Estimation of the Number of Rotor Slots and Rotor Speed in Induction Motors Using Current, Flux, or Vibration Signature Analysis

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ABSTRACT
Effective condition monitoring of induction motors requires knowledge of the number of rotor slots and the rotor speed. These were primarily obtained in the literature by multiple measurements and using design knowledge of the motor under test. Furthermore, the earlier studies have mainly concentrated on stator current analysis. This paper investigates the use of the stator current, axial flux, and vibration signals in order to provide accurate rotor speed and rotor slot number estimation by utilizing the eccentricity harmonics, slip frequency, rotor frequency, and rotor slot passing frequency. The proposed simple methods are verified using an extensive series of measurements on a 2.2 kW squirrel-cage and a 5 kW wound-rotor induction motor over a wide range of loading conditions.

1. INTRODUCTION
Induction motors are one of the most widely used electrical machines in industrialised nations as they are reliable and robust. However, a combination of environmental, duty-cycle, installation, and manufacturing related factors will deteriorate the condition of such motors. This deterioration can cause unexpected down-time and loss of production. In order to prevent this, induction motors need to be maintained.

One of the most cost-effective maintenance approaches is based on an online condition monitoring system. This monitors the condition of a motor through non-invasive sensors (e.g. current sensors, flux sensors, vibration sensors, etc.) while it is operational.

Most of the well-known condition monitoring techniques are based on the Fourier Transform (FT) [1-4]. These techniques usually compare and measure the magnitude of the fault frequency components, where the magnitude of these components in faulty motors is usually higher than in healthy motors.

However, identification of the exact frequency of the fault frequency components often requires knowledge about the operating speed. For example, the broken rotor bar (BRB) sidebands in (1) depend on the slip, which can be calculated if the rotor speed and the number of poles are known. The number of poles is given on the machine nameplate but other parameters such as the number of rotor slots is usually not provided.

Knowledge of the number of rotor slots is important to determine the eccentricity fault frequency components (2), which is used to detect static and dynamic eccentricity [4-6]. The number of rotor slots and eccentricity fault frequency harmonics have also been used for speed estimation in the past [7-9].

\[ f_{sffbrb} = f(1 \pm 2s) \]  
\[ f_{ecc1} = f \left( \frac{(kR \pm n_d)(1-s) \pm v}{p} \right) \]

where \( f_{sffbrb} \) is the broken rotor bar sideband frequencies, \( f \) is the supply frequency, \( s \) is the slip, \( f_{ecc1} \) is the eccentricity fault frequencies, \( k \) is any integer, \( R \) is the number of rotor slots, \( n_d = 0 \) (static eccentricity) and \( n_d = 1, 2, 3 \ldots \) (dynamic eccentricity), \( p \) is the number of pole pairs, and \( \nu \) is the order of the stator time harmonics.

It was reported in [8] that it is possible to estimate the steady-state speed of an inverter-driven motor (28 kW, 415 V, 50 A) by tracking the speed-dependent slot harmonic component, which is related to the number of rotor slots, within a certain frequency range. In this reference, the extracted harmonic was then compared to the 19th harmonic of the fundamental frequency in order to determine the rotor rotational speed. It was also reported that the number of rotor slots could be determined by examining the stator current spectrum as the load was decreased. The speed dependent harmonic would reduce in amplitude and change in frequency as the load decreased. The technique, however, required data taken under various loading conditions.

A similar speed estimation technique on an inverter-driven induction motor (4 kW, 4 poles, 28 rotor slots) was reported in [7]. It was shown in this work that the transient speed can be estimated by utilising the Short-Time FT (STFT). In addition, the research also incorporated zero padding (i.e. frequency interpolation) into the FT in order to improve the detection of speed dependent rotor slot harmonics. Another similar technique was also utilised in [9] to estimate the rotor speed of an inverter-driven motor (10 hp, 4 poles), which used decimation to alias the rotor slot harmonics to a single frequency. This process improved the ability to detect the desired slot harmonic. It was also reported that the number of rotor slots could be found by finding the most significant slot harmonics in (2) when \( R \) is varied between 30-54 (even numbers only), \( n_d \) is varied for 0
and \(\pm 1\), and \(v\) is varied for \(\pm 5, \pm 3, \pm 1\). However, the technique was not tested for a wide range of motors (i.e. motors with rotor slots other than 30-54) and the process was found to be computationally intensive.

Three different speed estimation techniques not employing rotor slot harmonics were also reported in the literature. In [10], the FT and Hilbert transform demodulation approach were utilised, and in [11] an extended Kalman filter (EKF) and a real-coded genetic algorithm (GA) optimisation were incorporated to estimate the rotor speed. The work in [12] involved injecting an extra rotor current with controllable frequency and matching that frequency to the rotating frequency of an induction motor.

In general, it can be concluded that most of the speed estimation techniques based on the rotor slot harmonics have focussed only on inverter-driven induction motors, under limited loading conditions, and have used only the stator current. Furthermore, the rotor slot number estimation techniques mentioned either requires data at various loads or is computationally intensive. Therefore, this paper aims to improve on the existing methods and to provide simple and accurate estimation of the speed and rotor slot number by utilising the current, flux, or vibration sensor signals. Several methods for speed and rotor slot estimation based on different signal frequencies and sensor types are investigated and their performance is compared over a wide range of loads.

## 2. EXPERIMENTAL SETUP

The experimental results given in the following sections of the paper were obtained using a purpose built test rig based on a high-speed data acquisition system (2 x DAQPAD-6052E boards from National Instruments, capable of simultaneous sampling at 5 MHz) with a custom written software (LabVIEW based). The test motors include two 2.2 kW, 415 V, 4 pole, 32 rotor slots, star-connected squirrel cage induction motors and two 5 kW, 415 V, 4 pole, wound rotor, star-connected wound rotor induction motors. The 2.2 kW motors were installed using a precision laser alignment tool (Optalign Plus from Prüftechnik) and a torque wrench (Norbar, set at 35 Nm) in order to ensure the accuracy and the repeatability of the data obtained. The motors were loaded by a separately-excited 5 kW dc generator.

During the tests, two current sensors, one external axial flux search coil, and a vibration sensor (drive-end horizontal) were attached to the motor under test and the sensor outputs were sampled simultaneously via an anti-aliasing filter, which was an 8th order Butterworth filter. Two sampling rates were utilised:

- 400 Hz sampling frequency and 100 seconds sampling time (low-frequency measurement), which allows a very high-resolution frequency analysis (0.01 Hz resolution),
- 8000 Hz sampling frequency with a sampling time of 5 seconds (high-frequency measurement).

The FT analysis was performed using zero padding (interpolation in the frequency domain) which is 16 longer than the number of samples, and spectral averaging, which divides the data into 5 segments for the 400 Hz data and no averaging for the 8 kHz data (due to the limited resolution), in order to improve the accuracy of the peak detection and to reduce noise interference.

Experimental data from the motor signals was collected using healthy motors (2.2 kW and 5 kW) and a faulty motor (2.2 kW) with 4 broken rotor bars (BRB) over a range of loads from no-load to full-load. The broken rotor bar fault was introduced by cutting a narrow slot through the end-ring next to the lamination stack using a small diameter milling cutter to break the electrical connection between the rotor bar and the end-ring. This method was used to minimise the disturbance to rotor end-ring currents which occur if more of the end-ring was removed.

## 3. ROTOR SPEED ESTIMATION TECHNIQUES

The rotor speed is an important piece of information in an on-line condition monitoring system. In this section we will examine speed estimation techniques which utilise stator current, vibration, and axial flux signals.

### 3.1. STATOR CURRENT

The eccentricity fault frequency components shown in (2) are easily detected in the stator current [4-6] and axial flux signals. These fault frequencies are a function of the supply frequency, the number of rotor slots, the number of poles and the slip. It is possible to reduce this eccentricity fault frequency equation into a function \(f_{ecc}\) of only the supply frequency and the rotor frequency, \(f_r\), as shown in (3) by setting the variables \(k = 0, n_d = \pm 1, v = 1\) [9]. This relation allows the rotor speed to be found using (4).

\[
f_{ecc} = f\left(\pm 1\right)\frac{1-s}{p} = f \pm f_r, \quad (3)
\]

\[
f_r = |f - f_{ecc}|\quad (4)
\]

![Figure 1: A sample frequency spectrum of stator current signal at 23% load illustrating the eccentricity harmonics (3).](image)

The frequency spectrum given in Fig. 1 illustrates that the eccentricity fault frequency components (3) are not particularly strong in the current signal but they are still detectable and can be used to calculate the rotor speed. Furthermore, the experimental results suggest that the lower sideband is stronger than the upper sideband. Hence, this paper will use the lower sideband to calculate the speed.
3.2. Vibration

Vibration sensors are widely used in on-line condition monitoring systems. The vibration signal can be used to detect eccentricity, stator and supply unbalance faults and is also useful for speed estimation. In particular the vibration signal contains a large amplitude component at the rotor frequency \( f_r \) (see Fig. 2). Based on the experimental results, this rotor frequency component has been proven to be strong under all loading conditions. As a result, rotor speed can be readily estimated using the vibration signal.

![Figure 2: Frequency spectrum of a vibration signal at 23% load showing the rotor frequency.](image)

\[ f_r = \frac{n_s - s \times n_s}{60}, \]  

(5)

where \( n_s \) is the synchronous speed of the motor in rpm.

3.3. Axial Leakage Flux

An axial leakage flux sensor is another non-invasive sensor, which can be easily installed without any modification to the motor under test. This sensor is a simple search coil located at the non-drive end of the test motor. There are two speed estimation methods that can be applied to the axial leakage flux signal. The first method is the same method as in the stator current signal, which is based on the eccentricity fault frequency harmonics in (4). The second method uses the fact that the axial leakage flux from the rotor end-windings contains a strong component at the slip frequency, \( sf \). This slip frequency can be used to determine the speed through the relationship described in (5).

Figure 3 (top) shows that the eccentricity harmonics, which are used for detecting the speed, are quite strong in the flux signal. The figure also suggests that the lower sideband is stronger than the higher sideband. Therefore, the lower sideband will be used in this paper to calculate the motor speed.

Figure 3 (bottom) shows that the slip frequency component in the flux signal is detectable and it can be used to calculate the speed. However, this slip frequency component is found to be weaker than the speed related component of the first method, which is based on the eccentricity harmonics. Therefore, the first speed estimation method is considered significant in the axial flux signal.

3.4. Speed Estimation Comparison

Table 1 presents a comparison of the performance of the speed estimation methods discussed in the previous sections. It shows measured results from a 2.2 kW motor under loading conditions from no-load to full-load. The table shows the load (in %, calculated from the motor under loading conditions from no-load to full-load). The table shows the load (in %, calculated from the motor under loading conditions from no-load to full-load). The table shows the load (in %, calculated from the motor under loading conditions from no-load to full-load).

![Figure 3: A sample frequency spectrum of an axial leakage flux signal at 23% load showing: (top) the eccentricity harmonics (3), and (bottom) the slip frequency.](image)

Figure 3 (bottom) shows that the eccentricity harmonics are used for detecting the speed, which are quite strong in the flux signal. The figure also suggests that the lower sideband is stronger than the higher sideband. Therefore, the lower sideband will be used in this paper to calculate the motor speed.

On the other hand, the speed estimation based on the slip frequency was found not to be as reliable as the other methods. This slip frequency method is found to be good for high loads but unreliable at light loads (i.e. less than 10%). At light loads, the slip frequency component is non-existent because it is very close to the DC component and its magnitude may be small. In this situation, the slip frequency component will blend with the DC component and the peak detection algorithm will

<table>
<thead>
<tr>
<th>Current: Eccentricity Harmonics</th>
<th>Vibration: Rotor Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta n ) rpm</td>
<td>( \Delta n ) rpm</td>
</tr>
<tr>
<td>( \text{Load} ) (%</td>
<td>( \text{Speed} ) (rpm)</td>
</tr>
<tr>
<td>1498.0</td>
<td>2.0</td>
</tr>
<tr>
<td>1480.0</td>
<td>13.0</td>
</tr>
<tr>
<td>1472.0</td>
<td>33.0</td>
</tr>
<tr>
<td>1436.0</td>
<td>5.0</td>
</tr>
<tr>
<td>1424.0</td>
<td>88.0</td>
</tr>
<tr>
<td>1416.0</td>
<td>97.5</td>
</tr>
</tbody>
</table>

The results given in Table 1 illustrate that the speed estimation methods, which are based on eccentricity harmonics and rotor frequency, are very accurate under all loading conditions. It can be noted that these methods can detect the speed within 0.1% accuracy when compared against an optical tachometer. This accuracy is well within the tolerance of the optical sensor.
mismistakenly detect the DC component as the slip frequency. Therefore, the slip based speed estimation method cannot detect the rotor speed when the load is less than 10%, as shown in Table 1.

Further clarification about how each of the speed estimation techniques performs at different loading conditions is shown in Fig. 4. It shows that the signal to noise ratio, SNR, which is described in (6), of the eccentricity component based speed estimation techniques are better at light load, and the SNR reduces as the load increases. However the techniques still maintain respectable SNR under all loading conditions. The SNR of the rotor frequency and slip frequency based speed estimation techniques shows an increasing pattern as the load increases. The rotor frequency based technique shows good SNR under all loading conditions while the slip frequency based technique fails at very light load (less than 10%).

\[
\text{SNR}(dB) = \text{Signal}(dB) - \text{Noise Level}(dB) \tag{6}
\]

![Figure 4: SNR of rotor speed estimation techniques as a function of load.](image)

In summary, simple and reliable speed estimation can be achieved from any one of the stator current, vibration, and axial flux signals. The most reliable speed estimation techniques are those which are based on the rotor frequency in the vibration and on the eccentricity component in the flux because of their high SNR at all loading conditions. Speed estimation based on the slip frequency is found to be the worst because of the low SNR at very light load.

4. **ROTOR SLOT NUMBER ESTIMATION**

After the rotor speed has been estimated, the next step is to estimate the number of rotor slots. This paper investigates two rotor slot number estimation techniques using the stator current, axial flux, and vibration signals.

4.1. **STATOR CURRENT AND AXIAL FLUX**

The first rotor slot number estimation technique is based on the eccentricity fault frequency components in (2), which are present in the stator current and axial flux. This eccentricity fault frequency equation can be reduced to a combination of rotor frequency and supply frequency by setting \(n_d = 0\) (for static eccentricity) and \(k = 1\). Furthermore, experimental results suggest that the first static eccentricity harmonics (i.e. \(v = 1\)) are one of the stronger and more reliable components. As such, the rotor slot number estimation technique will focus on this eccentricity fault frequency component \(f_{ecc}\).

\[
f_{ecc3} = f \left[ R \left( \frac{1-s}{p} \right) + 1 \right] = Rf_r + f \tag{7}
\]

The relationship described in (7) allows the estimation of the number of rotor bars (or slots), \(R\), by determining the value of \(R\) which corresponds to the largest amplitude component in the current or flux spectrum, that is not a harmonic of the fundamental.

Figure 5 shows typical power spectra for the stator current and axial flux signals under full-load for the 2.2 kW test motor. As highlighted in the figure, the eccentricity component (7) is the most dominant component, other than the harmonics of the fundamental. Furthermore, this component is also found to be consistently dominant across all tested loading conditions.

![Figure 5: Typical frequency spectrum of a stator current (top) and an axial flux signal (bottom).](image)

Typical results of the proposed rotor slot number estimation technique on a 2.2 kW motor at full load are depicted in Fig. 6. The figure shows the magnitudes of the frequency components given by (7) in the current and flux spectra, for a range of possible number of rotor slots \(R\). The highest magnitude component in both the current and flux spectra is achieved when the number of rotor slots is 32, which corresponds to the actual number of rotor slots. It was found that the highest magnitude component was more easily identified in the current spectrum compared to the flux spectrum.

Table 2 summarises the results of the rotor slot number estimation technique on four motors. This includes two 2.2 kW motors, one healthy and one with four broken rotor bars (BRB), and two 5 kW motors, both healthy, under multiple loading conditions. The results indicate that the proposed rotor slot number estimation technique can successfully determine the number of rotor slots for the four tested motors under all loading conditions. It was also proven that the rotor slot number estimation technique proposed here is equally effective in the current and flux signals, although the current signal is preferred due to the reason explained previously.
However, there are a few precautions that should be noted when utilising this rotor slot number estimation method. An issue may arise when the motor load is very low (less than 10%) and the number of rotor slots is few (less than 15 rotor slots). In this condition, the rotor frequency will be very close to the synchronous frequency and the frequency of the eccentricity component in (7) may be very close to the synchronous frequency and the fundamental. As a consequence, the two components can be difficult to distinguish. This problem can be reduced by making sure the sampling period is long enough to ensure a high frequency resolution.

Table 2: Summary of the Rotor Slot Number Estimates Based on Eccentricity Harmonics

<table>
<thead>
<tr>
<th>Load (%)</th>
<th># of Slots</th>
<th>Load (%)</th>
<th># of Slots</th>
<th>Load (%)</th>
<th># of Slots</th>
<th>Load (%)</th>
<th># of Slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>CURRENT</td>
<td>FLUX</td>
<td>CURRENT</td>
<td>FLUX</td>
<td>CURRENT</td>
<td>FLUX</td>
<td>CURRENT</td>
<td>FLUX</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2 kW, MOTOR 1 (Healthy)</td>
<td>2.2 kW, MOTOR 2 (4BRB)</td>
<td>2.2 kW, MOTOR 1 (Healthy)</td>
<td>2.2 kW, MOTOR 2 (4BRB)</td>
<td>2.2 kW, MOTOR 1 (Healthy)</td>
<td>2.2 kW, MOTOR 2 (4BRB)</td>
<td>2.2 kW, MOTOR 1 (Healthy)</td>
<td>2.2 kW, MOTOR 2 (4BRB)</td>
</tr>
<tr>
<td>3.4</td>
<td>32</td>
<td>3.4</td>
<td>32</td>
<td>3.4</td>
<td>32</td>
<td>3.4</td>
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<tr>
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<td>32</td>
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<tr>
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<tr>
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<td>63.8</td>
<td>32</td>
<td>63.8</td>
<td>32</td>
</tr>
<tr>
<td>74.6</td>
<td>32</td>
<td>74.6</td>
<td>32</td>
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<td>32</td>
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<td>32</td>
<td>96.6</td>
<td>32</td>
<td>96.6</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 2 presents the results of the rotor slot number estimation technique based on the rotor slot passing frequency, on the 2.2 kW and 5 kW motors. The table shows that the technique works 90% of the time for the 2.2 kW motors (squirrel-cage type) but it fails for the 5 kW (wound-rotor) motors. It should be noted here that the 2.2 kW motors were installed with precision tools, while the 5 kW motors are typical motors with an unknown installation procedure.

In Table 2 there are slight differences between the calculated loads from the current signal and the flux signal. These differences come from the fact that the loads are calculated based on the rotor speed from the corresponding signal. For example, the loads in the rotor slot number estimation using the current signal is also calculated from the current.
signal from the faulty motor also contains further strong
signal components.

Table 3: Rotor Slot Number Estimation Based on
Rotor Slot Component in the Vibration Signal

<table>
<thead>
<tr>
<th>Load (%)</th>
<th># of Rotor Slots</th>
<th>Load (%)</th>
<th># of Rotor Slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>36</td>
<td>1.7</td>
<td>32</td>
</tr>
<tr>
<td>13.8</td>
<td>32</td>
<td>4.7</td>
<td>32</td>
</tr>
<tr>
<td>23.2</td>
<td>32</td>
<td>16.1</td>
<td>32</td>
</tr>
<tr>
<td>33.3</td>
<td>32</td>
<td>21.0</td>
<td>35</td>
</tr>
<tr>
<td>43.4</td>
<td>32</td>
<td>29.2</td>
<td>32</td>
</tr>
<tr>
<td>53.0</td>
<td>32</td>
<td>41.4</td>
<td>32</td>
</tr>
<tr>
<td>63.4</td>
<td>32</td>
<td>61.3</td>
<td>32</td>
</tr>
<tr>
<td>74.0</td>
<td>32</td>
<td>83.9</td>
<td>32</td>
</tr>
<tr>
<td>85.3</td>
<td>32</td>
<td>105.3</td>
<td>32</td>
</tr>
<tr>
<td>96.9</td>
<td>32</td>
<td>119.0</td>
<td>32</td>
</tr>
</tbody>
</table>

5 kW, MOTOR 1 (Healthy) 5 kW, MOTOR 2 (Healthy)

<table>
<thead>
<tr>
<th>Load (%)</th>
<th># of Rotor Slots</th>
<th>Load (%)</th>
<th># of Rotor Slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>19</td>
<td>6.1</td>
<td>20</td>
</tr>
<tr>
<td>28.1</td>
<td>19</td>
<td>27.0</td>
<td>18</td>
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<td>49.9</td>
<td>18</td>
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<td>72.4</td>
<td>19</td>
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</tr>
<tr>
<td>85.3</td>
<td>12</td>
<td>87.8</td>
<td>20</td>
</tr>
</tbody>
</table>

In the 5 kW motors, the rotor slot number estimation
fails at almost all of the loading conditions. This is
because again the vibration signal of these motors is
found to contain further strong components, which may
be caused by installation issues, the type of load, and the
type of motor.

5. CONCLUSION

This paper investigated the use of stator current, axial
leakage flux and vibration sensor measurements to detect
the rotor speed and the number of rotor slots of a three-
phase induction motor based on measurements at a
single operating point. Operating points varying from
no-load to full-load were tested. Rotor speed estimation
techniques based on the eccentricity harmonics, slip
frequency, and the rotor frequency were investigated.
The rotor slot number estimation techniques proposed
are based on the eccentricity harmonics and the rotor slot
passing frequency. A summary of the key results are as
follows:

- the rotor speed can be accurately determined from any
  of the current, flux and vibration sensor
  measurements, at any value of load;
- speed estimation techniques which utilise eccentricity
  harmonics and rotor frequency, are able to operate
down to lower loads compared to utilising the slip
  frequency;
- the number of rotor slots can be detected accurately
  from the stator current and axial flux signals by
  utilising the rotor speed and the eccentricity
  harmonics;
- rotor slot number estimation using the vibration signal
  is dependant on the installation, the type of load, and
  the type of motor.

6. ACKNOWLEDGEMENT

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the workshop staff of the School of Electrical and
Electronic Engineering.

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