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THERMAL MODELLING
OF
DEEP BAR INDUCTION MOTOR
AT STALL

by

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To:

my wife, Mohanna,

and

my sons, Arshya and Aarash

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SUMMARY

As with all motors, the performance of an induction motor while at standstill, whether in the course of a normal starting sequence or as a result of stall, is of crucial importance to a designer. Since the motor is under full voltage, a fast temperature rise may occur in different parts of the motor before the power source is isolated, or substantial acceleration occurs. This may damage some parts of the motor, or cause a premature aging of the electric insulation in various parts of the motor, in particular the stator winding. In addition, in applications where the motor is surrounded by a potentially explosive atmosphere, an unexpected temperature rise at any point in a motor may be enough to ignite the existing mixture of gases. To avoid such phenomena, the temperature distribution in the motor should be predicted as accurately as possible to ensure reliable protection of the motor against overheating in critical points. This work is an attempt to improve the accuracy of prediction of transient temperature distribution in an induction motor, with particular attention to the modelling of deep-bar cage motors.

The accuracy of thermal models is strongly dependant on that of the initial data. This data includes both geometry-related parameters and the relevant material properties. Furthermore, an accurate picture of the distribution of the thermal loads in the motor is crucial to the final results.

The distribution of the loads in the thermal model is extracted from a two-dimensional magnetic analysis employing a harmonic finite element method. This procedure enables inclusion of the deep-bar effect in the rotor bars and consequently an accurate estimation of the distribution of losses in these areas. The effect of the non-linearity of the iron core is included in the magnetic analysis using the “effective reluctivity” and “simultaneous static and harmonic analysis” methods.

Although a three dimensional thermal model of the complete motor is ideally required, a reduced system including only half of one slot pitch is proposed as the main model. This is supplemented by a two-dimensional model to study the peripheral variation of temperature in the motor.

The proposed method is applied to two induction motors, 15kW and 250kW, used as models one and two respectively. The analysis results were verified by direct locked rotor tests on the motors. Two individual locked rotor tests with different voltages were performed on each model and the variation of temperature with time at 17 points on model one and 20 points on model two was recorded for this purpose. Finally, a transient analysis on the motor during start up was carried out where, a dynamic equivalent circuit is proposed for induction motors and a method to determine the parameters of this circuit is suggested. The validity of this analysis is checked against the test results on the 15kW motor only.

STATEMENT OF ORIGINALITY

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, for the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Mohammad Reza Feyzi

M.R. Feyzi

LIST OF PRINCIPAL SYMBOLS

Symbol	Description
A	Area of surface, area of convection surface, m^2
$\dot{A}$	The magnetic vector potential (in z direction), Wb/m
$\dot{A}_0$	The mean value of $\dot{A}$ over the cross sectional area, Wb/m
A_{sslot}	The apparent area of stator slots.
$\dot{B}$	The magnetic flux density, Wb/m^2
B_{peak}	Peak value of local flux density, Wb/m^2
$B_{x,i}$	The peak value of x component of the imaginary part, Wb/m^2
$B_{x,r}$	The peak value of x component of the real part, Wb/m^2
$B_{y,i}$	The peak value of y component of the imaginary part, Wb/m^2
$B_{y,r}$	The peak value of y component of the real part, Wb/m^2
$\dot{D}$	The electric flux density, C/m^2
$\dot{E}$	The electric field strength, V/m
$\mathcal{F}$	Functional
$\dot{H}$	The magnetic field strength, A/m
I_{nb}	Total rms value of current in rotor bar number n
$\hat{I}_1$ and $\hat{I'}_2$	Amplitudes of stator and rotor currents calculated from the equivalent circuit
$\hat{I}_{b,\,rotor}$	Amplitude of the bar current in the rotor cage;
$\hat{I}_{b,\,stator}$	Amplitude of the bar current in the equivalent stator cage winding;
I_ν	rms value of νth harmonic bar current
I_μ	rms value of μth harmonic bar current
$\dot{J}$	Current density, A/m^2

j_0 ....The average or low frequency current density in the bar, A/m^2

$|J_{z,e}(x,y)|$ ..Current density in the element in position *(x,y)*

K_{acc} ....Acceleration factor

L_0 ....Inductance of the gap above the bar (if there is any gap)

L_{mean} ......the mean length of turns in the stator winding,

L ....axial length of the cylinder, the significant (or characteristic) length (Ch3)

N_1 ....The number of turns per pole in the primary winding (stator)

P_a ....The apparent power per killo gram, VA/Kg

R_{ij} ....Thermal resistance between nodes i and j.

S_2 ....The number of slots in the secondary (rotor)

T_w ....Wall temperature, $^{\circ}C$

T_{∞} ....Bulk temperature of the fluid, $^{\circ}C$

T ....Temperature, $^{\circ}C$

T_i, T_j ......Temperature at nodes i and j respectively;

T_i ....Inside surface temperature

T_o ....Outside surface temperature

V ....Velocity of the fluid;

a ....The cross sectional area of each individual stator conductors, m^2

a_{mean} ......The mean area of the end ring, m^2

c ....Specific heat, $J/(Kg \cdot {}^{\circ}C)$

da_e ....Area of the element

$dW_i(x,y)$ ..Local iron losses

f ....Frequency, Hz

g ....Number of slots per pole; also, acceleration of gravity, N/Kg

g' ....Number of slots per pole and per phase

h_c ....Convective heat transfer coefficient, $W/(m^2 \cdot {}^{\circ}C)$

i_1 to i_n . . . . . The current flowing through segments *1* to segment *n*

j . . . . Imaginary unit equal to $\sqrt{-1}$

k_{w1} . . . . Winding factor of the primary winding

k_r . . . . Thermal conductivity of the wall in the radial direction, $W/(m \cdot {}^{\circ}C)$

k_x . . . . Thermal conductivity of the element in x direction, $W/(m \cdot {}^{\circ}C)$

l_{mean} . . . . . The mean length of each end ring, m

l_1 to l_n . . . . . Inductance of individual segment disregarding any mutual inductances

m . . . . The number of conductors in parallel in the stator winding.

m . . . . Number of parallel paths in the winding,

q . . . . Number of phases; also, heat flux, W

q . . . . The transferred heat in x direction, W

q''' . . . . The loss density in the stator slot area, or heat generation, W/m^3

q_i . . . . The heat delivered to node i by heat generation;

q_r . . . . Heat transfer in the radial direction

r_1 to r_n . . . . Resistance of individual segments

r_c . . . . The per phase equivalent resistance representing the iron losses.

$r_{2,\,eq}$ . . . . . . The equivalent rotor resistance including the end-ring effect, Ω

r_1 . . . . The per phase resistance of stator winding,

r'_2 . . . . The per phase resistance of the rotor winding transferred to stator side,

$r_{b,\,eq}$ . . . . . . Equivalent resistance of a bar in a cage rotor allowing end-ring effects,

r_b . . . . Resistance of a bar alone,

r_c . . . . Resistance of one ring segment between two adjacent bars,

r_i . . . . Inside radius

r_o . . . . Outside radius

t . . . . Time, *seconds*

x_1 . . . . The per phase leakage reactance of stator winding, Ω

x'_2	The per phase leakage of the rotor winding transferred to stator side, Ω
$x_{b,\,eq}$	Equivalent reactance of a bar in a cage rotor allowing end-ring effects, Ω
x_b	Reactance of a bar alone, Ω
x_c	Reactance of one ring segment between two adjacent bars, Ω
x_m	The per phase mutual inductance between rotor and stator windings, Ω
$x_{2,\,eq}$	The equivalent rotor reactance including the end-ring effects, Ω
α	Thermal diffusivity of the material (CH3)
α_ν	phase angle related to harmonics ν and μ respectively
α_μ	phase angle related to harmonics ν and μ respectively
μ	Viscosity of the fluid.
ν	Harmonic pole-pair numbers
μ	Harmonic pole-pair numbers
ν	Reluctivity, m/H
ν_{app}	Applied Reluctivity, m/H
ρ	Volume charge density, C/m^3; also, density of any solid, Kg/m^3
ρ_c	Density of iron (core), Kg/m^3
σ	Spread of phase group in electrical radians; electric conductivity, mho/m
τ	Time, *seconds*
τ_c	Time constant, *seconds*
ω	The angular frequency, *rad/seconds*

LIST OF ABBREVIATIONS

Abbreviation	**Definition**
FEM	Finite Element Method
LPM	Lumped Parameter Method
TC	Thermo Couple
TEFC	Totally Enclosed Fan Cooled

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