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ORIGINAL RESEARCH ARTICLE

COMPARATIVE STUDY OF TWO STATOR DESIGNS FOR THE INTERNATIONAL ELECTROTECHNICAL COMMISSION 100 MOTOR FRAME FOR 2.2KW SQUIRREL CAGE INDUCTION MOTOR

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ABSTRACT

The International Electrotechnical Commission totally enclosed, fan cooled 100 Motor frame for 2.2 kilowatts squirrel cage induction motor have been manufactured with both 24-slot stator and 36-slot stator. This study compared the two solutions along the lines of rated performance, material consumption, and robustness of design. Since the difference between the two motors is basically the number of slots in the stator, similar machine data were adopted for them. The unknown data were calculated from standard machine equations carefully suited for the motors. The data so obtained were used as input to the RMxprt model where the motors were simulated. The results show marginal difference in all the parameters considered such as efficiency (0.09% in favour of the 36-slot Stator), power factor (0.0014 in favour of the 24-slot Stator), annual cost of operation (N687.88 saved by the36-slot stator), and overload capacity. The inference of this study is that the two stator designs are adequate solutions for the 3hp motor having International Electrotechnical Commission totally enclosed, fan cooled 100 Motor frame, and that while the 24-slot stator design would be easier and cheaper to manufacture, the 36-slot stator design is however more robust and cheaper to operate.

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1.0 Introduction

Engineering standard was defined by Jawad and Greulich (2018) as a document prepared by a professional group or committee which is believed to be a good and proper engineering practice, and which contain mandatory requirements. The term mandatory in that definition implies that engineering standards pursue uniformity in engineering criteria and practices, which in turn provides options to users to satisfy their needs from a range of different product manufacturers and vendors, including interchanging units and components of the product. Standards represent a key requirement in globalization, to ensure compatibility and consistency, reliability, safety, and good economics.

In the electric machine industry, two standards stand out: the National Electrical Manufacturers Association (NEMA) and International Electrotechnical Commission (IEC). Most other standards like the BS 2613 and NF CS1 – 100 are derived directly from the IEC standard. The difference between NEMA and IEC may be seen in what each of them emphasizes. While NEMA emphasizes on robust designs that ensure ease of product selection and a wider range of application, IEC dwells on product performance and are application specific. Hence, an equivalent IEC machine would be smaller and less expensive than a NEMA machine, which in turn has a better overload capacity than the IEC product. Another difference is that while the IEC uses the SI system of measurement, NEMA uses the imperial system. However, some degree of flexibility exists between products of both standards, but it can only be exploited by users who have good understanding of the differences. An article on the blog of the vendor, c3controls (C3 Controls, 2023) suggested how to choose between NEMA and IEC products. A 2007 ABB Brochure (ABB, 2007), in recognition of the demands of globalization on Original Equipment Manufacturers (OEMs) to specify international standards, was more detailed in highlighting how to use products of NEMA and IEC interchangeably.

The IEC totally enclosed, fan-cooled (TEFC) motor frames for Induction motors have a wide application across many industries and can be commonly applied to conveyor systems, compressors, pumps, blowers, fans, etc. For low voltage applications (< 1000V), they are made of high-grade cast aluminium alloy. Since the year 2015, they are manufactured up to IE3 and IE4 efficiency classes according to IEC 60034-30, and with protection grades of IP 55 according to IEC 60034-5 (Challenge Power Transmission, 2023). These render them a convenient and eco-friendly solution to many industrial needs, while ensuring minimum operational costs.

In particular, the IEC TEFC 100 motor frame for SCIM may be rated 3 kW, 2.2 kW, 1.5 kW, or 1.1 kW with synchronous speeds of 3000rpm, 1500rpm, 1000rpm and 1000rpm respectively, at a supply frequency of 50Hz (ABB, 2022). The centre of the shaft measures 100 mm from the base. The 2.2 kW rated motor with 1500rpm synchronous speed is manufactured in both 24-slot and 36-slot stators. With so much emphasis on energy efficient products, efficient use of materials, operational cost reduction and ease of manufacture, it becomes important to study and analyse the IEC TEFC 100 motor frame for SCIM with 2.2kW rating manufactured with 24-slot and 36-slot stators comparatively, with a view to recommending the best use for either.

The selection of higher number of slots is attractive because leakage reactance and tooth pulsation losses are reduced while over-load capacity is increased (Asgharpour-Alamdari, 2022). However, it presents some challenges to the machine designer, such as increased fabrication costs, and weight, and magnetizing current and iron losses which diminish the efficiency; and also poor cooling with the attendant increase in temperature rise (Mittle and Mittal, 2017). The work of Gundogdu *et al.* (2017) is among several studies made on the influence of stator slot/pole number combination on the performance of the SCIM, and it observed that there is an indirect relationship between the stator slot and pole number and distortion level of the rotor bar current waveform, which in turn affects the key performance indices of the machine. It is important therefore to justify the manufacturing of the two stator designs by comparing their rated performance and operating costs.

2.0 Methodology

Electric Machines Lab of the Department of Electrical Electronic Engineering in the Michael Okpara University of Agriculture Umudike has a 3-phase, 2.2kW, 4-pole induction motor, with the IEC 100 frame, and having 36 stator slots. Most of the machine data presented in Tables 1 and 2 have been adopted from it. A few others were obtained from the vendor Teco (Te3) (2023) and Challenge Power Transmission (2023). Most of these data are common to both stator designs under study.

Due to the unavailability of the 24-slot stator SCIM, the preliminary design of the machines were performed in order to initiate an electromagnetic simulation using RMXPRT in the ANSYS Electromagnetic environment. Such designs begin naturally with the assumption of machine specifications. From the known specifications, the other unknown machine parameters were determined.

Table 1: Machine Parameters

S/N	Parameter	Symbol	Value
1	Rated Power	P_n	2.2kW
2	Phases	m	3
3	Winding Layers		1
4	Insulation Class		F
5	Rated Current	I_{in}	4.51A
6	Voltage	V	230/400V
7	Rated Speed	n	1462rpm
8	Frequency	f	50Hz
9	Number of Poles	P	4
10	Stator outer Diameter	D_{os}	158mm
11	Stator inner Diameter	D_{is}	98mm
12	Rotor outer Diameter	D_{or}	97.48mm
13	Shaft diameter	D_s	36mm
14	Stack Length	L	98mm
15	Lamination thickness	t_L	0.5mm

The preliminary design of the machine, according to the method set forth by Pyrhonen *et al.* (2008) and Boldea and Nasar (2010) requires that some values should be assigned to some variables. This was achieved in consideration of standard design procedures, and listed in Table 2.

Table 2: Preliminary Assigned Design

S/N	Parameter	Symbol	Value
1	Efficiency	η	0.84
2	Power Factor	$\cos\varphi$	0.82
3	Teeth Saturation Factor	K_{st}	1.4
4	Flux density shape factor	α_i	0.729
5	Form Factor	K_f	1.085
6	Airgap flux density	B_g	0.7
7	Current Density	J_{dc}	6.07A/mm^2
8	Coil pitch/Pole pitch	y/τ	5/6 and 8/9
9	Slot Filling Factor	K_{fs}	0.6
10	Stator tooth flux density	B_{ts}	1.55

The air gap apparent power is given by $S_{gap} = \frac{K_E P_n}{\eta \cos\phi}$ (1)

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The air gap voltage, is given by $E = 4fK_f TK_w \phi$ (2)

Where $K_E = \frac{E}{V_{ph}} = 0.98 - 0.005\frac{P}{2}$ (3)

V_{ph} is the per phase voltage, while T, K_w, and ϕ are the number of turns per phase, the winding factor, and the magnetic flux (webers), respectively.

The magnetic flux can be estimated from $\phi = \alpha_i \tau L B_g$ (4)

The pole pitch is given by $\tau = \frac{\pi D_{is}}{P}$ (5)

The whole coil, integral slot winding with star connection is employed in the stator. The coil pitch/pole pitch ratio, y/τ is taken as 5/6 for the number of stator slots, $N_s = 24$, and 8/9 for $N_s = 36$. Hence, the winding factor can be determined as

$$K_w = \cos\frac{\left(180 - y\left(\frac{\pi P}{N_S}\right)\right)}{2} \times \frac{\sin\frac{q\pi P}{2N_S}}{q\sin\frac{\pi P}{2N_S}} \quad (6)$$

Where q is the number of slots per phase per pole. With the appropriate substitution of the equations listed above, the number of turns per phase maybe obtained as:

$$T = \frac{K_E V_{ph}}{4fK_f K_w \phi} \quad (7)$$

Assuming a single current path, that is $a_1 = 1$, the number of conductors per slot is obtained as:

$$n_{sc} = \frac{2a_1 T}{qP} \quad (8)$$

The result of equation (8) is rounded off to the nearest whole number as it cannot be a fraction. Thereafter, equations (7) and (4) are recomputed and a new value obtained for B_g.

The magnetic wire cross sectional area may be determined as

$$A_c = \frac{I_{in}}{J_{dc}} \quad (9)$$

The conductor diameter is given by:

$$d_c = \sqrt{\frac{4A_c}{\pi a_p}} \quad (10)$$

Where a_p represents the number of strands per conductor. Assuming an insulation thickness of $t_i = 0.021mm$, the diameter of the wire is obtained as:

$$d_w = d_c + 2t_i \quad (11)$$

To determine the shape and dimensions of the stator slot, first a trapezoidal shaped stator slot was selected. See Fig. 1.

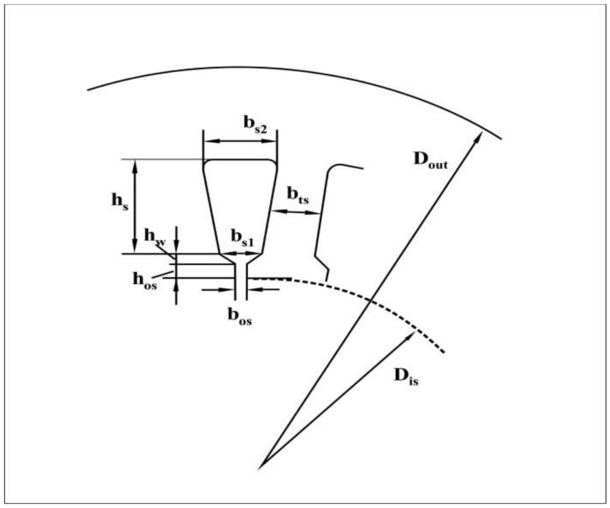


Fig. 1: The adopted Stator Slot and its parameters

The useful slot area,

$$A_{su} = \frac{\pi d_w^2 a_p n_{sc}}{4K_{fs}} \quad (12)$$

The stator slot pitch is obtained from $\tau_{ss} = \frac{\tau}{3q}$ (13)

Assuming all the air gap flux passes through the stator teeth, and assuming that the lamination insulation thickness factor is K_{il} = *0.96*, b_{os} = *2mm*, h_{os} = *0.68mm*, and h_w = *1.32mm*, then:

$$b_{ts} = \frac{B_g \tau_{ss}}{B_{ts} K_{il}} \quad (14)$$

$$b_{s1} = \frac{\pi\left(D_{is}+2(h_{os}+h_w)\right)}{N_s} - b_{ts} \quad (15)$$

$$b_{s2} = \sqrt{b_{s1}^2 + 4A_{su}\tan\frac{\pi}{N_s}} \quad (16)$$

$$h_s = \frac{2A_{su}}{b_{s1}+b_{s2}} \quad (17)$$

It was explained in (Boldea and Nasar, 2010) and (Konstantinos and Joya, 2013) why the selection of the number of rotor slots must be done with care, the reason including to reduce parasitic torque, noise, vibration, and additional losses and radial forces. Again, it is desired for the purpose of this study to use the same rotor for the two stator configurations. Hence, a 30-slot rotor was selected.

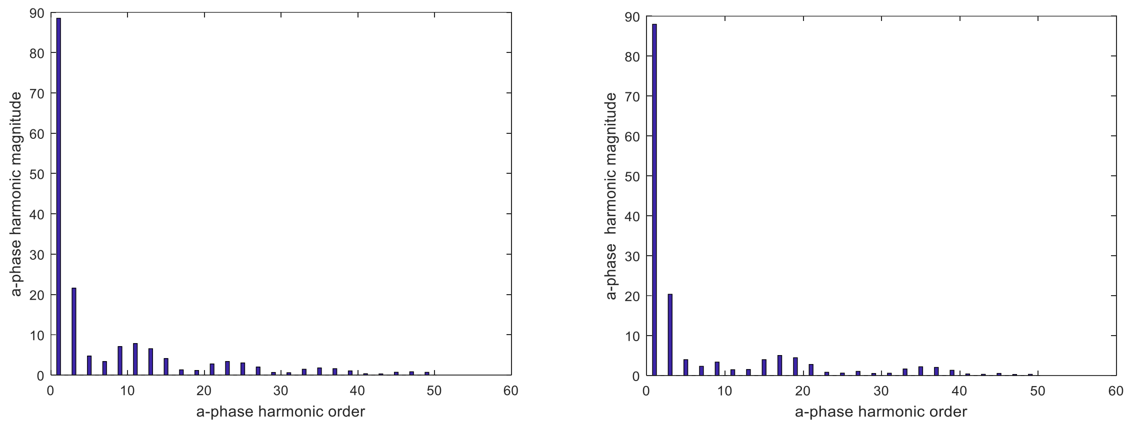
3.0 RESULTS AND DISCUSION

The above equations were very helpful in providing the data for the RMxprt simulation of the two motors. The simulation produced many results, but only the important indices relevant for a good comparison are presented in Table 3.

Table 3: Simulation Results

S/N	Name	Unit	24-Slot Stator IM	36-Slot Stator IM
	Rated Performance			
1	Stator Ohmic Loss	W	193.222	194.212
2	Rotor Ohmic Loss	W	127.968	121.035
3	Iron Core-Loss	W	54.4832	57.612
4	Frictional and Windage Loss	W	7.76543	7.7882
5	Stray Loss	W	67.14	67.14
6	Total Loss	W	450.579	447.787
7	Output Power	W	2237.91	2238.02
8	Input Power	W	2688.49	2685.80
9	Efficiency	%	83.2405	83.3276
10	Power Factor		0.875928	0.874546
11	Rated Torque	N-m	15.0589	15.0155
12	Rated Speed	rpm	1419.13	1423.29
13	Slip		0.0539121	0.0511378
	Material Consumption			
14	Total net weight	kg	12.4392	12.3671
15	Armature core Steel Consumption	kg	13.38	13.38
16	Rotor Core Steel Consumption	kg	5.49159	5.49159
	Breakdown Operation			
17	Breakdown Slip		0.43	0.46
18	Breakdown Phase Current	A	18.6024	20.0795
19	Breakdown Torque	N-m	41.8549	44.7692
20	Breakdown Torque Ratio		2.77942	2.98153
	Rated Electric Data			
21	Stator Phase Current	A	4.31953	4.32192
22	Rotor Phase Current	A	3.86673	3.78456
23	Armature Thermal Load	A^2/mm^3	142.916	143.074

There are a few bases to expect different performance outcomes from the IEC 100 frame made with either 24-slot stator or 36-slot stator. In the first place, apparently, the number of slots per pole per phase, q is 2 and 3 for the 24-slot and 36-slot stator designs, respectively. And one would have expected that higher q values would result in better winding function and mmf waveforms, that is, more sinusoidal in shape, resulting in better efficiency and power factor. Hence, one would expect the 36-slot stator to perform better than the 24-slot stator in this respect. But a look at the harmonic contents of the winding functions of the two stators shows a departure from this expectation (see Fig. 2). The methods used by Onwuka *et al* (2015) was employed. Due to half-wave symmetry, only odd harmonics are present. The fundamental component of the 24-slot stator is 88.5293, while that of the 36-slot stator is 87.9786, which gives some minor performance advantage due to higher flux linkages to the 24-slot stator as seen in Table 3. However, the total harmonic disorder of the winding function for the 24-slot stator is higher than that for the 36-slot stator, which also reduces the leakage inductance of the later, giving it some advantage over the former. Clearly, there is a levelling up, and hence only marginal difference exists in their rated performance.



(a) (b)

Fig. 2: Winding Function for the (a) 24-Slot Stator, and (b) 36-slot Stator

From the results of Table 3, the most important difference in performance is in the rotor ohmic loss, which resulted in a better efficiency for the 36-slot stator than for the 24-slot stator. All other variables returned negligible differences. With electricity tariff at ₦68.30/kwh, the induction motors with the 24-slot and 36-slot stators would be operated at a cost of ₦687, 487.76 and ₦686, 799.88 in a year of 12 months with 26 days/month and 12 hours/day, respectively, resulting in a savings of ₦687.88 per year in favour of the 36-slot stator motor. However, some of this cost would have gone into punching extra slots in the laminations of the 36-slot stator during manufacturing. The extra material consumption seen in the 24-slot stator is actually negligible.

However, the breakdown operation of the 36-slot stator was better than that of the 24-slot stator, albeit, marginally. The stator slot area of the two stators are in the ratio of 2/3, as also is their conductors per slot. So the slot depth of the 24-slot stator is larger than the slot depth of the 36-slot stator, while their slot opening width are equal. It is commonly known that decreasing the slot depth decreases the stator and rotor leakage reactances, which in turn increases the breakdown torque. The 36-slot motor has a better overload capacity, and more rugged, even though it is marginally so.

4.0 Conclusion

The results of this study show that both the 24-slot stator and the 36-slot stator used in the IEC TEFC 100 frame for 3hp induction motors are good options, both of them, as the differences in their performance and operation are marginal. More specifically, the 36-slot stator design is marginally more robust and has a better overload capacity than the 24-slot stator design. It also out-performed the 24-slot stator in terms of operating cost. The higher thermal load associated with the 36-slot stator wouldn't need any special design adjustment nor incur more production costs as the same fan can achieve the cooling of the two induction motors produced with the two stators under study. It is important to mention that in terms of production, the 24-slot stator is easier and cheaper to manufacture. Therefore, the choice of manufacturing the IEC 100 TEFC motor for 3hp with either 24-slot stator or with 36-slot stator is not a difficult one to make, as the results are quite similar.

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