

# **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**

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
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**Under supervision of**

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Approved by the  
Examining Committee

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Prof. Dr. Khairy Faraht Ali Helwa,

Thesis Main Advisor

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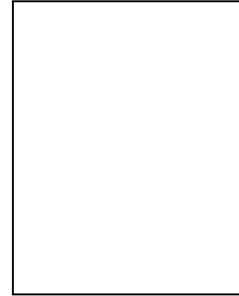
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**Title of Thesis: Dynamic Analysis of AC Machines Using Combined FEM-Circuit Modeling**

**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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## LIST OF SYMBOLS

$a_s$	: 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
$K_{SE}, \alpha, \beta$	: 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
$\epsilon_0$	: Electric permittivity of free space
$\epsilon$	: Electric permittivity
$\lambda_{as}, \lambda_{bs}, \lambda_{cs}$	: 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
$\lambda_d, \lambda_q$	: $dq$ -frame fluxes
$\delta$	: Torque angle
$\mu$	: Magnetic permeability
$\rho$	: Electric charge density
$\theta_r$	: Angle between $d$ -axis of the rotor and the axis of phase- $a$
$\sigma$	: Electrical conductivity of the used copper
$\omega_r$	: 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