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# A Pic Microcontroller-Based Protection System of Three-Phase Induction Motor

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**Abstract:** The use of microcontroller technology has enabled the design of energy efficient and cost-effective reliable control systems for induction motors. This study presents a PIC microcontroller-based control system for the protection of a three-phase induction motor. Fault types of induction motor like phase failure, unbalanced voltage, locked rotor, under voltage, overvoltage and more are considered in this work. Fault monitoring and diagnosis are performed using artificial neural network. Fault classification is achieved through the microcontroller which includes a program for fault classification. When a fault occurs, the microcontroller sends a signal to the interfaced digital relay to trip the motor circuit and another signal to an LCD to display the type of fault. The use of the microcontroller reduces the response time of the protection system and makes it more suitable for real time operation. The proposed protection scheme is simulated using Matlab Simulink. Matlab simulation results show that the well trained ANN scheme is able to detect all types of internal faults at different locations. The microcontroller used in this work is the high performance enhanced flash PIC18F4520 of microchip which has an on chip analog to digital converter peripheral, among other features. The microcontroller is programmed using 'C' and assembly language to control the function of the digital relay. MPLAB Integrated Development Environment (IDE) is applied for the development of the proposed embedded applications.

**Key words:** Artificial neural network, induction motor, fault classification, PIC microcontroller, Egypt

## INTRODUCTION

A microcontroller, also known as embedded controller, is a solitary chip microcomputer developed by VLSI fabrication. Microcontrollers comprise a central processing unit, memory and several peripherals. They are divided into categories according to their memory size, internal architecture, number of bits and instruction sets. The most universally employed sets of microcontrollers include the 8051 family, Peripheral Interface Controller (PIC) provided by microchip technology, Advanced Virtual RISC microcontrollers (AVR), among others. Microcontrollers are basically employed to control the functions of embedded systems in various applications like office machines, robots, home appliances, motor vehicles or any electric appliance that stores, measures and displays information. One of the most widely used areas of microcontrollers are parts of the control circuit in industrial automation systems. The input components, such as the sensors of pressure, of level and of temperature are interfaced as peripherals to the input. The driver components of the control circuit such as contactors and solenoid valves are interfaced to the output. Microcontrollers have the advantage of reducing the size, cost and power consumption compared to designs applying separate microprocessor and input-output devices. These features encouraged further evolution of microcontroller-based approaches in industrial applications like protection of induction motors. Induction motors are used in many industrial applications because of their simple and robust structure as well as low production costs. More features are versatility and good self-starting capability. The reliability of an induction motor is of great importance as the motors are frequently exposed to different hostile environments, mis-operation and manufacturing defects which result in failures causing industrial production losses. Avoiding the unexpected shutdowns is important task for industries. A fault tolerant control systems to avoid unexpected shutdowns implies early detection and correct diagnosis and classification of faults in early stages. Researchers have studied using microcontroller interfaces and integrated protection architectures to allow a reasonable approach to reduce total system cost and increase overall performance

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motor control systems. In the following a sample of previous research work is illustrated. In (Grag and Sinha, 2014), protection of three phase induction motor was done using the microcontroller, current transformer and step down transformer from single phasing, under voltage, over voltage and over current. The process was monitored by ATmega32 microcontroller. Sudha and Anbalagan (Sudha, 2009) proposed a technique to protect a three phase 2kW induction motor from single phasing using PIC16F877 microcontroller. The values of each phase are sampled and converted to low ac voltage by means of transformer. More recent research can be found by Thota and Reddy (2013) and Jaywant *et al*. (2014). This work presents the design of a PIC microcontroller-based digital protection system for three phase induction motor developed by Eldin *et al*. (2007). Artificial Neural Network (ANN) is utilized for detection and diagnosis of external motor faults. These faults include phase failure, unbalanced voltage, locked rotor, under-voltage, overvoltage, phase sequence reversal of supply voltage and mechanical overload. The main advantage of ANN method is the non-algorithmic parallel distributed architecture for information processing. Furthermore, the design does not require a complete mathematical model of the induction motor. The input signals for ANN-based systems are: stator currents and voltages, magnetic fields, frame vibrations, etc. In this work, stator currents and voltages are used because they allow the realization of noninvasive diagnostic systems and the sensors required are usually present in the drive considered. The results of the Root Mean Square (RMS) errors of stator voltages, currents and motor speed are used to train the neural network. The output signal of the ANN are then fed to the PIC microcontroller. The program included the microcontroller continuously compares the values with the predefined reference values of voltage and currents to classify the faults. Accordingly, the microcontroller delivers a signal to the interfaced relay to trip the circuit and disconnects it from the power supply. It also sends a parallel signal to the LCD unit to display the type of fault that has occurred. The proposed system has been simulated using Matlab/Simulink Software and tested for external motor faults. The simulated results clearly show that well-trained neural networks is capable of early fault detection and diagnosis of external faults induction motor. The use of embedded system microcontroller for fault classification decreases the response time to trip the motor circuit which improves the performance with real-time induction motor faults data when compared to a the protection system based on ANN as in (Eldin *et al*., 2007) and others systems mentioned in the literature.

**Fault detection methods of three phase induction motors:** In the following different types of faults and fault detection techniques are illustrated then the use of ANN for fault detection of three phase induction motors described in particular.

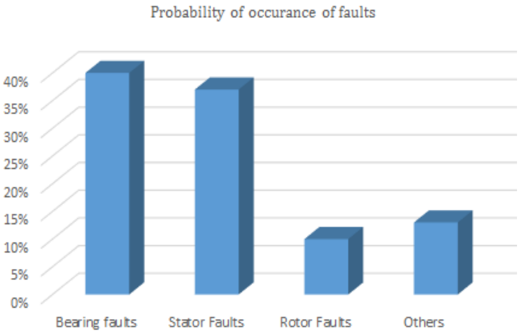

Fig. 1: The probability of occurrence of faults in an inductio motor

**Types of faults and fault detection methods:** Although induction motors are reliable and robust, their life span can be affected by thermal, electrical or mechanical stresses causing the occurrence of various types of faults (Ayhan *et al*., 2005). Internal faults of induction motor can be divided into: bearing failures, stator faults, rotor faults, air gap eccentricity, mechanical vibrations, etc. Fig. 1 illustrates the relative probability of occurrences of these faults (Bonnett and Soukup, 1992). Faults are classified into stator-or rotor faults depending on the location of the fault. Faults associated with the moving parts like bearing and cooling faults are categorized as rotor faults. External faults experienced by these motors are over loading, single phasing, unbalanced supply voltage, locked rotor, phase reversal, ground fault, under voltage and over voltage.

Detection of faults addresses whether or not a condition exists that is outside the normal system operation while fault diagnosis addresses the nature and root cause of a fault. The history of fault monitoring and fault isolation started with the use of electromechanical relays (Bellini *et al*., 2008). As electromechanical relays are slow in operation and consume significant power and were therefore replaced by solid state relays by the introduction of semiconductor technology. These relays are faster, less power consuming and more reliable. Microprocessor based protective relays, developed recently, allow the protection logic to be implemented by software programs. The progress in computer software based on artificial intelligent techniques such as fuzzy logic and Artificial Neural Networks (ANN) attracted the attention to use them in the diagnosis of faults in power system components such as induction motors (Mayur *et al*., 2013). Hence, microprocessor based

Table 1: Comparison of various fault detection technique

| Types of defected fault | Fault detection technique |
|---|---|
| Bearing, Roter, Store and Vibration | MCSA |
| Bearing and starter | Park transform |
| Bearing and roter | ANN |
| Bearing, roter, stator and vibration | wavelet transform |
| Roter, stator and vibration | Finite element method |
| Bearing and vibration | vibration analysis |
| Bearing | Concodia transform |
| Roter | Magnetic field analysis |
| Stator | Power decomposition,<br>KU transform and zero<br>Crossing time method |

protective relays have been developed, that allow the protection logic to be implemented by software programs. Other methods of monitoring and diagnosis of faults of induction motors were proposed in the literature. These methods include Finite Element Method (FEM) and transform based methods like Wavelet Transform (WT), Concordia Transform and others. Different Types of Faults and the corresponding fault detection techniques are summarized in Table 1. Examples of recent research work where the above mention methods are applied can be found by Abdi *et al*. (1999).

**Fault detection using artificial neural networks:** The first use of ANN for control and signal processing applications was in 1940’s. Some of the major networks of ANN are feed-forward networks, Kohonen network, Hamming network, Hopfield network, etc. They differ in their network structure and training algorithms. One of the main features of ANN is that the required response is approached after a short processing time in spite of the large number of iterations required during the learning phase. The architecture of a neural network is illustrated in Fig. 2. The architecture specifies the arrangement of the neural connection, the number of layers and neurons in each layer and the type of activation function. A typical perceptron will have many inputs and these inputs are all individually weighted. These weighted signals are then added together and passed into the activation function. The activation function is the processing algorithm which specifies how the neuron calculates the output vector for any input vector and for a given set of weights. There are many different types of activation function but one of the simplest would be step function. A step function will typically output a 1 if the input is higher than a certain threshold, otherwise the output will be 0. For proper operation of the network it is supposed to be trained with relevant and rich information. The training algorithm specifies how the ANN adapts its weights *w* for all given input vectors, called training vectors. Thus, the neural network can acquire knowledge through the training algorithm and store the knowledge in synaptic weights (Abdi *et al*., 1999).

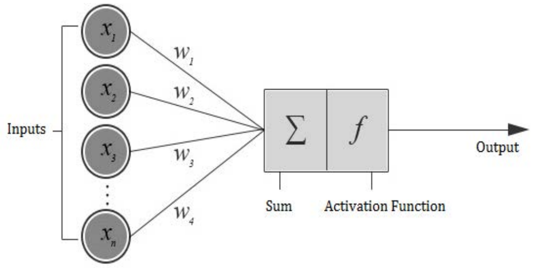

Fig. 2: The architecture of a neural network

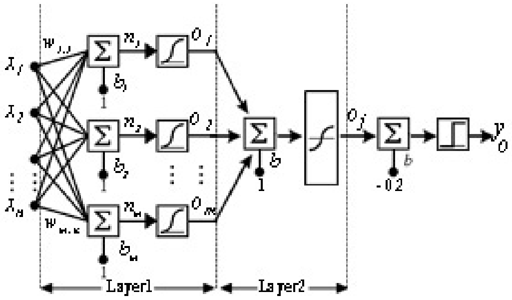

Fig. 3: The structure of the multilayer feed forward neural network with two hidden layers

Fig.3 shows the structure of the multilayer Feed Forward Neural Network (FFNN) with two hidden layers which will be used in this work. The bias unit whose activity level is fixed at one is connected to all neurons in the hidden and output layers to adjust the weighted sum input of each neuron. The output of the jth neuron is obtained by the following equation:

$$o_j = f_j(net_j) = f_j\left[\sum_i \left(w_{ij}x_i\right) + b_j\right] \tag{1}$$

Where:

$x_1, x_2, \ldots x_i$ = The input signals
$w_{1j}, w_{2j}, \ldots w_{ij}$ = The synaptic weights of neuron
$i, f_j$ = The activation function
$o_j$ = The output signal of the neuron

The sigmoid function is used as the activation function. The output of each FFNN is connected to a simple perceptron neural network.

$$y_o = f_h\left[\sum_i \left(w_i o_j\right) - \theta\right] \tag{2}$$

Where:

$y_o$ = Final output simple perceptron neural network
$f_h$ = A heavy side function.
$\theta$ = The value of is therefore known as the neuron bias

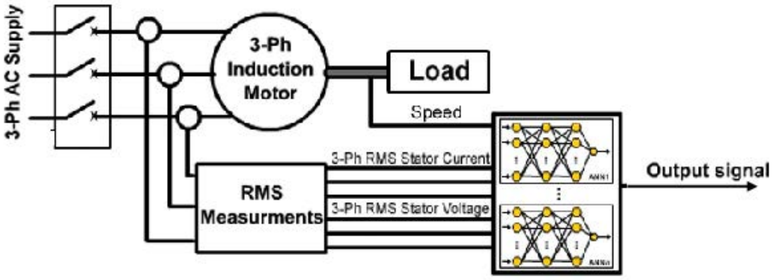

Fig. 4: The block diagram of the proposed ANN-based fault detection system

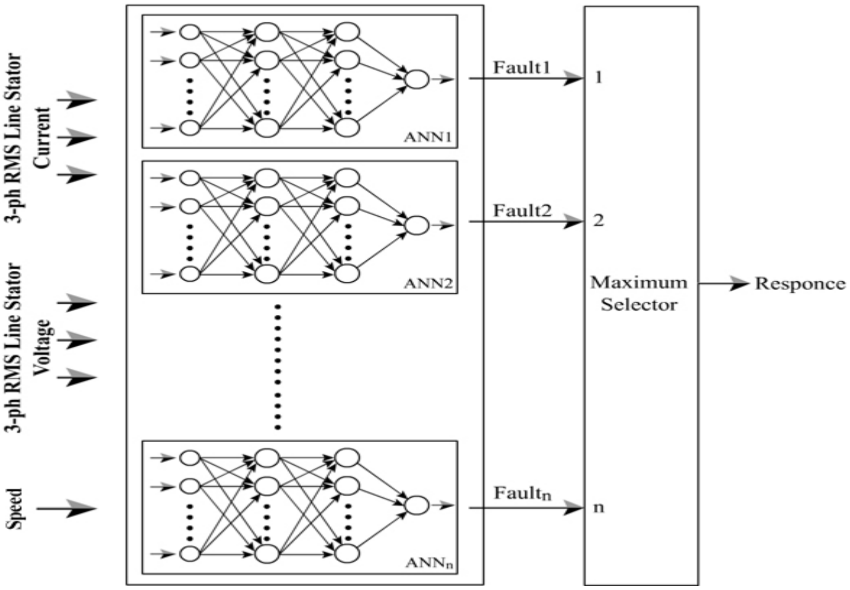

Fig. 5: The ANN structure for the motor fault detection system

**The proposed ann-based fault detection system:** In order to use ANN for identifying induction motor fault-and no fault conditions as a set of input data for each fault in question as a meaningful indicator of faults is required. Samples of recent work for the application of ANN for protection of induction motors can be found in (Kumar *et al*., 2012; Kolla and Altman, 2007; Kowalski and Orlowska-Kowalska, 2003).

Figure 3 illustrates the block diagram of the proposed ANN-based fault detection system. The network includes seven inputs and eight outputs. The inputs are the Root Mean Square (RMS) values of the 3-phase line stator voltages and of the 3-phase stator currents and motor speed signal. The motor speed signal is used to discriminate between motor starts and short circuits. The eight outputs are the external motor faults. These faults include phase failure, unbalanced voltage, locked rotor, under-voltage, overvoltage, phase sequence reversal of supply voltage and mechanical overload.. The binary output "0" correspond to "No Fault" according to normal input measurements. The binary output "1" corresponds to the condition "Faulty Motor". The detection system for external motor faults consists of a three-phase AC supply feeding a 3-phase squirrel-cage induction motor of a 2250 HP, 2400 V, 60 Hz and 1725 rpm. An RMS measurements device is connected in series to measure the currents and the voltages applied to motor. The motor speed signal from a speed sensor device is also feed to the ANN module (Fig. 4). The output signal of the ANN module is connected to a digital relay through the microcontroller as will be explained.

**Neural network structure:** The multilayer FFNN with two hidden layers used in this research is shown in Fig. 5. The Winner-Take-All (WTA) or maximum selectorneural network model is applied (Amari and Arbib, 1977). This networks constitute a basic and large class of neural networks. The network in response to an input pattern produces only one active neuron with a highest input. The total input of the neurons is compared to the

Table 2: The Features of PIC18F4520

| Channels | Group |
|---|---|
| CPU | CPU speed of 10 MIPS, C compiler, optimized RISC architecture |
| Memory | 32 k bytes flash program memory, 1,536 byte RAM data memory, 256 byte EEPROM data memory Channel 2 |
| System | Internal oscillator support-31 kHz to 8MHz, Watchdog timer with separate RC oscillator |
| Power managed modes | Idle and SLEEP modes, |
| Analog features | 10-bit ADC, 13 channels, 100K samples per second, two analog comparators multiplexing |
| Peripherals | Master synchronous, serial port supports master and slave mode, four timer modules, five PWM outputs |
|  | enhanced FLASH program memory, Power-on Reset (POR), Power-up Timer (PWRT) |
| Special Features | Oscillator Start-up Timer (OST), Programmable code protection, In-Circuit Debug (ICD) via two pins |

threshold value of the neuron. This thresholding process is accomplished by comparison as follows: if the weighted sum is greater than the threshold value, it is set to $\theta$. The resulting value is compared to -0.2. If the result is positive, then the output is 1, else the output is 0. The perceptron neural network has a hard limit function at 0 or 1. The value 1 represents an external motor fault (trip signal to digital relay) and the value 0 represents a normal operation condition for induction motor. Each ANN is trained with the data sets obtained from simulated faults on induction motor.

**Neural network training:** The objective of training the network is to adjust the weights so that application of a set of inputs produces the desired set of outputs. At the beginning of neural network training, the diagnosis of the ANN fault detector of the motor conditions will not be accurate. Therefore, an error is measured and used to adjust the internal parameter of the ANN to produce a more accurate output. This process is repeated until a suitable error is achieved. Once the network is sufficiently trained and the network parameters have been saved, the neural network contains all the necessary knowledge to perform the fault detection. The performance function for ANN is the Mean Square Error (MSE) between the network outputs and the target outputs. The training data set has been constructed by computer simulation of Matlab models measurements. This data is first used to train a back-propagation feed-forward network using Matlab neural network toolbox (Amari and Arbib, 1977). Levenberg-marquardt algorithm in MATLAB toolbox was used for training as it is a fast training algorithm for networks of moderate size and has a memory reduction feature. The trained network is placed in a Matlab model that monitors the voltages, currents and motor speed and displays the fault conditions. The step length of the moving data window is 1/4 cycle (4.16 m sec at 60 Hz frequency).

**Microcontroller based architecture for induction motor protection:** The Microcontroller section forms the control unit of the induction motor. It basically consists of the PIC microcontroller with its associated circuitry like crystal with capacitors, reset circuitry and pull up resistors. Each type of PIC microcontroller provides a set of different of features, thus the most suitable microcontroller can be selected for any given application. Some of the main selection criteria are: number of I/O pins available, program memory type and size, timers, interrupt sources, analog inputs (8-bit or 10-bit), serial communication interfaces (USART, SPI, I2C, CAN), internal oscillator, in-circuit debugging, etc. When developing an embedded system, the number and type of inputs and outputs need to be determined. After the hardware requirements have been established, the program is written and tested. According to the size of the program, the chip memory size can be determined.

**The microcontroller module:** In this work, the powerful PIC18F4520 8-bit microcontroller of microchip is used. It is specially chosen because of several features making it ideal for advanced level analog to digital applications in automotive, medical and consumer applications. These features include CMOS technology, low power, high speed FLASH/EEPROM, fully static design, wide operating voltage range (2.0V-5.5V), industrial and extended temperature ranges. Some of the features are mentioned in Table 2.

According to Amari and Arbib (1977), there are seven important non I/O pins of PIC. First is the MCLR (master clear) pin which is active low. A switch is connected from that pin to ground to reset PIC when necessary. Biasing are Vdd (pin 11 and 32) and Vss (pin 12, 31). An oscillator is connected across pin 13 and 14 to provide external clock and the timing signals necessary for program execution. The remaining 33 pin are configured as I/O pin. The analog signal received from the current transformers and board amplifier is interfaced with the ADC peripheral of the PIC microcontroller where it is converted to a digital outputs.

**The adc module:** This is used to convert the sensor values which are in analog form to digital m and provide it to microcontroller. The ADC module on the PIC has four special function registers associated with it: result high register (high byte) ADRESH, result low register (low byte) ADRESL to store the output from the converter, control register 0 (ADCON0) and control register 1 (ADCON1). The ADCONO register is used to set the conversion time and select the analog input channel. The

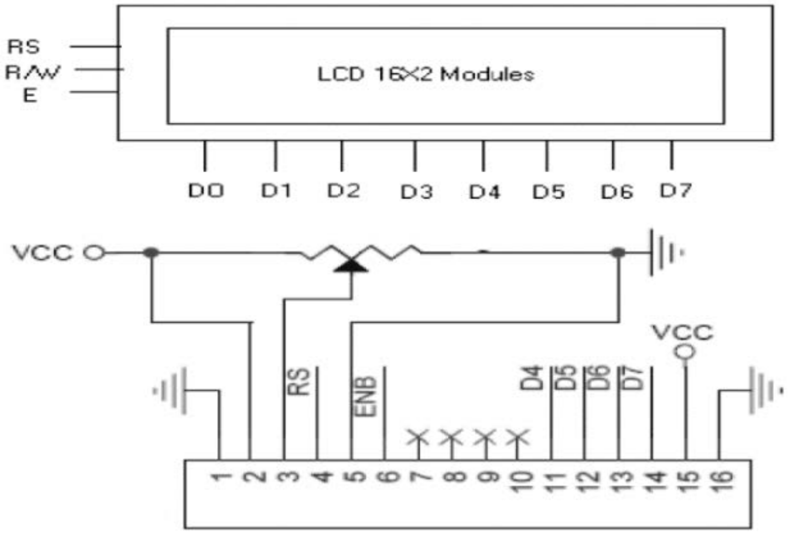

Fig. 6: LCD module

ADON bit is used to turn on the ADC else the ADC is turned off when the microcontroller is powered up to reduce power consumption. ADCS1 and ADCS0 set the conversion time. The GO_DONE bit is used to check if the conversion is finished. Setting this bit initiates the start of conversion then the bit is cleared when the conversion is complete. CHS2, CHS1 and CHS0 are the channel select bits to determine which input pin is routed to the ADC. ADCON1 is split into two sections. The first section is a single bit, the result format selection bit ADFM which selects if the output is right justified (bit set) or left justified (bit cleared). The advantage is the possibility to use as an 8 bit converter (instead of ten bit) by clearing this bit and reading just ADRESH and ignoring the two least significant bits in ADRESL. The second section includes the A/D port configuration control bits PCFG3-0. The default of PCFG = 0000 makes the 8 pins RA0-RA3 and RA5 as well as RE0-RE2 used for analog inputs. The internal RC oscillator is used for the conversion clock source.

**LCD modules:** The LCD used has 14 pins. Vcc and Vss provide +5v and ground respectively and Vee is used for controlling LCD contrast. There are two registers inside the LCD. The RS Register Select pin is used for third selection. If RS = 0, the instruction command code register is selected. If RS = 1 the data register is selected, allowing the user to send data to be displayed on the LCD. The working is dependent upon the interfacing done between the microcontroller and the LCD (Fig. 6).

**The microcontroller-based fault classification:** The block diagram and schematic diagram for the microcontroller based fault classification system are shown in Fig. 7 and 8, respectively. The motor starts at rated condition. The stator currents and line voltages are monitored through current and voltage transformers. The measured values are passed to computer through serial communication via RS 232 cable. The constructed simulation model in MATLAB Simulink involves The ANN system explained before. The ANN structure evaluates the inputs to diagnose the motor condition. The obtained output is transferred to PIC microcontroller. This microcontroller can sense 8 analog inputs up to 5V. Six analog inputs of microcontroller have been used for 3-phase voltages and currents individually for conversion to digital signal. The remaining inputs can be used for receiving the information from motor such as temperature, speed etc. The current transformer is an 1-4 converter (20A/20V) which gives output in terms of voltage and can be fed to the microcontroller directly. Step down transformer is (220V/6V). The output of these transformers will vary proportionately with respect to its input. The microcontroller senses the voltage, compares with the reference value and sends control signals to the respective protective relays. Then microcontroller performs fault classification according to the stored program in it. If any fault occurs microcontroller will send a signal to the relay circuit which isolates the motor from the supply and the type of fault is displayed on LCD (Fig. 8).

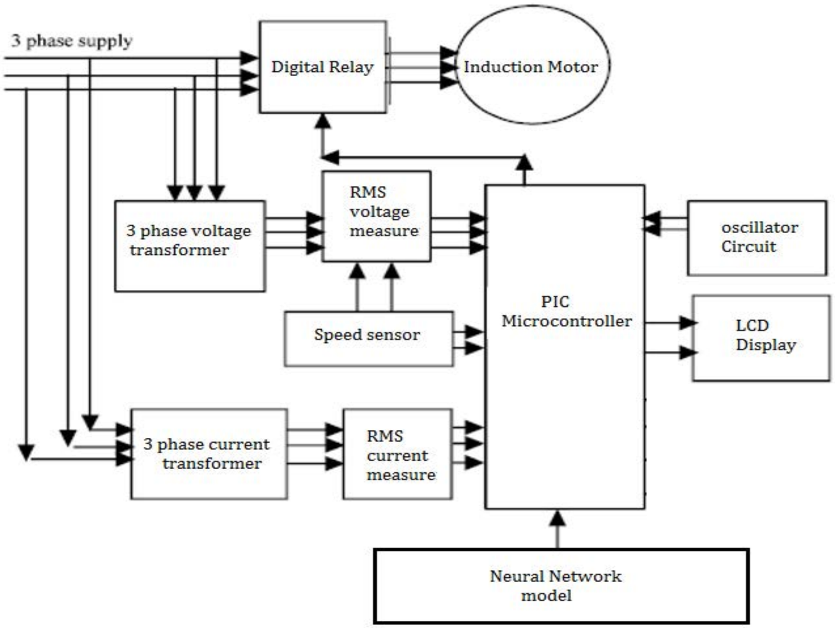

Fig. 7: The block diagram for the microcontroller based fault classification system

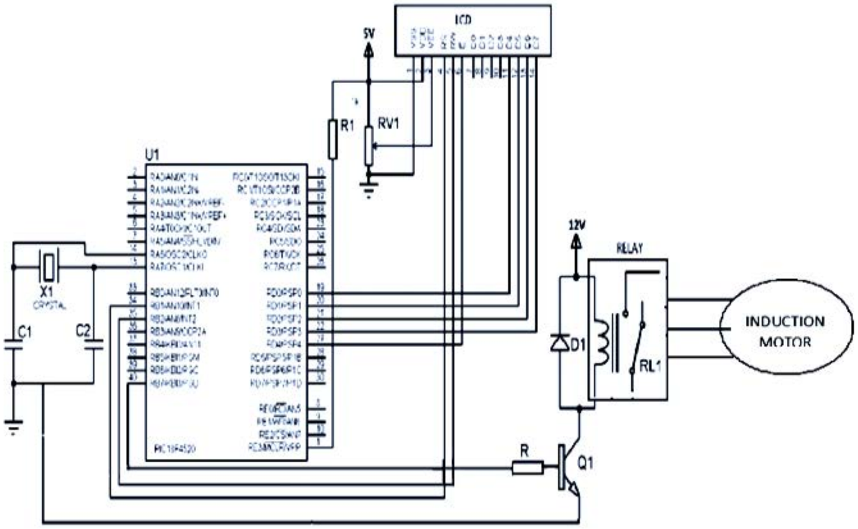

Fig. 8: The schematic diagram for the microcontroller based fault classification system

## RESULTS AND DISCUSSION

An extensive series of simulation studies have been carried out to obtain various motor faults for analysis using Matlab/Simulink. The microcontroller unit performs fault classification and delivers a signal to the relay to trip the motor according to the fault conditions It should be noted that for each protection scheme, the time delay and setting values could be individually adjusted according to the rating and characteristic of the protected motor, taking into account the coordination between different protection schemes. The description and cause of the different fault types as well as the corresponding response time are summarized in Table 3.

A sample of the simulation results is given in Fig. 9. Figure 7 show the waveforms of the stator current, the line voltage and the motor speed, respectively. As the figures show the time of fault occurrence is t =13 sec when the monitored current rise to 15 times of the rated value. The response time of the protection scheme is 4.16 m sec as shown in Fig. 9. The current drops to zero upon the tripping of the circuit protection. Figure 10 shows the

Table 3: The different fault types and the response time

| Type of fault | Description | Cause | Response time |
|---|---|---|---|
| Line to Ground Fault | The current rises to ten times of the rated current | A short circuit occurs at the connection between the feeder and motor | 4.16 |
| Phase Reverse Fault | The direction of rotation of the motor is reversed | A reversal in the phase sequence of. the supply voltage occurs | 4.16 |
| Locked Rotor Fault | The current rises to the startup value. which is five to eight times of the normal full load run current | The rotor becomes obstructed and prevented from rotation. | 8 |
| Phase Losses fault | The stator current rises on two of the three phases. | The voltage of one of the three phases becomes zero. | 12 |
| Over Load Fault | The motor is overloaded by up to 25% of its rated full-load current | | 41 |
| Unbalanced Voltage Fault | Excessive currents flow in the stator winding causing overheat to the point of burn out | The line voltages applied to the motor are not exactly the same | 8.3 |
| Under Voltage Fault | A large drop in voltage makes the motor running slower with a lower output and may cause the motor to stall. | The average line-to-line voltage that is lower than the minimum acceptable operating voltage | 4.16 |

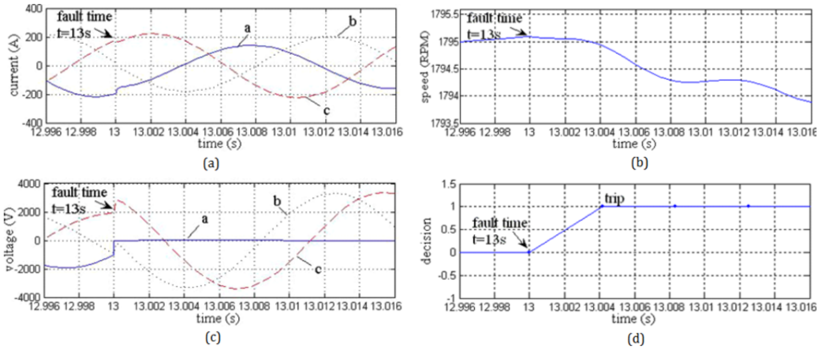

Fig. 9: Responses time of line to ground fault

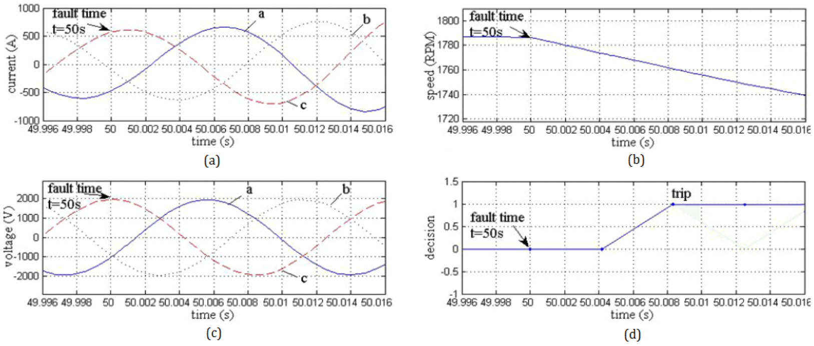

Fig. 10: Responses to locked rotor fault

response of the protection system for the locked-rotor fault. This fault occurs when the rotor becomes obstructed and prevented from rotation for some mechanical reason. The motor current changes from its normal run value to the stall or Startup value which is five to eight times greater than normal full load run current. As the motor is not design to carry such a large current continuously, the protection system disconnects the motor to prevent permanent damage of Fig 9 shows a response time of 8 m sec. The complete system is successfully tested by creating different faults on the simulated motor, testing measurement data sets to test the accuracy of the trained neural network to diagnose different external motor faults. The result demonstrates that with proper processing of the measured data and proper training procedure, the neural network motor fault diagnosis schema can diagnose external motor faults with desired accuracy. The motor is turned-off using the digital relay interfaced to the microcontroller, if a fault is encountered, that enable to test the trained network.

## CONCLUSION

External motor faults can cause unbalance in motor performance and failure to motor parts. In this study, a microcontroller-based protection system for three phase induction motor during external fault condition has been proposed. Artificial neural network is used for motor fault detection. The ANN model is trained and its performance was tested using back-propagation feed-forward network function. The monitoring and operational diagnosis of a three-phase induction motor was achieved by using eight outputs. The inputs to the ANN are the RMS 3-phase currents, voltages and motor speed while the outputs are fault or no fault. PIC microcontroller is used for fault classification and to control tripping the motor circuit through the interfaced digital relay. The application of microcontroller decreases the response time of the protection system by about 8-10% compared the protection systems based on neural network only and hence has become the limitations of ANN.

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