm

The rotor of SCIM does not have a winding unlike wound rotor induction motor. Instead of the windings, solid squirrel cage usually made of aluminum which is obtained by pouring into molds, is used.

In this study, aluminum was preferred for squirrel cage material. The parameters of the short circuit rings are like this; length is 9 mm, width is 13 mm and distance to the rotor core is 0 mm.

According to analytical and dynamic analysis, results were obtained as a result of the analysis of SCIM. (Shown in Table 5.)

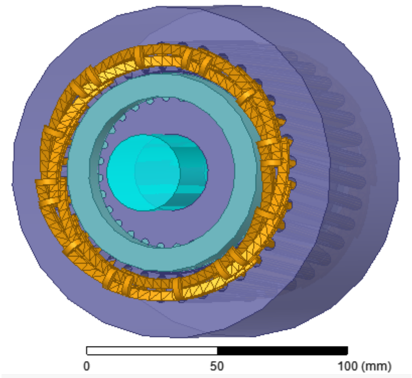


Figure 5. 3D view of SCIM.

Table 5. Performance parameters of SCIM.

SCIM Basic Performance Parameter	***Value***
Output Power	1100.2 W
Input Power	1351.36 W
Efficiency	**81.40 %**
Torque	7.35999 Nm

3. Optimetric Analysis and Modeling of Permanent Magnet Synchronous Motor with Finite Element Analysis

Physically measured, analyzed, modeled dynamically with FEM, SCIM was transformed into a permanent magnet synchronous motor. Thus, efficiency was increased.

Furtermore, it is possible to apply this transformation to the industry. Owing to the more efficient operation of the motor, it is foreseen that it will amortize the mechanical modification costs in a short time and is predicted that it will make company profit in time.

The stator of the permanent magnet synchronous motor is designed to be exactly the same dimensions with the previously designed SCIM, except the number of conductors per slot.

For stator design of PMSM, dimensions of SCIM has used. Outer diameter is 130 mm, inner diameter is 79.6 mm and length is 95 mm. The stator has 36 slots and steel_1008 was chosen for the material of the stator core. For the stator core package, 250 pieces of steel 1008 lamination were used and the stacking factor was determined as 0.95. For stator slots, PMSM was modeled exactly the same with the previously designed SCIM. For designing the stator winding , a single layer winding structure with 34 conductors per slot was used. For achieving the most efficient value of the number of conductors per slot, the optimetric analysis part of the program has used. It is a numerical method and according to this, 34 turns per slot were used instead of 62 turns that used for SCIM (Figure 6.). It has used to obtain more efficiency and reduce copper losses as much as possible. Main fact for this implementation that, applying the best practical and simple way to increase the motor torque, output power and efficiency.

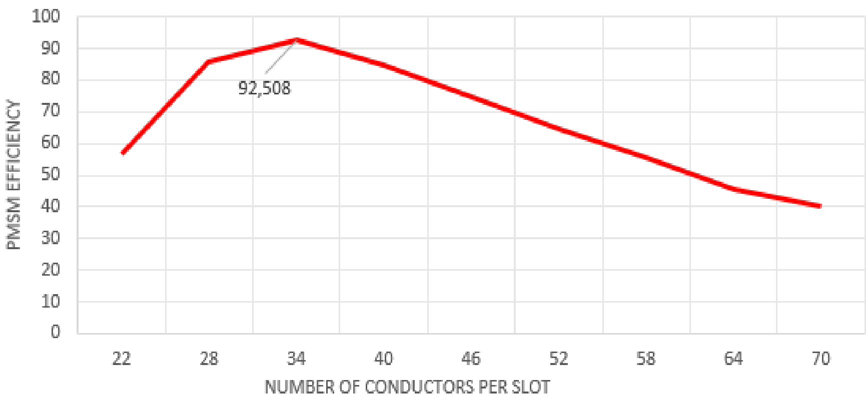


Figure 6. Variation of the efficiency of PMSM by the number of conductors per slot.

For rotor core of PMSM, following dimensions were chosen. Accordingly, outer diameter is 75.85 mm, inner diameter is 30 mm and length is 95 mm. The rotor has designed surface PM structure and steel_1008 has chosen for lamination material. NdFe35 is used as magnet material.

In order to find the most efficient value of magnet thickness, the optimetric part of the program was used and the optimum magnet thickness was determined as 2.75 mm. (Shown in Figure 7.)

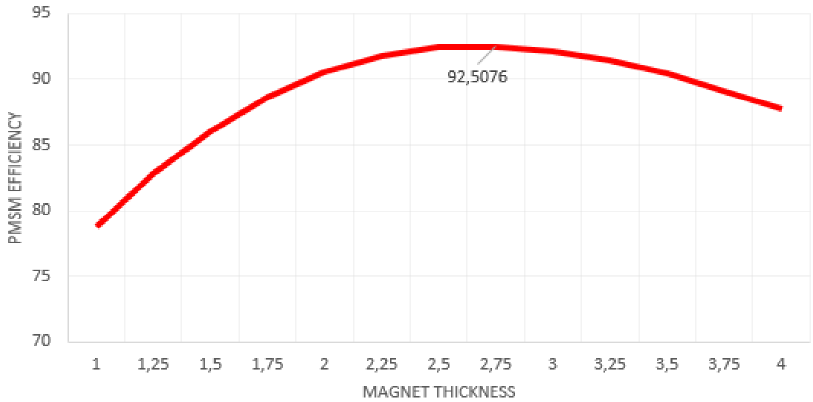


Figure 7. Variation of the efficiency of PMSM by magnet thickness.

According to analytical and dynamic analysis, results were shown in Table 6.

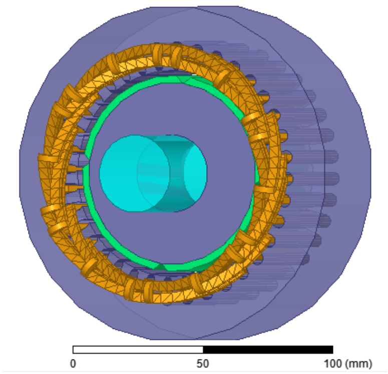


Figure 8. 3D view of PMSM.

Table 6. Performance parameters of PMSM.

PMSM Basic Performance Parameter	***Value***
Output Power	1101.18 W
Input Power	1190.37 W
Efficiency	**92.50 %**
Torque	7.43146 Nm

4. Conclusions

In this study, the conversion of 1.1 kW SCIM to PMSM in order to achieve a more efficient motor was examined. SCIM, that planned to modify, physical dimensions were measured in laboratory and analytical modelling of SCIM has been made. For designing, SCIM has been analyzed using 3D and optimetric FEM program. During the analysis, various optimizations like stator turn number analysis has been made to reach nameplate informations. After the modelling of SCIM, providing the stator dimensions remain the same, PMSM design has been made by adding permanent magnets to the rotor surface. Furthermore, various optimizations like magnet thickness and one slot turn number have been made to achieve a more efficient motor performance. According to the optimizations, During this conversion, the structural properties of the stator have not been changed because motor manufacturers do not want to change the producing lines.

In both motor designs, efficiency, torque and power factor, which are the most important parameters for the motor, were examined and as a result of this examination, it has been proved that PMSM has higher values than SCIM. For obtain 1100 W output power in SCIM, 1351.36 W input power must be given but for get the same output power, only 1190.37 W input power is enough in PMSM. A comparison table has been given below (Table 7.) for a practical understanding of these improvements.

Research results show that the energy efficiency and energy quality of SCIM, which was converted to SCIM, have increased. In the long term, the company which has too many motor, if convert to their SCIM to PMSM, it will not waste energy.

Table 7. Comparison between SCIM and PMSM performances and ımprovement values.

Motor Performance Parameter	*SCIM*	*PMSM*	*Improvement*
Output Power	1100.2 W	1101.18 W	1.16W
Input Power	1351.36 W	1190.37 W	160.99W
Efficiency	**81.40 %**	**92.50 %**	**11.10 %**
Torque	7.35999 Nm	7.43146 Nm	0.08Nm

A futurework will be applied to this study about restorations and improvements on different motor models and control techniques. Similar studies can help the improvements on efficiency, power and torque densities of various motors. However, energy quality of industry increase with usage of these kind of transformations.

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