Efficiency Improvement of Squirrel Cage Induction Motor by Rotor Slot Designs

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Abstract

This paper is an ultra high-energy efficiency 2200W four-pole three-phase asynchronous motor which comprises a stator and a rotor. Design of external diameters, internal diameters, length of iron cores, number of punching sheet grooves, and shape and size of the grooves of the stator and the rotor is systematically optimized so that stator winding loss, rotor winding loss, and iron core loss are substantially reduced. Compared with existing similar products, the total energy loss amount is reduced from 505.5W to 291.4W, and the reduction is 42.4% under the premise of the same output power of 2200W. The required input power is reduced from the original 2.706kW to 2.491kW, the energy conversion efficiency is increased from 81.3% to 88.3%, and the increment is 7.0%. Compared with the standard of IE3-86.7% Efficiency is improved to by changing the stator/ rotor slot number for 2.2kW -4 poles in this paper. An analytical program will investigate average torque and efficiency with different geometrical parameters of rotor bars considering the saturation of magnetizing current. The Squirrel Cage Induction motor-SCIM with 36 stator slots/ 44 and 40 rotor bars are verified underrated power. Their electromagnetic characteristics such as electromagnetic torque, losses, and efficiency are compared in between three configurations. The paper contributes that the proper rotor slot number selection has a strong impact on the induction motor and the best design is applied for a 2.2kW induction motor with fixed stator and rotor diameters.

Keywords: Electromagnetic force-EMF, Squirrel Cage Induction motor-SCIM

1.Introduction

Energy-saving and emission-reduction are the topics that cannot avoid in the world today, affecting the development of mankind's living environment and World Economics. Industrial circle as energy-saving and emission-reduction emphasis. Wherein, energy-saving of the motor system has a high potential, and power consumption accounts for 60% of national power consumption, causes that each side pays close attention to. The motor has had nearly two one-hundred-year histories so far from coming out, three-phase asynchronous also has more than 100 years history, be widely used at present all trades and professions such as each work, agriculture, woods, animal husbandry, and every field of life, become the essential equipment in industrial production and people's lives, but also become simultaneously produce and life in the maximum electric equipment that consumes energy, so how to make energy-saving motor environmental protection just become the important topic in face of people. Vietnam is one of the most serious developing countries of short of electricity at present in the world.

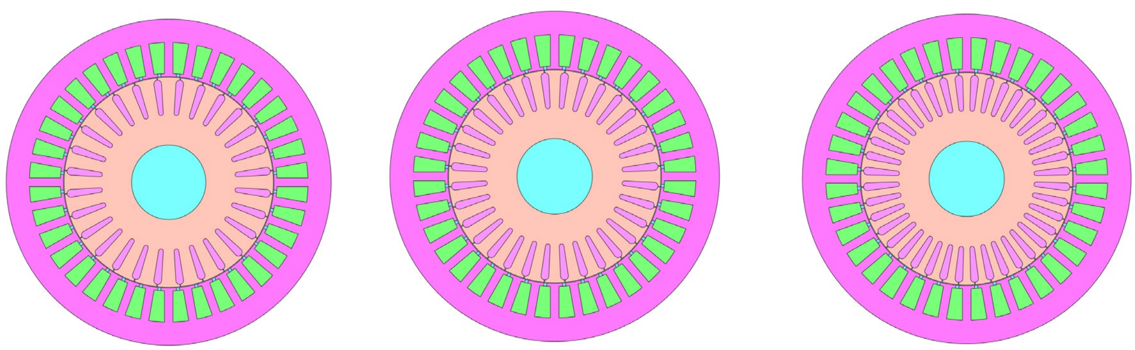
The energy shortage in Vietnam is because of energy waste mostly and utilizes improper causes; therefore, the raising of motor energy efficiency level is for Vietnam's energy conservation, and environmental protection and promotes economic development significantly. The national government has proposed the CO2 emission of the year two thousand thirty. The ultra-high efficient motor regulation is focusing on middle-size and small-size asynchronous machines. According to the investigation, the motor use amount of Vietnam IE1 Class still accounts for more than 85% of the total use amount, and more than IE2 high-efficiency energy-saving motor usage ratio only accounts for

11% of the total use amount, the ultra-high-efficiency energy-saving motor of IE3 class is still so small; This situation has produced great waste to entire society's resource, is the serious resistance of development low-carbon economy, so research and development high-efficiency electric motor is one of the important measures that improve energy utilization rate, meets the needs of Vietnam and development of world economy.

2200 watt of 4 poles three-phase asynchronous motor overwhelming majority using is in the market IE1 grade, its energy conversion efficiency is 79.7%, also has a small amount of IE2 grade, its energy conversion efficiency has risen to 84.3%, but its energy-saving effect still cannot meet the needs of current development low-carbon economy; For this reason, this paper will research and development an IM 2200 watt 4 pole with IE3 (86.7%) and IE4 (88.2%) applying for Hanoi Electromechanics Co-operation (HEM) in Vietnam. The production lines were invented by Hungary in the 1980s. This paper will introduce an analytical program of MATLAB coupling to FEM simulation for maximizing efficiency. The SCIM 2.2kW-4P was implemented by the same rotor diameter, the depth of the rotor bars, and the air-gap length. The used motor is a 3-phase, 4-pole, 2.2 kW, and 380 V aluminum cast-cage induction motor. Efficiency and torque and losses of some simulated induction motors with different rotor slot numbers have been shown and discussed. Three of the rotor slot selected numbers are 44 and 40 with skewing rotor slots. This paper presents an improvement related to a kind of motor, particularly a 2200-watt of 4 poles three-phase asynchronous motor of a kind of ultrahigh-energy efficiency.

Electromagnetic Designs

This study is based on 36 stator slots and 28,40 and 44 rotor bars and the three-phase SCIM specification and ratings are shown in Figure 1 and Table 1. The stator parameters are kept the same only rotor bars are changed but the rotor cage weight is kept constant at about 1.2 kg. Figure 1a is the conventional motor of 2.2kW-4P and the new configurations are IM 2.2kW with Stator 36 Slots and 40/44 rotor slots



(a) (b) (c)

Figure 1. SCIM 22kW-4P 36 stator slots and rotor bars 28 (a) 32 (b) and 40 (c)

In order to increase the efficiency of 2200 watts of 4 poles three phases asynchronous motor reach ultrahigh energy efficiency, the stator and rotor slots are optimized. The stator outer diameter is increased from 17cm to 18cm in that described stator core is 18.00cm, and diameter of stator bore is 11.20cm, and stator core length is increase from 10cm to 12.00cm, stator slots is kept the same 36 and is uniformly distributed in the form of a ring, and its flute profile is oblique shoulder round bottomed vessel, and wherein width of rebate is 2.50mm, notch height is 0.80mm, and groove top is 12.60mm deeply, and groove shoulder breadth degree is 5.30mm, groove shoulder height degree is 0.47mm, and bottom radius is 3.711mm, the quantity of described stator punching radiating groove is 36 and is uniformly distributed in the form of a ring, its flute profile is that the length of side is the equilateral triangle groove of 2.2mm, between stator outer diameter circumference and stator punching groove bottom land circumcircle contour, this leg-of-mutton base and stator outer diameter circumference are more approaching, namely this leg-of-mutton base is towards stator outer diameter circumference, between the groove of leg-of-mutton center line and stator punching groove two grooves, center line overlaps, the central point of the line segment that between the groove of leg-of-mutton center of gravity and stator punching groove two grooves, center line is cut out by stator outer diameter circumference and stator punching groove bottom land circumcircle contour overlaps, described stator cramp groove is also with fluted, and stator cramp groove center line passes from two groove centers of stator punching groove through the sideline of groove, the rotor diameter of described rotor core is 11.14cm, and rotor internal diameter is 3.20cm, and rotor core length is 12.00cm, described rotor punching comprises by rotor punching groove and rotor punching radiating groove combines the lamination structure body forming, the quantity of described rotor punching groove is 44 and is uniformly distributed in the form of a ring, and its flute profile is closed tip circle curve for circle, and wherein width of rebate is 0.00mm, and notch height is 0.55mm, and groove top is 9.00mm deeply, and groove top radius is 1.905mm, and bottom radius is 1.261mm, the quantity of described rotor punching radiating groove is 44 and is uniformly distributed in the form of a ring, its flute profile is that the length of side is the equilateral triangle groove of 1.0mm, between two grooves of rotor punching groove, this leg-of-mutton base and rotor internal diameter circumference are more approaching, namely this leg-of-mutton base is towards rotor internal diameter circumference, between the groove of leg-of-mutton center line and rotor punching groove two grooves, center line overlaps, and between the groove of vertex of a triangle and rotor punching groove two grooves, the Crosspoint of center line and rotor punching groove bottom land circumcircle contour overlaps.

Table 1. Technical parameters of SCIM 2.2 kW

Rated Output Power	7.5 kW
Number of Phases	3
Rated Voltage 400 V	380 VAC
Rated Current	4.72 A
Rated Speed	1440 rpm
Stator Slot	36
Rotor bars	28,32 and 40

Detailed geometry parameter and weight comparison of SCIM 2.2 kW are calculated in table 2 with the stator, rotor, and weight od component which is useful for a manufacturer to manage total cost of IM mass production
Table 2. Detail geometry parameter and weight comparison of 2.2 kW.

Table 2. Detail geometry parameters of SCIM 2.2 kW-28;40 and 44 Rotor Slots

Slot Number	36	36	36
Stator Lam Dia	170	190	190
Stator Bore	104	124	124
Tooth Width	5	5.45	5.45
Slot Depth	17	20	20
Slot Corner Radius	3	4	4
Tooth Tip Depth	1	0.8	0.8
Slot Opening	2.5	3	3
Tooth Tip Angle	30	30	30
Sleeve Thickness	0	0	0
Rotor Bars	28	40	44
Pole Number	4	4	4
Bar Opening Depth [T]	0.8	0.6	0.6
Bar Opening Radius[T]	2.87688	2.5906	2.20175
Rotor Tooth Width [T]	5	4	4
Bar Depth [T]	18	16.3	16.3
Bar Corner Radius[T]	1.33286	1.64395	1.28787
Airgap	0.3	0.3	0.3

Efficiency Result Analysis

The efficiency result of the SCIM model developed is given in table 3. This simulation is performed to find out why the rotor is skewed 7.5^0 degrees. To verify the efficiency of each design, three models have compared some outputs such as torque, power, and efficiency with different rotor bar numbers.

Table 4. Detail result of SCIM 2.2 kW-28;40 and 44 Rotor Slots

Parameter	Unit	**36Slot/28Bar**	**36Slot/32Bar**	**36Slot/40Bar**
Airgap Torque (on load)	Nm	14.862	14.93	14.91
Shaft Torque	Nm	14.461	14.409	14.388
Requested on load power	Watts	2200	2200	2200
Output Mechanical Power	Watts	2200.4	2200	2200.3
Input Active Electrical Power (from Power Balance)	Watts	2672.3	2541.1	2536.1
Input Active Electrical Power (ideal)	Watts	2676.9	2544.4	2539.5
Total Losses (Analytic on load)	Watts	471.92	341.1	335.8
Input Reactive Power (on load)	VA	1843.8	1135.3	1169
Apparent Power	VA	3250.4	2786.2	2795.6
System Efficiency	%	86.2	90.577	90.759

Table 5. Detail losses of SCIM 2.2 kW-28;40 and 44 Rotor Slots

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Parameter	**Unit**	**36Slot/28Bar**	**36Slot/32Bar**	**36Slot/40Bar**
Stator Copper Losses (Analytic on load)	Watts	276.1	125.8	120.7
Rotor Copper Losses (FEA on load)	Watts	72.61	56.77	53.71
Stray Load Losses (FEA on load)	Watts	43.65	38.74	38.7
Stator iron Loss [total] (on load)	Watts	34.7	38.1	0
Rotor iron Loss [total] (on load)	Watts	4.493	12.22	0
Loss [Windage]	Watts	15.84	34	34.14
Total Losses (FEA on load)	Watts	447.4	305.6	294.6

Efficiency are effected as follows due to by the size of stator-rotor iron core, the structure of rotor punching and size thereof have been carried out systematic optimization appropriate design, make stator winding loss only have 123.1W, rotor winding loss only has 88.2W, core loss only has 14.3W, comprise stray loss 43.1W, mechanical loss 22.7W, its energy total losses amount only has 291.4W, and the loss of existing 2200 watt of 4 pole three phase asynchronous motor stator winding has 242.8W, rotor winding loss has 137.8W, core loss has 67.9W, comprise stray loss 44.0W, mechanical loss 13.0W, its energy total losses amount has 505.5W, the energy loss amount of wanting required for the present invention has reduced 42.4%, greatly saved the energy, in power output, be all under the prerequisite of 2200 watts, the input power that existing like product needs is 2.706kW, energy conversion efficiency is 81.3%, and input power required for the present invention is only 2.491kW, energy conversion efficiency reaches 88.3%, improved 7.0%, to the Energy Efficiency Standard of 2200 watt of 4 pole three phase asynchronous motor, require 86.7% (IE3).

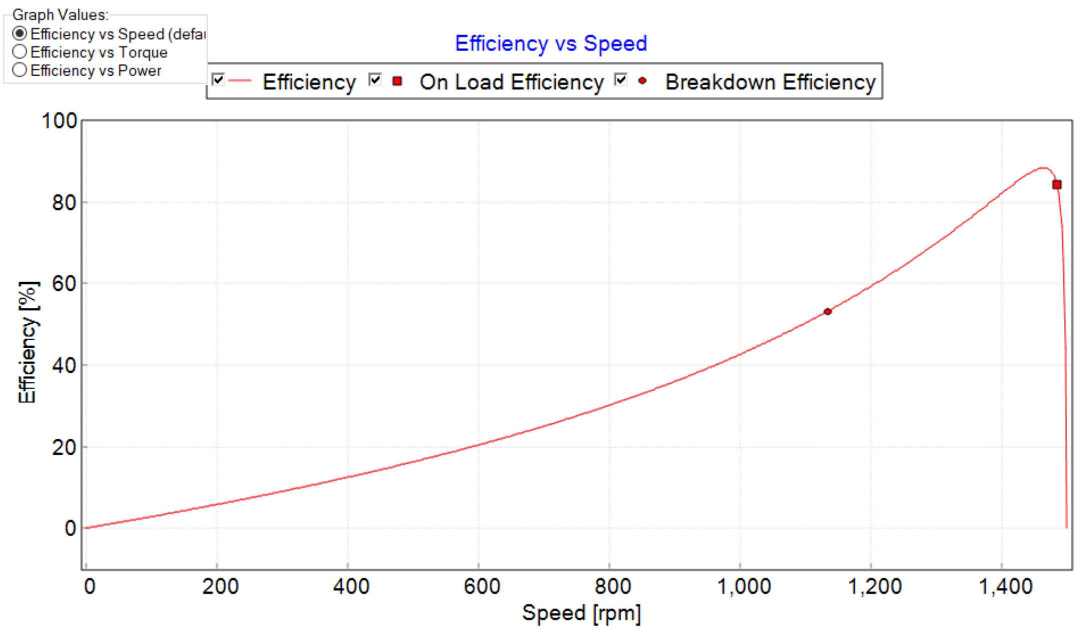

Figure 2. SCIM 22kW-4P 36 stator slots /40 rotor bars efficiency curve

Thermal Analysis by Finite Element Method

The finite element method (FEM) has been used to solve overheating temperatures of IM based on Iron and copper losses, mass transport, heat transfer, and fluid flow. For solving the thermal problem, an analytical model is combined with a finite element method such as Motor-CAD. it has a finite element solution for the stator winding only. The thermal study of the test motor by FEM is to determine the temperature distribution in the case of a steady state at any point of the induction motor. The heat loss is transferred by conduction in solid material such as stator and rotor and can be described by:

$$\rho c\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda x\, \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda y\, \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(\lambda z\, \frac{\partial T}{\partial z}) + Q \tag{1}$$

Where ρ is the density, λ is the thermal conductivity, T is the temperature, and Q is the dissipated power density. Fourier's law is used to connect the heat flux and the temperature gradient, The heat flux q is given by (2)

$$q = -\lambda \frac{\partial T}{\partial x} \tag{2}$$

The heat sources are transferred from one part to another part by the movement of fluids. In this study, the proposal motor is totally enclosed fan cooled (TEFC), where the air is pushed by forced convection on the frame of the motor. The equation for convection can be expressed as:

$$q = \alpha\, As\, (Tw-T\infty) \tag{3}$$

Where α is the heat transfer coefficient, A_s is surface area, T_w, and T_∞ are the temperature of the surface and the ambient cooling medium respectively. In a thermal model of a three-phase induction motor conduction, the radiation is ignored.

The motor power losses are divided into several types of iron losses iron, copper losses, mechanical losses, and friction and windage losses, stray load losses. These losses must be calculated to enter as heat sources before solving the test motor model.

A SICM 2.2 kW- 4 pole 36 slots/40 bars, TEFC, insulation class H is modeled by Motor-CAD. All dimensions of the machine were entered in the radial cross-section, as shown in Figure 1.
The two-layer winding pattern is set up with 196 turns per phase, and thermal resistance values are calculated automatically from motor dimensions and material data. The materials used in modeling the test motor are shown in table 2.

Table 6. Material weight of components

Components	**Materials**	**Density(kg/m3)**	**Weight (kg)**
Stator Lam (Back Iron)	M800-50A	7650	12.92
Stator Lam (Tooth)	M800-50A	7650	5.523
Stator Lamination [Total]			18.44
Armature Winding [Active]	Copper (Pure)	8933	2.67
Armature EWdg [Front]	Copper (Pure)	8933	2.059
Armature EWdg [Rear]	Copper (Pure)	8933	2.059
Armature Winding [Total]			6.788
Wire Ins. [Active]		1400	0.07071
Rotor Lam (Back Iron)	M800-50A	7650	4.326
Rotor Inter Lam (Back Iron)		1.127	1.97E-05
Rotor Lam (Tooth)	M800-50A	7650	4.468
Rotor Inter Lam (Tooth)		1.127	2.04E-05
Rotor Lamination [Total]			8.794
Rotor Cage Top Bar	Aluminium (Cast)	2950	1.302
Rotor Cage Top Bar Opening	Aluminium (Cast)	2950	0.01513
Rotor Cage (Front End)	Aluminium (Cast)	2950	0.2962
Rotor Cage (Rear End)	Aluminium (Cast)	2950	0.2962
Rotor Cage [Total]			1.91
Shaft [Active]	Iron (Pure)	7870	1.662
Flange Mounted Plate		2700	7.158
Total			38.14

The losses have been calculated at full load condition. The thermal model is set up with housing type, materials, and cooling options, etc. The model can be solved to calculate the temperatures at different motor regions as shown in the motor equivalent thermal model of Figure 3

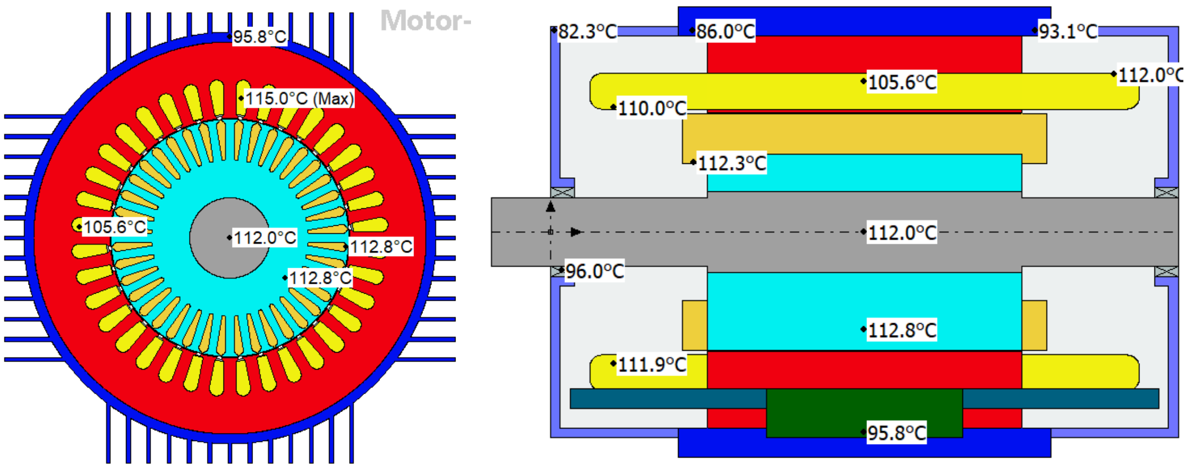

Figure 3. Radial and Axial view of the test motor temperature distribution

The temperature of each component of the test motor has been determined at an ambient temperature of 40 ºC. The losses of the test motor induction are used as the heat sources (stator and rotor copper losses, stator and rotor core losses in figure 4. The accuracy of the thermal model results at full load steady state obtained from Motor-CAD has been evaluated by comparing with the test bench in Figure 4. Table 4 shows the comparison of the test motor and simulation temperatures at full load conditions

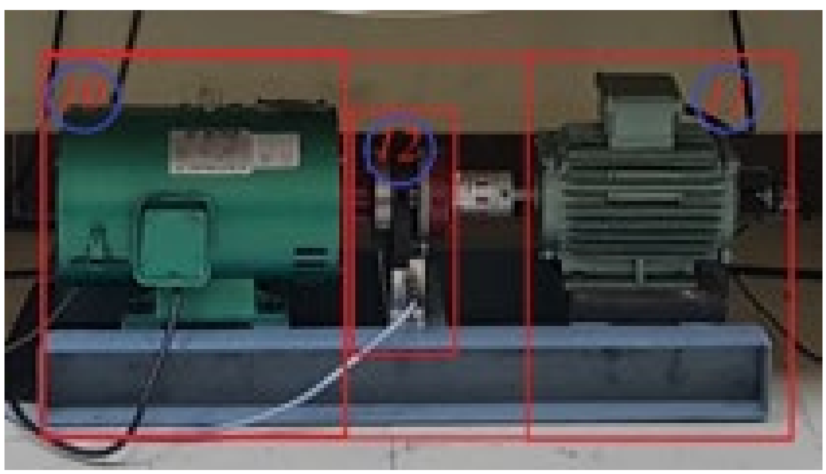

Figure 4. The test bench of SCIM 2.2kW

At steady state, the IM temperatures have been measured and compared with the temperatures obtained from the thermal model previously as table 6

Table 6. Material weight of components

Temperature points	**Simulation (ºC)**	**Test (ºC)**
T [Ambient]	40	39
T [Housing - Active]	95.81	94
T [Stator Lam (Back Iron)]	99.508	99
T [Stator Surface]	104.07	
T [Rotor Surface]	112.86	
T [Rotor Tooth]	112.84	

T [Shaft - Center]	111.96	
T [Rotor Bar]	112.84	
T [Winding (A) Average]	106.1	105
T [End Winding Average]	112.41	111

The comparison in Table 6 is a good agreement between the measured and the simulated values with reference to winding and housing temperatures. The temperature sensors of housing, winding, and stator core temperature were measured with the considerations concerning the hole drilled in the stator frame and the temperature probe insertion is still valid. The errors are from 1^0C to 2 ºC

Conclusions

This paper proposed an improved design for the rotor part, with a modified number of rotor bars, bar sizes, and rotor bar designs. This work has been investigated using two methods, specifically, FEM software theoretical calculation. A set of simulations showed a significant improvement in the energy efficiency of the new design. The theoretical calculation utilized MATLAB simulations. The comparison of efficiency between the existing design and the proposed new design was carried out using FEM simulation. The result showed that the proposed new design was an increased energy efficiency of 90.55% as compared to the existing design of 86.2%. The result was proven using MATLAB. In this paper, a thermal analysis of a TEFC, squirrel cage, three-phase induction motor has been performed successfully by approach use thermal network method based on analytical and FEM simulation under full load steady-state condition.. The results obtained from both methods show a good agreement with other results obtained from the CAD which can be considered as a comparative software. The straight forward methodology for this work can assist the motor designer to obtain well thermal motor results without needing to conduct tests based on a costly produced prototype motor.

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