DYNAMIC ANALYSIS OF AC MACHINES USING COMBINED FEM-CIRCUIT MODELING

By

Eng. Mohamed Sayed Ahmed Shalaby

A thesis submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
In

Electrical Power and Machines Engineering

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Title of Thesis: Dynamic Analysis of AC Machines Using Combined FEM-Circuit Modeling

Key Words: Modelling of Electric Machines – coupled FEM-Circuit model – Cross magnetic saturation – Synchronous Reluctance Motor – Self-excited Induction Generator

Summary:

In this thesis, accurate, simple and fast model of AC machines is presented. The proposed model can describe and explore the machine's behavior and performance accurately. The proposed models are categorized as coupled FEM-Circuit modeling approaches. A so called combined FEM-Circuit (or staged FEM-Circuit) model is proposed to investigate the model of SynRM including effect of cross-magnetic saturation. In addition, a coupled FEM-Circuit model is introduced to simulate the performance and dynamic behavior of a squirrel cage induction machine. Also, a simple and systematic design technique is presented to explore and select the optimum design parameters of a SynRM that can achieve optimal pullout torque and minimum ripples, and to study their effect on the motor performance. In addition, the evaluation of a proposed model of self-excited induction generator (SEIG) including the effect of inductance saturation and its rate of change is investigated. The model is validated experimentally using a test rig of 7.5 kW SEIG.

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a_s	: Cross-section area of the stator conductor
B	: Magnetic flux density
B_p	: Peak value of the flux density
B_m	: Mechanical friction coefficient
C	: Capacitance of excitation capacitor bank pre phase
D	: Electric displacement
E	: Electric field
F	: Per-unit frequency
f	: Frequency
f_{base}	: Base frequency
H	: Magnetic field intensity
i_{as}, i_{bs}, i_{cs}	: Stator phase currents of the IM
i_{ar}, i_{br}, i_{cr}	: Rotor phase currents of the IM
i_a, i_b, i_c	: Phase currents in *abc*-frame
i_{La}, i_{Lb}, i_{Lc}	: Load *abc* phase currents
i_m	: Magnetizing current
i_d	: Direct-axis current
i_q	: Quadrature-axis current
J	: Current density
J_m	: Mechanical Inertia coefficient
K_1, K_2, K_3	: Constants of magnetizing inductance exponential equation
K_{ec}	: Eddy current losses coefficient
K_{ex}	: Excess losses coefficient
K_{hys}	: Hysteresis losses coefficient
K_{SE}, α, β	: Steinmetz constants
L_{aa}, L_{bb}, L_{cc}	: Self-inductances of *abc*-phases
L_{ab}, L_{bc}, L_{ac}	: Mutual inductances between *abc*-phases
L_{La}, L_{Lb}, L_{Lc}	: Load inductances per phase in *abc*-frame
L_l	: Leakage inductance
L_{ls}	: Stator leakage inductance
L_{lr}	: Rotor leakage inductance
L_m	: Phase useful mutual inductance

L_0	: Mutual inductance between phases due to saliency
L_{md}	: Direct-axis mutual inductance
L_d	: Direct-axis inductance
L_{mq}	: Quadrature-axis mutual inductance
L_q	: Quadrature-axis inductance
L_s	: Stator self-inductance
L_r	: Rotor self-inductance
l_s	: Mean length of the stator turn
N	: Number of turns per phase
P	: Number of pole pairs
P_{ec}	: Eddy current losses
P_{ex}	: Excess losses
P_{fe}	: Iron losses
P_{hys}	: Hysteresis losses
R_{La}, R_{Lb}, R_{Lc}	: Load resistances per phase in *abc*-frame
R_{ro}	: Outer radius of rotor
R_{ri}	: Inner radius of rotor
R_s	: Stator resistance
r_s, r_r	: Stator and rotor per-phase resistances of IM
T_e	: Electromagnetic developed torque
T_L	: Mechanical load torque
v_{as}, v_{bs}, v_{cs}	: Stator phase voltages of the IM
v_{ar}, v_{br}, v_{cr}	: Rotor phase voltages of the IM
V_a, V_b, V_c	: Phase voltages in *abc*-frame
V_d, V_q	: *d*- and *q*-axis voltages
V_g	: Air-gap voltage across the magnetizing inductance
W_b	: Barriers width
W_n	: Notch width (q-axis cutout)
X_m	: Magnetizing reactance
X'_m	: Magnetizing reactance variation with magnetizing current
ε_0	: Electric permittivity of free space
ε	: Electric permittivity
λ_{as}, λ_{bs}, λ_{cs}	: Stator phase fluxes of IM in *abc*-frame

$\lambda_{ar}, \lambda_{br}, \lambda_{cr}$	: Rotor phase fluxes of IM in *abc*-frame
$\lambda_a, \lambda_b, \lambda_c$	: Phase fluxes in *abc*-frame
λ_d, λ_q	: *dq*-frame fluxes
δ	: Torque angle
μ	: Magnetic permeability
ρ	: Electric charge density
θ_r	: Angle between *d*-axis of the rotor and the axis of phase-*a*
σ	: Electrical conductivity of the used copper
ω_r	: Rotor speed in electrical degrees

LIST OF ABBREVIATIONS

2D	: Two Dimensional
3D	: Three Dimensional
ALA	: Axially laminated anisotropic
DTC	: Direct Torque Control
EV	: Electric Vehicle
FEM	: Finite Element Method
GSE	: Generalized Steinmetz Equation
IM	: Induction Machine
MEC	: Magnetic Equivalent Circuit
PM	: Permanent Magnet
SE	: Steinmetz Equation
SEIG	: Self-Excited Induction Generator
SynRM	: Synchronous Reluctance Motor