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Practical Implementation for Stator Faults Protection and Diagnosisin 3-Ph IM Based on WPT and Neural Network

Sadiq I. Hassan[1], Adel A. Obed[2], Khalid M. Abdul-Hassan[3]
[1]*College of Engineering -Basra University*
[2]*College of ElectricalEngineering Technology -Middle Technical University, Baghdad*
[3]*College of Engineering -Basra University*

ABSTRACT

This paper presents a real-time practical implementation for an online protection and diagnosis technique for induction motor stator faults. The Artificial Neural Network (ANN), the wavelet packet transform (WPT)-algorithms are developed as based approaches for protecting and diagnosing various stator faults occurring in three-phase induction motors. These approaches are based on the entropy of the WPT-coefficients of line currents using an optimized mother wavelet 'db3' at the second level of resolution with thresholds determined experimentally during the various conditions of the motor. The algorithm is implemented in real-time using the LabJack U3-HV instrument device as an interface between the WPT-algorithm which developed in Matlab program/PC and the 3-ph CT's which are used to sense the 3-ph current lines motor. The proposed technique is tested on a laboratory induction motor which is chosen with unknown parameters. It is a rewinded motor that realizes a different requirement. It has many output terminals from its windings in order to implement the various faults. The online test results give a tripping signal at an instant time that through applied a new moving frame technique. A few cycles presents to isolate the main C.B of the motor power supply in all cases of faults. In addition, the WPT-algorithm is developed to issue online a flagging fault message window which helped to diagnose the faults type.

Keywords:WPT,ANN,Entropy, IM, Flagging message, Fault diagnosis.

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I. INTRODUCTION

The induction motor faces various stresses duringoperation conditions. The conditions of monitoring, diagnosis of faults and protection become needful in order to avoid tragic failures. Stator faults show responsible for most of the faults in the induction motor. The faults of the stator in an induction motor are approximately (30-40)% of its total failures which caused by the windings damage. Insulation damages are usually caused the stator faults like a turntoturnfault in a coil, phasetoground or phaseto phase short-circuit faults [1-4]. Over the years, a general problem with respect to the protection of an induction motor is the absence of accessibility of complete data for a system which driven by the motor. Many techniques are used for failure diagnosis in induction machines which can narrative as the signal processing [5]. The fault diagnosis of the electrical motors can be achieved by motor current signature analysis(MCSA) which can detect most of the electrical faults [6]. Various types of wavelet transform are used with signal processing of start-up motor faults such as DWT, WPT and CWT. The wavelet transform is a powerful tool in the analysis of transient phenomena because of its ability to extract time and frequency information from the transient signal [7]. The evolution of the entropy of WPT-coefficients using an optimized mother wavelet 'db3' at the second level of decomposition provides an accurate and effective classification criterion for the faults in inductionmotor. The Artificial Neural Network (ANN) presentsa based approach for protecting and diagnosing of the stator faults of the induction motor. Artificial neural networks (ANN) have been used for many different applications. The feature that is most attractive in condition monitoring is their ability to represent complicated, non-linear relationships and to self-learn in pattern recognition tasks.

II. STATOR WINDING FAULTS IMPLEMENTATION

Typically, short circuits in stator windings occur between turns of one phase, or between turns of two phases, or between turns of all phases [8,9]. Figure 1 shows the types of stator faults which are assigned on the three-phase windings. A turntoturn phase short circuit fault in a 3-ph IM a high current to flow and consequently heat in the fault turns. So, the generated heat is proportionate to the square of the caused current which exceeds the limiting value, the motor may occur a completely failed [10]. The phase to ground fault is carried out by connecting a phase to the ground. The phasetophase fault was carried out by connecting two phases. Single phasing (loss of phase) is a type of fault may be created by the mechanical or electrical failure of an internal break, a machine terminal connector, or an electrical failure in one of 3-ph power supply [11].

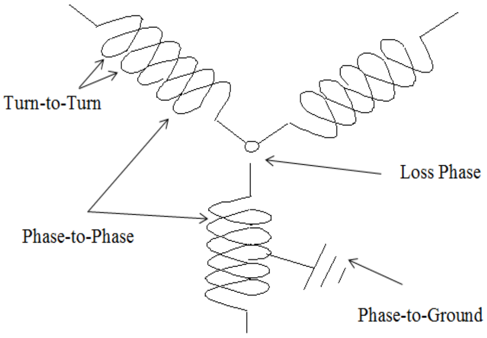


Figure 1: Various faults in the stator of induction motor.

III. WAVELET PACKET TRANSFORM (WPT)

The wavelet packet transform is an alternative base; it forms linear-collections wavelet components. They have to get a property like time-frequency location of their identical wavelet components. A wavelet packet component is composed of three indices (m), (k) and (n), as given in the following equation [12-14]:

$w_{m,k}^{n} = 2^{m/2} w^{n}(2^{m}t - k)$..... (1)

where: $m$is the scale operations index, k is the translation operations index, n is modulation parameter index, and w is wavelet packet component.

The wavelet packet transform allows making multi-resolution analysis of signals as they are possible to have a similarity of the connected scaling function and smooth wavelet with consolidated support through low pass filter (LPF) and high pass filter (HPF). The diagnostic faults are an important purpose for the induction motors. The signature diagnosis criterion uses the non-normalized Shannon entropy as a criterion. The Shannon entropy values represent the energy value of the coefficients.The entropy values$E(s)$ of the signal (s)of any subspace of wavelet packet tree is [11,15-18].

$E(s) = -\sum_{n=0}^{N-1} |s(n)|^{\wedge 2} * log\ |s(n)|^{\wedge 2}$.... (2)

IV. EXPERIMENTAL SETUP FOR PROTECTION BASED ON WPT ALGORITHM AND NEURAL NETWORK

The on-line implementation of theproposed protection technique involves the development of the experimental setup that includes both the hardware and a software component as present in following.

4.1 Hardware Experimental

The complete experimental setup for the testing of the proposed algorithm as well as the testing results of different faulted and normal un-fault conditions are provided in the following sections. A 1hp laboratory three-phase induction motor is used in the testing. The induction motor chosen is with unknown parameter values. It is rewinded motor used for experimental requirement. A box has many output terminals from its winding. They are three phase main winding terminals, 10% turns winding of phase-a which represents the end of the first coil, 25% turns winding of phase-b which represents the end of the second coil, 50% turns winding of phase-c which represents the end of the third coil, and the command point of three winding terminal box which as shown in Figs 2 and 3.

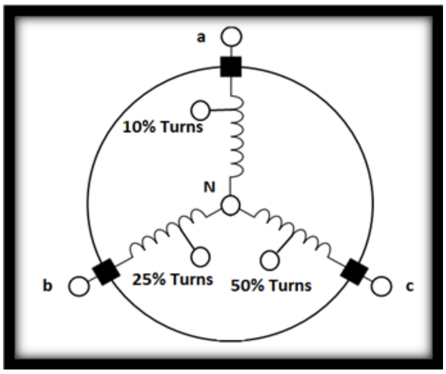


Figure 2: 1hp laboratory rewinded 3-ph I.M

Figure 3: Induction motor and terminal box

Three current transformers CT's (50/5 A, 5VA) are connected with the stator terminals of the induction motor. The current ratiois suitable of the high fault currents without any saturation in the sensed signals. The CT's are shown in Fig. 4.

Figure 4: The current transformers (CT's)

The signals of3-ph stator currents are converted usingA/D LabJackU3-HVdevice.A LabJack design manufacturesmeasurement and automation peripherals that enable the connection of a PC to the real-world as shown in Fig. 5. It is compatible with the Matlab and other programs [19]. For this purpose, a protection algorithm is written in the Matlab program which processed in a personal computer. The results are recording in through special program called a stream program.

Figure 5: Lab Jack U3-HV instrument

The hardware parts also are included a connection faults panel. It helps to simulate the actual faults of the induction motor, which consists of all electrical devices (CB's, contactors, timer relays, switches, lamps, etc.) to implement the multi-faults which provide safer during the fault period for searcher which is shown in Fig. 6.

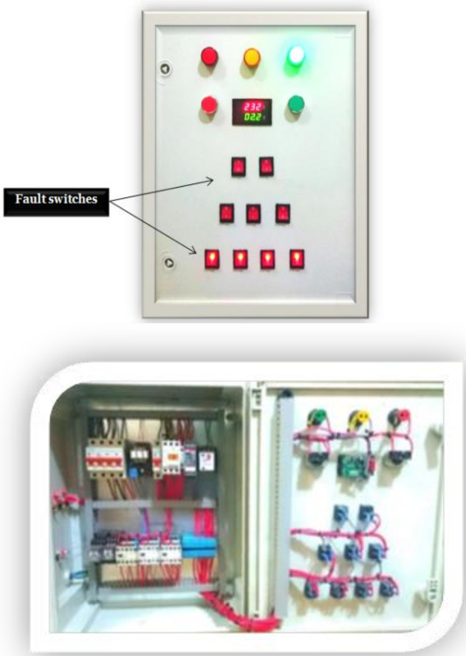


Figure 6: The designed faults panel

The hardware includes a relay control circuit, when WPT algorithm is reflected the digital signal processor to be used for making a decision on the status of the trip signal. The signal is fed back to the LabJack U3-HV device by the DAC terminal which uses as a pulse to the NPN relay control circuit. The circuit will operate the 12VAC contactor relay. Figures 7 and 8 show the schematic diagram and the actual implemented of the complete circuit for the control circuit system. A normally closed auxiliary contact of the contactor relay is connecting in series with the control supply of the three-phase main contactor coil as shown in Fig. 9 which is isolated the main power supply of the induction motor.

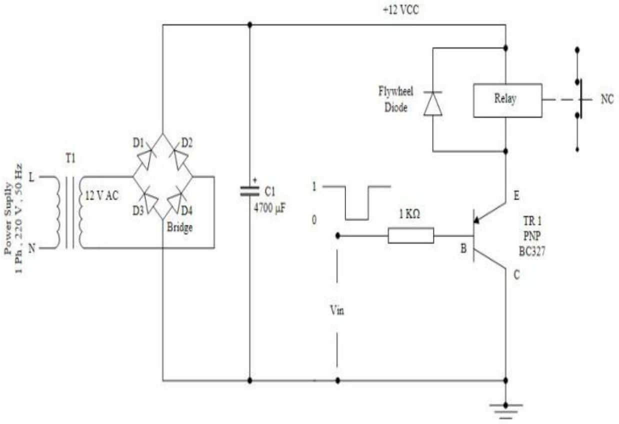


Figure 7: Schematic diagram of relay control circuit

Figure 8: The actual Schematic of relay control implemented circuit

The practical implementation for induction motor protection against stator faults is presented for this work. The tripping signal produced from the proposed WPT for different stator faults is used to drive a relay control circuit. Figure 9 shows the schematic diagram for the online testing of the motor protection. Switch (CS1) which is a normally closed to isolate the coil of the main contactor from the supply when a tripping signal is initiated. To ensure diagnosis of stator faults, the neural network is used which is assigned in the same block of PC WPT. The complete experimental implementation is shown in Fig. 10.

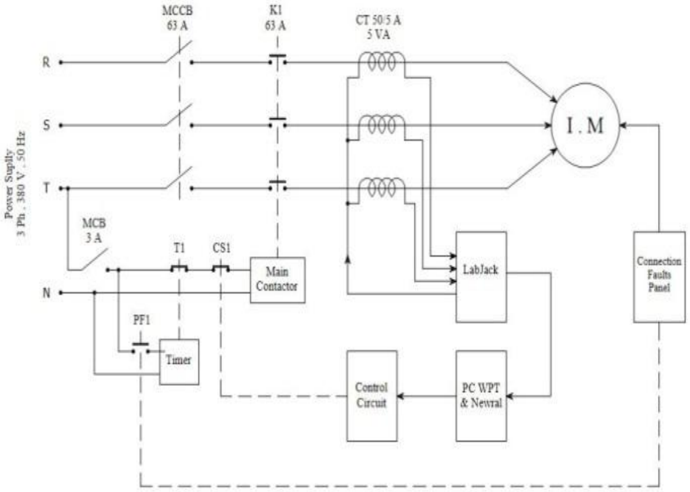


Figure 9: The protection schematic block for testing of the 3-ph IM.

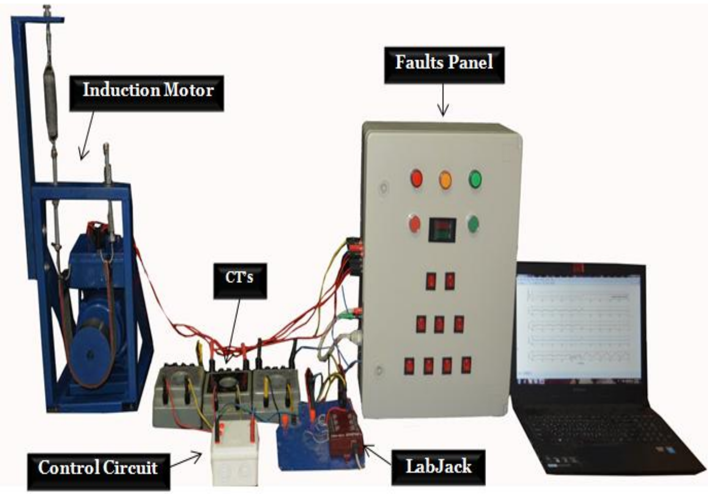


Figure10: The complete implementation experimental protection of the 3-ph IM.

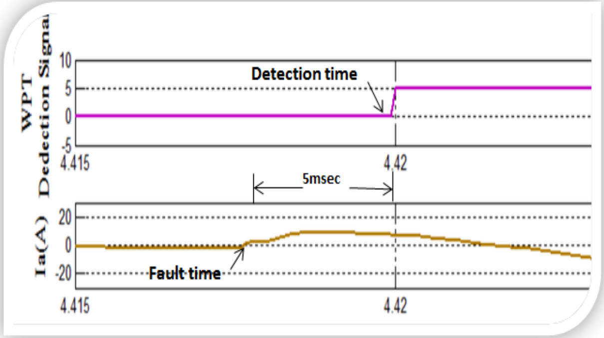
4.2 Software for Experimental Protection

The software part consists of the WPT based algorithm which can be employed to extract certain features for induction motor currents to detect the healthy and faulty conditions with diagnosis the fault types. The entropy criterion is applied to diagnose the stator faults. The wavelet packets transform (WPT) based algorithm on the samples of fault currents is used as signal processing technique. It is reflected the proposed signature method and decision on the status of the detection signal. The complete software setups for this testing of the proposed algorithm are provided in the following sections.

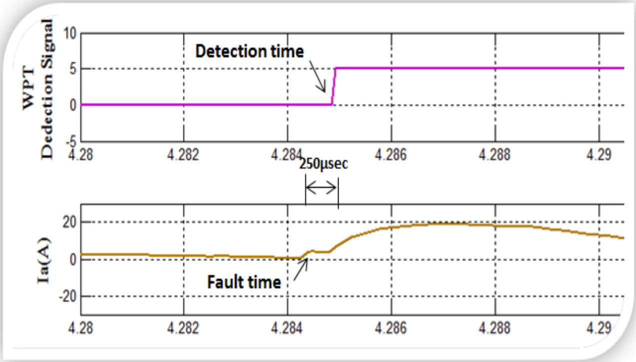
4.2.1 Moving Frame Technique

The technology followed the test to process the stator currents signal of the induction motor by the WPT algorithm requires data every quarter cycle. It collects the samples of every quarter cycle looks like a packaged frame periodically. The length of the quarter cycle is ‘64’ samples of the signal. In other words, it creates an enormous number of the frames with length ‘64’ samples of each one. A cause for concern that probability of occurring fault during this frame which means the WPT algorithm will waiting for the next frame for processing. Then, the delay in the processing time is more than quarter cycle time.

In order to reduce the time delay as less as possible, a new technique is adopted. At start time, the WPT algorithm waits for ‘64’ samples to create the first frame, then moving this frame with the same frequency of the sample rate current signal which takes the stream rate of LabJack U3-HV device. Conceivable that frame is moving on the tremendous amount of fixed samples signal. After created the first frame, the second frame is created by entering the sample number ‘65’ and outer the sample number ‘1’ which process by the WPT algorithm. The third frame creates by entering the sample number ‘66’ and outer the sample number ‘2’ and so on. Thus, this technique is able to detect a fault at early established which much less than a quarter cycle. A minimizing of a faulting time has a consideration in the motor protection systems. Figures 11 and 12 show the result of practical on-line WPT algorithm detector for each technique which applied on 10% turntoturn (phase a) stator fault. It is clear that the time needed to detect this type of fault is reduced from (5msec) to (0.25msec) approximately.



Figures 11: WPT delectation signal for a quarter cycle frame technique



Figures 12: WPT detection signal for moving frame technique.

4.2.2 Developing of ANN

In implementing the algorithm of faults protection for the induction motor using ANN, the 3-ph stator currents are used as the input to the network. To generate the realizable training pattern for the ANN-based protection, the samples of the summation of squared three-phase stator currents are framed as a packet each 64 samples, the signal is decomposed by wavelet packet transform with optimized mother wavelet ‘db3’ and optimized decomposition level (2^{nd} level). The coefficients of WPT entropy train the neural network so that it can recognize and differentiate these various faults condition.

In this section, the ANN involves two stages: network development and actual usage of the network. During the network development, the neural network is trained to capture the relationship between the input and output. A three-layer feed forward network is chosen in this work for implementing the ANN-based protection of the induction motor. The model outputs include healthy, loss-phase, turn-to-turn, phase-to-ground, phase-to-phase, respectively.Therefore, the values 0, 1, 2, 3 and 4 in the output neurons indicate to these cases, respectively. The optimal structure of the neural network is contained one neuron in the input layer, nine neurons hidden layer with tan-sigmoid activation function and five neurons in the output layer with linear activation function.

The best fit line for prediction properties for training and testing samples of ANN model is calculated using regression analysis as shown in Figs 13 and 14. It was observed that the cost function is 7.4e-16 and 2.5e-15 for training and testing samples, respectively.A comparison between the experimental and the predicted ANN model results for testing sample is shown in Fig. 15. It can be seen that ANN is able to predict of the entropy of the WPT-coefficients of induction motor currents with a reasonable accuracy.

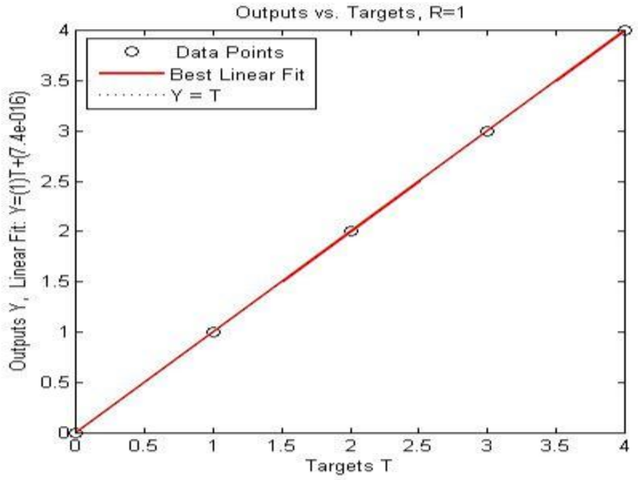


Figure 13: The best fit line for prediction of the WPT-coefficients entropy of I.M currents by ANN model for training samples

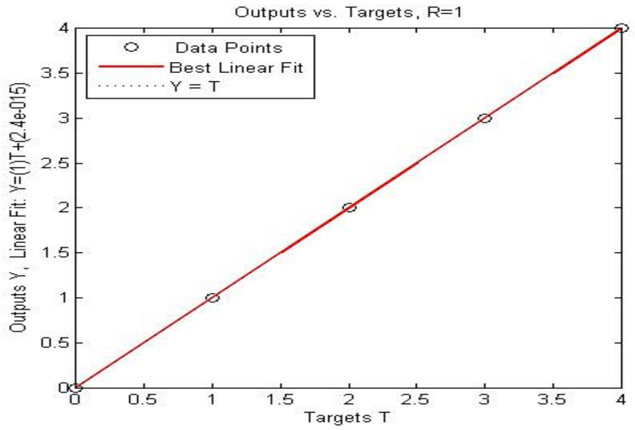


Figure 14: The best fit line for prediction of the WPT-coefficients entropy of I.M currents by ANN model for testing samples

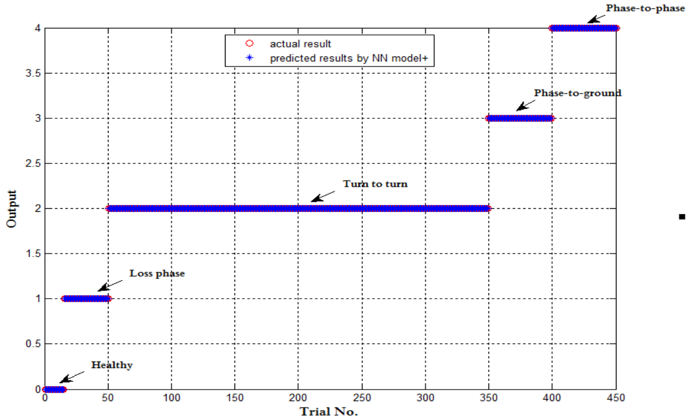


Figure 15: Comparison between the experimental and the predicted ANN model results for the WPT-coefficients entropy of I.M currents testing samples

4.2.3 Flagging Message of Fault

The WPT algorithm is developed to issue a message flagging fault, where an information type of fault monitors on the creating window. A simple design uses message-based to provide software flagging of the type faults in Matlab program. It is used to help the diagnosing fault which occurs in the stator of the induction motor. There are four flagging message type, loss phase (single phasing), turntoturn, phasetoground, and phasetophase faults. These messages will online be appeared after the tripping signal isolated the motor from the power supply.

V. THE INTERLOCK BETWEEN THE WPT ALGORITHM AND THE IM STARTER

The WPT algorithm is required to stopthe motor working at instant of fault initialized through the control circuit. From Fig. 9, the normally closed switch (CS1) will open and disconnect the main contactor coil from supply. Therefore, it is required to make interlock between the hardware of the motor starter and the software of the PC algorithm. The interlock signal is backed from the main contactor to the AIN3 input of the labjack and reached to PC as a condition to break the online WPT algorithm. The other advantage of this interlock is that the WPT algorithm does not work unless the backs signal from the starter of the induction motor that it is ready.

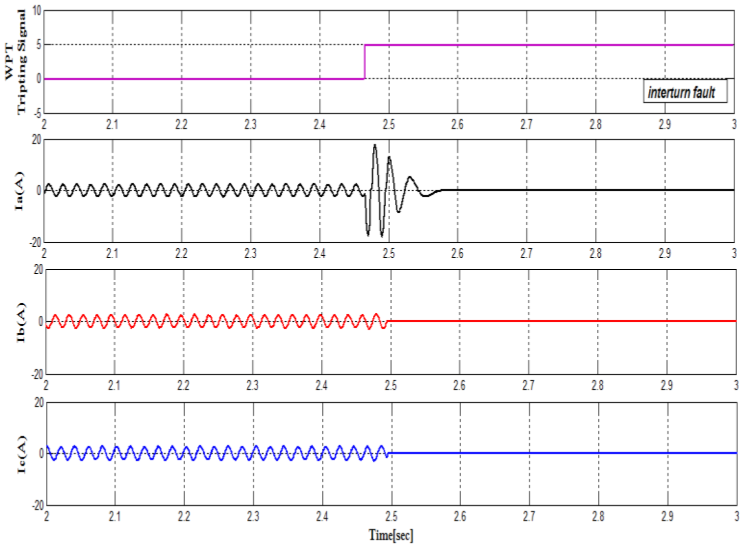
VI. EXPERIMENTAL RESULTS FOR ONLINE TESTING PROTECTION

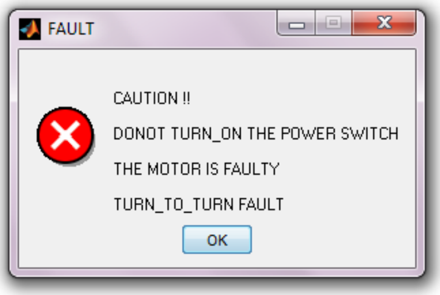
The testing for the proposed algorithm for this motor showed an excellent ability to protect and diagnosis and respond to the different type of current flowing through the motor in the stator. This motivates the application of the proposed algorithm with the modified experimental setup on it in order to show the capability of the WPT algorithm in protection the induction motor.

Four different faults current are investigated in order to test the WPT-based algorithm on stator motor: (a) loss phase (single phasing) fault (b) turntoturn fault, (c) phasetoground fault, and (d) phasetophase fault. Normal operation is investigated in order to test the WPT-based algorithm as healthy states. Each fault condition was performed that the proposed algorithm identified the disturbance properly and initiated the decision as a trip signal. The decision will back to the LabJack device which is using as feedback for a circuit breaker to isolate the main supply almost at the instantaneously or within much less than a quarter cycle. It is worth mentioning, that the figures almost appeared few cycles fault waves. It is implemented with a real-time fault which consists a delay time of the devices that passing through them (PC response, LabJack, switching signal transistor, auxiliary relays, and main contactor circuit).

6.1 Abnormal (Faulted) Conditions

The proposed WPT protection algorithm is tested for various stator winding faults. The WPT algorithm identifies all faults as abnormal condition and generated a trip for protection. The Trip signals,the three-phase currents and the flagging massages are shown Figs. 16-23.




FAULT

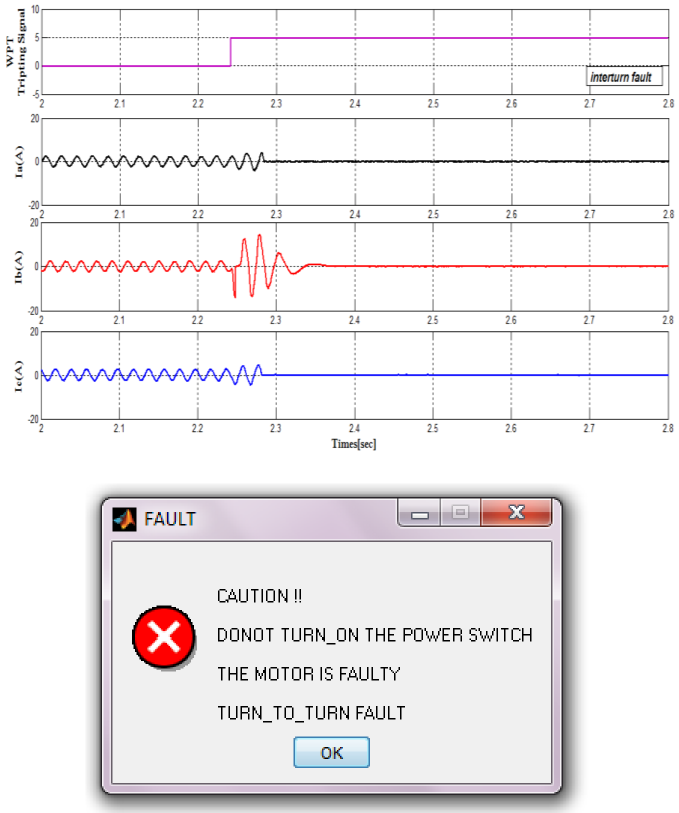
CAUTION !!

DONOT TURN_ON THE POWER SWITCH

THE MOTOR IS FAULTY

TURN_TO_TURN FAULT

Figure 16: Trip signal,three phase currents and flagging message of (10% turns of phase-a) fault condition response applied on-line test WPT-protection.



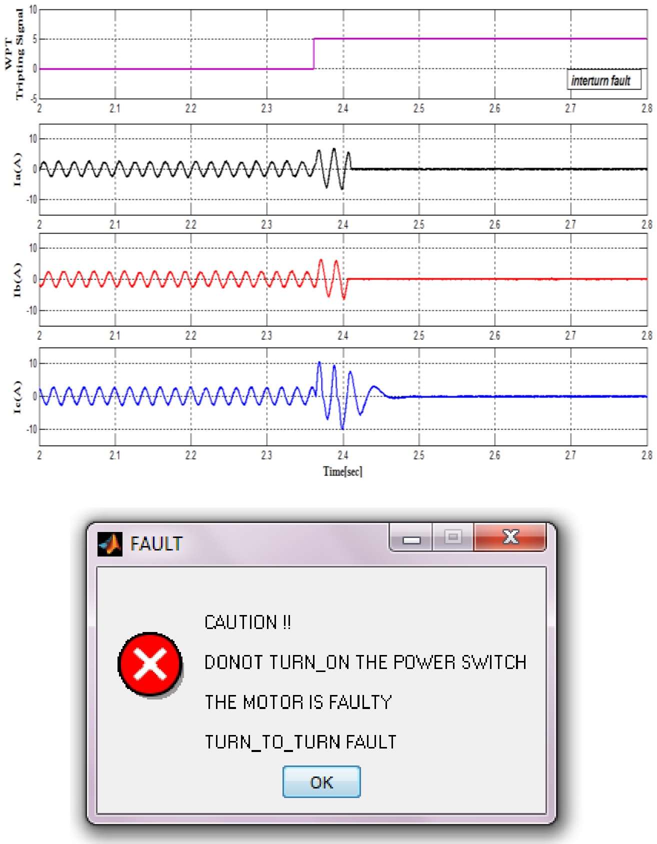
CAUTION !!

DONOT TURN_ON THE POWER SWITCH

THE MOTOR IS FAULTY

TURN_TO_TURN FAULT

Figure 17: Trip signal,three phase currents and flagging message of (25% turns of phase-b) fault condition response applied on-line test WPT-protection.



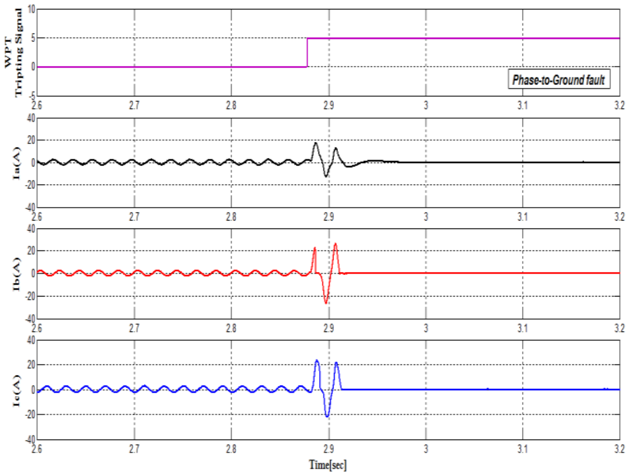
CAUTION !!

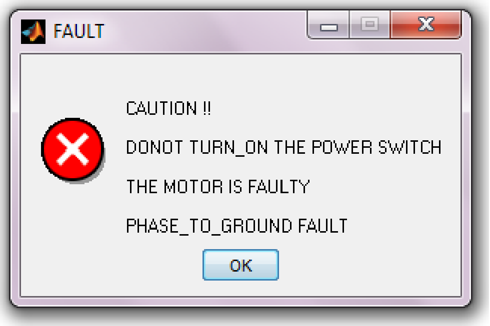
DONOT TURN_ON THE POWER SWITCH

THE MOTOR IS FAULTY

TURN_TO_TURN FAULT

Figure 18: Trip signal, three phase currents and flagging message of (50% turns of phase-c) fault condition response applied on-line test WPT-protection.





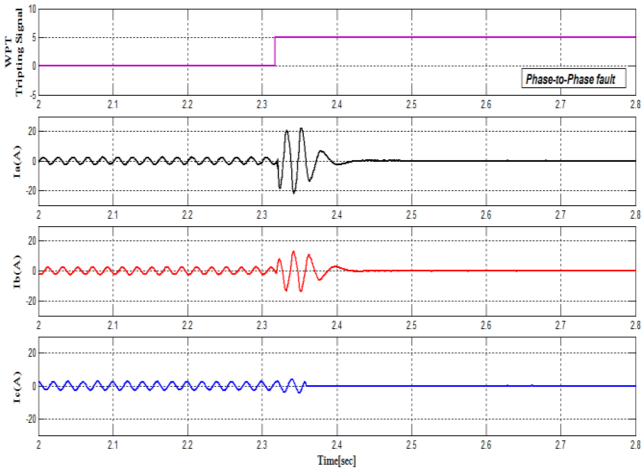
CAUTION !!

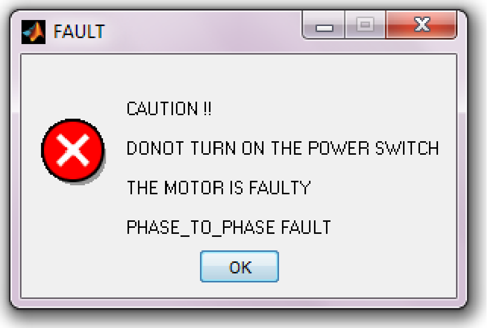
DONOT TURN_ON THE POWER SWITCH

THE MOTOR IS FAULTY

PHASE_TO_GROUND FAULT

Figure 19: Trip signal, three phase currents and flagging message of (phase-a to ground) fault condition response applied on-line test WPT-protection.





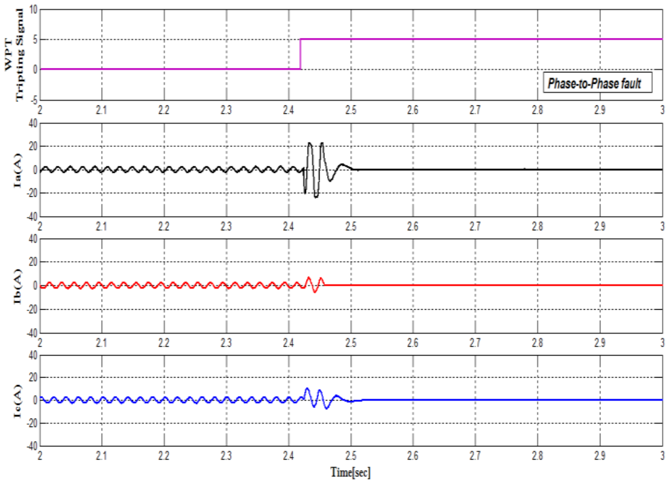
CAUTION !!

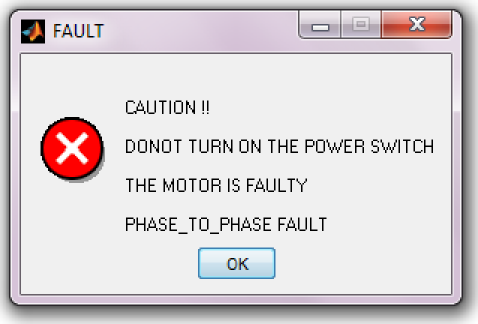
DONOT TURN ON THE POWER SWITCH

THE MOTOR IS FAULTY

PHASE_TO_PHASE FAULT

Figure 20: Trip signal, three phase currents and flagging message of (10% turns of phase-a and 25% turns of phase-b) fault condition response applied on-line test WPT-protection.





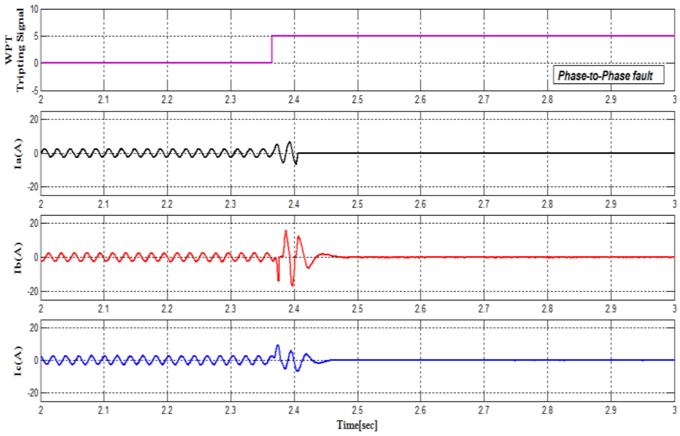
CAUTION !!

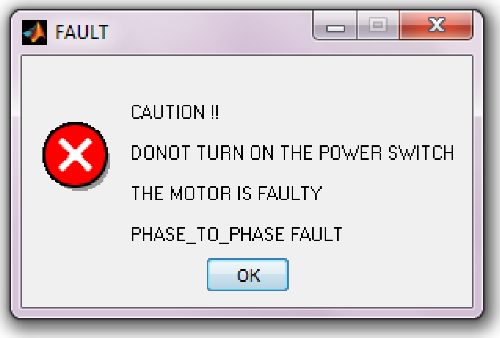
DONOT TURN ON THE POWER SWITCH

THE MOTOR IS FAULTY

PHASE_TO_PHASE FAULT

Figure 21: Trip signal, three phase currents and flagging message of (10% turns of phase-a and 50% turns of phase-c) fault condition response applied on-line test WPT-protection.





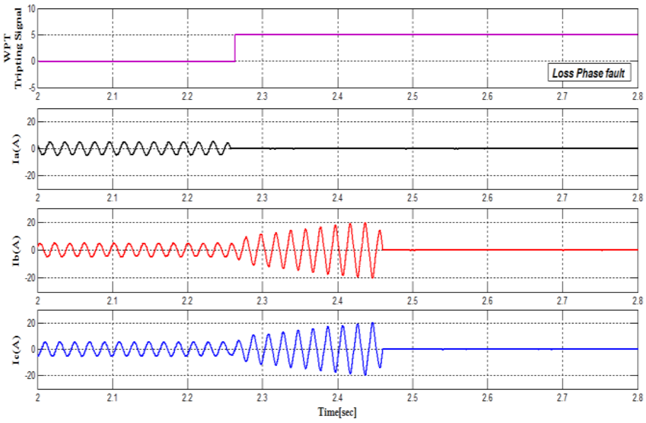
CAUTION !!

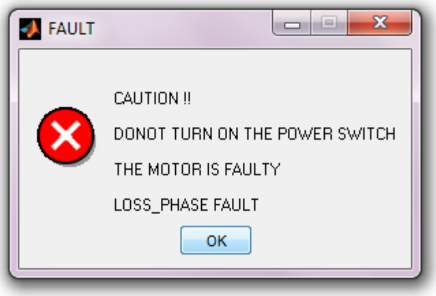
DONOT TURN ON THE POWER SWITCH

THE MOTOR IS FAULTY

PHASE_TO_PHASE FAULT

Figure 22: Trip signal,three phase currents and flagging message of (25% turns of phase-b and 50% turns of phase-c) fault condition response applied on-line test WPT-protection.





CAUTION !!

DONOT TURN ON THE POWER SWITCH

THE MOTOR IS FAULTY

LOSS_PHASE FAULT

Figure 23: Trip signal, three phase currents and flaggingmessageof loss phase-a fault condition response applied on-line test WPT-protection.

6.2 Normal (un-Faulted) Conditions

The proposed WPT algorithm protection was tested for normal and suddenly loads currents. The WPT algorithm identified them as normal conditions which never generate any trip signal as shown in Fig. 24.

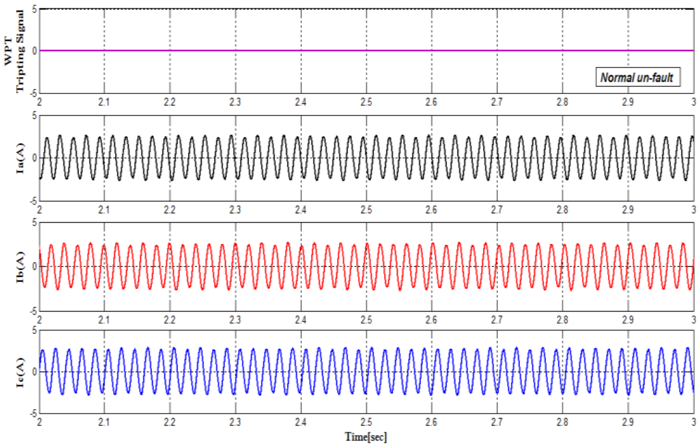


Figure 24: Trip signal and three phase currents of (normal un-faulted) condition response applied on-line test WPT-protection algorithm.

VII. I.M UNDER SUDDEN LOAD CHANGE

The stability is an important qualitative characteristic of induction motors, providing the reliability of its work. One example of the changes is suddenly external load. The type of sudden load is typical for hoisting mechanisms (hoists, lifts, elevators, cranes) [20-22]. The concern is with the behavior of the motor when a sudden load occurs it may be consider as a fault state.A practical testing is implemented on the induction motor. It is in unloaded-state at the starting up period. The sudden load can be considered through the release of the spring handle to strain at the full-load of the induction motor which is shown in Fig 25. The resulting test is no detection signal that shows for this case, therefore, the WPT algorithm identified it as a normal condition and isn't generated any detection signal. The three phase currents transient of the induction motor is presented in Figs26 and27.

Figure 25: The propped method of the sudden load change on IM.

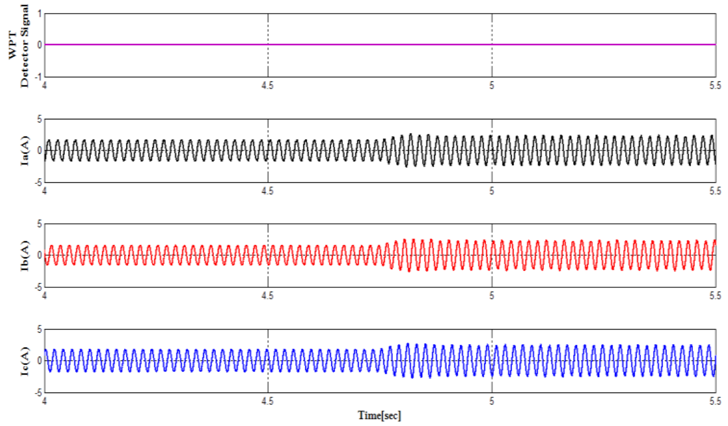


Figure 26: On-line test WPT based detection signal and 3-ph currents of suddenly Load duration condition.

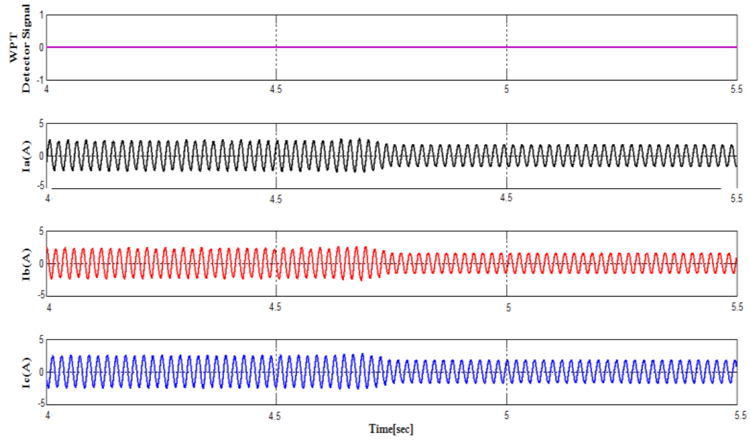


Figure 27: On-line test WPT based detection signal and 3-ph currents of suddenly Load-to-noload duration condition.

VIII. THE STARTING TEST OF WPT BASED ALGORITHM

The new WPT algorithm is developed based on signature current analysis of starting current of the induction motor operating under different transient faults (inter-turn and inter-coil short-circuits) for diagnostic purposes. The algorithm is applied to detect a healthy motor from the stator faulted motor which conducted on the entropy criterion.

The proposed WPT algorithm was tested for normal (un-faulted) currents at starting instant. The WPT algorithm identified it as a normal condition and does not generate any trip signal as shown in Fig. 28. A light density of entropy for this case due to transient starting that WPT algorithm sets as a normal healthy condition which is shown in Fig. 29. Figures 30 and 32 show different type of stator faults (10% turns fault of phase-a, phase-a to ground fault, respectively). The three-phase currents, as well as the WPT detection signal of the proposed algorithm, are shown. Heavy densities of entropy for these cases due to a fault during the starting time are shown in Figs. 31 and 33, respectively.

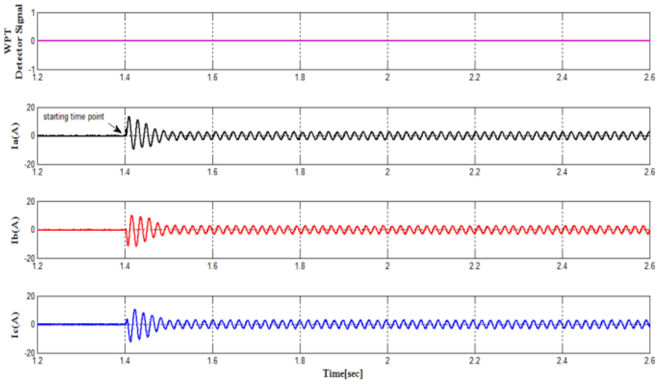


Figure 28: Online starting test WPT based detection signal and 3-ph currents of the normal condition.

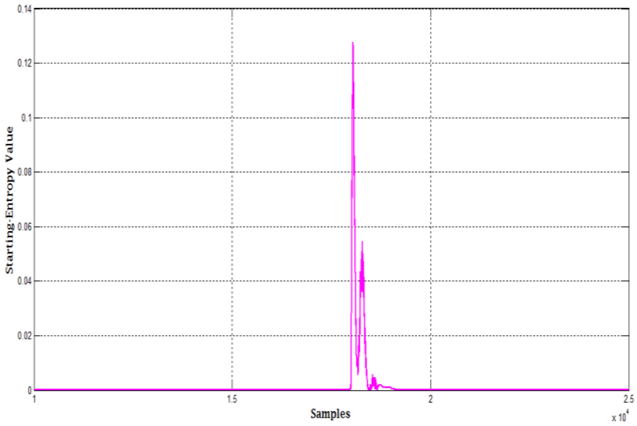


Figure 29: The density of entropy for online starting test WPT based indicator response and 3-Ph currents of the (normal un-faulted) condition.

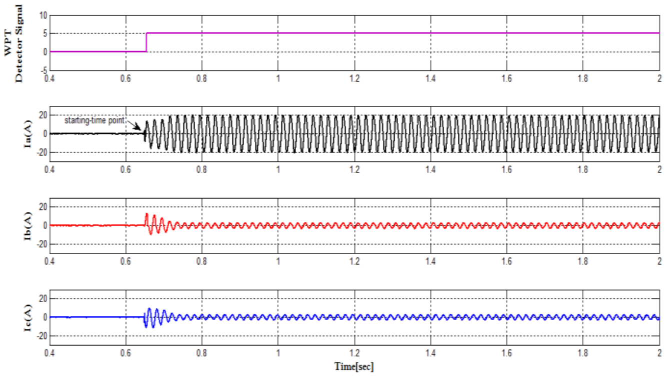


Figure 30: Online starting test WPT based detection signal and 3-ph currents of (10% turns of phase-a) fault condition.

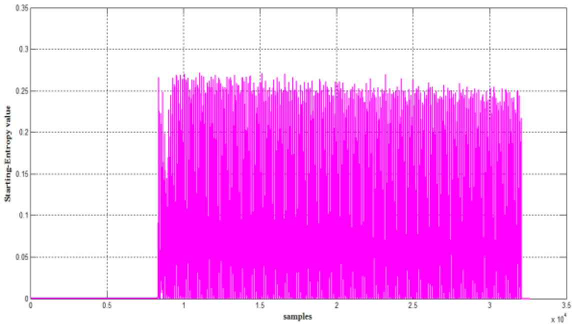


Figure 31: The density of entropy for online starting test WPT based indicator response and 3-ph currents of (10% turns of phase-a) fault condition.

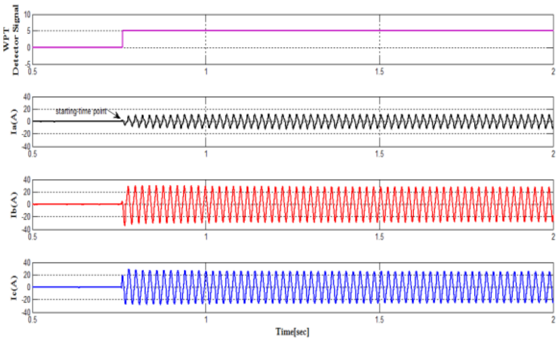


Figure 32: Online starting test WPT based detection signal and the 3-ph currents for phase-to-ground (phase a) fault condition.

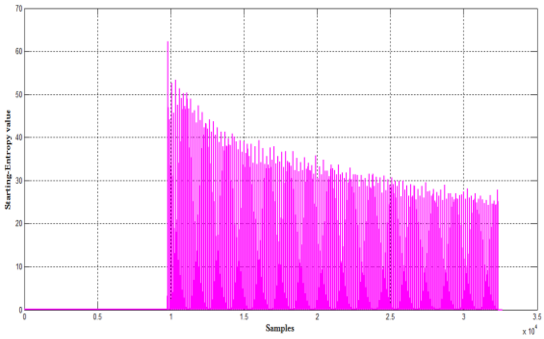


Figure 33: Online starting test WPT based indicator response and the 3-ph currents for phase-to-ground (phase a) fault condition.

IX. CONCLUSION

The online practical implementation ofthe proposed WPT-algorithm and neural networkare applied on3-ph I.M to protect and diagnose thestator faults. It can be concluding:

1. The WPT testing produce well results to diagnose between healthy and faulty motor case by using the entropy values in the second level of the wavelet coefficients of the stator currents.
2. A new moving frame technique is applied on the WPT based detection algorithm to reduce the time delay as less as possible which requires for detecting the various faults.
3. The resulting test of a sudden load of the induction motor is no detector signals that shown for this case. Therefore, there is no side effect when using WPT method for the induction motor leads hoisting mechanisms load.
4. The Artificial Neural Network (ANN) is used as a based approach for protecting and classifying of the stator faults of the induction motor.
5. The entropy-wavelet packet transform is applied to extract the features from the three-phase stator currents signal. The entropy data was developed by simulating various faults in the ANN network training and testing systems.
6. The WPT algorithm is developed to issue online a message flagging fault, where the diagnosing fault type monitors on the creating caution window.
7. The ability to make a complete protection for steady state and starting period cases of the induction motor uses unified algorithm. The algorithm includes these two modes, through the starting algorithm mode works during the starting time which requires as input value, and then the steady state algorithm mode works along the normal operation time. The operation of this algorithmbecomes more like an integrated protection device, as in the practical protection relays.

Appendix (A)

Induction Motor Parameters

Rated power	1hp
Rated stator voltage	380 V
Rated frequency	50 Hz
Rated speed	1470 rpm
Nominal Stator current	1.98 A
No. of poles	4

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