Simulation and Implementation for Detection and Protection of Stator and Rotor Faults in 3-Ph Induction Motor Using Wavelet Energy Approach

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Abstract. Induction motors are affected by many electrical faults that are caused by work stress. These faults need to be detected and treated during the first moments of its occurrence to avoid damage of these motors. In this work, an algorithm that based on wavelet packet transforms (WPT) and wavelet energy approach (WE) is proposed. The algorithm is developed depending on moving frame strategy to check the current motor signal with each digital sample. This algorithm is applied on two induction motors, the first represents modeling of induction motor in Matlab2019a while the second is an implementation of real 3-Ph induction motor. The results show accurate detection and diagnosis of the faults with high speed in isolating the power supply from the motor.

1. Introduction
The electrical motors are one of the dynamic loads in power systems which convert the electrical energy into mechanical energy to be utilized in different life fields. The electrical motors use 90% of electrical energy in power systems [1]. Moreover, the induction motors represent 90% of electrical motors because of the distinctive properties such as high reliability, low cost, simple constrain and relatively simple control. The squirrel cage induction motor has more importance than wounded rotor induction motor because of its strength and high efficiency [2]. Over the years, the protection systems on these motors have occupied a wide area of interest for researcher as protection requirement for these motors from damage. The protection system depends on studying the electrical equipment characteristics and operation conditions. There are many causes that make the protection system of electrical motors has less standardized from other electrical equipments such as different sizes, type of motors and different applications [3]. Therefore, it is necessary to develop an intelligent system to protect motors. The proposed protection system in this work depends on signal processing techniques and specifically using motor current signal analysis. The technique that is used in this work is wavelet energy based on WPT. Wavelet is a mathematical tool that transform continues data in time axis to spectral data in time-scale representation. In other words, the wavelet can be defined as a mathematical function that cutoff the signal to different components and then studies each frequency depending on a scale that adjusts itself according to the frequency. Many researches in the protection field are focusing on the type of signal processing techniques in their work. DWT and Hilbert transform (HT) is used as a method to diagnosis broken bars in the rotor of the induction machine [4]. The standstill frequency response (SSFR) is a method to diagnosis the induction motor faults that have been used by B. Bessam et al [5]. An extended Kalman filter (EKF) technique to detect and diagnosis the stator faults in induction motors has been suggested by W. W. Saad et al [6]. An artificial intelligence technique of type fuzzy logic has been proposed in [7] to detect the faults in the
rotor and the stator of induction motors. Shannon entropy index (SE) and artificial intelligence fuzzy logic techniques have been used in [8] to diagnosis the stator faults in induction machine.

2. Faulty and healthy modeling of 3-ph induction motor

In order to study the proposed algorithm and determine its effectiveness in the detection of electrical faults in induction motors, the modeling of induction motor for healthy and faulty conditions by Matlab environment has to be implemented.

2.1 Modeling of healthy condition

Depending on dynamic equations, the squirrel cage three phase induction motor equations can be written in state-space notation as following [9-11]:

- Flux equations for stator and rotor:

\[
\frac{dv_{d1}}{dt} = v_{d1} - id_1 \cdot R_1 + \omega_c \cdot \psi_{q1} \\
\frac{dv_{q1}}{dt} = v_{q1} - iq_1 \cdot R_1 + \omega_c \cdot \psi_{d1} \\
\frac{dv_{d2}}{dt} = -id_2 \cdot R_2 + (\omega_\tau - \omega_c) \cdot \psi_{q2} \\
\frac{dv_{q2}}{dt} = -iq_2 \cdot R_2 + (\omega_\tau - \omega_c) \cdot \psi_{d2}
\]

Where \(v_{d1,q1}\) are stator voltages in d-q axis, \(v_{d2,q2}\) are rotor voltages in d-q axis, \(R_1\) is the stator resistance, \(R_2\) is the rotor resistance, \(id_1,q1\) are the stator current in d-q axis, \(id_2,q2\) are rotor currents in d-q axis, \(\omega_\tau\) is the rotor speed, \(\omega_c\) is the synchronous speed, \(\psi_{d1,q1}\) are stator flux linkage in d-q axis, \(\psi_{d2,q2}\) are rotor flux linkage in d-q axis.

- The current equations:

\[
\begin{align*}
    id_1 &= \frac{1}{L_1} \cdot (\psi_{d1} - L_n \cdot id_2) \\
    iq_1 &= \frac{1}{L_1} \cdot (\psi_{q1} - L_n \cdot iq_2) \\
    id_2 &= \frac{1}{L_2} \cdot (\psi_{d2} - L_n \cdot id_1) \\
    iq_2 &= \frac{1}{L_2} \cdot (\psi_{q2} - L_n \cdot iq_1)
\end{align*}
\]

Where \(L_n\) are the stator, rotor and mutual inductances, respectively
The speed equation will be:

\[ \frac{d\omega_r}{dt} = \frac{P}{J}[\Psi_{d1}i_{q1} - \Psi_{q1}i_{d1}] - T_l \]  \hspace{1cm} (9)

Where \( P \) is the number of pole pairs, \( J \) is the moment of inertia, \( T_l \) is the load torque.

2.2 Modeling of the faults in stator side

The stator faults can be represented as new windings that have been added to the original windings of the stator, the mathematical equation of the faulty windings can be written as [12]:

\[ 0 = [R_{cc}]i_{cc} + \frac{d}{dt}\psi_{cc} \]  \hspace{1cm} (10)

Where \( i_{cc} \) represent the short circuit current, \( \psi_{cc} \) is the short circuit flux and \( R_{cc} = \eta_{cc}R_t \) is the short circuit resistance.

To detect the stator faults, two parameters can be added:

1- The localization parameter \( \theta \): which represent the angle between the windings resulting from fault with first phase winding (a) and the value of this angle is (0 or 120 or 240) according to the three phases (a, b, c).

2- The detection parameter \( \eta_{cc} \): which represent the percentage of inter-turn short circuit winding, where this ratio is produced by dividing the number of inter-turn short circuit winding on the total number of stator windings in one phase. The short circuit current is expressed under d-q axis frame as in the following equation [12]:

\[ i_{cc} = \frac{2}{3} \eta_{cc} p(-\theta).Q(\theta_{cc})p(\theta).\psi_{dqs} \]  \hspace{1cm} (11)

\[ P(\theta) = \begin{bmatrix} \cos(\theta) & \cos(\theta + 90) \\ \sin(\theta) & \sin(\theta + 90) \end{bmatrix} \]  \hspace{1cm} (12)

\[ Q(\theta_{cc}) = \begin{bmatrix} \cos(\theta_{cc})^2 & \sin(\theta_{cc}) \cdot \cos(\theta_{cc}) \\ \sin(\theta_{cc}) \cdot \cos(\theta_{cc}) & \sin(\theta_{cc})^2 \end{bmatrix} \]  \hspace{1cm} (13)

The equation of the stator faults (11) represents the fault in the stator on one of three phases but practically, if the fault was present in two phases or three phases, this equation cannot be used, to solve this problem, a new equation is proposed as follows

\[ i_{dqs} = i_{dqs} + \sum_{k=1}^{3} i_{ck} \]  \hspace{1cm} (14)

Where \( i_{dqs} \) represents the stator current in the normal conditions.

2.3 Modeling of faults in rotor side

Similarly to the stator faults, the rotor faults of induction motor can be represented as a new windings that have been added to the rotor electrical windings as such that [12]:
To detect the rotor faults in the induction motors, two parameters can be considered [12]:

1. The localization of the fault, which is represented by the angle ($\theta$), this angle is between the rotor broken bar axis and the first phase axis in the rotor ($a_r$).
2. The ratio of the fault that explains the amount of the fault ($\eta$) and it equals to the number of inter-turns in the fault divided by the full number of inter-turns of the healthy phase.

The current equation in faulty winding has the form [13]:

$$\dot{i}_{dq} = R_o \frac{d\psi_{adv}}{dt} = \frac{2}{3} \frac{\eta_0}{R_2} \frac{\dot{Q}(\theta)}{Q(\theta)} \frac{d\psi_{adv}}{dt} \tag{16}$$

Where $i_{dq}$ is the faulty rotor current, $\psi_{adv}$ is the faulty rotor flux, $R_o$ is the fault resistance, $d\psi_{adv}/dt$ is the magnetizing flux. According to equation (16) the fault winding can be represented as a resistor element that is connected to the rotor resistance and the magnetizing inductance in parallel.

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_0} \tag{17}$$

$$R_{eq}^{-1} = R_1^{-1} + \frac{2}{3} \eta_0 \cdot R_1^{-1} \cdot \frac{\dot{Q}(\theta)}{Q(\theta)}$$

Where $Q(\theta)$ is the localization matrix. The equivalent resistance is,

$$R_{eq} = R_1 + R_{fault} = R_1 - \frac{\alpha}{1-\alpha} \cdot R_1 \cdot \frac{\dot{Q}(\theta)}{Q(\theta)} \tag{18}$$

Where $\alpha = \left(\frac{2}{3}\right) \cdot \eta_0$.

3. Wavelet energy approach

The wavelet energy (WE) is an approach that has been used in this paper to detect and diagnose faults in induction motor after reducing the features of original current signal. These features represent the events in current signal. Analysis of the current signal is introduced using WPT to obtain the optimal level of decomposition [14-15]. These signals are detected by a current transformer that is connected to the line supplying the motor terminal. In addition, the optimal mother wavelet function can be selected from the same current signal using the non-normalized Shannon energy criterion [16]. The decomposition of the current signals are performed from a pyramid constructive tree using the WPT. This structure will result in a tree with many levels $j$, where $j$ is the number of levels in the tree and each level contains $2^j$ filters namely, low pass filter (LPF) that passes low frequencies, and high pass filter (HPF) that works on high frequencies, the signal pass through these filters to produce a number of sub-signals.

4. Data gathering and election of mother wavelet function and level of decomposition.

4.1. Gathering data for different conditions

Using a Simulink model as shown in Figure 1 and depending on equations (1-18) for healthy and faulty conditions, the current signals for different cases are presented in Figure 2, which shows the stator current signals for 25% inter-turn fault on phase-c. Figure 3 shows phase-a to ground fault, Figure 4 shows the line-a to line-b fault and Figure 5 shows the broken one bar rotor fault.
Figure 1. Simulation blocks of induction motor in d-q axis

Figure 2. Current signal for 25% short circuit fault on the phase (c)

Figure 3. Current signal for phase a to ground fault
4. 2. Selection of mother wavelet function and level of decomposition

The choice of mother wavelet is based on the similarity between the original signal and the resulting signal of analysis after reconstruction [17]. The mother wavelet is a mathematical function that represents a type of wavelet and each type has a certain figure, where the types of mother wavelet are Daubechies 3, Daubechies 44, symlet, dmey etc. This method depends on taking five cycles from the stator current signal, the criteria is used as [18]:

$$S = \sum_{i=0}^{n} X_i - R_i$$

(19)

Where n is the number of samples, Xi are the samples from the original signal, Ri are the samples of the reconstructed signals and S are the different ratios. The lowest value of the different ratios is used to choose the mother wavelet as in table 1.
Table 1. The entropy values for different current singles

| Faults              | db3        | db44       | dmy        | sym5       | db4        |
|---------------------|------------|------------|------------|------------|------------|
| 10% phase-a         | 1.15E-12   | -0.0036    | 2.41E-04   | 4.05E-13   | 1.36E-12   |
| 15% phase-b         | 2.25E-12   | -0.0046    | 1.53E-04   | 4.96E-13   | 1.28E-12   |
| 20% phase-c         | 3.31E-12   | -0.0055    | 7.07E-05   | 4.61E-13   | 1.15E-12   |
| 25% phase-a         | 4.47E-12   | -0.0063    | -6.66E-06  | 5.75E-13   | 8.13E-13   |
| 30% phase-b         | 5.77E-12   | -0.007     | -7.89E-05  | 3.49E-13   | 6.43E-13   |
| Broken 1-bar        | 3.94E-11   | 0.026      | 0.0011     | 2.67E-13   | 1.01E-11   |
| Loss phase-a        | -9.2E-11   | 1.0E-11    | -0.0026    | 1.32E-11   | -2.90E-11  |
| Phase-a to ground. | 1.33E-10   | 0.0838     | 0.0025     | 2.74E-12   | -8.79E-12  |
| Abs. sum            | 9.67E-11   | 0.0828     | 1.38E-03   | 1.85E-11   | 2.24E-11   |

From the given data in the above table, symlet 'sym5' mother wavelet is chosen as a mother wavelet because it has the lowest sum of different ratios \( S \). While, the choice of the best level of decomposition depends on the energy values for the coefficients of WP tree, the energy values of apparent sub-space can be compared to the energy values of the children sub-space and by using,

\[
E(s)_j \geq E(s)_{j-1}
\]  

Where \( j \) is the number of decomposition levels. Figure 6 shows the wavelet packet tree with the energy result. From Figure 6 and equation (20), it is shown that the best level of decomposition is the second level.

![Wavelet packet tree with entropy values](image)

Figure 6. Wavelet packet tree with entropy values.
5. Proposed detection and diagnosis faults algorithm

The proposed algorithm for faults detection is mainly based on calculating the WL energy values for WPT-coefficients in the second level according to results of section 4. The information to any disturbance is extracted from high frequency component side da2, dd2 where, da2 is the best coefficient that can be used to detect all electrical faults in the induction motor. The algorithm which is shown in the flow chart of Figure 7 depends on the moving frames strategy. This strategy takes the part of 64 samples and makes the process for detection, then the sample 65 will replace sample 1 and repeat the process and so on. This algorithm has been applied in the block diagram shown in Figure 8.

![Flow chart for moving frame detection and diagnosis algorithm](image)

**Figure 7.** Flow chart for moving frame detection and diagnosis algorithm

![Proposed electrical faults detection](image)

**Figure 8.** Proposed electrical faults detection

6. Detection, isolation and diagnosis of faults

The result of the proposed algorithm is shown in Figures 9-11. Each figure presents the 3-ph stator current signal before and after detecting the trip signal, in addition to the fault type. Figure 9 shows the stator current for healthy condition and the motor state varying from no-load to full-load. No trip
signal is generated by the WL energy proposed approach. Figure 10 shows the same results for 25% inter-turn fault in phase b and 10% inter-turn fault in phase a, the trip signal is invited directly and the supply is isolated to protect the motor. Finally, Figure 11 shows the stator current and trip signal for electrical fault (broken two bars). The trip signal is also initiated directly and the supply is isolated directly.

![Figure 9. Stator current and trip signals for no-load to full load condition](image)

![Figure 10. Stator current and trip signals for 25% inter turn fault in phase-b and 10% inter turn fault in phase-a](image)

![Figure 11. Stator current and trip signals broken two bars fault](image)

7. Setup of Experiment Equipment
This section discusses the practical implementation of the proposed algorithm on 1-hp, 3-Ph induction motor. The motor is over wound for experiment requirement. A current transformer is used to read the current signal and analog to digital converter (ADC) to transform the data to the personal computer to
apply the proposed algorithm. For this purpose, the data acquisition (labjack u3-hv) is used. The schematic diagram and the practical implementations are shown in Figure 12.

![Figure 12](image-url)

**Figure 12.** Block diagram and practical implementation for the protection system

The proposed algorithm is implemented on real motor. Figures 13-15 shows the stator current signals and the trip signal before and after the occurrence faults for different types of stator faults.

![Figure 13](image-url)

**Figure 13.** Stator current signals and trip signal for loss phase (b)

![Figure 14](image-url)

**Figure 14.** Stator current signals and trip signal for 40% stator fault phase (b)
8. Conclusion

In this paper, a proposed system for the protection of induction motors against the electrical and mechanical faults is implemented based on WPT and WE. This paper includes modeling of the induction motor using the Matlab environment with its electrical faults and applying the proposed algorithm on the data that are collected from the model and implementing the experiment practically. Based on the results, the advantages of using WPT and WE in protecting the system can be summarized as follows, applying the proposed technique on two 3-Ph induction motor squirrel cage, the first is induction motor modeling in Matlab with 10-hp, and the second is a real induction motor with 1-hp. The results have shown high speed and high accuracy in detecting and diagnosing the electrical faults in the induction motor due to the accuracy of the proposed technical and the speed of the used algorithm by moving along signal by 1-sample.

The similarity between the results of the real motor and results of the motor modeled by Matlab proves the possibility of using the proposed technique for any motor without the need of its parameters.

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