A non-intrusive method for estimating motor efficiency using vibration signature analysis

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Abstract

An accurate method of estimating the efficiency of in-service motors is needed in order to determine the performance of installed motors without disrupting the motor driven process.. In this paper, the motor efficiency is estimated using a non-intrusive implementation of the compensated slip method. The motor speed is accurately estimated using motor vibration signature analysis. A few other efficiency estimation techniques are implemented and their performance is compared to the proposed method. It was found that the non-intrusive compensated slip method produced relatively accurate results without having an adverse impact on the availability of the motor under test. This method provides an attractive alternative to highly intrusive techniques that offer similar accuracy.

Keywords: motor efficiency; speed estimation; online estimation; vibration signature analysis; energy efficiency.

1. Introduction

Electric motors are key components in industry. They are used in a wide variety of equipment which amongst others includes fans, pumps, compressors, conveyor drives, and machine tools. Their wide spread industry processes has led to motors being a leading power consumer. Motors account for more than two-thirds of the electrical power consumption in some countries [1]. It is evident that as the cost of electricity continues to increase and environmental concerns about sustainable development grow; motors provide a great opportunity to reduce energy consumption. This can be accomplished by replacing inefficient motors with high efficiency motors and making the motor driven processes more efficient. An accurate method for estimating the efficiency of in-service motors is needed in order to determine the performance of installed motors.

Motor speed is an important input in determining the output power of a motor. Estimating the efficiency of an in-service induction motor, without withdrawing it from service, remains a challenge in industry. The torque and the rotor speed are needed to calculate the output power. The input power measurement requires power meters which are intrusive. Alternatively, the motor loss components have to be determined. Once the motor is installed, it is usually not possible to take these measurements without stopping the motor driven process and in some cases,

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decoupling the motor from the equipment. This results in downtime leading to financial losses due to lost production.

A non-intrusive method of accurately estimating the motor speed is presented in this paper. The motor speed is estimated using the motor vibration signature. The vibration signal of a motor contains a component at the frequency of the rotor mechanical speed [2].

The motor speed estimate can be used with traditional motor efficiency estimation techniques such as the slip based and air gap torque methods. In this paper, the motor speed estimated from the vibration signature is used with the compensated slip method to estimate the efficiencies of three test motors. This method is compared to conventional motor current based efficiency estimation techniques.

2. Experimental setup

The experimental setup that was used in this work is shown in Fig. 1. The three test motors that were used are 3 kW, 11 kW and 15 kW squirrel cage induction motors. All the test motors were 380 V, 4 pole and 50 Hz machines. The test motor data is summarised in Table 1.

Table 1. Test motor data.

Motor Parameters	Motor 1	Motor 2	Motor 3
Rated output power (Watts)	3000	11000	15000
Phase	3-phase	3-phase	3-phase
Rated voltage (Volts)	220/380	380/660	380/660
Rated current (A)	11.4/6.63	22.9/13.2	30.0/17.3
No load current (A)	5.70/3.30	10.0/5.76	12.0/6.91
Rated speed (rpm)	1390	1455	1455
Rated Frequency (Hertz)	50	50	50
Rated slip	0.073333	0.03	0.03
IEC Design	N	N	N

A National Instruments USB 6251 BNC data acquisition device was used to sample the vibration, voltage, current, torque, and encoder signals. The motors were loaded using a DC generator. The DC generator is driven by the test motor. A 3-phase controlled inverter is used to convert the generated power to AC. This is fed back into the supply grid. The load torque of the motor under test is varied by using a current controller to adjust the armature current set-point of the DC generator.

A signal conditioning circuit was used to supply the accelerometer with a 20 mA excitation current. A magnetically mounted ICP accelerometer with a sensitivity of 100 mV/G was used measure the motor vibration. Software was developed in LabVIEW for the signal analysis. Fig. 2 shows a functional block diagram of the implementation of the motor efficiency estimation techniques.

The vibration signal was sampled at 100 kHz for 10 s. A second test was done using a 20 s data sample to improve the frequency resolution. An edge counter was used to determine the motor speed that is used for comparison. The input power and supply frequency are calculated from the measured stator current and voltage signals. The experimental setup and software developed is used to simultaneously estimate the motor speed and test several motor efficiency estimation techniques. The proposed test setup can be converted into a portable instrument
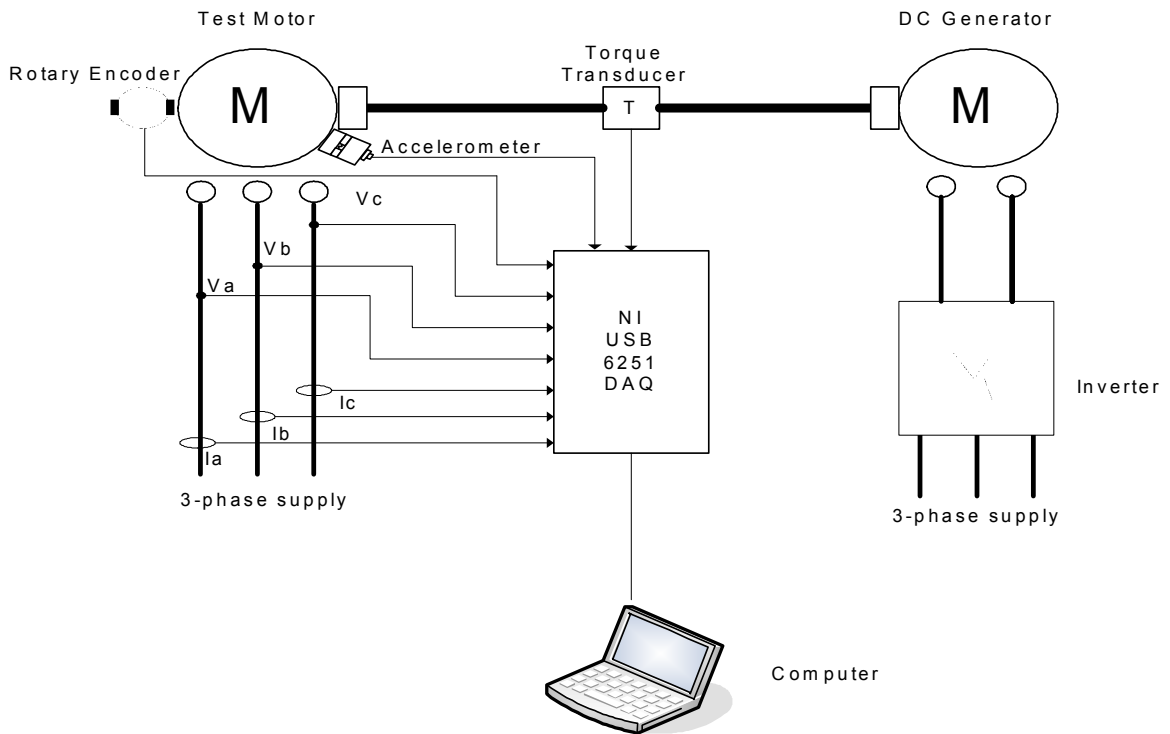
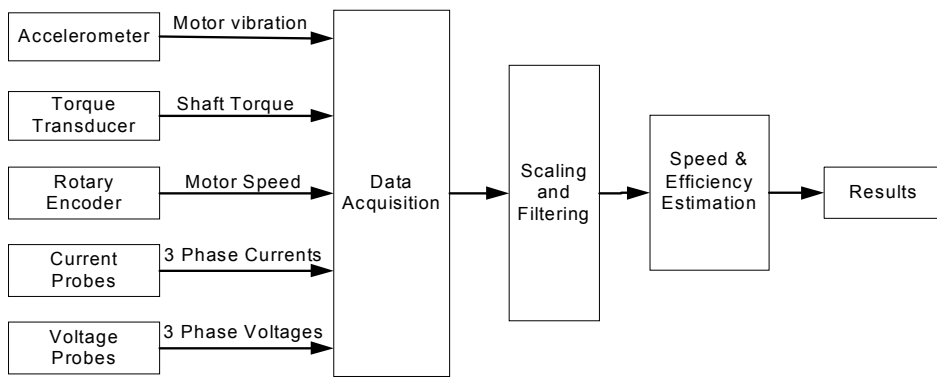Fig. 1. Block diagram of experimental setup.

Fig. 2. Experimental setup functional block diagram.

3. Speed estimation technique

All rotating equipment produces some level of vibration and electric motors are no exception. Vibration in electric motors occurs as a result of a combination of mechanical and magnetic forces acting on the machine structure and the mounting of the motor [3]. The mechanical forces are due to unbalance in the rotating assembly. The rotating assembly consists of the rotor, shaft and bearings. The out of balance rotor forces have the same frequency as the rotor rotating frequency. Although motor manufacturers attempt to design and manufacture motors with minimal vibration, the rotating assembly will always contain some residual unbalance. This results in vibration [4]. Magnetic forces are from the flux in the air gap. The air gap flux also contains harmonics of the fundamental magnetic flux. The magnetic forces act radially on both the stator and rotor. These forces are known as Maxwell's forces [5]. The magnitude of motor vibration at any point is determined by the magnitude of the force and the mechanical response of the motor structure and mounting [6].

Motor vibration has been widely studied in the area of motor condition monitoring. Various types of motor faults can be detected from the vibration signature of a motor. The faults occur at harmonics of the motor rotor frequency. The vibration signal of a motor also contains a large amplitude component at rotor rotating frequency [2].This signal is prominent across all loading points.

The rotor speed can be determined by analysing the frequency components of the motor vibration signal. This is achieved by applying a Fast Fourier Transform (FFT) to the sampled motor vibration signal. The motor vibration signal is obtained from an accelerometer that is mounted to the motor. The amplitude of the rotor is the largest frequency component in the frequency region of interest. The frequency of this signal is the only parameter of interest in determining the rotor speed.

The rotor frequency can be obtained by using a peak detection algorithm and narrowing the search area. A boundary is selected a boundary that corresponds to the minimum and maximum expected frequency derived from the motor nameplate rated speed. The motor rated speed is used as to obtain the minimum rotor frequency whilst the synchronous speed is used to obtain the maximum frequency.

$$f_r^{min} = \frac{n_r}{60} \tag{1}$$

Where f_r^{min} is the low frequency boundary and η_r is the motor's rotor speed in rpm.

$$f_r^{max} = \frac{2f_s}{P} \tag{2}$$

Where f_r^{max} is the upper frequency boundary and P is the number of poles. The peak search is then limited to the frequency range as expressed in (3). The minimum and maximum boundaries of the search window can be increased by 5 % to account for speed variation that may occur as a result of supply voltage variation. This may also account for motors that are operated under overload conditions that result in a reduction in the operation speed.

$$f_r^{min} \leq f_r \leq f_r^{max} \tag{3}$$

When selecting the sampling frequency and the number of samples for the FFT, (4) should be taken into consideration [7].

$$\Delta f = \frac{f_s}{N_{fft}} \tag{4}$$

Where Δf is the frequency resolution, f_s is the sampling frequency and N_{fft} is the number of samples used in the FFT. From (4), the resolution of the vibration frequency component of the rotor speed can be obtained. This can be improved by taking longer data lengths for a given sampling frequency.

The rotor speed in revolutions per minute (rpm) can be calculated from the rotor frequency by using the time conversion factor expressed in (5).

$$\eta_r = 60 \times f_r \tag{5}$$

Where η_r is the motor's rotor speed in rpm and f_r is the rotor frequency in Hz.

4. Speed estimation technique

The vibration signal of the motor was measured both at no load and full load for the three test motors. Analysis of the frequency components contained in the vibration signal showed a high amplitude component at the rotor frequency. This is shown in Fig. 3 where an FFT of the vibration signal measured from the 11 kW motor is applied.

A comparison of the speed estimate and accurate measured speed for the three test motors is shown in Table 2. The motor speed was measured using a rotary encoder for comparison. The experiments were repeated three times at each loading point. The results were found to be consistent. The accuracy of the speed estimate can be improved by increasing the frequency resolution of the vibration signal through reducing the sampling rate or using longer data samples.
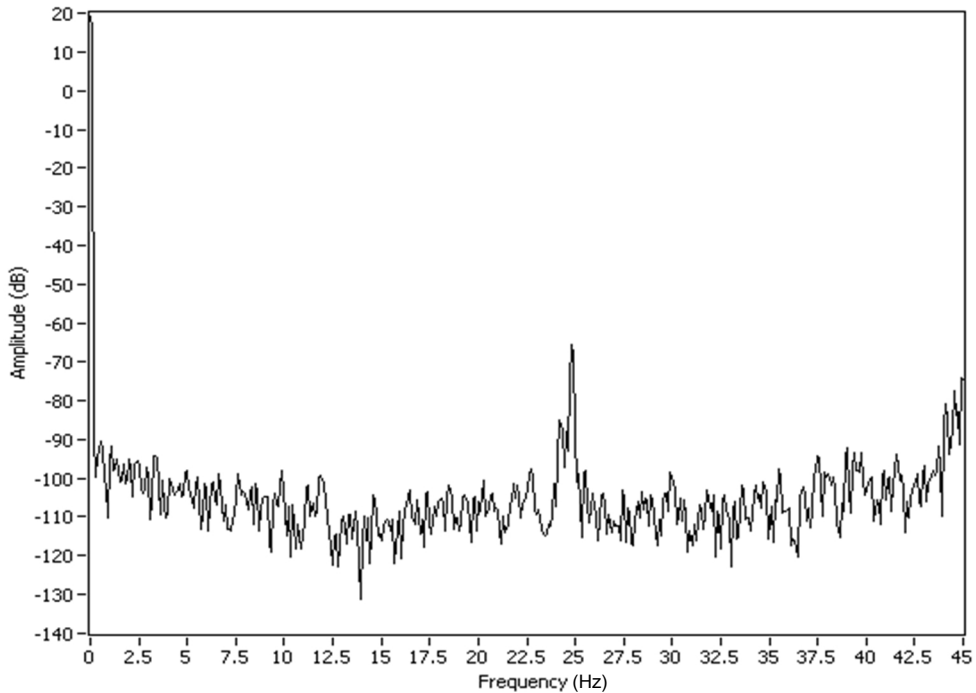

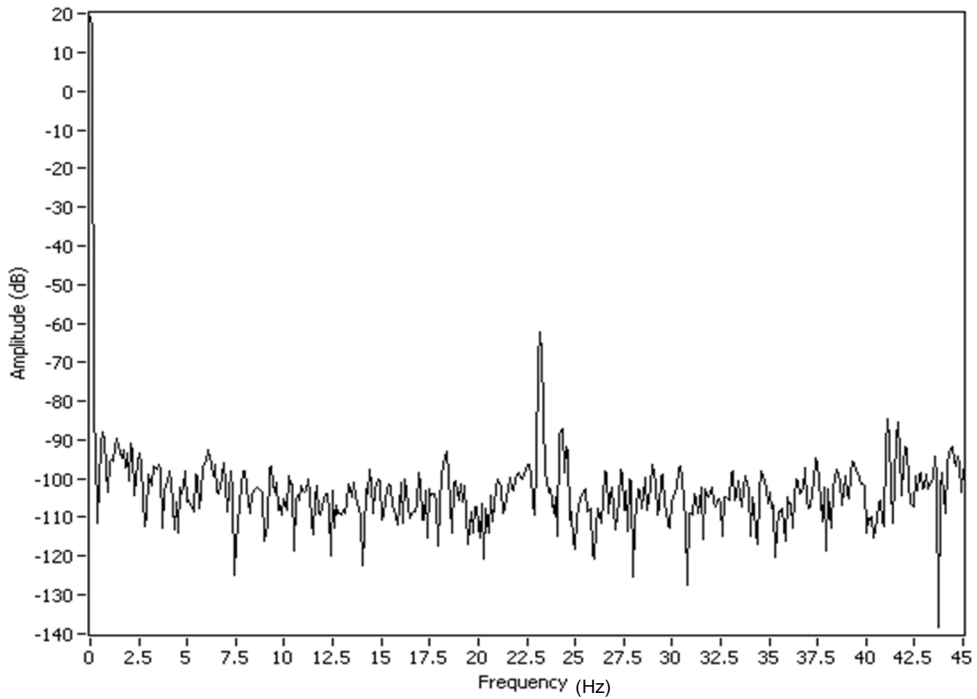Fig. 3. FFT of the 11 kW motor's vibration signal at no load.

Fig. 4. FFT of the 11 kW motor's vibration signal at no load.

Table 2. Motor speed estimation results.

15 kW motor	Frequency (Hz)	Speed estimate (rpm)	Measured speed (rpm)	Error (%)
No load	25.01	1500.62	1502.3	0.11
Full load	24.37	1461.97	1454	0.55
11 kW Motor				
No load	24.95	1496.98	1498	0.07
Full load	24.41	1464.36	1463	0.09
3 kW Motor				
No load	24.82	1489.08	1491	0.13
Full load	23.20	1392.2	1396	0.27

   The vibration signature analysis method for estimating the mechanical speed of a motor is preferred over other speed estimation techniques. This is due to its high accuracy and ease of implementation. The vibration component at the rotor frequency has a high amplitude across all the motor loading conditions. It is not influenced by the motor supply conditions. This signal can be detected in both new and used motors. The rotor frequency signal is not close to any other signals of interest. Errors due to spectral leakage are not introduced. The signal will always be lower than the stator supply frequency. This means that low sampling frequencies are required. A low sampling frequency allows this method to obtain a high resolution without requiring long data samples. This results in a fast computation time as compared to other FFT based techniques. A further advantage of using low sampling frequencies is that relatively cheap analogue to digital conversion circuitry can be used. The motor vibration signature is not parameter dependant, unlike observer based methods. As long as the motor is rotating, the signal will exist under all supply conditions. It results from the mechanical unbalance in the rotating assembly. The method does have a drawback of requiring the installation of an accelerometer. This increases the initial cost of the method. The benefits provided outweigh this shortcoming.

5. A non-intrusive compensated slip method

There are numerous different motor efficiency estimation methods that are proposed in literature. These methods vary in their level of intrusion and accuracy. The least intrusive efficiency estimation techniques are based on the motor stator current or the motor slip [8].A non-intrusive compensated slip method that uses the motor speed estimation based on vibration signature analysis is presented. Other motor efficiency estimation techniques were also implemented in this research. This was done to evaluate the performance of the non-intrusive compensated slip method in comparison to other methods based on the measured efficiency of the test motors.

The motor efficiency estimation techniques that were implemented are discussed below.

5.1. Slip methods

The slip based motor efficiency estimation methods are based on the assumption that the slip in an induction motor is directly proportional to the load of the motor [9]. These methods rely on measuring or estimating the speed of the motor. The speed is estimated using the motor vibration signature at the operating point. The main advantage of the slip methods is their simplicity [10].Disadvantages of these methods are that the slip is not proportional to the loading of the motor across all loading points and the nameplate ratings are not always very accurate. Slip based methods can underestimate the load in practice.

5.1.1. Standard slip method
The standard slip method is given by

$$\eta = \frac{Slip}{Slip_{rated}} \times \frac{P_{output,rated}}{P_{input}} \tag{6}$$

Where η is the estimated motor efficiency. The motor speed is measured to calculate the slip and the input power is calculated from measuring the terminal voltage and current.

5.1.2. Ontario Hydro's compensated slip method
In the standard slip method, the effect that voltage has on efficiency is not considered. The Ontario Hydro method improves on the standard method by factoring the voltage into the calculation as shown in (7).

$$\eta = \frac{Slip}{Slip_{rated}} \times \frac{P_{output,rated}}{P_{input}} \times \left(\frac{V}{V_{rated}}\right)^2 \tag{7}$$

Where η is the estimated motor efficiency, V is the input voltage and V_{rated} is the motor rated input voltage.

5.2. Current methods

Current based motor efficiency techniques are amongst the least intrusive methods. Only the input current of the motor has to be measured. They are based on the assumption that the load is directly proportional to the current [11]. The efficiency from this method is given in (8).

$$\eta = \frac{I}{I_{rated}} \times \frac{P_{output,rated}}{P_{input}} \tag{8}$$

Where I is the measured input current and I_{rated} the motor rated current. (8) results in an output power estimate that is higher than the actual load. This can be corrected by using (9) which factors in the no load current [12].

$$\eta = \left(\frac{I - I_{no\ load}}{I_{rated} - I_{no\ load}} + \frac{I}{I_{rated}} \right) \left(\frac{P_{output,rated}}{2P_{input}} \right) \tag{9}$$

An alternative current method that can improve accuracy by factoring the no load current of the motor is given in (10) [6].

$$\eta = \frac{2I - I_{no\ load}}{2I_{rated} - I_{no\ load}} \times \frac{P_{output,rated}}{P_{input}} \tag{10}$$

5.3. The non-intrusive compensated slip method

The novelty of this method for motor efficiency estimation is the non-invasive speed estimation technique that is used. The speed estimation technique is used together with the Ontario Hydro compensated slip method. This allows for a non-intrusive efficiency estimation technique that can be applied to test motors whilst they are in service. The motor driven process is not interrupted. A magnetically mount accelerometer and clamp-on current and voltage transducers are required to implement the method. The speed estimation technique can be adjusted for implementation with motors driven by variable speed drives.

A flowchart of the implementation of the non-intrusive motor efficiency estimation technique is shown in Fig. 5. The technique starts with the user/operator entering the required nameplate data. In order to implement the method, the rated speed, supply frequency, rated output power, and supply voltage are required. The nameplate data is used to calculate the upper and lower frequency boundary for the peak search. The 3-phase stator currents, 3-phase stator voltages and radial vibration signal are acquired from the transducers. Three phase current and voltage measurements are preferred. This allows for accurate computation of the input power even under unbalanced supply conditions. It should however be noted that single phase measurements of the current and voltage can also be used. In this case the assumption of a balanced supply is made. The input power is calculated using the measured input currents and voltages. A FFT of the vibration signal is calculated to obtain the frequency components. A peak search algorithm is performed in the calculated frequency window. The frequency of the determined peak is the rotor frequency. The motor mechanical speed is detected from the rotor frequency. A FFT of one of phase of the stator voltages is calculated to obtain the fundamental frequency of the supply voltage. The synchronous frequency of the air-gap field is calculated using the fundamental supply frequency. An accurate calculation of the motor slip at the specific operating point is obtained. The motor efficiency is estimated using (7).
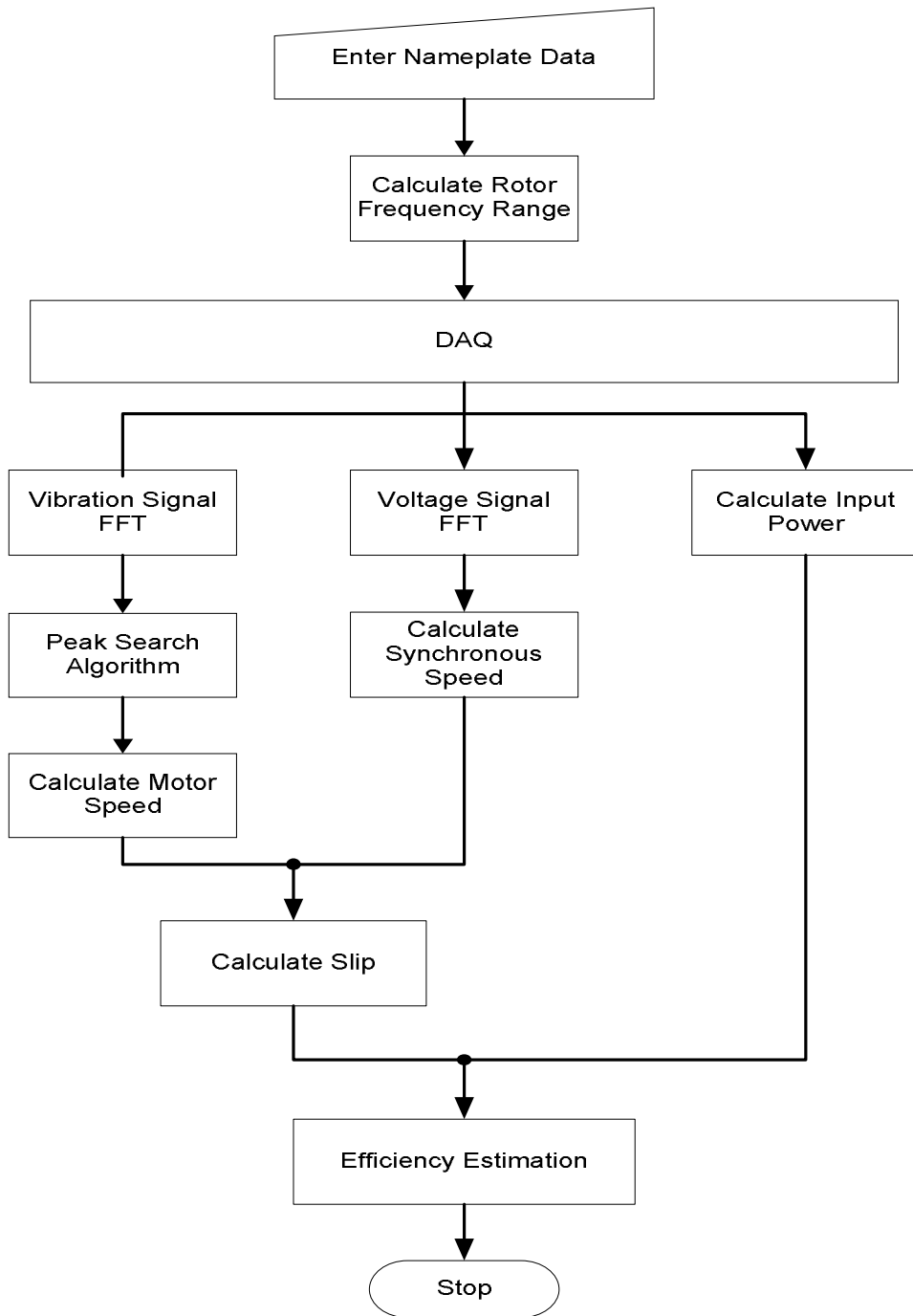
Fig. 5. Flowchart of Motor Efficiency Estimation Technique

6. A non-intrusive compensated slip method

The results from the implementation of the efficiency estimation techniques are presented in this section. The efficiency of the test motors are determined by using the measured shaft torque and speed of (11) and (12).

$$P_{output} = T_{shaft} \times \omega_r \tag{11}$$

Where T_{shaft} is the shaft torque in Nm and ω_r is the rotor speed in rad/s. The motor efficiency is given by (12).

$$\eta = \frac{P_{(output)}}{P_{input}} \tag{12}$$

Fig. 6 shows the efficiency curves by implementing the estimation techniques on the 3 kW motor. The current methods are poor at estimating the efficiency at low motor loads. The slip based methods follow the motor efficiency curve across all loading points. Fig. 6 shows that the non-intrusive compensated slip method is the most accurate technique.
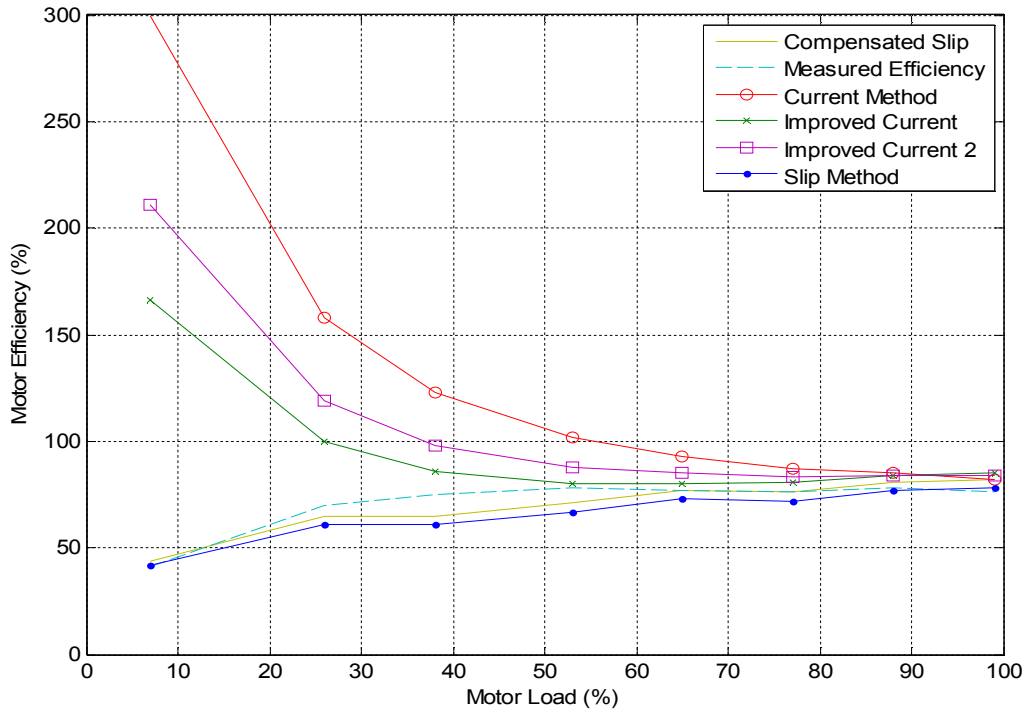

Fig. 6. 3 kW motor efficiency estimate curves.

The non-intrusive compensated slip method was implemented on the 11 kW and 15 kW motors. The results obtained from testing these motors are shown in Figs. 7 and 8. The efficiency curves obtained from the tests on the two motors show that the non-intrusive compensated slip method follows the measured efficiency curve across the full loading range of the motor. The efficiency curves of the three motors are typical efficiency curve for small motors. The efficiency of the motor drops significantly for loading points that are below 50 percent of the rated output power. The efficiency curves of all the motors tested show that the compensated slip method provides an accurate estimation of the motor efficiency.
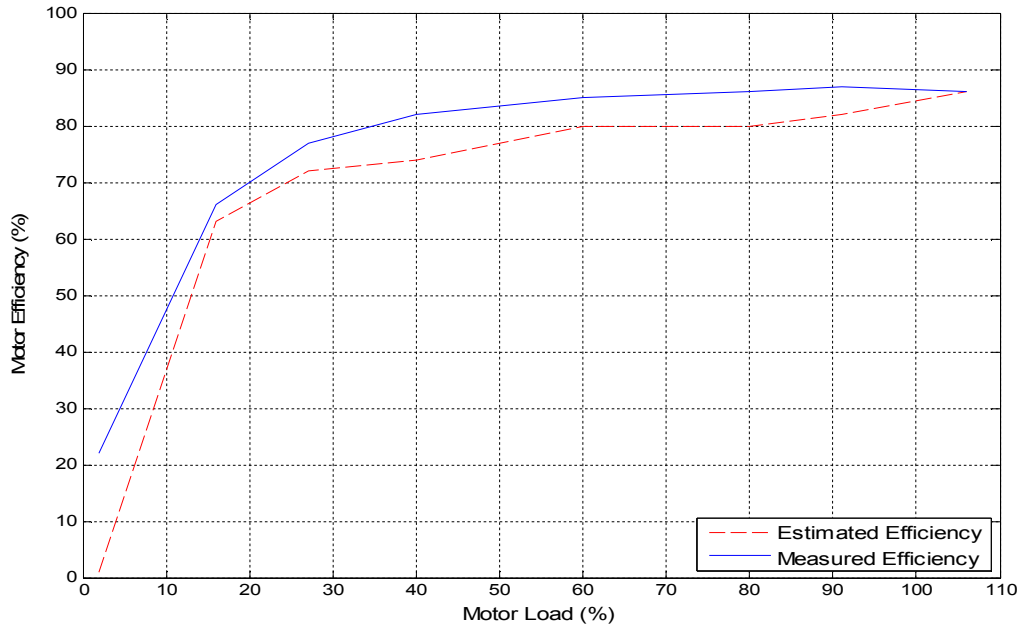
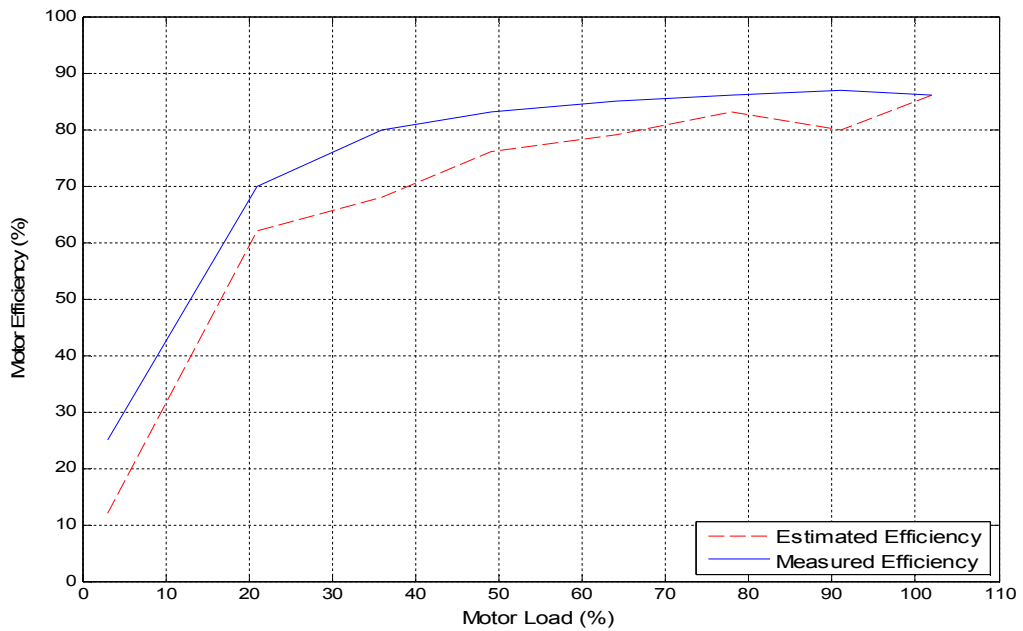Fig. 7. 11 kW motor efficiency estimate curves.

Fig. 8. 15 kW motor efficiency estimate curves.

A comparison of the percentage error in the non- intrusive compensated slip method for the three motors is

shown in Table 3. The average error for all the tested motors is below 10 %.

Table 3. Percentage error in compensated slip method.

3 kW Motor		11 kW Motor		15 kW Motor	
Motor Load	Error	Motor Load	Error	Motor Load	Error
7.3	-3.31	2.99	12.91	2.19	20.74
25.76	4.97	21	8.65	16.15	2.95
38.3	10.3	35.67	11.74	26.65	5.05
53.15	6.87	49.49	7.21	40.27	8.61
65.07	0.56	64.06	6.66	60.04	5.16
76.88	0.39	77.59	3.2	79.51	5.92
88.15	-3.34	91.44	6.35	91.05	4.2
99.32	-5.78	101.78	0.87	106	0.05
Average	1.33	-	7.2	-	6.59
Average > 50%	-0.26	-	4.86	-	4.79
Average > 75%	-2.91	-	3.47	-	3.39

In Fig. 9, the power factor and efficiency of the 11 kW motor is plotted against the motor load. The figure shows that the power factor of the motor decreases as the motor loading point is reduced. The efficiency of the motor follows a similar trend. Operating motors at an optimal power factor has several advantages: the apparent power required by the motor is reduced, which frees up capacity in the power system. Additional equipment can then be installed [13]. Alternatively, it can allow for installing smaller equipment to achieve the same process requirements. An improved power factor results in a reduction of transmission losses due to a smaller current required for the same amount of active power. All the test motors were found to be at their most efficient when operating at loads above 75% of the rated output power. This is the same when considering the power factor. The optimal operating region for the motors is above 75% of rated power. In the operating region above 75% of the rated output power, the average error for all three test motors in within 3.5%.
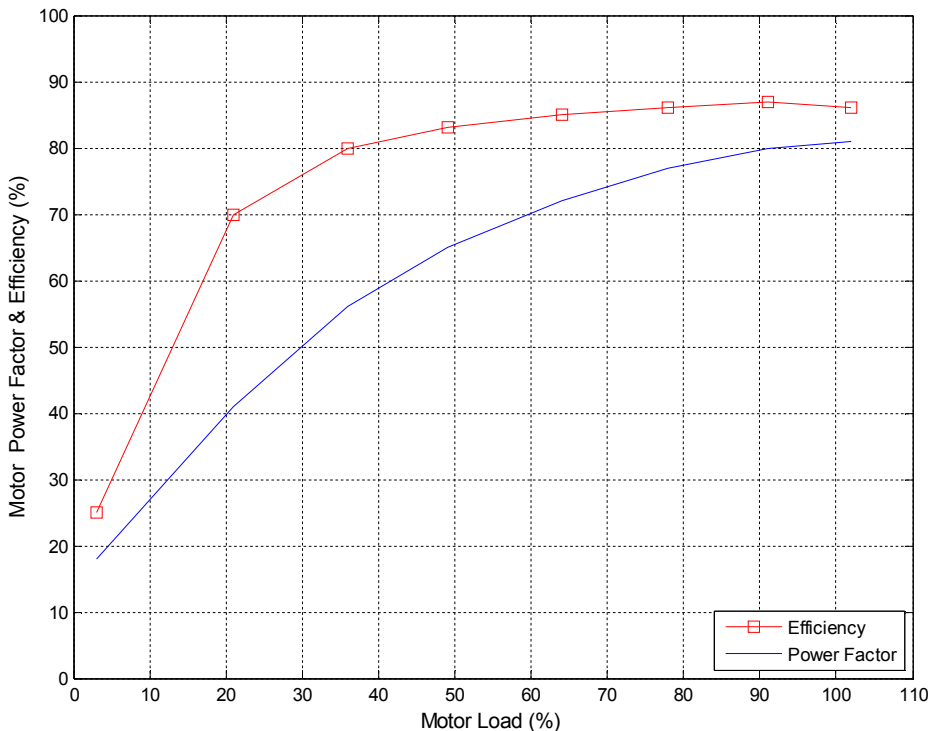

Fig. 9. 11 kW motor efficiency and power factor curves.

The results obtained from the implementation of efficiency estimation techniques show that the non-intrusive compensated slip method presented offered improved accuracy than the standard slip and current based method. Due to the limited accuracy obtainable across all the motor loading points, the method can only be used to get an indication of the motor efficiency. Results obtained from implementing the method cannot be used as a basis for motor replacement studies when the rated efficiencies of the motors under consideration are within 10 percent of each other. However, when the motor is operated in the ideal operating range between 75 and 100 percent of the rated load, the method is accuracy of the results obtained from all three test motors is sufficient for performing motor replacement studies and monitoring the deterioration in performance of an installed motor. This can be accomplished through taking a baseline efficiency reading for a motor after it is installed and monitoring the efficiency of the motor whilst it is in use. A decline in the motor efficiency over time can then be used as a basis for a motor replacement study.

In order to apply the non-intrusive compensated slip method an accelerometer, voltage and current transducers have to be purchased and installed. The method can be implemented as a portable instrument to test one motor at a time or a permanent field instrument for online monitoring of each motor in a plant. The later will require a higher initial investment which will depend on the numbers of motors in the plant. Knowing the efficiency of an in-service motor can enable analysis and decision to be taken can result in significant savings in motor operating costs. The value of these benefits far out weight the initial investment.

When compared to other methods which require more expensive equipment such as variable voltage power supplies and variable loads, the proposed method is cheaper to implement. Another cost component that has to be considered is the cost of the downtime that is required to apply a selected efficiency estimation technique. In order to conduct intrusive tests such no load tests and blocked rotor test as required by some methods, the motor driven process has to be interrupted and the motor has to be decoupled from the load. The cost of labour and lost production can be very high. Implementing the method presented will not result in any significant process interruption; therefore the costs of downtime are avoided.

One of the main drawbacks of slip based methods articulated in literature is that the NEMA and IEC standards allow motor manufacturers a tolerance of 20 percent on the rated slip of a motor [8]. This would introduce a significant error in the efficiency calculation. In this research it was found that all of IEC motors tested had accurate datasheets and nameplate ratings from the manufacturer. In order to be able to successfully implement the presented method and maintain and acceptable level of accuracy, specifications for the purchased of new motors would have to include more stringent testing from the supplier to determine accurate speed and slip ratings.

7. Conclusions

A non-intrusive method of accurately estimating the motor efficiency using the motor vibration signature was presented in this paper. A speed estimation algorithm was used to implement the compensated slip motor efficiency estimation technique. The use of the speed estimation technique allows for a truly non-intrusive method of implementing the compensated slip method. Results that were obtained are within 1 percent of the measured motor speed. In the operating region above 75% of the rated output power, the average error for all three test motors with the efficiency estimation algorithm was within 3.5%.

The proposed method for estimating motor efficiency is easy to implement and it does not result in expensive plant downtime. It has useful practical applications for on-line motor management and condition monitoring. Data obtained from implementing the efficiency estimation technique can be used for motor replacement studies so that potential cost savings can be calculated. The new motor can be compared to the installed motor based on the estimated efficiency across the load profile for the application that the motor is used for.

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