Smart Technique for Induction Motors Diagnosis by Monitoring the Power Factor Using Only the Measured Current

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Abstract. This paper is concerned with accurate, early and reliable induction motor IM fault detection and diagnosis using an enhanced power parameter measurement technique. IM protection devices typically monitor the motor current and/or voltage to provide the motor protection from e.g. current overload, over/under voltage, etc. One of the interesting parameters to monitor is the operating power factor (PF) of the IM which provides better under-load protection compared to the motor current based approaches. The PF of the motor is determined by the level of the current and voltage that are drawn, and offers non-intrusive monitoring. Traditionally, PF estimation would require both voltage and the current measurements to apply the displacement method. This paper will use a method of determining the operating PF of the IM using only the measured current and the manufacturer data that are typically available from the nameplate and/or datasheet for IM monitoring. The novelty of this work lies in detecting very low phase imbalance related faults and misalignment. Much of the previous work has dealt with detecting phase imbalance faults at higher degrees of severity, i.e. voltage drops of 10% or more. The technique was tested by empirical measurements on test rig comprised a 1.1 kW variable speed three phase induction motor with varying output load (No load, 25%, 50%, 75% and 100% load). One common faults was introduced; imbalance in one phase as the electrical fault. The experimental results demonstrate that the PF can be successfully applied for IM fault diagnosis and the present study shows that severity fault detection using PF is promising. The proposed method offers a potentially reliable, non-intrusive, and inexpensive CM tool which can be implemented with real-time monitoring systems.

1. Introduction
CM and condition based maintenance aim at increasing machine reliability, maintaining performance, reducing spare parts inventories and reducing break-down maintenance. IMs are common prime movers and faults including winding faults, unbalanced stator and, broken rotor bars, eccentricity and bearing faults all of which have been extensively studied [1]. Three-phase IMs are widely used in industrial devices, and most of them are connected directly to the electric power distribution system. Therefore, it is very important to clarify the effect of voltage variation in the supply voltage on the characteristics of the IM [2].

The unbalance voltage is caused by asymmetrical transformer windings or transmission impedances, unbalanced loads, or large single phase loads. Voltage unbalance exists in almost all three-phase power system networks. The level of unbalance is considerably large in weak power.
systems and those supplying large single phase loads. ANSI have reported that the voltage unbalance of 66% of the electrical distribution systems in USA is less than 1%, and that of 98% of the distribution systems is less than 3%, whilst in the remaining 2% it is larger than 3% [3].

As an unbalance in the voltage source can cause excessive losses, heating, noise, vibration, torsional pulsations, slip, and motor accelerating torque, detecting an unbalance of even a few % in the voltage supply is important.

Probably the most common faults that occur in three-phase IMs is air-gap eccentricity [1; 4]. Almost all mechanical faults such as faulty bearings, shafts and couplings lead to this condition. These faults result in the displacement of the axis of symmetry or the rotation axis of the rotor. Machine eccentricity is the condition of unequal air-gap that exists between the stator and the rotor. Therefore, existing asymmetry between stator and rotor generate other faults in motors. Furthermore, if these faults are not diagnosed and prevented, the rotor may touch the stator and result in irreparable damage of the machine [5].

Various fault diagnosis techniques have been proposed for detection and diagnosis in three-phase IM faults. Some detection techniques evaluate the measured line current of the induction machine. If they are based on the analysis of the Fourier spectrum of a line current [6; 7], they are called motor current signature analysis techniques. From the machine line currents, Park’s vector (a space pharos) can also be derived. This vector can be used for diagnosing air-gap eccentricities [8]. Fault-specific signals are also present in the electromagnetic flux which can be measured by coils sensing the axial leakage flux [2; 3]. Instantaneous power signature analysis is also used. The single-phase instantaneous power has been proposed for the diagnosis of mixed rotor faults [9]. Recently, this technique was proposed by the authors for the detection of mixed eccentricity in squirrel cage IMs, where both simulation and experimental results demonstrated the effectiveness of this approach [10; 11]. Partial power as well as the total instantaneous power can be used for the detection of such faults. The complex apparent power was also proposed for the detection and diagnosis of an air-gap eccentricity condition [12].

One of the interesting parameters to monitor is the operating PF (sometimes also referred as the $\cos \phi$) of the IM. Traditionally, to monitor the operating PF of the IM, one would require both the voltage and the current measurements, and then apply the displacement method. However, that would require both voltage and current sensors.

In this paper, a method of CM of IM using the PF determined from only the measured current and manufacturer’s data. The method requires no voltage measurement and so can provide a low-cost solution. For low loading conditions, PF is more reliable than the motor current-based approaches as will be described in details later. PF is particularly useful for applications such as under-load protection of pumps with PF compensation for improving the power quality.

This paper is organized as follows. In the second section effect of IM faults in current introduced. PF calculations are introduced with the current-only method for estimating the operating PF presented in Section 3. Section 4 describes the test rig, instrumentation and data collection. Results, discussions and conclusions are presented in Sections 5 and 6 respectively.

### 2. Static and dynamic air-gap eccentricity

Air-gap eccentricity takes two forms: static and dynamic eccentricities. Static eccentricity is characterized by a displacement of the axis of rotation where the position of the minimal air-gap length is fixed in space. It can be caused by the stator ovality or by the incorrect positioning of the rotor or stator at the commissioning stage. Since the rotor is not centred within the stator bore, the field distribution in the air-gap is no longer symmetrical. The non-uniform air-gap gives rise to a radial force of electromagnetic origin, which acts in the direction of minimum air-gap and which is called unbalanced magnetic pull (UMP). However, static eccentricity may cause dynamic eccentricity [7] when the rotor is not rotating on its own axis. In this case, the centre of the rotor is not at the centre of the rotation and the minimum air-gap rotates with the rotor. This kind of eccentricity may be caused by a bent shaft, mechanical resonances, bearing wear or misalignment or even static eccentricity as
mentioned above. Therefore, the non-uniform air-gap of a certain spatial position is sinusoidally modulated and results in an asymmetric magnetic field, too. This, accordingly, gives rise to a revolving UMP [7]. Air-gap eccentricity in induction machines causes characteristic harmonic components in electrical, electromagnetic, and mechanical quantities. Therefore, either mechanical quantities such as vibrations or torque oscillations or electrical quantities such as currents or instantaneous power can be analyzed to detect eccentricity conditions [13].

2.1 Non-active power of an eccentric induction motor
When eccentricity takes place in an induction motor, the stator current, \( I_{ecc}(t) \) is given by [9-12]:

\[
i_{ecc}(t) = I_M \cos((2\pi f)t - \varphi) + \sum_{m=1}^{\infty} \{ I_{ec,m1}\cos[2\pi(f - mf_r)t - \alpha_{m1}] + I_{ec,m2}\cos[2\pi(f + mf_r)t - \alpha_{m2}] \}\]

where \( I_{ec,m1} \) and \( \alpha_{m1} \) are the amplitude of the current component at a frequency \((f - mf_r)\) and its initial phase angle, respectively; \( I_{ec,m2} \) and \( \alpha_{m2} \) are the amplitude of the current component at a frequency \((f + mf_r)\) and its initial phase angle, respectively. Clearly, in the current spectrum, two sideband components will appear around the fundamental component at frequencies \((f - f_r)\) and \((f + f_r)\) [9-12].

2.2 Unbalanced voltage
In this part the unbalance in the phase and the magnitude of the voltage are considered. To model the electrical motor symmetrical components can be used. A wide variety of research has been done on modelling of the unbalanced condition. For unbalanced voltage operation the torque can be written as [14; 15]:

\[
T = \frac{P}{\omega} = \frac{P_0 + P_2}{\omega} = T_0 + T_2
\]

In which, \( T_0 \) is the DC torque. \( T_2 \) is the torque component whose frequency is twice the supply frequency. Assuming the IM as a RL load the torque can be written as:

\[
T = \eta * E * I / \omega
\]

In which \( E \) and \( I \) are input voltage and current of each phase respectively. Assuming sinusoidal waveforms for voltage and current this equation can be rewritten as:

\[
T = K \cos(2\pi 50t + \alpha) \cos(2\pi 50t + \beta)
\]

So

\[
T = K'\{ \cos(\alpha - \beta) + \cos(2\pi 100t + \alpha + \beta) \}
\]

Based on Equation (5) the resulting torque would include a DC term and a term whose frequency is twice the fundamental frequency of the applied voltage. In order to detect the unbalanced supply voltage this extra torque component can be used.
3. The proposed method: Current only power factor calculation

The total input electrical apparent power \( P^* \) to the motor is given as [16]:

\[
P^* = \sqrt{3}VI
\]

(6)

Where \( V \) and \( I \) are the line voltage and current, respectively.

The active power supplying the load is:

\[
P = \sqrt{3}VI\cos\phi
\]

(7)

The PF is then defined as

\[
PF = \frac{p}{p^*} = \cos\phi
\]

(8)

The motor current, \( I \), would have two components, \( I_{active} \) and \( I_{reactive} \). The active part of the current \( (I_{active}) \) accounts for the torque, changing according to the load (from no-load to full/over-load). The reactive part of the current \( (I_{reactive}) \) accounts for the magnetizing current of the IM, and does not change much from the no-load to the full-load condition, practically remaining constant [16]. This is because for IM, the magnetizing circuit, i.e., the stator coil inductances remain the same:

\[
I = \sqrt{I_{active}^2 + I_{reactive}^2}
\]

(9)

\[
I_{active} = I\cos\phi
\]

(10)

\[
I_{reactive} = I\sin\phi
\]

(11)

Substituting Equation (8) in (11)

\[
I_{reactive} = I\sin(\cos^{-1}PF)
\]

(12)
Equation (8) can be rewritten using

\[ PF = \cos \phi = \sqrt{1 - \sin^2 \phi} = \sqrt{1 - \left(\frac{I_{\text{reactive}}}{I}\right)^2} \]  

(13)

Figure 2. Current presentation.

As the reactive component remains constant, it can be estimated from the nominal condition given by the manufacturer data and/or nameplate data using (12). Now, as the motor load increases, the total motor current \( I \) in (13) would increase, while \( I_{\text{reactive}} \) remains constant. Hence, the ratio \( \frac{I_{\text{reactive}}}{I} \) in Equation (13) decreases, causing the PF to increase and approach closer to unity. Theoretically, at no-load condition, there is no active current flow. So, at no-load, \( I = I_{\text{reactive}} \), making the PF = 0. That is, physically, at no-load, there is no mechanical resistance, so the whole circuit is almost wholly inductive due to the stator coils, causing a low PF. Increase in motor load is essentially similar to adding resistances to the circuit, causing the PF to increase.

Therefore, in the current-only PF estimation approach, we would estimate the \( I_{\text{reactive}} \) using (12) from the nominal PF from the nameplate data. Using the measured motor current and assuming constant \( I_{\text{reactive}} \), we can estimate the operating PF from Equation (13). Synchronized voltage and current measurement are not required as in displacement PF measurements.

4. Instrumentation and data collection
The schematic diagram for the test rig and instrumentations is shown in Figure 3. It comprises a 1.1kW variable speed induction motor, a DC Generator and a resistor bank to act as a load and to dissipate the electrical energy. The measured data is then transferred to the computer using 24-bit resolution data acquisition system. The sampling frequency was set to 50kHz. The LabVIEW based system was developed to allow the user to monitor and store machine variables, and subsequently a Matlab code was used for further signal processing.

The Universal Power Supply 60-105 receives a three phase input from the mains supply through input connections hard wired at the rear of the unit. After being connected to the 60-105 unit, the supply is protected using a three phase circuit breaker which when closed provides power to three phase variable and fixed ac outputs and variable and fixed dc outputs (as indicated by a green 'power on' indicator light).

The Multichannel I/O 68-500 unit allows a number of different parameters associated with the operation of the motors and generators to be measured with a Virtual Instrumentation system. Used with a PC, the software provides on-screen ac and dc voltmeters and ammeters, dc wattmeter, single and three phase wattmeters, ac phase meter, ac power meter, ac frequency meter and single and three phase PFs.

4.1 Equipment setup
This setup could be simply connected straight into the power supply with no problem. To simulate supply voltage drop only one of the three phases will not be 100% of the rated voltage with no need for any external resistance. Then using the I/O system the measured data can be recorded.
5. Experimental Results
The motor was tested at 1410 rpm and 100% load in a healthy condition and then under four different phase imbalance voltages of 10V (fault1), 15V (fault2), 20V (fault3), and 25V (fault4); these represented 4%, 6%, 8% and 10% respectively, of the main nominal voltage level.

The measured current for the test motor at different loading conditions and the calculated PFs using Equation (9) are shown in Figure 4. It can be seen that there is a direct relationship between the loads and the PF because the current motor increases when the load increases to maintain the same output power.

![Power Factor for 1.1 kW 3 phase induction motor for healthy condition at various loads.](image)

Figure 4. Power factor for 1.1 kW 3 phase induction motor for healthy condition at various loads.

The values of PF were calculated for the motor running under various conditions and at different loads. Figures 5 shows the PF for all the cases tested. It can be seen that there is a direct relationship between the fault severity and the PF.
Figure 5. Power factor for 1.1 kW 3 phase induction motor at various load, healthy and with various imbalance phase faults.

6. Conclusions
For the IM, the operating PF is one of the interesting parameters to monitor, which provides better CM compared to motor current-based approaches. Traditionally, PF estimation would require both the voltage and the current measurement in order to apply the ZC displacement method. In this paper, a method of determining the operating PF of the IM using only the measured current and the manufacturer’s data typically available from the nameplate and/or datasheet was presented. From the rated conditions (from the nameplate data), the reactive component of the motor current is estimated, which remains constant for different loading conditions, as per the IM principle. Then, using the measured total motor current and the estimated constant reactive part, the PF can be estimated at different loads. Experimental results are shown using a realistic test setup. The accuracy of the proposed method is very promising when compared to the state of the art methods (power rating, pole pairs, etc.,) for the class of motor used. This would provide a cheaper solution to monitoring IM, e.g., in pump applications, using the operating PF, without requiring the voltage sensors. Operational PF can also be used for PF compensation to improve the power quality.

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