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Evaluation, Categorization, Distribution and Methods of Reduction of Losses to Improve Thermal Design of SCIM Motor

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Abstract
For any thermal design and improvements of the motor accurate evaluation of the losses and reasons for existence of these losses because of which they occur is very important. Experimental techniques aiming at determining total losses and temperature rise in squirrel cage induction motors (SCIM) are expensive and their effectiveness is often limited to specific types of motors. Accurate estimation of these losses and how they are distributed along with feasible techniques to reduce them will result a scope to optimize the thermal design of the motor. In the present report evaluation, categorization, distribution and methods of reduction of all losses in SCIM Motor are presented. This has been done with relevant mathematical expressions and presenting properties of important materials.

I. INTRODUCTION

In the process of energy conversion taking place in a SCIM motor, certain amount of energy gets lost in the form of heat. These losses can be called as stable losses [1] occurring without charge changing and losses depending on charge changing in line with square of the armature current. Stable losses include iron, friction and wind losses and copper losses resulting from magnetizing current. Charge depended losses are primarily those stemming from copper losses. By means of thermal classification of insulating materials used in cooling of the SCIM motor, it was rendered possible to make the working temperature of certain parts of the SCIM motor stable. Every insulating material has a certain working temperature complying with expected life of SCIM motor and allowing the SCIM motor to safely function within this expected period. Even a small increase in temperature beyond the permitted values can considerably decrease working life of insulating material.

It is well known that experimental techniques aiming at determining total losses and temperature rise in electric induction motors are expensive and their effectiveness is often limited to specific types of motors. It is, therefore, important to estimate analytically or numerically power losses of motor in order to use the loss estimations obtained as input parameters for thermal modeling.
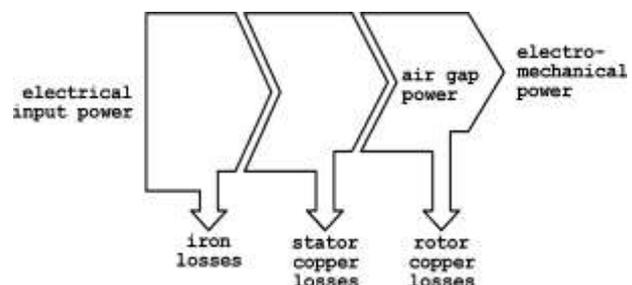

Fig. 1 Power flow of a SCIM motor

II. MECHANISM OF HEAT GENERATION INSIDE AN INDUCTION MOTOR [1]

Losses in SCIM motors can be categorized according to the causes or phenomena that produce them. For performance analysis of any motor, one important parameter to be considered is the motor loss. Determination of efficiency of motor and investigation of safe operating thermal mechanisms of heat generation in induction electric motors are generally divided in to four groups, related mainly to the places where they occur.

These are Joule losses, iron losses, stray load losses and mechanical losses. Each one of these kinds of energy conversion from electric to thermal energy is detailed below.

The importance of study surrounds from the magnitude of these losses and the ability of known techniques to reduce within the limitations of motor capabilities.

Table I
Losses and Methods of Their Reductions in SCIM Motors

Copper Losses:		Core Losses/ Iron losses	Stray Load losses:	Wind-age and Friction Losses:
Stator	Rotor			
Explanation of the loss in section				
III A		III B,C,D	IV A,B	V A,B,C
Approximate magnitude of the loss as % of total losses				
36	24	24	10	6
Loss depends on				
Conductor area, mean length of turn	Bar and end ring area and material	Material of lamination steel, air gap, magnetic saturation intensity	Manufacturing process, slot design, air gap and other parameters	Fan efficiency, Lubrication, bearing, power consumed by fan
Methods to reduce losses (more details of losses by strategic techniques in table IV)				
Using higher conductivity copper in the windings and increasing conductor cross-sectional area for decreasing primary losses.	Change of rotor bar material and end ring from aluminum to copper.	Better grades and thinner gages of steel laminations also reduce losses	.Thermal treatment, rotor bar insulation, non machining of rotor surface etc.	Methods such as improved fans and bearing performances, reduced air gaps and closer machining tolerances are also used for building of more efficient motors

Limits in turn influence the operating cost, determines the heating of given motor which gives the motor rating without the deterioration of insulation and for accounting the voltage drops or current component associated with cause of losses.

A. Copper Loss or Ohmic Loss or Joule Losses or Resistive Losses

Copper Loss or Ohmic Loss is I^2R_e loss which is caused when a current I flows through the winding (copper in most cases) having a resistance R_e.

This mechanism corresponds to the conversion of electric energy into thermal energy in electrical conducting media. The type of losses are directly related to the electric resistance of the conductor and changes proportionally to the square of the current, i.e. $P_j = I^2 R_e$ Energy conversion by Joule effect in squirrel cage induction electric motors occurs in the stator (copper windings) and in the squirrel cage (aluminum bars). The fundamental resistive losses of the stator and rotor are given by

$$P\,Cu_s = 3\,R_{e,s}\,I_s^2 \qquad\qquad \text{………(1)}$$
$$P\,Cu_r = 3R_{e,r}\,I_r^2 \qquad\qquad \text{………..(2)}$$

Where R_e and I are the electrical resistance and current per phase, respectively, and the indices s and r stand for the stator and rotor, respectively. For the small wire diameter used in the stator windings of smaller TEFC motors, the skin effect of the stator windings can be neglected when the supply voltage is sinusoidal. Concerning the resistive losses in the rotor, it is assumed that the skin effect can be neglected for the fundamental rotor current. Correction for the resistance [9] change with temperature for aluminum or copper can be made by (The constant value K is 245 for Aluminum and 235 for Cu bars)

$$R_e = R_{e,0}\ \frac{(K\,°C + T)}{(K\,°C + T_0)} \qquad\qquad \text{…………(3)}$$

The I^2R_e (copper) loss in stator is divided between the slot winding and end windings, nodes corresponding to rotor bar and rotor end ring in proportion to the quantity of conductor in each component. In rotor to separate the losses of end rings from losses of the bars, the following ratio of bar losses to ring losses can be used

$$\frac{P_{bar}}{P_{ring}}\ = 2\sin^2\frac{\pi p}{S_2}\ \frac{l_b\,A_r}{A_b\,l_r} \qquad\qquad \text{……..(4)}$$

Where p is the number of pole pairs, S_2 is the number of rotor slots, A_b and l_b are the area and lengths of a rotor bar, respectively. A_r and l_r are the area and lengths of a ring segment (i.e. between two bars), respectively.

B. Core Loss

Core loss also highly affects the performance of the SCIM motor. This loss is due to the conversion of electric energy into thermal energy in the iron (core) of the SCIM motor as the name depicts. In simple words, it is caused due to the presence of time varying i.e. pulsating or rotating magnetic field in the magnetic material. There are two kinds of core losses namely hysteresis losses and eddy current losses.

C. Hysteresis Losses

Hysteresis losses are proportional to frequency and proportional to $B_{max}^{1.6-2.4}$ (depending on saturation) where B_{max} is the peak flux density. In practice, hysteresis losses are commonly assumed to be proportional to B_{max}. Hysteresis loss is the loss because of hysteresis produced by time varying magnetic field in the magnetic material

D. Eddy Current Loss

Eddy current losses are Joule losses that occur in iron due to flow of an induced electric current. When a conductor is placed in a changing magnetic field, due to the relative motion

Table II
PROPERTIES OF IRON CORE MATERIALS

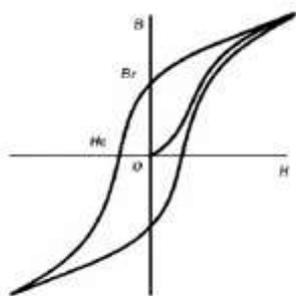| Sl. No	Property	Symbol	Units	Value	
				Report [7]	Report [3]
				M270-35 A	Silicon Iron Lamination
1	Hysteresis coefficient	K_h	[Ws/T^2/m^3]	118.6	93.89
2	Electric conductivity	σ	[(Ωm)$^{-1}$]	1.92 x10^6	2.22 x10^6
3	Lamination sheet thickness	Δ	[m]	0.35x 10^{-3}	0.35x10^{-3}
4	Excess loss coefficient	ke	[W/(TS^{-1})$^{3/2}$/m^3]	0.74	1.33
5	Packing factor	kf		0.98	0.98
6	Density	ρ	[Kg/m^3]	7650	7650

Fig.2 Plot of the Electric Induction (B) Versus Magnetic Field (H) for the Iron

of field and conductor or time variation of magnetic field, a current is induced in the conductor which circulates over the conductor body. These circulating currents cause heating in conductor core and also induce magnetic field which may oppose or add to the original field. It also causes the skin effect which is the phenomena where the current density is distributed towards the peripheral surface of the conductor.

III. General Expression - Iron Losses In Magnetic Materials Of Motor

The eddy current loss varies with square of the flux density (B_{max}), the frequency (f), and thickness of the lamination (Δ).
Under normal condition, the eddy current loss can be approximately expressed as

$$P_e = K_e (B_{max} \, f \, \Delta)^2 \quad \ldots\ldots\ldots..(5)$$

Where K_e is the proportionality constant and core losses per mass unit are

$$Q = (k_{Hy} f + k_{Ft} f^2) B_{max}^2 \quad \ldots\ldots..(6)$$

Where k_{Hy} and k_{Ft} are loss factors of the material for Hysterisis and eddy currents.

The eddy current loss factor is given below:[7]

$$k_{Ft} = \frac{(6.44 \, \Delta^2)}{12 \, \rho \, \rho e} \quad \ldots..(7)$$

Where ρ_e is the resistivity, ρ the density of lamination material. The sum of the eddy current losses and hysteresis losses is usually available from Epstein tests at 50 or 60 Hz. However, the real losses of a stator core can be 50–100 % larger than the calculated ones. The losses are increased due to harmonics of the field variation and due to manufacturing (e.g. punching of the sheets). Temperature also affects the losses.

The magnetic fluxes and magnetic flux densities of the yoke (B_y) and teeth (B_t) respectively, are determined by means of equivalent circuit, winding data and geometry of SCIM motor in usual way.

TABLE III
EXPRESSIONS FOR CORE LOSSES

	Expression for total core losses	
Report 2,3	$(k_{Hy} f + k_{Ft} f^2) B_{max}^2$	
	Hysterisis losses	Eddy current losses
	$k_{Hy} f \, B_{max}^2$	$k_{Ft} f^2 B_{max}^2$
More detailed expression for total core losses is		
Report 4	$c \, [\alpha \frac{f}{50} B^x + (1-\alpha) [\frac{f}{50}]^2 B^2] \, \Delta V_i$	
	Hysterisis losses	Eddy current losses
	$c \, \alpha \frac{f}{50} B^x \Delta V_i$	$c \, (1-\alpha) [\frac{f}{50}]^2 \, \Delta V_i$
	$k_{Hy} = c \, [\alpha \frac{B^x}{50}] \, \Delta V_i$	$K_{Ft} = c \, (1-\alpha) [\frac{1}{50}]^2 \, \Delta V_i = \frac{(6.44 \, \Delta^2)}{12 \, \rho \, \rho e}$
c=constant is a good approximation		
The exponent x of B is equal to 1 for very low flux densities and 1.5 to 2 for the usual densities		

of SCIM motors. Calculations with x = 1.5/1.8/2.0 and α = 0.7/0.5/0.3 are carried out generally.

Where: f is the frequency (in **Hz**), c a lamination factor (in W/kg), $\Delta V_i \sim$ the element volume (in m^3),

B the **flux** density (in Tesla) and 0 < α < 1.

B = B_y if the element i is at yoke and B = B_t if it is at teeth.

A. Stray Load Losses or Additional Losses [6]

The Stray Load Loss (also called additional losses) is one kind of losses in electrical SCIM motors. Stray load loss arises from the non-uniform distribution of current in winding and additional core losses produced in the iron due to distortion of the magnetic flux caused by the load current.

However the stray load losses are minor losses in the electric motor operation and at the same time their quantification is very difficult. They include the losses due to the skin effect, high frequency, among others, that are unknown not easily quantified.

B. Causes for the Stray Load Losses

Slots in SCIM motors cause permeance waves that produce no load stray losses both in stator and rotor. The non sinusoidal mmf distribution in air gap and the saturation of the magnetic circuit further add to space harmonics. Some of the no load stray losses are caused by eddy currents in the rotor teeth. These losses are usually divided into surface losses and tooth pulsation losses, where the surface losses are treated separately because they only appear in a thin surface layer, while the pulsation losses penetrate deeper. Penetration depth of pulsations depends on design of rotor cage.

Since each rotor tooth is surrounded by short-circuited rotor bars, circulating currents will occur which limit the penetration depth of the permeance waves. Surface losses are influenced by finish of the rotor surface. Magnitude and nature of stray losses depend on whether rotor bars are skewed or not.

Additional losses are the total load losses minus the fundamental resistive losses. They are basically of the same kind as the no-load stray losses, but much increased due to the mmf waves occurring at load. A part of the additional losses is also the end losses, which depend on axial leakage flux that penetrates the rotor and stator ends and to a certain extent the end shields and the frame. The end losses are influenced by the distance between the end windings and other conducting SCIM motor details.

In summary these losses are due to the non uniform current distribution in the copper and the additional core losses produced in the iron by distortion of the magnetic flux by the load current. The stray load losses consist of the following

components- especially when the motor is operated at high frequency.

1. Surface losses in the stator
2. Surface losses in the rotor
3. Pulsation losses in the stator teeth
4. Pulsation losses in the rotor teeth
5. Losses in the squirrel cage winding
6. Losses due to skewing with un insulated cast aluminum squirrel cage windings.

IV. MECHANICAL LOSSES

The two main mechanical losses found in electric machines are the bearing and windage losses. Bearing loss is caused by friction between the moving parts of the bearing, i.e. between the balls and sleeves in the case of ball bearings. Lubrication is used to lower the frictional loss, but the viscosity of the lubrication also influences the total bearing loss. Other factors that influence bearing loss are shaft speed, bearing type and bearing load. The latter is composed of static and dynamic loading, the former is associated with gravitational forces and the latter with dynamic effects like unbalance forces and rotor dynamics. The bearing loss (P) can be calculated using:

Bearing Losses due to a) friction in bearing b) viscous losses due to air gap friction and c) windage together are considered as mechanical losses.

A. Friction Losses in Rolling Bearings

Friction losses are losses in rolling bearings (balls/rings interface) and bearing seals. Viscous losses are small compared to the fan losses. Losses due to the seals may in fact be larger than the actual bearing losses. Bearing friction torque consists of a constant part that depends on the bearing forces and a hydro dynamical part, which is strongly temperature-dependent and speed-dependent. The hydro dynamical part is usually dominant over the constant part.

Bearing friction loss can be calculated as

$$P_{bearing} = 0.5\ \omega\ k_{f\,r}\ F\ d_{Bearing} \qquad \ldots\ldots\ldots\ldots\ldots(8)$$

Where k_{fr} is the frictional co-efficient of the bearing, F is the dynamic bearing load and $d_{Bearing}$ is the inner diameter of the bearing.

The bearing load is greatly increased when a bearing needs to carry loads in a direction it was not designed for, e.g. axial loading in a bearing designed for radial operation. The second important mechanical loss mechanism is windage loss. The mechanical air gap in an electric machine is filled with a fluid, usually air. The fluid is moving at the same speed as the rotor on the rotor surface and on the stator surface, it is stationary. This results in a drag torque and frictional loss.

B. *Losses in Air Gap or Viscous Losses*

A narrow air gap requires less no-load current than a wide air gap, so motor designs incorporate the narrowest air gaps possible. This improves efficiency and power factor.

However, if the air gap is too small there is a danger that the rotor may actually contact the stator, short circuiting it. Maintaining precise air gap requires precision rotor bearings

The windage loss

$$P_{wind} = (\frac{1}{32} \ k_s \ C_M \ \pi \ \rho_a \ \omega^3 \ d_{bearing}^4 \ L)$$

…………..(9) Where k_s is the surface roughness coefficient (usually between 1-1.4), C_M is the torque coefficient, ρ_a is the air density, $d_{bearing}$ is the rotor outside diameter and L is the active length of the motor.

TABLE IV
METHODS FOR REDUCTION OF LOSSES

	Improvement technique	Reduction of losses
1	Increased stator slot fill factor	Reduction of stator copper losses because of higher dimension of stator conductors or reduced total insulation content in slots.
2	Coating laminations with higher thermal conductivity material	Effective dissipation of heat leading to reduction of overall losses.
3	Increased diameter	Less magnetic and electric specific values and thus reduction of losses for the higher size motors.
4	Core axial lengthening	
5	Rotor bars insulation	Rotor slots are insulated before the casting, highly increasing the inter-bar resistance and reducing the inter-bar currents.
6	Non-machining of rotor surface	Reduced surface losses and thus reduction of eddy current losses
7	Low-loss electrical steel	Reduction of core losses
8	Decreased lamination thickness	
9	Heat shock /Thermal treatment	
10	Slot dimensions	Optimized dimensions of these two techniques will reduce core losses
11	Core dimensions or lamination sizes	
12	Annealing	
13	Magnetic/semi-magnetic wedges	Reduced leakage flux and reduction of losses
14	Reduction of air gap	
15	Amorphous steel	
16	Stator magnetic insulation	
17	Current densities	Number of stator conductors is more -current density required will be less since amp conductors/surface area is flux density (B_{av}). Product of B_{av} and ac/m of circumference will be decreased for higher values of D^2L and vice versa for same performance of motor.
18	No. of Stator conductors	
19	Conductor insulation (material and thickness)	Better materials need thinner insulations and improved heat transfer thus less rise in temperature leading to lower losses.
20	Manufacturing methods	Uniform and precise air gap to reduce flux leakage and reduced losses
21	Copper rotor bars	Reduced specific resistance and reduced stator copper losses
22	Use of combination of Al/Cu rotor bars	Optimization of starting current and reduction of rotor losses is possible.

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Table V
DISTRIBUTION OF LOSSES

Iron losses	Copper losses	Mechanical losses	Additional losses
Stator			
SCIM motor yoke, $P_{Fe\ (s)}$ Y. Iron losses in the stator teeth, $P_{Fe(S,T)}$	Embedded Windings and end windings	Windage losses do not add to heat Viscous losses get added to rotor and stator teeth proportionately	a) 40% is added to Stator windings b) 30% of additional losses is added to stator teeth and
Rotor			
Iron losses in the rotor laminations, $P_{Fe\ R}$.	Bars End rings	Bearing losses get added to the shaft	c) 30% of additional losses is added to rotor iron

The torque coefficient is dependent on the Reynolds number and can be calculated

$$C_M = 10 \frac{(\frac{2\,l_g}{d})^{0.3}}{Re} \qquad Re <64 \qquad \ldots\ldots.(10)$$

and careful machining.

C. Windage Losses [11]

$$C_M = 2 \frac{(\frac{2\,l_g}{d})^{0.3}}{Re^{0.6}} \qquad 64<Re <5 \times 10^2 \ldots\ldots.(11)$$

$$C_M = 1.03 \frac{(\frac{2\,l_g}{d})^{0.3}}{Re^{0.5}} \qquad 5 \times 10^2 < Re <5 \times 10^4 \ldots\ldots.(12)$$

$$C_M = 0.065 \frac{(\frac{2\,l_g}{d})^{0.3}}{Re^{0.2}} \qquad 5 \times 10^4 < Re \qquad (13)$$

Where l_g is air gap length

The stator must draw extra current to increase the flux density of its magnetic field and bridge the air gap.

V. CATEGORISATION AND DISTRIBUTION OF MOTOR LOSSES

The core (iron) loss is distributed among the stator and rotor components in such a way that the majority of the loss occurs in the components (corresponding nodes) that model the stator teeth and combined rotor bars and teeth. Mechanical losses are generally included as heat generation in the shaft.

A. *Contribution of Each Category Of Loss* [5]

For the correct modeling, it is important to quantify the suitable value and location of the heat generation. In general, the quantification of the losses is directly related to the location where these losses occur in the electric motor, excepting the stray losses. Power loss classification based on the location of the losses is as below:

TABLE VI
BREAK UP OF TOTAL LOSS

Stator yoke	Tooth body	Stator slot winding	End winding	Rotor bars and End rings

The total loss is separated into the five separate bulk regions indicated as above:

Copper loss (both in stator and rotor) was subdivided based on the respective length of conductor in the slot and end winding regions in the lumped models where an extra node is provided for the end winding regions and rotor copper losses are distributed as given in the equation (4).

Table VII
SUMMARY OF MOTOR LOSSES

Total losses			
Load losses(current dependent)		No Load Losses (voltage dependent)	
Stray Load losses	Copper losses	Mechanical losses	Iron Losses
Skew leakage losses	Surface losses	Windage losses	Hysterisis losses
End leakage losses	Slot leakage flux losses	Friction losses	Eddy current losses
Losses due to leakage flux			
Rotor pulsation and copper loss due to zig-zag mmf			
Load losses (current dependent)		No-load losses (voltage dependent)	
Losses at sinusoidal supply voltage	Losses at non-sinusoidal supply voltage		
(a) resistive losses in the stator winding (b) resistive losses in the rotor	The dominating harmonic losses are a) Resistive losses in the stator	The following losses can be expected at no load with sinusoidal supply (a) Core losses in the stator teeth and	

winding (c)Additional losses due to leakage flux and m.m.f. space harmonics. The additional losses consist of similar components as the no-load stray losses. End losses and losses due to the skew leakage flux are also part of the additional losses.	and rotor windings caused by the harmonic currents and by skin effect b) Core losses and surface losses caused by the harmonic flux. It is often assumed that the harmonic losses are of the no-load type, but the harmonic losses increase with the load. This effect is due to saturation of the harmonic leakage flux path, which decreases the leakage reactance and thus increases the harmonic currents.	yoke, due to the main flux (b) No-load stray losses (c) Losses due to friction and wind-age: The term no load stray losses is here used for losses that are due to space harmonics and consequently are not of fundamental frequency. These are tooth pulsation losses, surface losses, losses due to inter bar currents and circulating currents in the rotor. Apart from the terms (a) to (c), there are of course also some resistive losses due to the no-load current.

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