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CONDITION MONITORING OF WOUND-ROTOR INDUCTION MACHINES

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CONDITION MONITORING OF WOUND-ROTOR INDUCTION MACHINES

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Certificate

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as part of the collaborative doctoral degree and/or fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

فَإِنَّ مَعَ الْعُسْرِ يُسْرًا (٥) إِنَّ مَعَ الْعُسْرِ يُسْرًا (٦) [سورة الشرح]

For indeed, with hardship [will be] ease (5). Indeed, with hardship [will be] ease (6).
[Quran, The Soothing/ash-Sharh 94]

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Abstract

Condition monitoring enables diagnosis of the inception of fault mechanisms in electrical machines, thus averting failure and the need of expensive repairs. Therefore, it is valuable to develop efficient methods of condition monitoring. The idea would be relatively low cost and/or non-invasive system, which is still sufficiently powerful in terms of monitoring by online detection of developing faults. In this research, an overview of existing condition monitoring techniques is given, and issues related to induction machine faults are discussed. Therefore, this research develops a relatively simple yet powerful model for studying the behaviour of a wound rotor induction machine (WRIM) or doubly fed induction generator (DFIG) in healthy and faulty conditions based on the impedance matrix.

The first part of the work presented in this dissertation builds the fundamental impedance matrix that can predict the behaviour of the WRIM or DFIG in a healthy condition. A theoretical model is necessary so that any stator or rotor winding configuration in the machine can be incorporated. The effect of rotor skew is considered in this model. Then, the Motor-CAD package is employed to predict the electromagnetic behaviour of the induction machine during steady-state and transient-state operation. Motor-CAD has been used for examining the induction machine parameters.

The second part of the work develops the impedance matrix to detect unbalanced rotor-phase impedances. This can simulate rotor faults in the machine. The method leads to the calculation of stator current components when there are unbalanced rotor-phase impedances and it is verified experimentally using a four-pole wound rotor. The method is verified by inversion of the voltage matrix equation and solving for the currents in the wound motor. Experimental results (torque and current characteristic) are compared with computer predictions for the test machine.

The third part of this thesis develops the fundamental impedance matrices for both rotor eccentricity detection and unbalanced magnetic pull (UMP) calculation. It puts forward a concept for detecting and measuring eccentricity faults in the WRIM. A simple and new approach using pole-specific search coils is introduced, and a theory is developed to illustrate that rotor eccentricity leads to the generation of air-gap flux waves with pole-pairs of $p_m \pm 1$, where p_m is the number of pole-pairs of the machine. Once again, this technique is used here to detect rotor eccentricity in a four-pole wound rotor machine and is verified experimentally using a rig for measuring UMP. The investigation uncovers several aspects of the damping effects of pole-specific search windings which can also be used to suppress UMP.

Keywords— Condition monitoring; doubly fed induction generator; DFIG; eccentric rotors; impedance matrix; induction motor; rotor eccentricity; squirrel cage induction machine; SCIM; unbalanced magnetic pull; UMP; wound rotor induction machine; WRIM.

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Acronyms and Abbreviations

Notations

k	Average air-gap radius
$e(y,t)$	Axial electrical field of air gap
$\bar{N}_r$	Coefficient of rotor
$\bar{N}_{st}$	Coefficient of stator
c	Coil number of turns on stator
g	Effective air gap length
g_{av}	Effective air gap length when rotor is concentric
$g_{(x,y)}$	Effective axial air gap length
R_a, R_b, R_c	External rotor resistances
F_x	Force at x component
F_y	Force at y component
F_z	Force at z component
$j_r(y,t)$	Harmonic current density distribution of rotor
$j_s(y,t)$	Harmonic current density distribution of stator
$i_x(t)$	Harmonic current flow
V_D	Induced voltage
L_{st}	Length of the stator
σ_n	Maxwell stress (radially)
σ_t	Maxwell stress (tangentially)
ω_r	Mechanical angular frequency
P_{mech}	Mechanical power
n_r	Mechanical speed of rotor
T_{mech}	Mechanical torque

$b_n(y,t)$	Normal radial flux density of air gap
k_s^n	n^{th} harmonic stator slot opening factor
c_ω	Number of conductors in the ω^{th} slot
p_m	Number of pole-pairs
P	Number of poles
N_R	Number of slot at which winding is located in rotor
N_S	Number of slot at which winding is located in stator
Λ	Permeance
μ_o	Permeance of free space
$b_s(y,t)$	Radial flux density of air-gap
$b_r(y,t)$	Rotor air-gap flux wave components
I_r	Rotor current
$\bar{J}_r^n$	Rotor current density coefficient of the n^{th} current harmonic
f_r	Rotor frequency
Ψ_r	Rotor magnetic field
R_r	Rotor resistance
b_r	Rotor slot opening
k_r^n	Rotor slot opening factor
V_r	Rotor voltage
$Z_{r,r}$	Rotor-rotor coupling impedance
$Z_{s,r}$	Rotor-stator coupling impedance
k_{sk}	Skew factor
s	Slip of the motor
K_s	Slot opening factor
α_s	Slot-angle of the stator in mechanical radians
$\bar{J}_s^n$	Stator current density coefficient of the n^{th} current harmonic
Ψ_s	Stator magnetic field

b_{st}	Stator slot opening
V_s	Stator voltage
R_s	Stator winding resistance
$Z_{r,s}$	Stator-rotor coupling impedance
t_{ratio}	Stator-rotor turns ratio
$Z_{s,s}$	Stator-stator coupling impedance
f	Supply frequency
ω_s	Synchronous angular frequency
n_s	Synchronous speed
$b_t(y,t)$	Tangential flux density of air gap
y	Variation in axial direction
n	Harmonic number

Abbreviations Used in Thesis

BCW	Bridge configured winding
DE	Drive end
DFIG	Doubly fed induction generator
FEA	Finite element analysis
FFT	Fast Fourier transform
IM	Induction machine
MCSA	Motor current signature analysis
NDE	Non drive end
SCIM	Squirrel cage induction machine
UMP	Unbalanced magnetic pull
WRIM	Wound rotor induction machine

Superscripts

av	Average
x	Axial distance along machine
b	Backward component
$1, 2, 3$	Corresponding to stator and/or rotor phase windings

f	Forwards component
y'	linear distance around air-gap in rotor reference frame
y	linear distance around air-gap in stator reference frame
r	Rotor
s	Stator
n	Stator harmonic