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Original Citation

Lane, Mark, Ashari, Djoni, Gu, Fengshou and Ball, Andrew (2015) Investigation of Motor Current Signature Analysis in Detecting Unbalanced Motor Windings of an Induction Motor with Sensorless Vector Control Drive. In: *Vibration Engineering and Technology of Machinery*. Springer, pp. 801-810. ISBN 978-3-319-09918-7

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Investigation of Motor Current Signature Analysis in Detecting Unbalanced Motor Windings of an Induction Motor with Sensorless Vector Control Drive

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Abstract Maintaining the efficiency of AC motors in site equipment is important, given the increasing cost of energy. Reduction of motor efficiency from baseline manufacturer data can go undetected until total failure of the equipment is experienced. This paper introduces motor current signature analysis methods used to detect the early onset of motor efficiency reduction in AC motors controlled by modern Sensorless-Vector Variable Speed Control inverters. A step increase in the resistance of one stator winding is simulated in stages. Off-line processing of motor current data signals using data analysis methods developed for the MATLAB platform is used to identify imbalances caused by subtle stator resistance increases. Initial results indicate that small increases in stator resistances can be observed in the motor current signals received after data processing techniques have been used on the measured signals. The test results are presented herein along with details on the research work to be continued.

Key words Unbalanced, Efficiency, Single Stator Resistance Increase, MCSA, PWM, Random Switching Pattern, IAS.

1.0 Introduction

The model system of a standard PWM (Pulse Width Modulated) inverter, operating in Sensorless Vector mode and utilizing noise-reducing random PWM-pattern generation technology is used for this study. This research is intended to detect the incipient increases in the resistance of one single motor stator phase as a fault develops and before critical failure occurs.

Increases in single stator resistance of a 3-phase induction motor can lead to voltage imbalances in the motor, causing a reduction of motor efficiency, increase in motor temperature and oscillatory running conditions. This in turn can lead to other electrical or mechanical failures occurring. Conditions such as corroded termi-

nals, dissimilar metals, different conductor sizes, insulation breakdown of cables or connections have been reported as common causes of high resistance connections [1]. Installing a motor in these conditions can result in premature failure of the motor. However, this fault will remain undetected by the drive system because the motor is still functionally operational under these imbalanced conditions, but operating less efficiently.

A study on the detection of winding resistance faults in an AC squirrel cage induction motor fed directly from the mains supply is not a new research area. There have been a number of studies undertaken to detect critical stator faults in AC motors such as phase-phase or phase-neutral faults [2]. Modern inverter systems have fast fault detection systems in place to protect the IGBT (Insulated Gate Bipolar Transistor) device from failure and most drives indicate which phase of the IGBT device has experienced an overcurrent trip or other phase failure, allowing the engineer to trace the fault to one or more motor phase switching devices [3]. However, this is only effective in detecting critical faults such as open circuit or short-circuits. If these faults are not significant, the inverter drive will not detect an error and the drive system will continue to operate as normal.

The effects of unbalanced supply voltage feeds to an AC motor are well understood and result in the motor operating efficiency being reduced. The voltage imbalances are documented in the NEMA standards for AC induction motor performance [4] and can result in a loss of efficiency of up to 75% for a voltage imbalance of 5%.

The purpose of this paper is to examine the effects of small step changes in rotor resistance and develop a reliable means of detecting the change. The study of motor temperature using only the standard PT100 device and attempt to correlate this to an increase in motor temperature is included as are IAS (Instantaneous Angular Speed) and vibration measurements.

2.0 Test Facilities and Fault Simulation

A test rig consisting of a PWM inverter with 3kHz switching frequency and a carrier frequency selected by a random pattern generator enabled by default was used. For the research to be valid with future drive systems, it is important that valid test results can be obtained from equipment that utilizes the very latest motor control technology and with these advanced switching techniques enabled. A standard inverter-rated 690V AC motor was used, connected in Delta to the 415V output inverter.

A shunt-wound DC motor is used to apply different loading to the AC motor drive system. The speed, load and test duration are all programmable and repeatable. The DC motor regenerates to the mains supply through a 4-quadrant 2-phase DC drive.

Previous research studies in this area have been limited to Volts/Hertz mode inverters – these being the most simple of variable speed control drives and traditionally the favoured workhorse. However, due to the reduced cost of sensorless vector drives, their use in industry is now more widespread [5] and their use is even applied to applications that traditionally a Volts/Hertz inverter would have sufficed, such as fan or pump applications. If this research was carried out using standard Volts/Hertz drives, the findings would have only been limited to a small, dwindling part of the AC drives market. Indeed, out of the Parker SSD Drives offering of 8 drive variants ranging from 0.5kW to 2000kW, only one variant offers standard Volts/Hertz mode, the 650 model with a maximum size of 7.5kW. By basing the research on latest drive technology, the results are able to be applied to existing and newer installations with confidence.

2.1 Healthy operating conditions

It is important to have a meaningful and consistent baseline data set from which to measure simulated faults. To this effect, healthy baseline data was measured in three separate tests, each with the same operating data applied. The design of the test rig is such that a Programmable Logic Controller provides a predictable load change to the AC driven motor system at precise, repeatable intervals.

A sampling rate of 96kHz with a 40 second sample time was used for each test run. A total of 15 data sets were therefore obtained for the baseline data.

The baseline data measurement test parameters are shown in table 1.

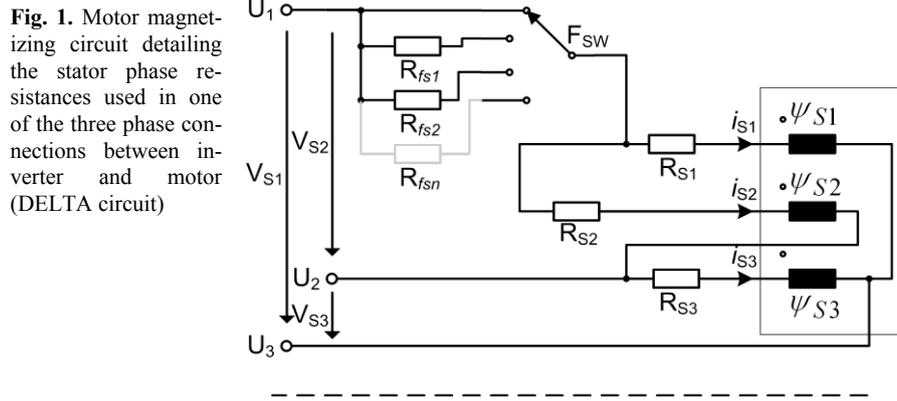
Table 1. Test run speeds, duration of test and AC motor loading.

Test	Speed (RPM)	Test Duration(s)	Load (% of motor FLC)
1	1470	40	0
2	1470	40	25
3	1470	40	50
4	1470	40	75
5	1470	40	100

2.2 Fault Simulation

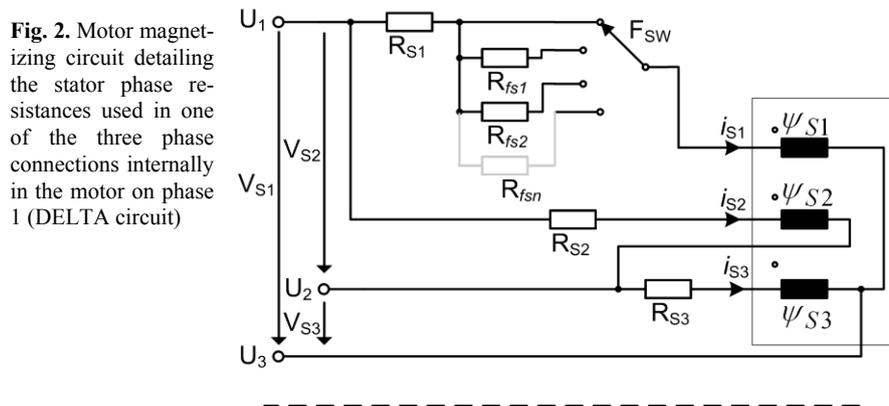
There are a number of phase resistance increments available on the test rig in 0.1Ω steps obtained by changing the wiring tapping on the custom-built resistor unit.

It is proposed to simulate two types of phase resistance faults on the test rig. The first fault is one that develops in the supply connection between the inverter drive and AC motor shown in figure 1. On the test rig delta-connected motor, this increase in resistance affects two of the motor phase circuits.



The second fault is simulated to occur in one winding inside the AC motor thereby affecting only one motor phase. This is indicated in Figure 2.

The same test as used for the baseline data tests was run for each fault condition.



2.3 Measuring devices

A current and voltage measurement unit was designed and constructed to measure the supply connection between drive and motor. Closed-loop hall-effect current

transformers from ABB with a 200kHz bandwidth fed from a high-precision voltage source were used for each of the motor phases. So that motor power can be calculated, voltage measurement devices with a 15kHz bandwidth also from ABB have been fitted for each phase.

Vibration, temperature and IAS measurements are also taken from the test rig.

3.0 Phase Winding Resistance Increments

After a series of baseline healthy tests are run, a stator resistance was applied to the stator winding. This was done in series with the winding and will be referred to as the resistance R_{fs} . The effect on the equivalent circuit of the stator is shown in figure 1 and the effect on one phase resistance increase on the stator equivalent circuit equation is as below:

$$V_{s1} = R_s i_{s1} + \frac{d\psi_{s1}}{dt} \rightarrow V_{s1} = (R_{fs} + R_s) i_{s1} + \frac{d\psi_{s1}}{dt}$$

This creates an imbalance in the stator circuit and the effect is to reduce the magnetic flux generated by one of the stator windings in proportion to the value of R_s . The effect of this is to be studied for motor instability and winding temperature increase compared to normal running conditions.

It is proposed to use the developed algorithms in MATLAB to indicate differences in the following motor parameters for each resistance increase.

- Voltage imbalance of 3 phases
- Current imbalance of 3 phases
- Baseline vs. fault efficiency differences
- Effect on rotor asymmetry
- Effect on vibration
- Effect on IAS

4.0 Data Analysis and Results

Initial data results are included that demonstrate the difference between standard fixed-PWM frequency carrier drives and the more modern random pattern drives to illustrate the difficulties that could be present when attempting to harvest data from such drive systems.

4.1 Random carrier pattern measurements

It was noted from initial motor current measurements that the random switching pattern generator introduces a noise floor to the data as can be seen in the measurements taken in figure 3. Compare this with figure 4, where the central carrier frequency and the associated sidebands can be readily identified and with post-signal processing potentially notch-filtered out.

Fig. 3. Random pattern generation disabled; Speed 1470RPM, Load 100%;

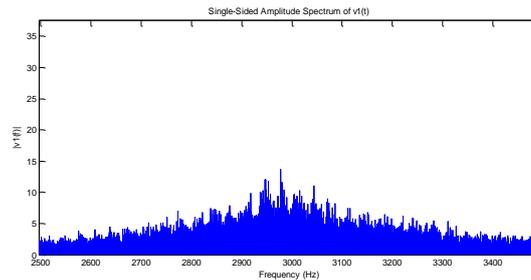
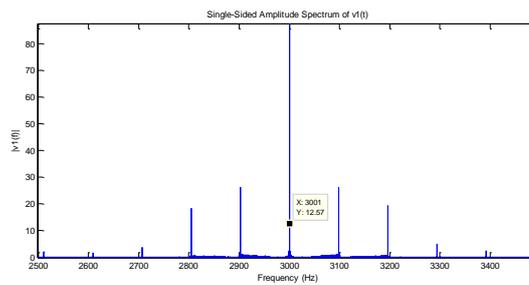


Fig. 4. Random pattern generation enabled; Speed 1470RPM, Load 100%.



The more random nature of measurements taken in the motor current signals may impact adversely on the ability to detect the small resistance changes to be applied. Nevertheless, the random pattern generation was enabled and test measurements taken under this condition. It is intended to run further tests to identify if the random pattern generation does affect any test results obtained.

4.2 Resistance measurement results

The test results taken from initial fault conditions generated show that at resistance increases 0.4, 0.6 and 0.8 Ω , there is a measurable increase in the voltage imbalance compared to the three baseline (BL) data sets. This is illustrated in Figure 5. Current imbalance in each of the 3 phases is less obvious and this is given in figure 6.

Fig. 5. Voltage imbalance (Asymmetry) by means of NEMA definition

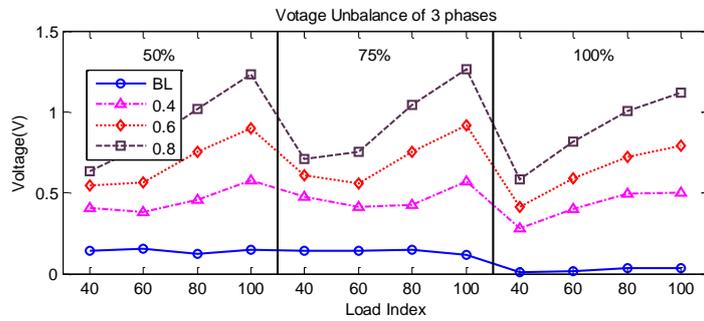
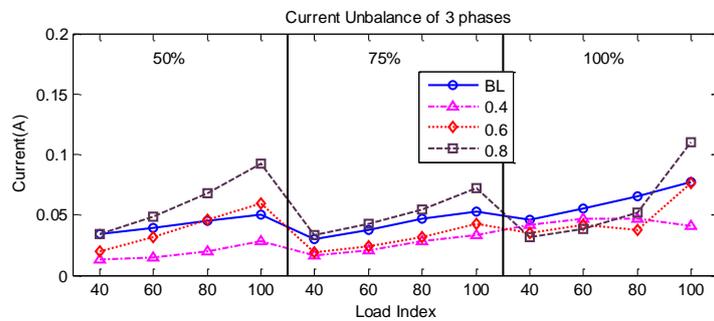


Fig. 6. Current imbalance (Asymmetry) by means of NEMA definition



The efficiency of the motor was also then examined and compared to the baseline data. The Efficiency by Air-Gap Torque is concerned with the losses as a product of the slip and air gap power calculated from the motor current, voltage measurement and IAS. No noticeable efficiency decrease was observed for the increase in stator resistance fault value shown in figure 7.

Fig. 7. Motor efficiency by air gap torque

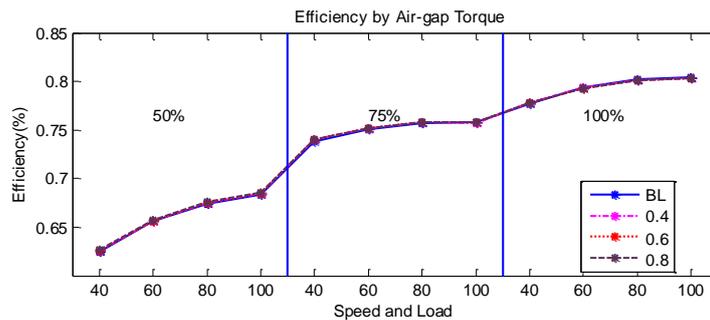


Fig. 8. Motor efficiency decrease from baseline data for each fault resistance increment

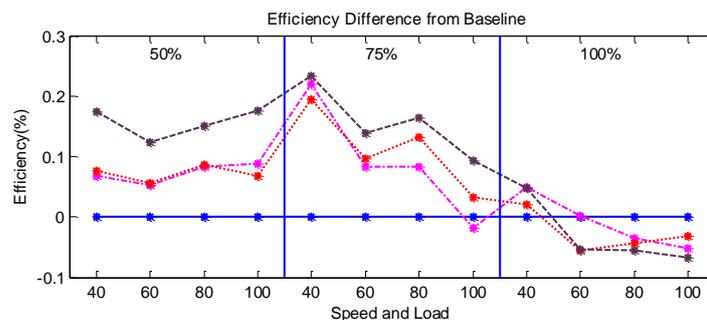


Figure 8 details the changes of efficiency measurements taken from the baseline data. It shows that the efficiency is increasing slightly at speeds lower than the motor rated base speed, indicating that the controller performs better at these speeds. However, when the motor operates at the rated speed, the efficiency shows a slight decrease. This reduction may be due to the controller being unable to compensate for the resistance imbalance due to the increased resistance exceeding the motor specification for one phase.

Figures 9 and 10 show the results from vibration and IAS speed analysis on the motor. No noticeable differences were observed from each test data run. This is inconsistent with previous findings that the vibration increases with unbalanced supply conditions. The reasons behind may be due to the speed adjustment performance of the drive system.

Fig. 9. Effect of resistance increase on rotor vibration

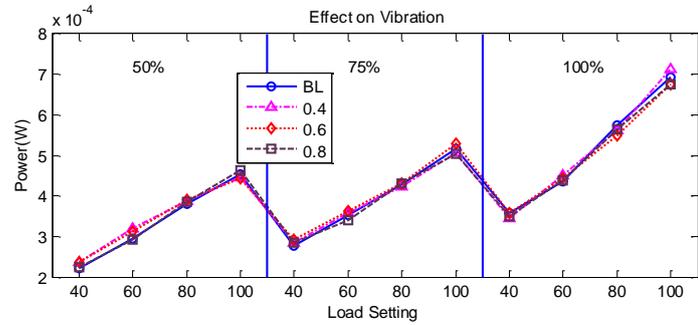
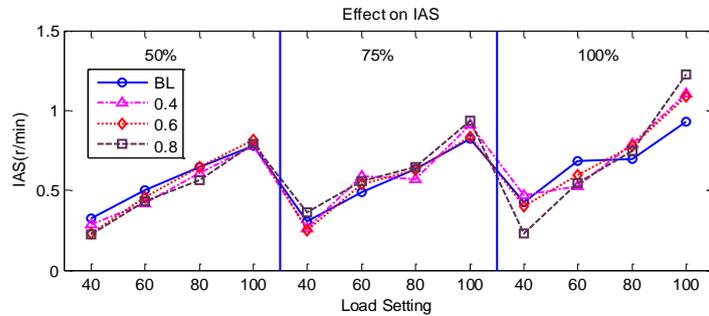


Fig. 10. Effect on rotor instantaneous angular speed



6.0 Conclusion

Initial results taken from the baseline and faulty data sets for the two resistance placements indicate that the small resistance increases in the stator windings of 0.2Ω increments from 0.4Ω to 0.6Ω can be readily observed by voltage and current imbalances in the supply. This change of resistance also leads to a slight increase in motor efficiency at the speed range below the motor rated speed, whereas there is a reduction in efficiency at the rated speed.

The small difference in IAS and vibration could be attributed to the inverter drive operating in sensorless vector control mode. This is likely to result in the rotor speed being maintained more accurately than for a Volts/Hertz unit. More tests are required under the two different inverter modes to confirm this behaviour.

At the time of writing, the motor temperature measurements based on internal (the motor thermistor included as standard) and external measurements have been inconclusive with respect to the efficiency decreases at full load but further tests will be carried out with a view to correlating this temperature data with efficiency reductions.

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