Field analysis of Three-Phase Induction Motors with Skewed Slots

M. Sc. Thesis

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Electrical power and machines Dept.,
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For the partial fulfillment of obtaining
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CONTENTS

ABSTRACT

Chording of the stator winding and skewing the rotor slots are introduced mainly to minimize the effects of the stator space harmonics on the overall torque of the three phase induction motors. By these methods the parasitic torques and hence the noise of the motor is reduced.

Instead of using the well known skewing factor and in order to get accurate results, a two dimensional mathematical model is introduced for representing the three-phase squirrel cage induction motor with skewed rotor slots. In this model the magnetic circuit saturation is neglected and two systems of coordinates are used. The first is orthogonal x, y and z coordinates used in representing the Maxwell's differential field equations for the electromagnetic quantities produced by the stator excitation. The second system is a skewed u, y and v coordinates used in representing the Maxwell's differential field equations for the electromagnetic quantities produced by the rotor excitation.

The final solution of the Maxwell's field equations expressed in the orthogonal and skewed coordinates, are obtained by the separation of variables and superposition techniques. The constants of integration are obtained using the appropriate boundary conditions.

The analysis in this thesis yield to more accurate forecasting of the motor torques developed by each of the stator's space harmonics and shows explicitly the effects of rotor skewing on each of the parasitic torques.

Expressions for the radial force and for the axial force, which appears as a result of the skew, are also derived.

The theoretical analysis is also extended to represent the squirrel cage motors having zigzag skewed rotor, in which the axial force is eliminated.

The theoretical results introduced in this thesis are realized using the design constants of two three-phase squirrel cage induction motors of different ratings. The theoretical results are compared with the results of experiments performed, on the two motors, in the laboratory of Madco motor factory. This factory produces various types of induction motors with skewed rotor slots.

The results obtained from the above mentioned analysis proved to be more accurate than those determined using the conventional equivalent circuit of the motor in which the winding factor includes the skewing factor.

LIST OF SYMBOLS

$\mathbf{A}$ = magnetic vector potential, (amp. turn/m.).

$\mathbf{a}_x, \mathbf{a}_y, \mathbf{a}_z$ = unit vectors in the x, y and z direction respectively.

$\mathbf{a}_u, \mathbf{a}_y, \mathbf{a}_v$ = unit vectors in the u, y and v direction respectively.

$\mathbf{B}$ = Magnetic flux density, tesla.

b_s = Slot width, m.

b_t = Tooth width, m.

D = Stator bore diameter, m.

E = Electric field intensity per meter.

e = Base of natural logarithms.

F = Magneto-motive force (m.m.f.).

F_y = Radial force, in the y-direction, N.

F_t = Tangential force, in the x-direction, N.

F_z = Axial force in the z-direction, N.

f = Supply frequency.

g = air gap length.

$\mathbf{H}$ = Magnetic field intensity, (Amp. m.).

h_s = Slot height, m.

h_t = Tooth height, m.

I = Stator phase current, Amp.

I_{ring} = ring current per meter depth, (Amp. / m.).

i = Index.

$\mathbf{J}$ = Current density vector, (Amp./ m.^{2}).

j = $\sqrt{-1}$; index.

$K_{w\upsilon}$ = Stator winding factor for the υ harmonic.

K_{sk_υ} = Skewing factor for the υ space harmonic.

l = Length of excited region of the machine in the axial direction, m.

l_b = Rotor bar length, m.

l_o = Stator's overhang length in the axial direction.

N = Number of turns.

P	= Active Power, watt.
p	=Number of pole pairs of the stator winding.
q	= Number of slots per pole per phase of the stator winding.
Re	= Real part.
R_{st}	= Stator winding resistance per phase, ohm.
r_r	= Ring resistance per meter length, (ohm / m.).
S	= Number of slots; area.
SFF	= Slot filling factor.
s	= slip .
t	= Time, second.
V_{ph}	= Machine phase voltage.
x	= Distance along the stator bore.

Greek letter symbols

θ_s	= Skewing angle, radian.
α	= Complement of the Skewing angle $= 90^\circ - \theta_s^\circ$
Δ	= Incremental element.
η	= Efficiency.
$\hbar$	= Linear current density vector (Amp. turn / m.)
$\Re$	= Reluctance.
μ_o	= Permeability of free space = $4\pi \times 10^{-7}$ (H / m.)
μ	= Relative permeability.
μ_x . μ_y	= Relative permeabilities in the x and y directions
υ	= Order of the space harmonic.
ρ_b	= resistivety of bar material, (ohm . m.).
Σ	= Summation sign.
τ	= pole pitch of the stator winding.
$\tau_\upsilon = \dfrac{\tau}{\upsilon}$	= Pole pitch of the υ m.m.f. space harmonic.
ϕ	= Magnetic flux.
$\omega = 2\pi f$	= Supply frequency.
ω_s	= Synchronous angular speed of the stator rotating magnetic field.

Subscript

Subscripts 1, 2, ... stands for the different regions of the machine, or indexes.

s, g, r	=	Stator, air gap an rotor region respectively.
x, y, z	=	Perpendicular axes.
u, y, v	=	Skewed axes, the u-axis has the same direction as the x-axis, the y-axis coincides with the y-axis of the orthogonal axes and v-axis is inclined on the u-axis by an angle (α°),
$av.$	=	Average value.
$eq.$	=	Equivalent.
$max.$	=	Maximum value.
$ph.$	=	Phase value.
υ	=	Order of harmonic.

Superscript

s	indicates stator excitation.
r	indicates rotor excitation.

The vector quantities are denoted by boldface, while Scalar ones are denoted by italic type.