A COMPARATIVE STUDY ON PERFORMANCE OF 3KW INDUCTION MOTOR WITH DIFFERENT SHAPES OF STATOR SLOTS

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Abstract:
Cage induction motors are widely used in industries because of their rugged construction and low cost. The drawback with an induction motor is that, it draws high magnetising current. The magnetising current drawn by an induction motor depends on air gap length between stator and rotor, and shape of stator slots. Air gap length in an induction motor is already very less; therefore it is not reduced below a certain level. There are three shapes of stator slots- parallel sided, tapered and circular; generally, the tapered or parallel sided shape of stator slot is adopted by manufacturers of induction motors. Here, a comparative study on performance of 3KW induction motor with different shape of stator slots is presented. It is shown that, the induction motor with circular shape of stator slots shows better efficiency, reduced magnetising current and better overload capacity, than the motors with other shapes of stator slots. Therefore, circular shape of stator slot is the best choice for 3KW induction motor.

Keywords- induction machine design, slots, magnetising current.

1. Introduction

Induction motors are the most common motors used in industrial motion control systems, as well as in main powered home appliances. Simple and rugged design, low-cost and low maintenance are the main advantages of induction motors. Various types of AC induction motors are available in the market. Different motors are suitable for different applications. Although, induction motors are easier to design than DC motors, the speed and the torque control in various types of induction motors require a greater understanding of the design and the characteristics of these motors.

Like most motors, an induction motor has a fixed outer portion, called the stator and a rotor that spins inside with a carefully engineered air gap between the two. The stator is made up of several thin laminations of cast iron. They are punched and clamped together to form a hollow cylinder (stator core) with slots. The rotor consists of a cylindrical laminated core with axially placed parallel slots for carrying the conductors. Each slot carries a copper or aluminium bar. These rotor bars are permanently short-circuited at both ends by means of the end rings. This total rotor assembly resembles the look of a squirrel cage, which gives the rotor its name.

2. Effect of air gap length and shape of stator slots

One of the drawbacks of induction motor is that it draws high magnetising current. Magnetising current in an induction motor is 20% to 40% of rated current; however, it is 1% to 2% of rated current in case of a transformer. High magnetising current makes the supply power factor poor. The main reason of high magnetising current in induction motor is the existence of air gap between stator and rotor; larger the air gap length, higher will be the magnetising current. Because of this reason the air gap length between stator and rotor is kept as short as possible; the air gap length, in small and medium rating induction motors, lies between 0.3 mm to 1 mm. The air gap length is not reduced below a certain value, as it has certain disadvantages like- more noise, more tooth pulsation loss, large unbalance magnetic pull and poor cooling (Alger 1965, Say 1970).

Magnetising current in an induction motor is also affected by shape of stator slots. There are two types of slots, used in ac machines; these are open type and semi-enclosed type. Semi-enclosed slots are usually preferred for induction motors. An induction motor with semi-enclosed slots has low tooth pulsation loss, less noise, less magnetising current and reduced overload capacity. There are three shapes of semi-enclosed slots- parallel sided, tapered and circular; generally, the parallel-sided or tapered shapes of stator slot is adopted by motor manufacturers, the reason may be the less machining cost. The machining cost of a slot with circular shape is comparatively higher. For a tapered slot, the tooth has parallel sides; a parallel sided tooth is mechanically stronger (Sawhney 2009, Besnerais 2009).

Iron loss is another important parameter. Iron loss in a part depends on flux density in that part of a machine; higher the flux density more will be the iron loss. In stator tooth, the flux density is higher as compared to another part of the motor; therefore, a considerable amount of total iron loss in an induction motor occurs in stator teeth. The flux density in a tooth is affected by shape of slot. For a wider slot, tooth width is narrow, giving higher flux density in a tooth; it leads to more iron loss. For a given area of stator slot, the peripheral length of a circular slot is minimum compared to other shapes of slots, which provides shorter magnetic path to flux; it helps in reducing magnetising current and iron losses both (Boldea and Nasar 2010).

In past, some efforts have been made to improve power factor of induction motor by adopting special types of control techniques also (Fernando et al 2006, 2008).

Here, three cage induction motors of same ratings are designed and compared. First one is designed with parallel sided stator slots, second one with tapered type stator slots and third one with circular type stator slots, keeping all other design parameters same.

3.Design cosiderations

3.1. *Main dimensions*

Main dimensions of stator of an induction motor are shown in **Figure-1**.

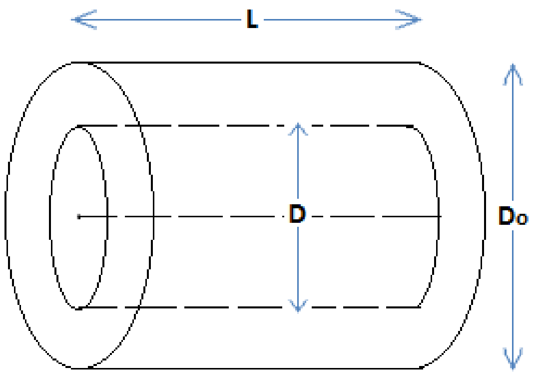

Figure-1: Main dimensions of stator

For an induction motor, having KVA input Q, output coefficient C_0, synchronous revolutions per second (rps) n_s, dia of stator bore D, length of stator L and number of stator poles P, the main dimensions are obtained by following equations (1) and (2)-

$D^2.L = Q/C_0.\ n_s$ ------(1).

$L= \pi.\ D/\ P$ ------------(2).

Output coefficient is given by-

$C_0 = 11.\ B_{av}.\ ac.\ k_{ws}./1000.$ -----(3).

Here, B_{av} is average flux density in air gap, ac is ampere conductor per meter of stator periphery, and k_{ws} is stator winding factor. Selection of B_{av}, ac, and k_w is done according to motor specifications. The selected values are- Bav = 0.45 T, ac= 22000 ampere conductor per meter and K_{ws} = 0.955.

3.2. Stator conductors and slots

Flux per pole $\Phi m = B_{av}.(\pi. D/ P). L$;
Stator turns per phase, $Ts = Es/(4.44. f. \Phi m. k_{ws})$;
Numbers of stator slots $Ss = 3.P.q_s$;
q_s is slots/pole/phase for stator; it is taken equal to 2 for small and medium rating induction motors.
Stator conductors per slot Zss = 6.Ts / Ss.
Current per phase $Is = output / (3. Es. \eta. pf) = I_{fl}$.
Here, η is efficiency and pf is power factor at full load.
To start the design, efficiency and power factor are taken as 0.82.
Cross sectional area of stator conductor, $a_s = Is / \delta$.
Current density δ is selected between 3.0 and 4.5 A/mm^2.
Dia of stator conductor $d = \sqrt{(4. a_s/\pi)}$.

3.3. Stator slot dimensions

Area of one stator slot Ass= Zss/space factor. Space factor lies between 0.25 and 0.4.
For parallel sided slot of stator, minimum tooth width of stator (Figure-2), is given by-
Wtsmin=(P. Φm)/(1.7 L. Ss); Here, maximum allowable flux density in stator tooth is 1.7 T.

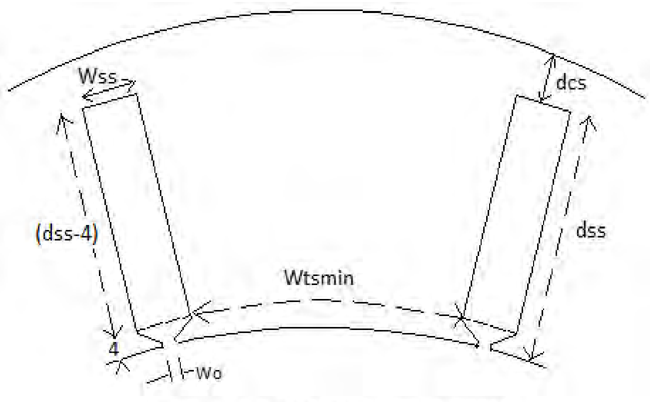

Figure-2: Parallel sided slots in stator

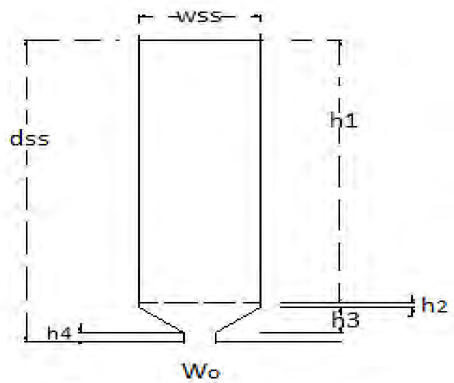

Figure-3:Parallel sided slot

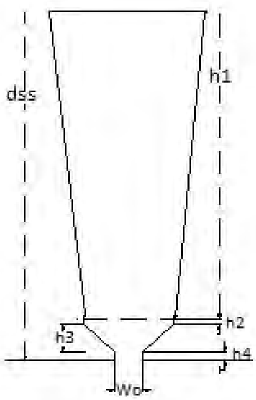

Figure-4: Tapered slot

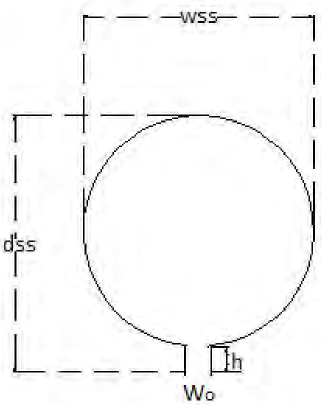

Figure-5:Circular slot

Stator slot width Wss= π.(D+8)/Ss – Wtsmin.
To calculate, depth of stator slot dss, the calculated area of slot 'Ass' should be equal to geometrical area of the same slot is represented by equation (4)-
Ass= (3 x 1) + 3. {(Wss+3)/2} + Wss.(dss – 4). ------(4)
Following the same concept, physical dimensions of tapered slots and circular slots may be calculated (Vallecha et al 2012). Shapes of parallel sided slot, tapered slot and circular slot of stator side are shown in Figure-3, Figure-4 and Figure-5, respectively.

3.4. Stator core

Cross sectional area of stator core, Acs = (Φm/2)/ Bcs. Here, Bcs is flux density in stator core, which is taken about 1.2 Tesla.
Depth of stator core, dcs = Acs/L; Outer dia of stator, Do = (D+2.dss+2.dcs).

3.5. Air gap

Legth of airgap,lg = [0.2 +2 √(D.L)]; Here, D and L are taken in meters, then lg is obtained in mm.

3.6. Rotor slots

Numbers of stator slots and rotor slots are Ss and Sr. To avoid problem of magnetic locking, synchronous crawling and noise, (Ss-Sr) should not be equal to: 0,1,2, P, P±1, P±2, 2P,3P,5P.
Example- if Ss=24 and P=4, then (Ss-Sr) should not be equal to : 0,1,2,3,4,5,6,8,12,20.
Therefore, (Ss-Sr) may be taken =7. With this, Sr=17.

3.7. Rotor bars

Rotor bar current, I_b= (6.Ts.K_{ws}./Sr).Is. pf.
pf is power factor at full load. If current density in rotor bar is δ_b, then cross sectional area of each rotor bar is-
$a_b = I_b/ \delta_b$; for bar of copper, δ_b=6A/mm^2.
$A_b = h_b . w_b$; here h_b and w_b are height and width of rotor bar.
For good starting torque, deep bar is preferred; for deep bar, the ratio (h_b/w_b) is taken between 2 and 5. It also depends on physical dimensions of rotor slot (Sawhney 2009, Nee 1965). Shape of a rotor slot is shown in Figure-6.

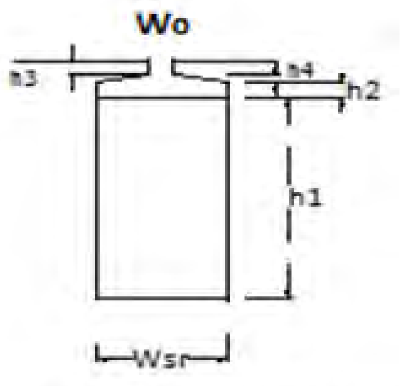

Figure-6: Rotor slot

3.8. No-load loss

Iron loss in stator teeth= specific iron loss x mass of stator teeth.
Iron loss in stator core = specific iron loss x mass of stator core.
Total iron loss = Iron loss in stator teeth + Iron loss in stator core;
Iron loss in in rotor is negligible, because of low frequency.
Total No load loss = Total iron loss + Friction and windage loss;

3.9. No-load current (Io)

Magnetising current per phase, Im = 0.427. P. AT/ (K_{ws}. Ts);
Total magnetising mmf, AT = (Magnetising mmf for air gap + Magnetising mmf for stator teeth + Magnetising mmf for stator core + Magnetising mmf for rotor teeth + Magnetising mmf for rotor core).
Magnetising mmf is calculated by the help of magnetising curve and physical dimensions of stator teeth, stator core, rotor teeth, rotor core and air gap.
Loss component per phase Ic = Total No load loss /(3. Es);
$Io = \sqrt{(Im^2 + Ic^2)}$;
No load power factor (pf_{nl}) = Ic/Io;

3.10. Leakage reactance

A parallel sided slot is shown in Figure-3; specific slot permeance for this slot is given by-
$\lambda = \mu o.[h_1/(3Wss) + h_2/Wss + 2.h_3/(Wss+Wo) + h_4/Wos]$;
Specific slot permeance for a tapered slot (Figure-4) is given by-
$\lambda = \mu o.[(2.h_1/3)/(Wss+W_2) + 2.h_2/(W_1+W_2) + h_3/(W_1+Wo) + h_4/Wo]$;
Specific slot permeance for a circular slot (Figure-5) is given by: $\lambda = \mu o.[0.66+ (h/Wo)]$;
Total specific slot permeance, λs = (specific slot permeance for stator + specific slot permeance for rotor).
Slot leakage reactance, $Xs = 8.\pi.f.Ts^2.L. \lambda s/(P.q_s)$;
Overhang leakage reactance, $Xo= 0.64. \pi.f.Ts^2. \mu o.\tau^2/(\pi. y_{ss}.P. q_s)$;
Here, $\tau = (\pi.D/P)$ and $y_{ss} = (\pi.D/Ss)$.
Zigzag leakage reactance $Xz = (5/6).(Xm/9).[1/ q_s^2 + 1/ q_r^2]$.
Here, rotor slot per pole per phase, q_r = Sr/(3.P); Xm=(Es/Im).
Total leakge reactance per phase X_l = (Xs+Xo+Xz).
Short circuit current, $I_{sc}=Es/X_{l.;}$ Overload capacity = I_{sc}/Is.

3.11. Load loss

Load loss = stator copper loss + rotor copper loss;
On basis of physical dimensions, resistances of stator and rotor conductors are calculated, and then copper losses are calculated.

3.12 .Efficiency (η)

η = output/(output+Noload loss+Load loss);
M. Stator Temperature rise:
Loss dissipation from back of core, $L_1= (\pi.Do.L)/C_1$;
Loss dissipation from inner surface of stator, $L_2=(\pi.D.L)/C_2$;
Loss dissipation from sides, $L_3= (\pi/4).(Do^2 – D^2)/C_3$;
C_1,C_2,C_3 are cooling coefficients.
Stator Temperature rise, θm = Total stator losses/($L_1+L_2+L_3$).

4. Results and Discussion

Motor Specifications: 3KW, 400V, 50 Hz, 3 phase, delta connected, 1500 synchronous rpm, cage type Induction motor (I.M.).

On basis of specifications, main dimensions of stator are calculated. After obtaining main dimensions, height and width of parallel sided slot, tapered slot, and circular slots are obtained. Air gap between stator and rotor is calculated by given empirical relation. On rotor sides, physical dimensions of parallel sided slots are obtained following the design concept of stator slots. Stator and rotor winding resistances are calculated on basis of physical dimensions of stator and rotor conductors. After obtaining slot leakage reactance, zigzag leakage reactance and overhang leakage reactance, total leakage reactance is calculated. Finally, no load loss, load loss, efficiency and temperature rise are calculated for three different types of stator slot configurations. Above simulation is done in MATLAB-7.5; obtained results are shown in Table-1.

Leakage reactance for all three shapes of slots is almost same. The magnetising reactance is highest in case of circular slots; it reduces the magnetising current and improves no load power factor. For circular slots, efficiency is comparatively better; it is because of reduction in no load loss; however, the stator temperature rise is slightly higher, but within limit. As the outer diameter reduces, surface area reduces; so, heat dissipation reduces, it gives more temperature rise. Comparative values of- efficiency, magnetising current, temperature rise, leakage reactance, no-load power factor and overload-capacity are also represented by bar-graphs in Figure-7a,7b,7c.

5. Conclusion

An induction motor with circular shape of stator slots has comparatively better efficiency, reduced magnetising current and better overload-capacity. Therefore, circular shape of stator slot is the best choice for 3KW induction motor.

Table-1

Description	**I.M. with Parallel-sided slots**	**I.M. with Tapered slots**	**I.M. with Circular slots**
Dia of stator bore (D); mm	112.4	112.4	112.4
Length of stator (L); mm	92.8	92.8	92.8
Numbers of stator slots	24	24	24
Dimensions of stator slot; mm	W_o=3, h_1=44.24, h_2=0.5, h_3=3, h_4=1, dss=46.74, Wss=11.65	W_o=3, h_1=53.47, h_2=0.5, h_3=3, h_4=1, dss=57.97, W_1=9.74, W_2=9.8, Wss=11.17	W_o=3, h=3, dss=29.69, Wss=26.69
Outer dia of stator (Do);mm	244.78	263.14	206.5
Air gap (lg), mm	0.4	0.4	0.4
Numbers of rotor slots	17	17	17
Dimensions of rotor slot; mm	Wo=1.5, h_1=13.92, h_2=1, h_3=0.5, h_4=1, dsr=16.42, Wsr=7.71	Wo=1.5, h_1=13.92 h_2=1, h_3=0.5, h_4=1, dsr=16.42 Wsr=7.71	Wo=1.5, h_1=13.92, h_2=1, h_3=0.5, h_4=1, dsr=16.42, Wsr=7.71
Stator turns per phase	512	512	512
Stator conductors per slot	128	128	128
Cross sectional area of stator conductor; mm^2	1.1	1.1	1.1
Cross sectional area of rotor conductor; mm^2	89.7	89.7	89.7
Total Leakage reactance (X_l); Ω	55.98	55.44	55.23
Magnetising reactance (Xm); Ω	428.6	383.9	446.4
%Magnetising current (Im)	25.1	28.02	24.1
% No load current (Io)	25.4	28.3	24.45
Overload capacity (I_{sc}/I_{fl})	1.83	1.85	1.86
No load p.f. (cos Φo)	0.15	0.14	0.168
No load loss; watts	167.7	184.8	136.9
Load loss; watts	341.7	341.7	341.7
%Efficiency (η)	85.48	85.07	86.24
Temperature rise (θm); °C	50.2	48.4	51.3

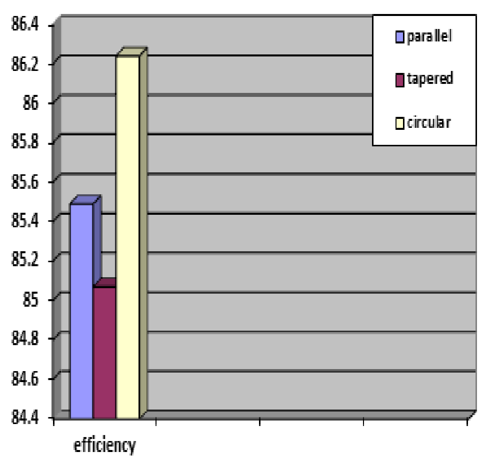

Figure-7a

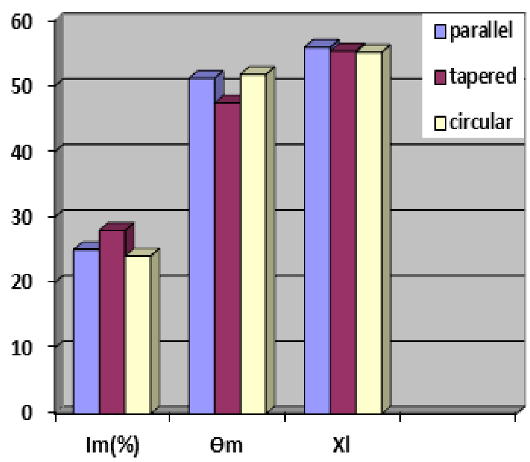

Figure-7b

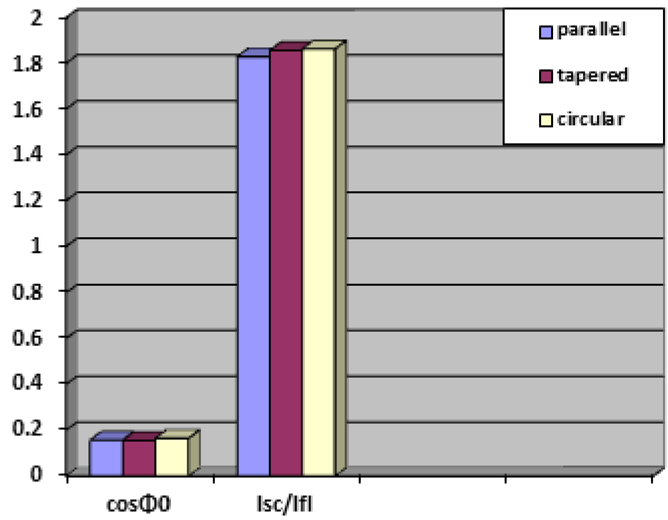

Figure-7c

Acknowledgements
Authors are thankful to their teachers, friends and family members.

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