DESIGN AND ANALYSIS OF A PREMIUM EFFICIENCY (IE3) INDUCTION MOTOR

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For designing an induction motor complete dimension of all the parts of the machine must be known in order to satisfy the customers required specifications. This paper presents the calculation of following design details. (a) The dimensions of the stator that includes stator packet length and diameter. (b) Details of stator windings and stator slots. (c) Design details of rotor and rotor slots. (d) Finally, the performance of motor. In order to get the above design details the designer needs the required customer specifications such as rated power output, rated voltage, speed, frequency, type of stator winding and its connection, type of rotor winding, working conditions, shaft extension and dimension details etc. The design example of 45kW cage motor is presented and various tests are also performed.

Keywords: *Induction Motor; Designing; Premium Efficiency Motor; Efficiency; Losses; IEC 60034-30-1; IEC 60034-1 standard.*

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Symbols:

cos ϕ = power factor
f = supply frequency, Hz
I = average line current, A
n = operating speed, s–1
p = number of pole pairs
P = power, W
P_0 = input power at no-load, W
P_1 = input power, excluding excitation2, W
P_2 = output power, W
P_{fe} = Iron losses, W
P_{fw} = Friction and windage losses, W
P_L = load losses, W
P_{LL} = additional-load losses, W
Pmech = mechanical power, W
P_T = total losses, W
R = winding resistance, Ω
s = slip, in per unit value of synchronous speed
T = machine torque, N·m
U = average terminal voltage, V
U_0 = voltage at no-load, V
U_N = rated voltage, V
X = Reactance, Ω
Z = Impedance, Ω
η = Efficiency, %
θ_0 = initial winding temperature, °C
θa = ambient temperature, °C
θw = winding temperature, °C
τ = time constant, s
ac = ampere conductors
K_w = winding factor

I. INTRODUCTION

Induction motors are widely used in domestic, commercial and various industrial applications. Mostly, the squirrel cage induction motor is used because of its simplicity, robustness and low cost, which has always made it very attractive, and it has therefore captured the leading place in industrial sectors.

High efficiency motors lead to significant reductions in energy consumptions and also reduces the environmental impact. Sustainable use and investments also demands increased motor reliability. Major energy savings are also gained through the use of variable speed drives (VSDs). An important measure for wide market acceptance of high efficiency motors is availability of harmonized standards, dealing with motor performance testing, efficiency classification, and display of ratings.

In this paper, motor is designed as per the design catalogues with this designed parameters the motor is tested. Its performance is calculated and compared with the actual performance obtained from the test results.

In the IEC 60034-30-1 the following efficiency classes are defined for induction motors (IE = International Efficiency):
1. Standard Efficiency (IE1)
2. High Efficiency (IE2)
3. Premium Efficiency (IE3)
4. Super Premium Efficiency (IE4)

In order to increase the efficiency the designer must calculate the losses check the motor performance. These losses may include stator copper losses, iron losses, friction and windage losses. In comparison with the standard (e.g. IE1) electrical motor, more iron and copper material are used.

Ac compared to IE1 motor the IE3 motors are heavier and bigger. Hence in order to increase the efficiency higher slot fill in the copper winding should be used, thinner laminations of improved steel properties should be used, air gap should be reduced, better design of cooling fan should be used to decrease the windage losses, use of special and improved bearings etc. can ensure higher efficiency in the motors.

II. DESIGNING OF INDUCTION MOTORS

A. Main dimensions

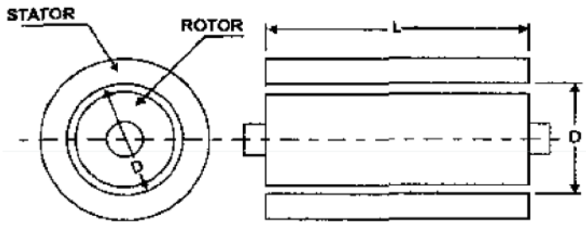


Figure 1.

D = Stator inner diameter,
L = length of stator packet.

Separation of D and L: The operating characteristics of an induction motor are mainly depend upon the ratio L/τ i.e. by the ratio L/D for a fixed number of poles. The factors influencing this choice are:

For minimum cost $L/\tau = 1.5$ to 2, for good power factor $L/\tau = 1$ to 1.25, for good efficiency $L/\tau = 1.5$, and for good overall design $L/\tau = 1$. The value of L/τ should vary between 0.6 to 2 depending on the size of the machine and the characteristics required [1][2].

B. Details of stator winding

Total loadings:

1. Total Magnetic Loading: It's the total flux around the stator periphery at the air gap.
2. Total Electric Loading: It's the number of ampere conductors around the stator periphery.

Specific Loading:

1. Specific magnetic loading: it's the ratio of total flux around the air gap and area of flux path at the air gap. Basically, the specific magnetic loading is determined by: (a) maximum flux density in iron parts of machine, (b) magnetizing current and (c) core losses.
2. Specific electric loading: it's the ratio of total ampere conductor and stator periphery at air gap. Factors which influence the choice of specific electric loading are: (a) Temperature rise (b) size of machine (c) current density.

Output equation:
$Q = C_0 * D^2 L * n_s$ where, (1)

$C_0 = 11 B_{av} * ac * K_w * 10^{-3}$ where, (2)
C_0 is output coefficient.

C. Number of stator slots selection criteria

For selection of stator slots following points should be considered:

1. Tooth pulsation loss: In open type slots, the slots should be so proportioned that minimum variations in air gap are produced. The effect of these variations is to produce tooth pulsation losses and noise. This effect can be minimized by using large number narrow slots.
2. Leakage reactance: With large number of slots, larger the number of slots to insulate. Hence width of insulation becomes more and the leakage flux has longer path through air. Hence the leakage flux reduces.
3. Magnetizing current & iron losses: With large number of slots there will be excessive flux density in the teeth. Hence high magnetizing current and iron losses.
4. Cost: With large number of slots, large number of coils to wind and insulate and this involves increase in the cost.

So use many slots as economically as possible. Hence q should not be less than 2; otherwise leakage reactance would be high.
Number of conductor per slots should be even for double layer winding.

D. Design details of rotor

a. Length of air gap: In order to estimate the air gap length, the following expression is used

$l_g = 0.2 + 2\sqrt{DL}$ mm (3)

Factors to be considered while estimating air gap are:

1. Power factor: The mmf required to send the flux through air gap is proportional to the product of flux density and length of air gap. Hence larger the air gap, large magnetizing current is drawn by the machine and the power factor is small.
2. Overload capacity: If the length of air gap is greater, the over load capacity is greater.
3. Pulsation losses: With larger air gaps, pulsation losses are less.

Hence, the length of air gap should be small as mechanically possible in order to keep down the magnetizing current and improve the power factor.

b. Number of rotor slots selection criteria:

Following rules should be followed for selecting the number of rotor slots: The number of stator slots should not be equal to rotor slots. The difference between stator slots and rotor slots should not be equal to p, 2p or 5p to avoid synchronous cusps. The difference between stator slots and rotor slots should not be equal to 3p to avoid magnetic locking. The difference between stator slots and rotor slots should not be equal to 1.2, $(p \pm 1)$ or $(p \pm 2)$ to avoid noise and vibrations.

E. Performance

In an induction motor the total losses consist of copper losses, core losses and friction and windage losses are occurred. Hence the efficiency can be calculated as:
Efficiency at full load η: Output/ (Output + losses)

III. DESIGN EXAMPLE OF 45KW CAGE INDUCTION MOTOR

A. Table I: Reference Data

This data consists of required customer specifications, based on this data calculation of the parameters of motor is done.

Frequency Hz	Voltage V	Current A	Power kW	Poles
50.0	415.0	76.00	45.00	2

B. Table II: Parameters

Parameters	Calculated values
D (diameter)	187 mm
L (packet length)	220 mm
Turns per phase	63
Stator conductor Per slot	10.5 = 11
Coil span	18
Line current	75.6 A
Outside diameter	374 mm
Rotor diameter	185.81 mm

C. Calculations

Following are the calculations of motor dimensions, stator design, rotor design, stator slots design, and the motor performance.

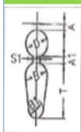
	V	415	F	50	PF	0.88	EFF	0.94	Poles	2	KW	45000
Main Dimensions												
Ns(r.p.s)	50											
Assume												
∂ current density	4.28 A/mm²		Space Factor	0.4	Width/toot	6	Flux density	1.2 Wb/m²				
Bav	0.48	ac	28000	Kw	0.955	0.001	L/τ Factc	0.75	Slots/pole/ph	6		
O/p Coeff (C0)	141.19						L/D	1.1781				
							D³	0.0065				
KVA i/p	54.4											
							D	0.187 m	187.0187598 mm			
D²L	0.0077						L	0.2203 m	220.3262857 mm			
τ	0.2938			The value of L/τ lies between 0.6 and 2 depending upon the size of machine.								
				For 50Hz machine of small design,Bav = 0.3 to 0.6 Wb/m2								
Net iron Length	0.1983											
				For machines where a large overload capacity is required,Bav = 0.65 Wb/m2								
Lmts	1.3563											
				The value of 'ac' varies between 5000 to 45000 ampere conductors per metre								

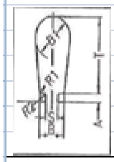
STATOR DESIGN				
Flux/pole	0.0311			
		Stator Slot pitch	16.31219 mm	
turns/phase	63.006			
		Coil Span	18	
Stator Slots	36			
		angle of chording	10 degree	
Stator Condr	378.03			
Stator Condr/slots	10.501			
Conductor Size				
Stator Current/ph	43.695			
Line Current	75.68			
Area (Stator Condr)	10.209			
Slot Dimensions				
Space reqd for bare conductor	107.21		**Slot Height**	**0.0285**
Area of each slot	268.01			
Stator Teeth				
Width of stator teeth	0.0051			
Flux Density in teeth	1.7 Wb/m²			
Stator Core				
Flux in teeth	0.0155		Depth Approx	0.065282
Area of stator core	0.0129			
Outside Diameter	0.3746 mm			
Copper Loss in Stator Wdg				
Resistance/ph	0.1758 ohms			
Total Cu loss	1006.8 W			
Friction n windage loss	2% of o/p 900 W			

ROTOR DESIGN							
Air Gap Length	0.606 mm	**Rotor Slots**	22				
Diameter of rotor	185.81 mm 0.1858 m						
Assume							
∂ current density	6.5 A/mm²	***Rotor condr/slot***	1		***Kwr***	1	
Rotor Slot Pitch	0.0265 mm	Rotor Bar resistar	3.99E-05				
Ir'	37.141 A						
		Cu loss in bars	325.7892 W				
I_b	609.48						
		End ring Current	2135.137 A	***Mean diameter of the end ring (Dme) is assumed as 4 to 6 cms less than that of the roto***			
Cross sectional Area of rotor conductor	142.4 mm²			Dme	144.8068 mm	0.144806798 m	
		Area of cross sec of end ring	328.4826 mm²	lme	0.454693		
L_b Length of rotor bar (L+allowance for (skewing+ b/w end rings & rotor core)	0.2703			Resistance end rings	2.91E-05		
		Cu loss in end rin	265.0373 W				
Total Cu loss	590.83 W	Equivalent rotor Resistance	0.14277 ohms				

Iron Loss in Stator			
Lohy's Steel Laminations	6		
Vol of stator teeth	0.001	Vol of stator Core	0.007602
Weight	8.1252 kg	Weight	59.294 kg
Iron loss	48.751 W	Iron loss	355.764 W
Total Iron Loss	404.52 W		
EFFICIENCY			
%Eff	0.9394 93.941		

IV. SLOT DESIGN

ROTOR						
Area	142.403					
	A1	3	B	8	B/2	4
	S1	2	B2	10	B2/2	5
	D	4	h	6.608111		
	D/2	2	T	15.60811		
AREA 1	12.56					
AREA 2	6					
AREA 3	25.12					
AREA 4	39.25					
AREA 2	59.473	59.473				
TOTAL AREA	142.403					

STATOR				
Area of each slot	268.014			
	A	1.5	B1	13
	S	5	T	24.88535
	B	10	B1/2	6.5
AREA 1	194.1815	Formula	194.1815	
AREA2	66.3325			
AREA 3	7.5			
Total AREA	268.014			
h	16.88535			

V. MOTOR TYPE TEST RESULTS

Following are the tests performed on motor:

- No load test
- Short Circuit test
- No-load characteristics

A. Table III: No load test

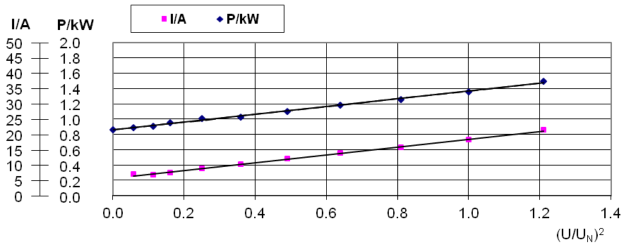
Frequency Hz	Voltage V	Current A	Power input kW	Power factor
50.0	456.5	21.48	1.570	0.09
50.0	415.0	18.27	1.408	0.11
50.0	373.5	15.87	1.299	0.13

B. Table IV: Short Circuit test

Frequency Hz	Voltage V	Current A	Power input kW	Power factor
50.0	72.0	76.03	3.409	0.32

C. No load characteristics

Graph 1 shows the no load characteristics with voltage on X axis and power and current on the Y axis.

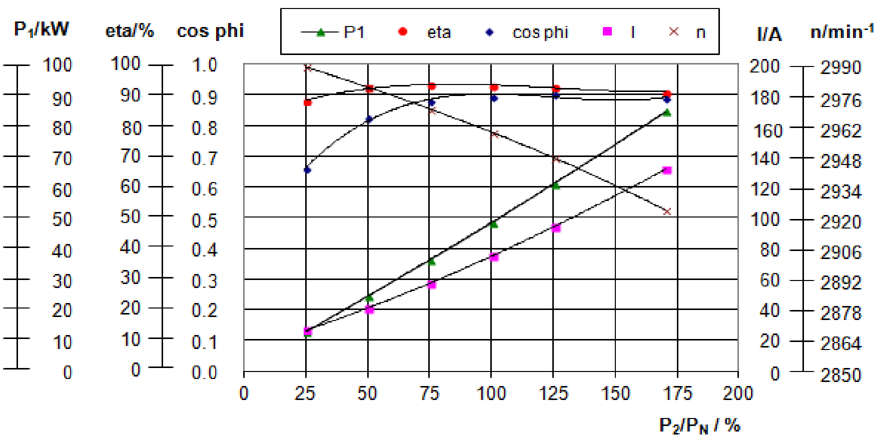


Graph 1

Friction losses: 0.857 kW
Iron losses: 0.499 kW

D. Table V: Load charcteristics

Measured values							Calculated values			
f Hz	U V	I A	P_1 kW	Cos ϕ	n min^{-1}	T Nm	P_2	P_t	P_2/P_n %	η %
50	415.5	131.4	84.49	0.89	2923	250	76.69	7.8	170.42	90.77
50	415.3	93.92	61.01	0.90	2947	182	56.37	4.6	125.28	92.39
50	415.1	75.13	48.53	0.89	2958	145	45.10	3.4	100.23	92.94
50	415.1	57.46	36.38	0.88	2969	108	33.85	2.5	75.24	93.06
50	415.2	41.04	24.49	0.83	2979	72.2	22.59	1.9	50.21	92.23
50	415.2	26.92	12.85	0.66	2988	35.9	11.31	1.5	25.15	88.02



Graph 2

E. Calculation of individual losses

Table VI: Load data

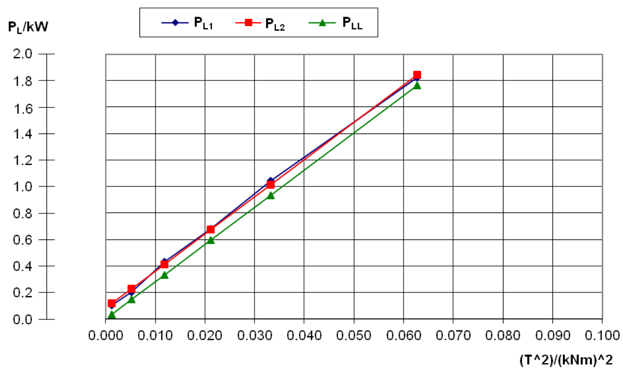
Measured Values (UN)									
P_2/P_N	f Hz	U V	I A	P1 kW	Cos ϕ	T Nm	N Min^{-1}	S	R Ω
170.42	49.96	415.5	131.40	84.492	0.89	250.3	2923.3	2.484	0.10388
125.28	49.96	415.3	93.92	61.019	0.90	182.3	2947.3	1.658	0.10388
100.23	49.96	415.1	75.13	48.531	0.89	145.3	2958.7	1.303	0.10388
75.24	49.96	415.1	57.46	36.384	0.88	108.6	2969.4	0.949	0.10388
50.21	49.96	415.2	41.04	24.498	0.83	72.2	2979.4	0.614	0.10388
25.15	49.96	415.2	26.96	12.855	0.66	35.9	2988.5	0.311	0.10388

Table VII:

Calculation acc. to IEC 60034-2-1									
P_2/P_N	P_{fw}	P_{fe}	P_s	P_r	P_{LL}	P_T	P_1	P_2	η %
170.42	0.857	0.47	2.690	2.020	1.762	7.802	84.49	76.69	90.77
125.28	0.857	0.47	1.375	0.997	0.935	4.642	61.01	56.37	92.39
100.23	0.857	0.48	0.879	0.615	0.594	3.427	48.53	45.10	92.94
75.24	0.857	0.48	0.514	0.336	0.332	2.525	36.38	33.85	93.06
50.21	0.857	0.49	0.262	0.146	0.147	1.903	24.49	22.59	92.23
25.15	0.857	0.49	0.113	0.038	0.036	1.540	12.85	11.31	88.02

Table VIII: Calculation of additional losses

Measured values							Calculated values		
f Hz	U V	I A	P1 kW	Cosϕ	n min^{-1}	T Nm	P_{L1} kW	P_{L2} kW	P_{LL} kW
50.0	415.5	131.40	84.492	0.89	2923.3	250.3	1.823	1.842	1.762
50.0	415.3	93.92	61.019	0.90	2947.3	182.3	1.045	1.105	0.935
50.0	415.1	75.13	48.531	0.89	2958.7	145.3	0.682	0.674	0.594
50.0	415.1	57.46	36.384	0.88	2969.4	108.6	0.429	0.411	0.332
50.0	415.2	41.04	24.498	0.83	2979.4	72.2	0.202	0.227	0.147
50.0	415.2	26.96	12.855	0.66	2988.5	35.9	0.104	0.116	0.036
							A	B	γ
							2.81E+01	0.080	0.999



Graph 3

VI. RESULT ANALYSIS AND DISCUSSIONS

The analytical results of motor are compared with the actual motor parameters in terms of dimensions of stator, stator design, rotor design, performance characteristics, losses and efficiency. This motor was tested at Siemens Advance motor Testing Centre.

Table 1 shows the reference data required for designing of motor. Table 2 shows the calculated parameters of the motor.

In section V, Type tests performed on the motor and the results of the type test are shown. Graph1 shows the No load characteristics and according to the type test the friction losses and the iron losses are more as compared to calculated losses. Hence these losses are needed to be reduced.

From Table V i.e. Load characteristics, at rated values of voltage, frequency and current, the efficiency obtained is 92.94%. Table VI shows the calculation of individual losses such as friction and windage loss, Iron loss, stator and rotor copper loss, stray load loss etc. The stray load losses can be calculated as per IEC 60034-2-1 by the following formula:
P_{LL}: $P_1[0.025-0.05*\log_{10}(P_2/1kW)]$

As per IEC 60034-30-1 for premium efficiency motor the minimum efficiency should be 94%. Hence the calculated efficiency is 93.94% but the type test results shows the efficiency is 92.94%. Hence the motor has failed in efficiency test.

Hence the task is to increase the efficiency as per IS/IEC 60034-1 which shows that for motor up to and including 150kW should have 15% (of (1-η)) tolerance. Hence as per this tolerance calculation the efficiency of this IE3 motor should be increased up to 94% with subject to tolerance and 93.1% inclusive to tolerance.

VII. CONCLUSION

This paper has presented a Premium efficiency motor (IE3). The actual motor parameters such as stator design, rotor design, and performance is compared with the analytical results. The following conclusions are obtained:

1. As per IEC 60034-30-1 for premium efficiency motor the minimum efficiency should be 94%. Hence the calculated efficiency is 93.94% but the type test results shows the efficiency is 92.94%.
2. The calculated losses such as friction loss, iron loss are less as compared to motor type test results.

The future work will investigate the various losses in motor and try to reduce those losses in order to increase the efficiency. Following are the approaches to modify the design of motor in order to reduce the losses.

A. Table IX:

Problems	Causes	Solutions
Low efficiency	Large stator copper loss	1. Increase wire diameter 2. Decrease stator turn or coil pitch 3. Increase power factor
	Large core loss	1. Decrease flux density by increase stator turn or coil pitch, and increase length 2. Use better steel
	Large stray loss	1. Modify Ns/Nr combination 2. Increase airgap 3. Modify rotor skew
	Large rotor copper loss	1. Increase rotor slot area 2. Decrease stator turn or coil pitch to decrease rotor current

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