Acquisition of Current and Vibration Data for Rewound Burnt Three-Phase Induction Motor

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ABSTRACT: Induction motors are used in the industries for various applications because they are reliable and rugged. However, late detection of faults and inappropriate maintenance of the machine often leads to damage of the windings which results in production losses and outright replacement. This study presents the use of a data acquisition system (DAS) to acquire current and vibration data of re-designed and re-wound burnt three-phase induction motor for the purpose of the motor faults analysis. The designed number of turns per pole per phase is 253 turns which were distributed in four slots per phase at 64, 63, 63 and 63 turns respectively. The DAS developed was used to acquire the current and vibration data at both normal and fault conditions through tapings prepared for the purpose. The average value of normal current data in the red, yellow and blue phases from the sampled data are 3.4 A, 3.1 A and 2.7 A respectively. The average currents during short circuit between phase A and phase B are 11.3 A and 12.2 A respectively while vibration fault data stands at 1.62. Also, for the inter-turn short circuit in phase A, the average value of the currents in the phases are 12.1 A, 3.1 A and 2.7 A respectively. The Mean Square Error value of the acquired and measured data is 0.00002.

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Induction motors are broadly used in industries among electric machines because they are reliable and rugged. Thus, they are referred to as the workhorse of industries due to their use in various applications. Natural ageing and other factors such as misuse, late detection of faults and inappropriate maintenance of this machine often lead to repair or damage which results in production losses and outright replacements (Al-Ali and Dabbousi, 2013). These losses may be prevented or reduced if the conditions of the motor are monitored in real time rather than conventional manual inspection/testing. The cost incurred due to unexpected breakdown could be very high as a lot of other equipment depend on continuous and parallel operation of induction motors in the industries (Subha, 2018). Hence, there is a need for adequate real time monitoring and fault diagnoses in order to prevent damage and total breakdown since induction motors are expensive to replace. Real time monitoring is possible if data of parameters relating to the performance of the machines are acquired and processed. Among several parameters that can aid fault analysis/monitoring of the machine, current and vibration data stand out and play a significant role in that they give an opportunity to diagnose, in advance, any faults or failures in the machines (Doolan et. al, 2017). Thus, the availability of these parameter’s data are important to studying the machine’s characteristic and behaviour which, are necessary indices for fault monitoring and detection. One of the most common faults in induction motors is the stator fault which accounts for 30-40% of failures in the machine (Siddique et. al., 2005). Stator fault could be as a result of a failure in the stator winding which includes phase to phase short circuit and inter-turn short circuit. These faults need to be detected at the incipient stage before they damage the machine windings and consequently break down the motor. To achieve this, the current and vibration data that give vital information about the status of the machine, for both normal and faulty operating conditions are required. These data can be accessed using the data acquisition system. Data acquisition system (DAS) involves the sampling of signals which measure real world physical conditions and converting the sampled signal into numeric values that can be understood and operated upon by computer systems. It is made up of sensors/transducers, communication links, signal processing units, computers, database and software (Ofei, 2010; Park et. al., 2003). Various studies have proposed different DAS for different purposes. (Fisher and Gould, 2012; Lockridge et. al., 2016; Mandal and Singh, 2017; Sarma et. al., 2018). Although, there exist data acquisition equipment and

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data logger which could be used to acquire current and vibration data from the machine as well as log the data into a storage device or computer system, these are often expensive and out of reach when required for laboratory experiments. This has necessitated the need to develop a low-cost data acquisition system that can work efficiently for acquiring these data as well as processing them for further usage. In this study, a DAS based on microprocessor is developed to acquire the current and vibration data of the induction motor. Accordingly, the objective of this study is to design and develop a data Acquisition system for current and vibration data of rewound burnt three-phase induction motor for fault analysis.

MATERIALS AND METHODS

Three-phase Induction Motor Winding Development:
Stator winding is significant in the operation of an induction motor in that they produce the magnetic field required for electromagnetic induction to take place in the induction motors when excited by voltage source (Gupta, 2009). In this study, the winding of a bad/burnt/disuse three-phase motor was re-designed and rewound in order to simulate faults and acquire the data of such faults for the analysis and performance of the motor.

Table 1: Measured values from disused motor

| Symbol | Meaning               | Dimension (mm) |
|--------|-----------------------|----------------|
| L_s    | Axial length of stator| 85             |
| D_s    | External diameter of  | 125            |
| D      | Bore diameter of stator| 75.5          |
| w_1, w_2 | Width of stator slot | 6.621          |
| h_s    | Height of stator slot | 13.3           |
| w_0    | Opening of stator slot| 2              |
| h_n    | Height of slot "neck" | 0.64           |
| w_t    | Tooth width           | 3.98           |

Three phase induction motor (TPIM) consists of three stator windings designed to operate at the same voltage levels. The design is affected by various constraints such as thermal limit and utility of stator slots. To design the number of winding in a machine, the bore diameter and axial length of the machine’s stator are essential. These values were measured from the bad motor via the vernier calliper and tabulated in Table 1.

Relevant mathematical equations for the winding design

(a) Number of pole pairs, P

\[ P = \frac{60 \times f}{N_s} \]  

Where P is the number of pole pairs, f is the nominal frequency and N_s is the rotation speed of the magnetic filed

(b) Number of slots per pole and phase, \( S_p \)

\[ S_p = \frac{S}{2 \times P \times m} \]

Where \( S_p \) is the number of slot per pole and phase; S is the number of slot; P is the number of pole pairs and m is the number of phases in winding

(c) Cross section area of teeth of one pole (cm²), \( A_t \)

\[ A_t = \frac{S \times w_1 \times l_z}{2 \times P} \]

l_z = clean iron length

(d) Yoke cross sections area (cm²), \( A_y \)

Yokecrosssection=heightof statoryoke \times cleanironlength

Clean iron length is conventionally assumed to be 80.04 for stators.

Table 2: Winding factor of different phase slot

| S_p   | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|-------|----|----|----|----|----|----|----|----|
| K_w1  | 1  | 0.966 | 0.960 | 0.958 | 0.957 | 0.956 | 0.956 | 0.955 |

Source: (“Neven Srh Elektromotor” by Pogoni, 2007) and (instructable by Niko)

(e) Magnetic flux per pole, \( \Phi \)

\[ \Phi = \frac{B_\Phi \times d_p \times 10^{-4}}{1.57} \]  

(f) Winding Factor

Table 2 shows the winding factor and their corresponding number of slots per pole.

Winding factor \( K_w1 = 0.958 \) corresponding to number of slot per pole and phase, \( S_p = 4 \)
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(g) Number of turns \( N_t \)

Number of turns is a function of the working voltage, the flux and some constants, is derived from the output equation expressed as

\[
\text{Output in KVA} = 3 \times (V_p) \times (I_p) \times 10^3 \quad (5)
\]

Where the input voltage per phase \( V_p \) is expressed as

\[
V_p = 4.44 f N_t \Phi K_{wl}
\]

\[
\text{KVA} = 3 \times 4.44 f N_t \Phi K_{wl} \times 1_p \times 10^3 \quad (6)
\]

\[
N_t = \frac{V_p}{4.44 \times f \times \Phi \times K_{wl}} \quad (7)
\]

\( \Phi \) is flux/pole, \( f \) is the nominal frequency (Hz)

(h) Number of turns per phase;
= number of turns/phase/pole \times number of pole

(i) Number of turns per slot;
= \frac{\text{No of conductor per phase per pole}}{S_p} \quad (8)

(j) Total number of turns in the whole slots;
= Number of turns per phase \times number of phases

(k) Conductor Size
Having calculated the number of turns per pole, next is the selection of the conduction size. This could be achieved using the slot fullness approach.

Slot fullness approach uses the slot surface as well as the filling factor

(l) Slot surface, \( A_s \)
Slot surface depends on the shape of the slot

\[
A_s = \frac{\pi}{8} \left(w_1^2 + w_2^2\right) + \frac{h}{2} \left(w_1 + w_2\right) \quad (9)
\]

(m) Determine the Filling Factor

Figure 2. Show the graph for selecting suitable filling factor (Instructable by Niko)

Filling factor of 0.34 was selected from the graph above based on the slot surface \( A_s \) of 93.4. Filling factor must be between the upper and bottom recommended line.

(n) Cross section area of the wire, \( A_v' \)

\[
A_v' = \frac{A_u \times f_u}{S_u} \quad (10)
\]

\[\text{Fig 1: Stator Slot Surface}\]

\[\text{Fig 2: Graph of filling factor}\]

Where \( A_v \) is the cross section of the wire, \( A_u \) is the slot surface, \( f_u \) is the filling factor and \( S_u \) is the number of turns in gap

(o) Thickness of wire, \( D \)

\[
D = 2 \times \sqrt{\frac{A_v}{\pi}} \quad (11)
\]

Using equations 1 to 11, the values of the re-designed motor is shown in Table 3 while the winding development is illustrated in Figure 3.

| S/N | Parameters                          | Values |
|-----|------------------------------------|--------|
| 1   | Number of pole pair                | 1      |
| 2   | Number of slots per pole per phase | 4      |
| 3   | Winding Factor                     | 0.9804 |
| 4   | Number of turns per pole per phase | 253    |
| 5   | Number of turns per slot           | 63     |
| 6   | Slot surface                       | 93.4mm |
| 7   | Winding Filling Factor             | 0.34   |
| 8   | Cross section area of the wire     | 0.504mm² |
| 9   | Diameter of the wire               | 0.8mm  |
The rewound motor involves disassembly of the motor; removal of windings; insulation of the slots; coil making; insertion of the coil into the appropriate slots; making necessary tapping for fault simulation and connection. Some of these steps are illustrated in Figure 4. Materials and tools used to achieve the aforementioned steps are copper wire, lacquer insulation (slot liner), thread, plier, coil packer, wood hammer, scissors, spanner, soldering iron and winding machine.

The motor was coupled after various connections and necessary fault simulations tapping have been extended out from the motor. In the process, adequate care was taken not to damage the most delicate parts such as winding insulation. In addition, ground and open circuit tests were carried out to ascertain the functionality of the motor before it was connected to the power source.

**Data Acquisition System for Current and Vibration Data:** Data acquisition system was developed for the rewound induction motor. It consists of four steps; circuit design and components layout; selection of appropriate components; programming and compilation of the programmed code on the Arduino board; Calibration of sensors and testing of the DAQ system. Figure 5 shows the block diagram of the experimental set up for data acquisition. The data of interest that were acquired are the current and vibration data that signifies the status of the machine in real time.

An Arduino Uno board based on Atmega328 chip microcontroller was used as the main signal processor. It consists of fourteen digital input/output pins, six of which can be used as pulse width modulation outputs. It also has six analogue inputs, each having a resolution of 10 bits and 16 MHz crystal oscillator which supplies the desired frequency to the system. It operates on a power supply of 5V and has a 32kB flash memory (Atmega328p, 2015). An analogue current sensor ACS712ELC-30A (range: ± 30A based on the output of 66mV/A) shown in Figure 6 was used. (ACS712 Datasheet, 2007). The MEAS Vibration sensor used is a piezoelectric film which generates a certain level of voltage with mechanical strain. It generates approximately 0.2V per micrometre of movement it is subjected to (MEAS-SPEC, 2010).
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Figure 7 shows the circuit diagram of the DAQ device. Three current sensors, ACS712 of 30A range are connected to the analogue pins of the Arduino board, A1, A2 and A3 in series to the machine. The piezoelectric film is also connected to an analogue input through 1MΩ resistor which serves as a current limiter for the Arduino board in order to prevent the board from exceeding the 5V handling limit. The voltage data read by the Arduino board is in bits and was converted into voltage using equation 12

$$ V_{out} = \frac{reading \times 5}{1023} \quad (12) $$

Where $V_{out}$ represents the output voltage produced by the piezo-disk.

The Arduino board operates based on 9V voltage supply and manage the data readings of the sensors with Atmega328p chip as a controller and signal processor.

Figure 8 shows a display of the programming code written in C++ language in the Arduino IDE software (Arduino Products, 2019).

The programming code was uploaded unto the Arduino board via a USB cable after it was debugged for any error. The acquired data is transferred from the board through the USB cable as well.

Test rig: Figure 9 shows a picture of the DAQ experimental setup. It consists of a 1.5hp three-phase rewound induction motor with its
windings extended on each phase for the purpose of short circuit faults simulation. The current sensors are connected in series with the induction machine and the vibration sensor is attached directly to the surface of the machine. The Arduino board was connected to the PC through a USB cable for programming code uploading and data acquisition. The acquired data is displayed on the computer in the Arduino IDE environment through its serial monitor.

**RESULTS AND DISCUSSIONS**

The samples of current and vibration data acquired via the developed data acquisition system are shown in Table 4 to Table 6.

**Table 4. Sample of Acquired data under normal condition**

| Red phase current (A) | Blue phase current (A) | Yellow phase current (A) | Vibration | Time (ms) |
|-----------------------|------------------------|--------------------------|-----------|-----------|
| 3.37                  | 3.09                   | 2.72                     | 1.1       | 3032      |
| 3.37                  | 3.11                   | 2.72                     | 1.03      | 6132      |
| 3.4                   | 3.11                   | 2.72                     | 1.1       | 9234      |
| 3.4                   | 3.16                   | 2.67                     | 0.91      | 12335     |
| 3.4                   | 3.11                   | 2.72                     | 0.91      | 15436     |
| 3.37                  | 3.09                   | 2.72                     | 0.91      | 18538     |
| 3.35                  | 3.09                   | 2.72                     | 0.89      | 21638     |
| 3.35                  | 3.06                   | 2.72                     | 0.89      | 24738     |
| 3.37                  | 3.06                   | 2.72                     | 1.01      | 27840     |
| 3.37                  | 3.09                   | 2.67                     | 0.71      | 30941     |
| 3.4                   | 3.09                   | 2.67                     | 1.12      | 34041     |

**Table 5. Sample of acquired data under an inter-turn fault condition in the red phase**

| Red phase current (A) | Blue phase current (A) | Yellow phase current (A) | Vibration | Time (ms) |
|-----------------------|------------------------|--------------------------|-----------|-----------|
| 11.15                 | 3.09                   | 2.72                     | 1.58      | 151886    |
| 12.12                 | 3.11                   | 2.72                     | 1.86      | 154988    |
| 13.26                 | 3.11                   | 2.72                     | 1.76      | 158089    |
| 12.81                 | 3.16                   | 2.67                     | 1.91      | 161191    |
| 11.56                 | 3.11                   | 2.72                     | 1.87      | 164293    |
| 12.27                 | 3.09                   | 2.72                     | 1.73      | 167394    |
| 12.56                 | 3.09                   | 2.72                     | 1.91      | 170494    |
| 11.54                 | 3.06                   | 2.72                     | 1.87      | 173596    |
| 12.35                 | 3.06                   | 2.72                     | 2.02      | 176698    |
| 12.45                 | 3.06                   | 2.67                     | 1.91      | 179799    |
| 12.11                 | 3.09                   | 2.67                     | 1.88      | 182900    |
| 11.56                 | 3.09                   | 2.72                     | 1.88      | 186002    |

In particular, Table 4 shows the normal current and vibration data. It is observed that the current values in the phases are not the same. The red phase ranges from 3.35 to 3.4 ampere while the blue phase is from 3.06 to 3.11 ampere.

The yellow phase reading is the lowest and ranges between 2.67 and 2.72 amperes. This is not unconnected to the unbalance in the value of the three phases supply voltages. In addition, the vibration data is between 0.71 and 1.12. Table 5 shows the current and vibration data during the inter-turn fault in the red phase. It is observed that the current values in the shorted phase increases abnormally and ranges from 11.15 to 12.81 amperes while the blue and yellow phase reading remains normal. In addition, the vibration data under this fault increases and ranges from 1.58 to 2.02. Table 6 shows the current and vibration data during phase to phase fault in red and blue phase. During phase to phase fault, the current in the red phase ranges from 9.99 to 13.09 ampere and the blue phase ranges from 11.10 to 12.65 amperes, while the yellow phase current remains normal. In addition, the vibration data under this fault increases and ranges from 1.56 to 1.78.

**Data Validation:** The values of the current data were validated with a standard digital multimeter to get rid of possible discrepancies in the reliability of acquired data. The sample of the data is plotted in Figure 10 and the validation error based on Mean Square Error is $2 \times 10^{-5}$.

**Conclusion:** A three-phase induction motor stator winding has been re-designed and rewound for the purpose of stator phase-to-phase and inter-turn short circuit faults analysis. Data acquisition system was developed and used to acquire the current and vibration data under both normal and faults conditions.
The acquired data were validated and would be useful for the study of stator faults analysis of the three-phase induction motor.

Table 6. Sample of acquired data under phase to phase short circuit condition in red and blue phases.

| Phase-to-phase short circuit condition | Red phase current (A) | Blue phase current (A) | Yellow phase current (A) | Vibration time (ms) |
|---------------------------------------|-----------------------|------------------------|-------------------------|--------------------|
| 13.09                                 | 12.35                 | 2.72                   | 1.56                    | 158089             |
| 11.04                                 | 12.58                 | 2.72                   | 1.67                    | 161191             |
| 10.33                                 | 11.74                 | 2.72                   | 1.73                    | 164293             |
| 12.32                                 | 11.11                 | 2.67                   | 1.43                    | 167394             |
| 10.93                                 | 12.03                 | 2.72                   | 1.68                    | 170494             |
| 9.99                                  | 12.42                 | 2.72                   | 1.63                    | 173596             |
| 10.09                                 | 12.45                 | 2.72                   | 1.4                     | 176698             |
| 11.38                                 | 12.32                 | 2.72                   | 1.78                    | 179799             |
| 11.6                                  | 12.65                 | 2.72                   | 1.75                    | 182900             |
| 12.63                                 | 12.49                 | 2.67                   | 1.62                    | 186002             |
| 11.25                                 | 12.05                 | 2.67                   | 1.62                    | 189103             |

Fig 10: Current sensor validation

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