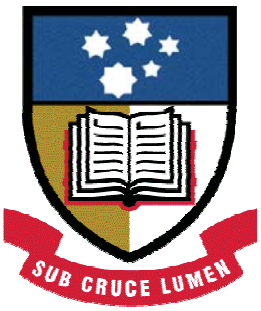

THE UNIVERSITY OF ADELAIDE

School of Electrical and Electronic Engineering

On-line Condition Monitoring and Detection of Stator and Rotor Faults in Induction Motors

Randy Supangat

A thesis presented for the degree of Doctor of Philosophy

2008

Dedicated to my wife

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Abstract

Induction motors are reliable and widely used in industrialised nations. However induction motors, like any other machine, will eventually fail. If the failure is not anticipated, it can result in a significant revenue loss. Therefore, there is a strong need to develop an efficient maintenance program. The most cost-effective solution is condition-based maintenance. An effective condition-based maintenance program requires an on-line condition monitoring system that can diagnose the condition of an induction motor in order to determine the types of faults and their severity while the motor is under a normal operating condition.

The work in this thesis investigates the detection of stator and rotor faults (i.e. shorted turn faults, eccentricity faults, and broken rotor bar faults) using three types of sensor signals (i.e. current, leakage flux, and vibration) under different loading conditions. The work is based on an extensive series of sensor measurements taken using a number of nominally identical healthy machines (2.2 kW) and custom-modified machines (2.2 kW) with configurable stator and rotor fault settings.

The thesis starts by investigating the estimation of rotor speed and rotor slot number. These two parameters are important in determining the fault frequency components that are used for detecting the stator and rotor faults. The rotor speed investigation compares four different estimation methods from the three different sensor signal types. It is found that the speed estimation techniques based on the eccentricity harmonics and the rotor frequency in the stator current, the axial leakage flux, and the motor vibration sensor signals can detect the rotor speed very accurately even when the load is as low as 2%. Similarly, this thesis proposes three different rotor slot number estimation techniques from the three different types of sensors and demonstrates that all three techniques can estimate the rotor slot number accurately. In addition, it is shown that the reliability of the estimation techniques can be increased significantly when the three techniques are combined.

The shorted turn investigation in this thesis examines and compares potential shorted turn features in the three sensor signal types under five different fault severities and ten different loading conditions. The useful shorted turn features are identified in the thesis, and then examined against variations between the healthy machines in order to determine the loads and the fault severities in which the feature can reliably detect the faults. The results show that the feature based on the EPVA (extended Park's vector approach) is the best method. This feature can detect turn to turn faults with a severity of 3.5% or greater at loads greater than 20% and phase to phase turn faults with a severity of 1.7% or greater under all loading conditions. However, estimating the fault severity is generally found to be difficult.

The thesis also examines the feasibility of detecting static eccentricity faults using the different types of sensor signals under ten different loading conditions. The thesis compares potential eccentricity features under nine different fault severities. The useful features are identified and then combined through weighted linear combination (WLC) in order to produce a better eccentricity fault indicator. The indicator begins to show significant magnitude variation when the fault severity is greater than or equal to 25% and the load is greater than or equal to 25%. The experimental results show that detecting the static eccentricity faults is possible but estimating the fault severity may be difficult. Furthermore, the effects of misalignment faults on the useful eccentricity features are investigated.

In this thesis, the analysis of broken rotor bar faults is performed under motor starting and rundown operation. The starting analysis introduces a new approach to detect broken rotor bar faults that utilises the wavelet transform of the envelope of the starting current waveform. The results of the wavelet transform are then processed in order to develop a normalised parameter, called the wavelet indicator. It is found that the wavelet indicator can detect a single broken bar under all loading conditions during motor starting operation. The indicator also increases its magnitude as the severity of the fault increases. On the other hand, the rundown analysis proposes several broken rotor bar fault detection techniques which utilise the induced voltage in the stator windings and the stator magnetic flux linkage after supply disconnection. The experimental results show that detecting the faults during rundown is generally difficult. However, the wavelet approach, which is based on monitoring changes in the motor torque for a given slip, seems to give the best result.

Declaration and Publications

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The author acknowledges that copyright of published works contained within this thesis (as listed below) resides with the copyright holder(s) of those works.

List of Publications

[P1] I. Ahmed, R. Supangat, J. Grieger, N. Ertugrul, and W. L. Soong, "A Baseline Study for On-Line Condition Monitoring of Induction Machines," in Australasian Universities Power Engineering Conference (AUPEC), Brisbane, Australia, 2004.

[P2] J. Grieger, R. Supangat, N. Ertugrul, and W. L. Soong, "Induction Motor Static Eccentricity Severity Estimation Using Evidence Theory," in IEEE International Electric Machines & Drives Conference (IEMDC), Antalya, Turkey, 2007, pp. 190-195.

[P3] J. Grieger, R. Supangat, N. Ertugrul, W. L. Soong, D. A. Gray, and C. Hansen, "Estimation of Static Eccentricity Severity in Induction Motors for On-Line Condition Monitoring," in 41st IAS Annual Meeting Conference Record of the IEEE Industry Applications Conference (IAS), Tampa, FL, 2006, pp. 2312 - 2319.

[P4] R. Supangat, N. Ertugrul, W. L. Soong, D. A. Gray, C. Hansen, and J. Grieger, "Broken Rotor Bar Fault Detection in Induction Motors Using Starting Current Analysis," in European Conference on Power Electronics and Applications, 2005.

[P5] R. Supangat, N. Ertugrul, W. L. Soong, D. A. Gray, C. Hansen, and J. Grieger, "Detection of Broken Rotor Bars in Induction Motor Using Starting-Current Analysis and Effects of Loading," IEE Proceedings - Electric Power Applications, vol. 153, pp. 848 - 855, November 2006.

[P6] R. Supangat, N. Ertugrul, W. L. Soong, D. A. Gray, C. Hansen, and J. Grieger, "Estimation of the Number of Rotor Slots and Rotor Speed in Induction Motors Using Current, Flux, or Vibration Signature Analysis," in Australasian Universities Power Engineering Conference (AUPEC) Melbourne, Australia: Victoria University, 2006.

[P7] R. Supangat, J. Grieger, N. Ertugrul, W. L. Soong, D. A. Gray, and C. Hansen, "Investigation of Static Eccentricity Fault Frequencies using Multiple Sensors in Induction Motors and Effects of Loading," in IECON - 32nd Annual Conference on IEEE Industrial Electronics, Paris, France, 2006, pp. 958 - 963.

[P8] R. Supangat, J. Grieger, N. Ertugrul, W. L. Soong, D. A. Gray, and C. Hansen, "Detection of Broken Rotor Bar Faults and Effects of Loading in Induction Motors during Rundown," in IEEE International Electric Machines & Drives Conference (IEMDC), Antalya, Turkey, 2007, pp. 196 - 201.

Pending Publications

[P*] R. Supangat, N. Ertugrul, W. L. Soong, D. A. Gray, C. Hansen, and J. Grieger, "Estimation of the Number of Rotor Slots and Rotor Speed in Induction Motors Using Current, Flux, or Vibration Signature Analysis," Australian Journal of Electrical & Electronics Engineering (AJEEE).

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Contents

List of Figures

Symbols

a	wavelet scale
a_{brb}	amplitudes of the BRB component
a_f	amplitudes of the fundamental signal component
c	number of coils of each stator phase
D_r	external rotor diameter
$\boldsymbol{F}$	Fourier transform
f	supply frequency
f_{brb}	broken rotor bar sidebands
f_{de}	dynamic eccentricity fault frequency component
f_{de}	dynamic eccentricity fault frequency components
f_r	frequency corresponding to the rotor mechanical speed
f_{rsp}	rotor slot passing frequency
f_s	sampling frequency

f_{se}	static eccentricity fault frequency components
f_{sede}	static and dynamic eccentricity fault frequency components
f_{st}	shorted turn fault frequency components
ft	feature
$i(t)$	steady-state stator current
i_{brb}	BRB component
i_f	fundamental signal component
$i_{rb}(t)$	rotor bar current
$I_{rv\ max}$	maximum value of the vrth harmonic rotor current
I_s	maximum value of the stator phase current
$i_s(t)$	steady-state signal components
$i_{s1}(t)$	steady-state BRB sideband modulated at the fundamental frequency
$i_{so}(t)$	other steady-state signal components that make up the stator current
$i_{sw}(t)$	stator winding current
k	real integers
k_s, k_r	factors associated with the leakage inductance in the stator windings and the rotor cage
l	loading conditions
l_c	core length
N	number of samples
$n(t)$	noise components
n_d	eccentricity constant
N_{ft}	number of features selected for a load
N_s	number of turns of each stator coil
n_s	synchronous speed

p	number of pole pairs
R	number of rotor bars/meshes
$\boldsymbol{S}$	power spectrum
s	per unit slip
t	time variable
t_s	sampling frequency
$V_{a(rms)}$, $V_{b(rms)}$, $V_{c(rms)}$	RMS values of the three phase voltages of the motor
$\boldsymbol{W}$	wavelet transform
w	weight of a feature
x	circumferential angular position
x_1, x_2	defined angular positions of the α^{th} mesh
α	real integers
β	real integers
δ	air gap length
$\varepsilon(t)$	induced back emf
$\lambda(t)$	stator magnetic flux linkage
μ_o	magnetic permeability of air
v	order of the stator time harmonics
v_s	stator MMF space harmonic rank
τ_{cb}	b^{th} coil pitch
τ_{cr}	rotor equivalent coil pitch
τ_p	pole step
φ	wavelet position
$\psi(t)$	wavelet function
ω	angular frequency

ω_r	angular rotor frequency
ω_s	angular supply frequency

Abbreviations

A/D	analogue to digital
BRB	broken rotor bar
CU	current unbalance
CWT	continuous wavelet transform
DE	dynamic eccentricity
DEH	driving end horizontal
DEV	driving end vertical
DFT	discrete Fourier transform
DOL	direct-on-line
DWT	discrete wavelet transform
EPVA	extended Park's vector approach
FFT	fast Fourier transform
FT	Fourier transform

MRF	multiple reference frame
MUSIC	multiple signal classification
NDEH	non-driving end horizontal
OTFT	order tracking Fourier transform
PSH	principal slot harmonics
s.d.	standard deviation
SE	static eccentricity
SNR	signal to noise ratio
STDFT	short time discrete Fourier transform
STFT	short-time Fourier transform
UF	unbalanced factor
UMP	unbalanced magnetic pull
WFA	winding function approach
WLC	weighted linear combination
WT	wavelet transform