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Induction Motor Fault Diagnosis by Motor Current Signature Analysis and Neural Network Techniques

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***Abstract*—Early detection of faults occurring in three-phase induction motors can appreciably reduce the costs of maintenance, which could otherwise be too much costly to repair. Internal faults in three phase induction motors can result in significant performance degradation and eventual system failures. Artificial intelligence techniques have numerous advantages over conventional Model-based and Signal Processing fault diagnostic approaches; therefore, in this paper, a soft-computing system was studied through Neural Network Analysis to detect and diagnose the stator and rotor faults. The fault diagnostic system for three-phase induction motors samples the fault symptoms and then uses a Neural Network model to first train and then identify the fault which gives fast accurate diagnostics. This approach can also be extended to other applications.**

***Index Terms*—Condition Monitoring, Fault Diagnosis, Induction Motor, Neural Network, Signature Analysis.**

I. Introduction

INDUCTION motors as electrical machines offer most versatility in industry due to their low cost, ruggedness, low maintenance, and easy operation and control. Although they are very reliable, they may encounter different types of failures/faults. These faults may be inherent to the machine itself or due to operating conditions of the motor. Mechanical or electrical forces are mostly responsible for failures. A variety of machine faults have been studied in the literature [1, 2] such as winding faults, unbalanced stator and rotor parameters, broken rotor bars, eccentricity and bearing faults.

Recently soft computing techniques such as expert system, neural network, fuzzy logic, etc. have been employed [3, 4, 5] to correctly interpret the fault data with proper analysis. Their improved performance apart from the ease of application and modification for various machines and fault scenarios make them extremely popular for diagnostic purposes. The use of above techniques increases the precision and accuracy of the monitoring systems. Condition monitoring of electrical machines and associated drives is a large arena which is inter-linked with different subjects like signal processing and intelligent systems, methods of monitoring, and associated instrumentation.

II. Faults in Three-Phase Induction Motors

Induction motors are very popular in industry and ruggedly used. Due to this reason, these types of motors also undergo various types of faults, mostly of electrical and mechanical nature. Different types of faults are shown in Fig. 1. They are short circuits in stator windings, open-circuits in stator windings, broken rotor bars and broken end rings. The effects of these faults are various, some of them being unbalanced stator voltages and currents, torque oscillations, efficiency reduction, overheating, excessive vibration, and torque reduction.

This section is focused on four types of induction motor faults, namely: broken rotor bars, inter-turn short circuits in stator windings, bearing faults and air – gap eccentricities.

A. Broken Rotor Bars

An induction motor has two parts – stator and rotor. The rotor has bars with slots for the rotor windings and end rings to short the ends of the windings. The rotor bars may crack or break due to a lot of reasons (explained in detail later), which gives rise to broken rotor bars.

A broken bar causes several effects in induction motors. A well-known effect of a broken bar is the appearance of the so-called side-band components in the frequency spectrum of the stator current. These are found on the left and right sides of the fundamental frequency component. Consequent speed ripples caused by the resulting torque pulsations [6] gives rise to the right side band and the lower side band component is caused by electrical and magnetic asynchronies in the rotor cage of an induction motor [7]. The frequencies of these sidebands are given by:

$$f_b = (1 \pm 2s)f \qquad (1)$$

where s is the slip in per unit and f is the fundamental frequency of the stator current (power supply). Other electric effects of broken bars are used for motor fault classification purposes including speed oscillations, torque ripples,

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instantaneous stator power oscillations, and stator current envelopes.

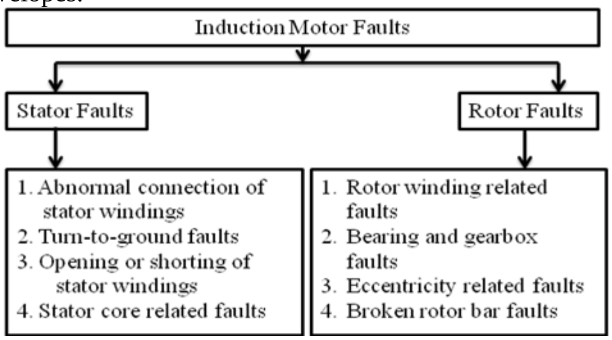


Fig. 1. Types of Induction Motor Faults

B. Inter – turn short circuits of stator windings

Short circuits in stator windings are most common in induction motors. Generally, short circuits in stator windings occur between turns of one phase, or between turns of two phases, or between turns of all phases. Moreover, short circuits between winding conductors and the stator core also occur. The different types of winding faults are summarized below as follows:

1) Inter-turn short circuits between turns of the same phase (Fig. 2a), winding short circuits (Fig. 2b) , short circuits between winding and stator core (Fig. 2c and Fig. 2d), short circuits on the connections (Fig. 2e), and short circuits between phases (Fig. 2f) are usually caused by voltage transients and abrasion.
2) The winding insulation and consequent complete windings are short circuited in the event of burning which are usually caused by motor overloads and blocked rotor, as well as lower/ higher rated voltage supplied to the stator. This type of fault can be caused by frequent starts and rotation reversals. These faults are shown in Fig. 3a and 3b.
3) Short circuits of the stator windings are also due to voltage transients as shown in Fig. 3c that can be caused by the successive reflection resulting from cable connection between motors and ac drives. These drives produce extra voltage stress on the stator windings due to the swings of the voltage applied to the stator windings. Again, long cable connections between a motor and an ac drive can induce motor over voltages.
4) Complete short circuits of one or more phases can occur because of phase loss, which is caused by an open fuse, contactor or breaker failure, connection failure, or power supply failure. Such a fault is shown in Fig. 3d and 3e.
5) Short circuits in one phase are usually due to an unbalanced stator voltage, as shown in Fig. 3f. Voltage imbalance is caused by an unbalanced load in the power line, anomaly in the connection of the motor terminals or in the power circuit.

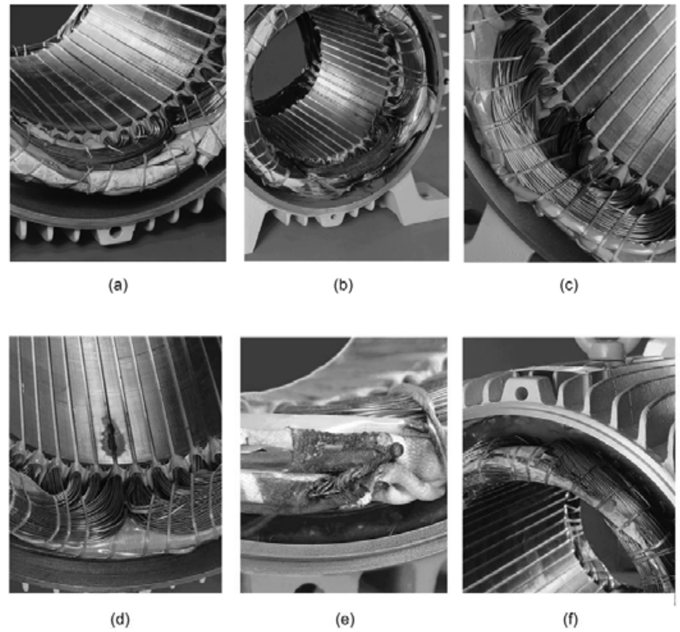


Fig. 2. Typical insulation damage leading to inter-turn short circuit of the stator windings in three-phase induction motors. (a) Inter-turn short circuits between turns of the same phase. (b) Winding short circuited. (c) Short circuits between winding and stator core at the end of the stator slot. (d) Short circuits between winding and stator core in the middle of the stator slot. (e) Short circuit at the leads. (f) Short circuit between phases. [Courtesy of Electromotors WEG SA, Brazil]

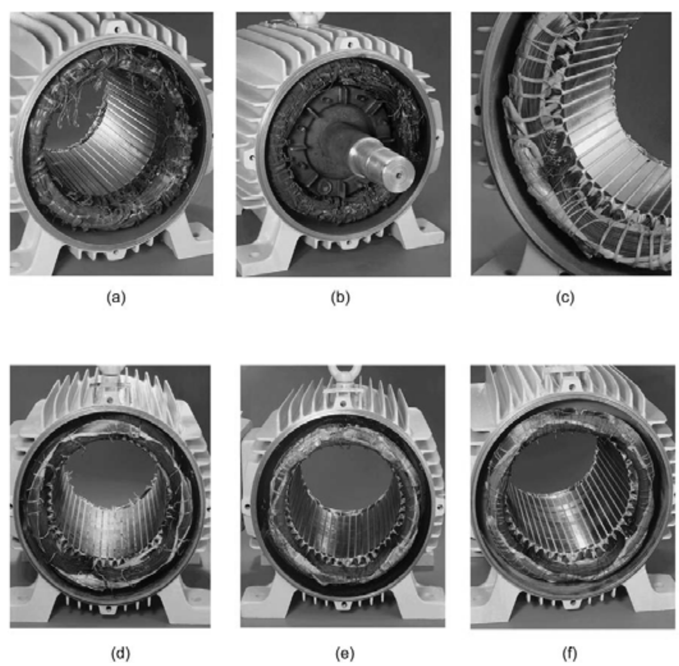


Fig. 3. Inter-turn short circuit of the stator winding in three-phase induction motors. (a) Short circuits in one phase due to motor overload (b) Short circuits in one phase due to blocked rotor. (c) Inter-turn short circuits are due to voltage transients. (d) Short circuits in one phase due to a phase loss in a Y-connected motor. (e) Short circuits in one phase due to a phase loss in a delta-connected motor. (f) Short circuits in one phase due to an unbalanced stator voltage. [Courtesy of Electromotors WEG SA, Brazil]

C. Bearing Faults

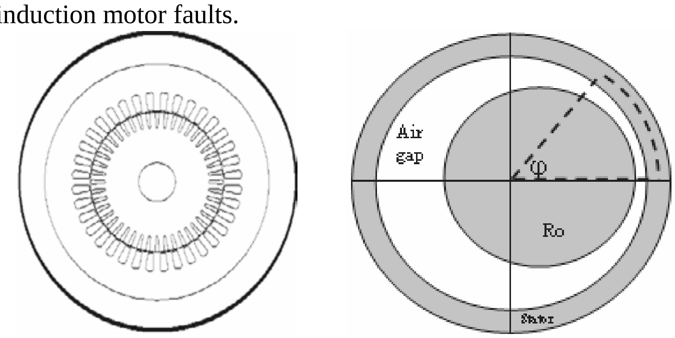
Bearing faults account for almost half of all motor failures. Although motor bearings may cost between a tenth of the actual cost of the motor, but the costs involved in stalled production combine to make bearing failure rather expensive. Ball-bearing related defects can be categorized as ball defects, outer bearing race defects and inner bearing race defects.

A bearing has different stresses acting upon it, leading to excessive audible noise, uneven running, reduction in working precision, and mechanical vibrations and as a result, increased wear and tear. More than twenty years ago, few bearing failures were electrically induced but at the beginning of the 90's a study showed that bearing failures are about 12 times as common in converter – fed motors as in direct on – line motors. However mechanical issues remain the major cause of bearing failure.

D. Air – gap eccentricities

Any mechanical fault leads to stator and rotor imbalances. This is due to the development of non-uniformity of the air-gap, which is a result of the rotor and stator axes falling out of synchronism. Of course, this eccentricity may occur during the process of manufacturing and fixing the rotor. There is different eccentricity including static, dynamic and mixed. When the static eccentricity occurs, the rotor rotational axis coincides with its symmetrical axis, but has displacement with the stator symmetrical axis. In this case, the air gap around the rotor misses its uniformity, but it is invariant with time. Fig. 4a shows the cross section of the proposed induction motor and Fig. 4b exhibits the corresponding figure with static eccentricity.

In practice, the air gap magnetic field can be measured by a small search coil where a sensor is fixed in the air gap and the noise effect upon the sent signals is eliminated. Winding function method (WFM), equivalent magnetic circuit method (MECM) and finite element method (FEM) are the three most popular methods used for modelling, analysing and diagnosing induction motor faults.



(a) (b)

Fig. 4. (a) Cross-section of proposed induction motor. (b) Cross-section of stator and rotor positions with static eccentricity.

III. INDUCTION MOTOR FAULT DIAGNOSTIC METHODS

In this section, a discussion of the features of induction motors used in the diagnostic and monitoring methods to classify motor faults is presented. The method classifies broken rotor bars and inter-turn short circuits in stator windings and also identifies the fault severity. The most commonly used traditional diagnosis methods are the motor current signature analysis (MCSA) [8], wavelet analysis [9], which require complicated signal pre-processing like fast Fourier transformation (FFT) or wavelet transformation (WT) and demodulation of the voltage and/or current. Several other techniques are used which are depicted in Fig. 5.

Normally, Phases A, B, and C are balanced in a healthy motor, so when the balance is lost, the motor must have a fault, with absolute phase value difference (APVD) [10] used to reflect this fault. For example, Table 1 lists experimental voltage data and Table 2 lists the corresponding APVD for healthy motor and motor with various faults [10].

The next sub-sections discuss the most common type of fault detection diagnostic method using the MCSA for broken rotor bars and application of neural networks for detection of short circuits in stator windings.

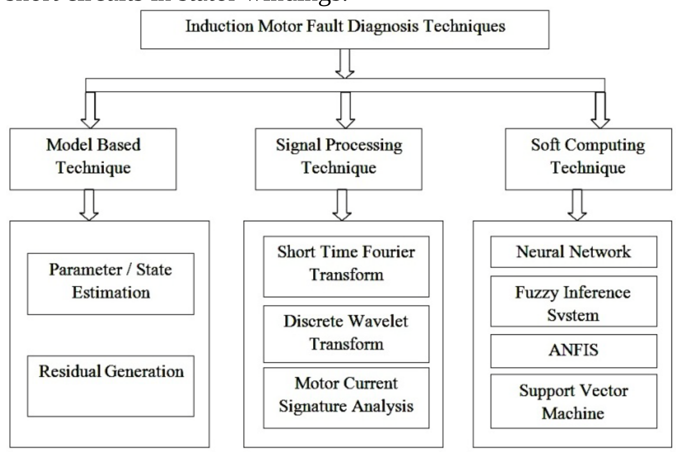


Fig. 5. Types of Fault Diagnosis Techniques of Induction Motor

TABLE I
Voltage data of healthy and faulty motors

Condition		**Voltage (V)**		
State	**Fault**	**Phase A**	**Phase B**	**Phase C**
Healthy State	N/A	129.100	129.400	129.700
Stator Fault	One phase short circuit	127.825	126.844	128.324
	Two phase short circuit	127.420	127.537	126.450
	Three phase short circuit	147.027	145.265	149.242
Rotor Fault	One bar broken	121.008	128.665	127.140
	Two bars broken	125.233	132.782	131.071
	Three bars broken	123.584	131.571	130.140

TABLE II
APVD of the voltages in healthy and faulty motors

Condition		**APVD of the Voltage (V)**			**Average APVD of the voltage (V)**
State	**Fault**	**Phase AB**	**Phase BC**	**Phase CA**	
Healthy State	N/A	0.300	0.300	0.600	0.400
Stator Fault	One phase short circuit	0.981	0.520	1.501	1.001
	Two phase short circuit	0.117	1.087	0.970	0.725
	Three phase short circuit	1.762	3.977	2.215	2.651
Rotor Fault	One bar broken	7.657	1.525	6.132	5.105
	Two bars	7.549	1.711	5.838	5.033

	broken				
	Three bars broken	7.987	1.431	6.556	5.325

A. *Motor Current Signature Analysis (MCSA)*

MCSA is a frequently used method for analysing faults of induction motors. Whenever a fault occurs in a three-phase induction motor, it is mostly due to broken rotor bars, air-gap anomalies and stator windings short circuits. As a result of these faults, various magnetic flux components are produced in the magnetic circuit of the induction motor. This gives rise to harmonic components in the line current of the stator, which is detectable by current transducers and spectrum analysers. This method is very commonly used in industries and laboratories and it is very effective and cost efficient. Online monitoring can also be done by this method, that is, the motor can be monitored effectively when it is in operation. This reduces the risk of failure and damage.

Fig. 6 shows a current spectrum which is the result of broken rotor bars. The frequency sidebands near the main harmonic can be observed.

Different faults have different characteristics in their fault patterns, which gives rise to unique current signature patterns. For detecting the same, a decibel (dB) versus frequency spectrum is used [11, 12].

The reason for the appearance of the frequencies in the spectrum will be discussed next.

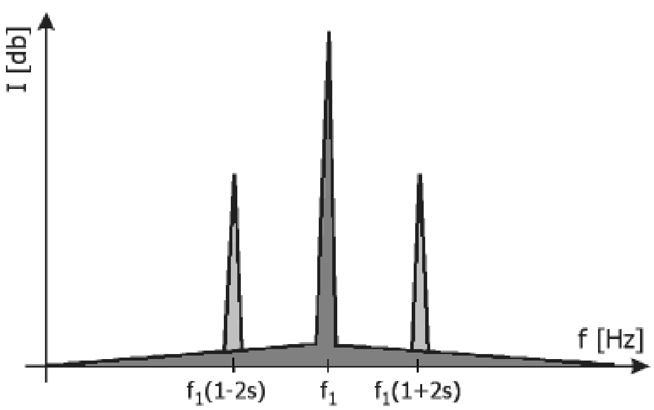


Fig. 6. Idealized Current Spectrum

In the three-phase induction motor under perfectly balanced conditions (healthy motor) only a forward rotating magnetic field is produced, which rotates at synchronous speed, $n_1 = f_1/p$, where $f1$ is the supply frequency and p the pole-pairs of the stator windings. The rotor of the induction motor always rotates at a speed (n) less than the synchronous speed. The slip, $s = (n_1 - n)n_1$, is the measure of the slipping back of the rotor regarding to the rotating field. The slip speed, $n_2 = n_1 - n = sn_1$ is the actual difference in between the speed of the rotating magnetic field and the actual speed of the rotor.

The frequency of the rotor currents is called the slip frequency and is given by:

$$f_2 = n_2 p = sn_1 p \tag{2}$$

The speed of the rotating magnetic field is given by:

$$n + n_2 = n + n_1 - n = n_1 \tag{3}$$

Both the stator and rotor fields are locked together and a steady torque is produced by the induction motor.

The broken rotor bars in the motor produces a backward rotating magnetic field apart from the already existing fields, which rotates at the slip speed with respect to the rotor.

The broken bars of the rotor results in the production of backward rotating magnetic field, the speed of which, with respect to the rotor is:

$$n_b = n - n_2 = n_1(1 - s) - sn_1 = n_1 - 2sn_1 = n_1(1 - 2s) \tag{4}$$

There is a rotating field now with respect to the stationary stator winding at:

$$n_b = n_1(1 - 2s) \tag{5}$$

which, in terms of frequency, is:

$$f_b = f_1(1 - 2s) \tag{6}$$

This means that a rotating magnetic field at that frequency cuts the stator windings and induces a current at that frequency (f_b). This in fact means that f_b is a twice slip frequency component spaced $2s\, f_1$ down from f_1 . Thus speed and torque oscillations occur at $2sf_1$, and this induces an upper sideband at $2s\, f_1$ above f_1 .

Classical twice slip frequency sidebands therefore occur at $\pm\, 2s\, f_1$ around the supply frequency:

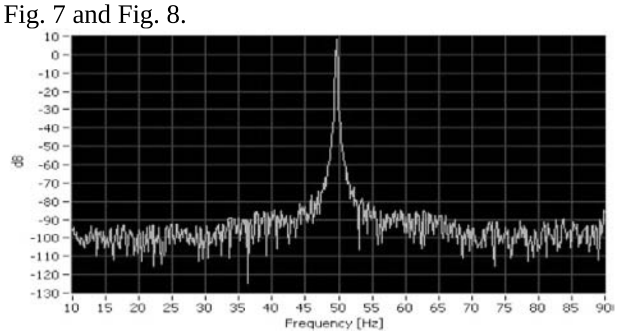
$$f_b = (1 \pm 2s) f_1 \tag{7}$$

While the lower sideband is specifically due to broken bar, the upper sideband is due to consequent speed oscillation. In fact, several papers show that broken bars actually give rise to a sequence of such sidebands given by equation [3]:

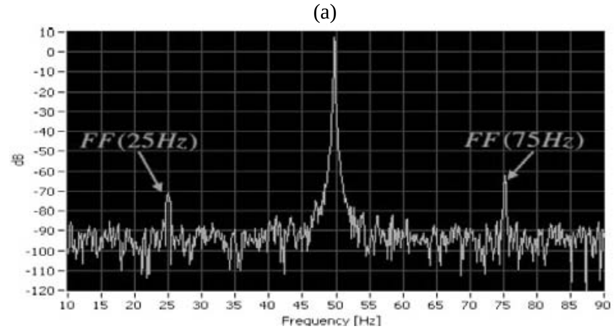
$$f_b = (1 \pm 2ks) f_1, k = 1,2,3, \dots \dots \tag{8}$$

Therefore the appearance in the harmonic spectrum of the sidebands frequencies given by (7) or (8) clearly indicates a rotor fault of the induction machine.

The spectral analysis of the stator current of a 0.5HP, 4-pole, 50 Hz induction motor [13] shows the results as depicted in Fig. 7 and Fig. 8.

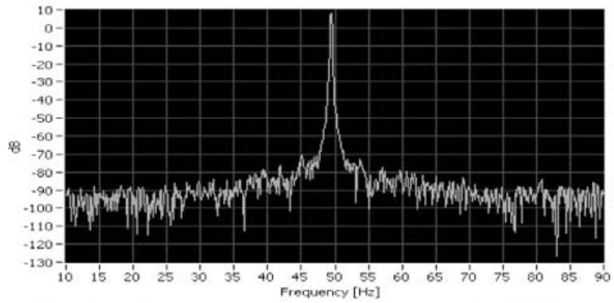


(a)

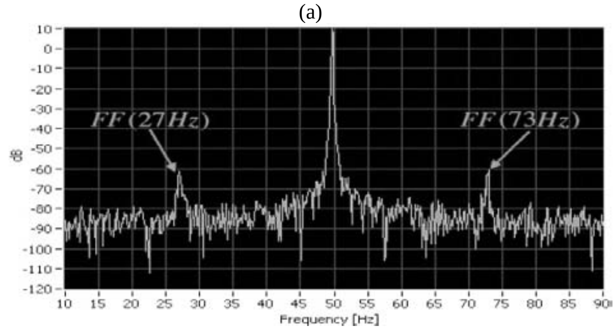


(b)

Fig. 7. (a) Power spectrum of healthy motor under no-load condition (b) Power spectrum of 30% short stator windings motor under no-load condition



(a)



(b)

Fig. 8. (a) Power spectrum of healthy motor under full-load condition (b) Power spectrum of 30% short stator windings motor under full-load condition

The above figures show the presence of harmonics in the motor current in case of short – circuited stator windings. For no – load, the harmonics due to the faults occur at 25 Hz and 75 Hz (Fig. 7b) and for full – load, the harmonics occur at 27 Hz and 73 Hz (Fig. 8b), whereas these harmonics are totally absent for a healthy motor, running at either no – load or full – load (Fig. 7a and Fig. 7b). It can also be noted that with increased load, the magnitude of fault frequency increases from about -70dB for no – load (Fig. 7b) to -60dB for full – load (Fig. 8b) conditions.

B. Neural Network approach for IM fault analysis

This system consists of detection and the location of a fault on the stator windings of a three phase induction motor by using the Neural Networks, which is the result of inter-turn short circuit. The Fig. 9 shows the block diagram of the fault location procedure in the stator winding of an induction motor.

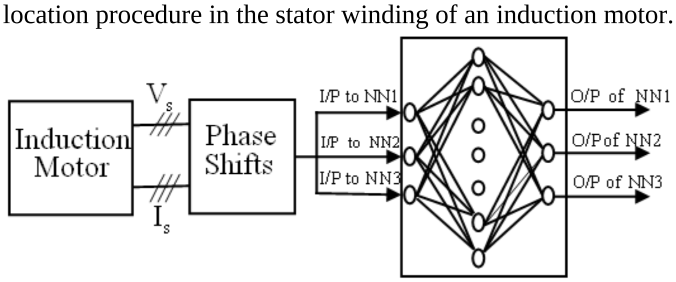


Fig. 9. Block diagram of the fault location procedure

This process starts with the acquisition of the three line currents and phase voltages from the induction motor in order to extract the three phase shift between the line currents and the phase voltages. The Neural Network is trained to identify the difference between the NNs inputs and outputs and map a relationship between them. The training is done on the basis of line current and phase voltage shifts on three-phase. The NNs output is zero (0) in healthy condition and one (1) when an inter-turn short circuit occurs.

There are three inputs of the neural network which is employed for fault detection. The input is done to the NN after phase shift. The three outputs vis-à-vis the 3-phase induction motor is used for reading the result : zero for normal and one for short circuit fault, if detected [14]. The schematic is shown in Fig. 9.

The induction motor used for obtaining the following experimental data is a 2-HP, 400V, 4-pole SRIM. The details of the motor's nameplate has been given in Table III.

TABLE III
INDUCTION MOTOR CHARACTERISTICS

Power (HP)	2
Voltage (V)	220 / 400
Current (I)	13.63 / 3.75
Speed (r/min)	1410
Number of poles	4
Number of coils / phase	12
Number of turns per coil	46
Type of stator windings	Double layer, Lap
Number of stator slots	36

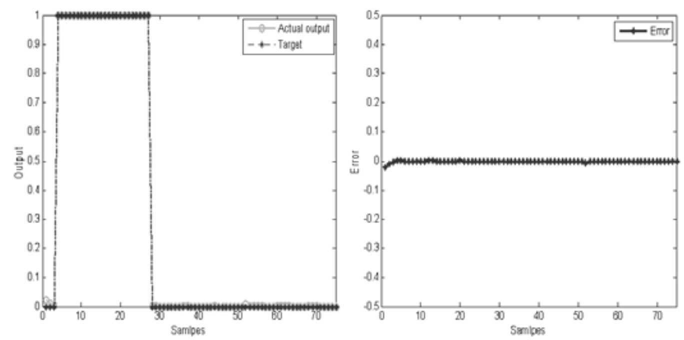


Fig. 10. (a) NN Output & error for fault on phase A

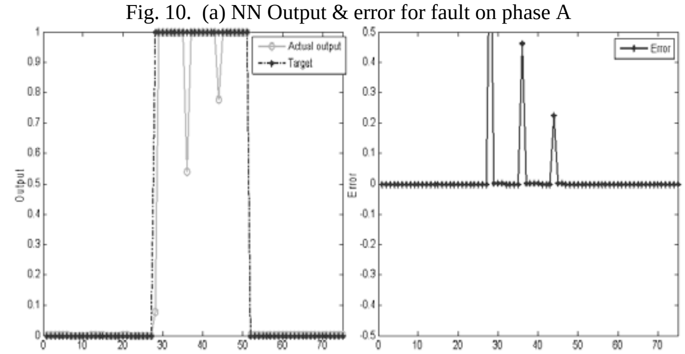


Fig. 10. (b) NN Output & error for fault on phase B

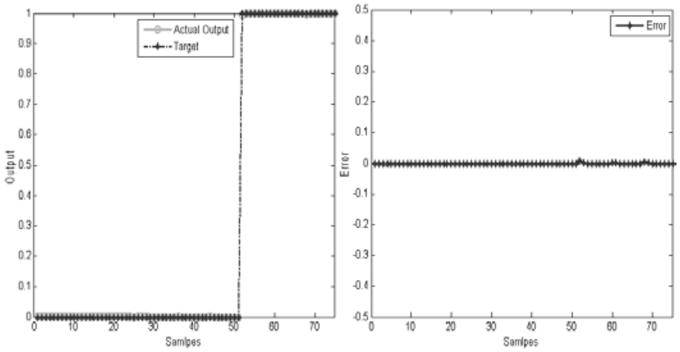


Fig. 10. (c) NN Output & error for fault on phase C

A fault occurring in phase A is signified by the output of that phase to be one and others to be zero. In Fig. 10(a), the output and percentage error of the NN is shown when fault occurs in phase A. The error is the calculation error of the NN in computing the target value. From the figure, we can see that the difference between the actual and target values is 9.1701 x 10^{-6}, which implies that the NN is capable enough to detect phase faults in induction motors.

The output and percentage error, when an inter-turn short circuit fault occurs on phase B of an induction motor, is shown in Fig. 10(b). From Fig. 10(b) it is clear that the error, which is the difference between the target value and the actual output, is 1.4800×10^{-2}.

Figs.10(c) depicts the output and percentage error when an inter-turn short circuit fault occurs on phase C of an induction motor. When a stator inter-turn fault occurs on phase C then the output of that phase is one and others are zero. From Fig. 10(c), it is clear that the NN has correctly reproduced the desired output. The error is 9.0743×10^{-7} as shown in Fig.10(c).

IV. Conclusion & Future Scope

The common types of faults and their diagnostic methods have been investigated in this paper. Various static factors, such as the load condition, saturation effect, imbalance of power supply, and motor misalignment can strongly affect the accuracy and speed of standard motor fault diagnostics. The statistical data reveals that –

(1) Fault detection using the stator phase current signature is the simplest and cheapest technique. However, it is significantly affected by motor loading (some rotor faults may not be detected at light loads). Hence, it is recommended to monitor more than one peak to improve the sensitivity of detection for some fault cases. Also detection of stator faults is quite difficult because of the narrow range of change of the detected peaks.

(2) Although some mathematical models have been developed, designing exact mathematical models for all possible faults in induction motors is not possible. Therefore, mathematical model-based diagnosis methods need to be replaced by mathematical model independent artificial intelligence (AI)-based methods, such as expert systems, Neural Networks, fuzzy logic, or various hybrids. Since the approach is based on test data, expert knowledge, and experience, the Neural Network can easily distinguish fault symptoms from static factors. The hardware-software system can quickly and accurately diagnose motor faults. The scheme can be used for other similar applications, such as fault diagnostics of other types of equipment and even the prognosis.

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