Experimental Design of a Bidirectional Single Phasing Protection for a Three Phase Induction Motor with Voice Notification.

[1]C.O. OMEJE, [2]S.O. OKOZI, [3]E.O. EZUGWU

[1] Department of Electrical/Electronic Engineering, University of Port Harcourt, Rivers State Nigeria.
[2&3] Department of Electrical/Electronic Engineering, Federal University of Technology Owerri, Imo State Nigeria.

Abstract: This paper analyzes a protection scheme for a three phase induction motor based on a single phasing fault. Two stages were considered in the analysis of this work. The first stage presents the dynamic modelling of the induction motor under a healthy and a faulty running condition for simulation purposes. All simulation results were realized using MATLAB 7.14 software. The second stage considered the experimental design of a single phasing and bidirectional protection system of the induction machine with voice notification. The overall process was monitored by a PIC 16F877A microcontroller which senses the sudden occurrence of the single phase fault and triggers a relay to open a magnetic contactor. This process turns off the induction motor and simultaneously sends a voice message through a buzzer for fault notification. The usefulness of this design can be applied in the detection of under-voltage or brown-out in induction motor voltage supply.

Keywords: Three-Phase Induction Motor, Dynamic Modelling, Single-Phasing Fault, Analog-Digital Converter, PIC 16F877A microcontroller, Magnetic Contactor,

1.0 Introduction.

Induction motor has formed an integral part in the present era of automation [1]. Although it is reliable and robust in application, its lifespan can be affected by mechanical, electrical or thermal stress leading to the occurrence of various types of faults [1]. Induction machine faults can be classified as internal and external based on the location of the fault occurrence [2]. Mechanical vibration, air gap eccentricity, bearing and rotor failure are classified as internal faults whereas overloading, single-phasing, unbalanced voltage supply, ground fault, locked rotor, phase reversal, under-voltage and over-voltage are classified as external faults [2]. The single-phasing being a prevalent external fault, arises when one phase out of a three phase motor is suddenly open-circuited during machine operation [3]. Single-phasing fault condition can also arise when there is a blown fuse, a loosed connection of the phase and partial failure of the switch gears [4]. It is pertinent to state that one adverse effects of single-phased fault is overheating which can lead to insulation breakdown. When a three phase induction motor in operation is suddenly single phased, it operates continuously but draws excessive current in the two remaining phases [5]. A single-phased induction motor does not have a starting torque and when an attempt is made to power the machine from rest, it only produces a humming sound. It is an established fact that thermal overloading and single-phasing make up to 44% of machine malfunction [6]. Excessive heat, therefore, causes a rapid deterioration of motor winding insulation. Several literature reviews have been carried out on machine protection against single-phasing with pertinent to under voltage and voltage imbalance [7].

2.0 Related Works

A literature reviewed in [8] stated that when one phase of the machine is opened, the three phase induction motor will continuously run as a result of a blown out fuse. At this state, the induction motor heat up quickly and is protected by a total shut-down. Advanced single phasing control without a microcontroller for a three motor control was presented in [9]. Therefore when any of the phases goes out on load, the motor continues to run with two phases but draws large amount of current from the same load. This occurrence is avoided by switching off the entire motor. In [10] a PIC16F877 microcontroller based technique was invented to protect a three phase induction motor from single phasing. The PIC microcontroller used samples the values of each phase through a low voltage conversion obtained from a stepped down transformer. The voltage signal produced is converted to digital value using ADC converter. The controller continuously compares the digital value with the reference voltage value until a fault occurs. During fault occurrence, the normally closed contactor is opened to disconnect the motor from the power supply. In [11] it showed that single phasing of a three phase induction motor can result to thermal effect which greatly affects the insulation of the motor. Thermal impacts shorten the longevity of the motor. Modern motor relays must be protected against these effects which may occur for medium and large motors and for all voltage operational levels. In [12], the protection of the induction motor under various conditions like over voltage, under voltage, voltage imbalance and over current using PIC16C84 microcontroller was discussed. The connection for running a three phase induction motor with zig-zag transformer for single phasing fault was explained in [13]. It also stated that three phase induction motor does not start during single phasing, because negative sequence current does not allow induction motor start operation. In [14], it stated that for single phasing the three phase reclosers are widely used on distribution feeders. The majority faults are single phase. Its disadvantage occurs on the other two phase users with high current value. In [15], a paper was presented on a PIC microcontroller based protection system of three phase induction motor. Fault types like phase failure, voltage imbalance, locked rotor, under voltage, overvoltage, and many more were considered in this research. In [16], it analyzed the stator current of three phase induction motor by measuring the phase angle, symmetrical components, skewness, kurtosis and harmonic distortion. 8085 microprocessor was applied for sensing stator current and phase shift. The phase shift helps to protect the motor from any increased or decreased phase difference that may result to single phase fault. Single-phasing is not desirable for the proper operation of induction motors, therefore appropriate measures are taken to protect the machine from this fault. This paper therefore applied a fault sensitive correction method achieved through the design and construction of a bidirectional single phasing protection device. The process was realized using A PIC16F877 microcontroller with an Analogue to Digital Converter programmed to sense a drop in voltage on the three phase supply to the machine. The voltage values of the phases are indicated on the liquid crystal display (LCD). A switch controlled by the PIC16F877 microcontroller and voice module was used to trigger a buzzer sound that notifies the operator on the single phase fault.

3.0 Dynamic Modelling of a Three Phase Induction Motor with a Single-Phasing Fault.

Induction motor is conventionally modelled in either synchronously rotating reference frame or stationary reference frame [17]. The stationary reference frame for convenience and ease in simulation is usually preferred over the synchronously rotating frame. In the stationary reference frame, the angular speed ω is always set to zero while in the synchronously rotating reference frame it is set to ω_e [17].

The induction machine equations in stationary reference frame are presented in (1)-(10).

$$V_{qs}^{s} = \frac{\rho}{\omega_b}\psi_{qs}^{s} + r_s i_{qs}^{s} \tag{1}$$

$$V_{ds}^{s} = \frac{\rho}{\omega_b}\psi_{ds}^{s} + r_s i_{ds}^{s} \tag{2}$$

$$V_{os} = \frac{\rho}{\omega_b}\psi_{os} + r_s i_{os} \tag{3}$$

$$V_{qr}^{is} = \frac{\rho}{\omega_b}\psi_{qr}^{is} - \frac{\omega_r}{\omega_b}\psi_{dr}^{is} + r_r^{i} i_{qr}^{is} \tag{4}$$

$$V_{dr}^{is} = \frac{\rho}{\omega_b}\psi_{dr}^{is} + \frac{\omega_r}{\omega_b}\psi_{qr}^{is} + r_r^{i} i_{dr}^{is} \tag{5}$$

$$V_{or}^{i} = \frac{\rho}{\omega_b}\psi_{or}^{i} + r_r^{i} i_{or}^{i} \tag{6}$$

Where: $\boldsymbol{\psi = \omega_b\lambda}$, $\boldsymbol{\psi_{qs} = \omega_b\lambda_{qs}}$, $\boldsymbol{\psi_{ds} = \omega_b\lambda_{ds}}$, $\boldsymbol{\psi_{os} = \omega_b\lambda_{os}}$, $\boldsymbol{\rho = \frac{d}{dt}}$, $\boldsymbol{\omega_b}$is called base electrical angular velocity in rad./sec. Also, $\boldsymbol{\omega_b L_{LS}} = \mathbf{X_{LS}}$, $\boldsymbol{\omega_b L_m} = \mathbf{X_m}$, $\boldsymbol{\omega_b L_r^{i}} = \mathbf{X_{Lr}^{i}}$

A modified stator and rotor flux linkage equations are compactly written in matrix form in terms of reactances as shown in (7).

$$\begin{bmatrix} \psi_{qs}^{s} \\ \psi_{ds}^{s} \\ \psi_{os} \\ \psi_{qr}^{\prime s} \\ \psi_{dr}^{\prime s} \\ \psi_{or}^{\prime} \end{bmatrix} = \begin{bmatrix} A & 0 & 0 & X_m & 0 & 0 \\ 0 & A & 0 & 0 & X_m & 0 \\ 0 & 0 & X_{LS} & 0 & 0 & 0 \\ X_m & 0 & 0 & B & 0 & 0 \\ 0 & X_m & 0 & 0 & B & 0 \\ 0 & 0 & 0 & 0 & 0 & X_{Lr}^{\prime} \end{bmatrix} \begin{bmatrix} i_{qs}^{s} \\ i_{ds}^{s} \\ i_{os} \\ i_{qr}^{\prime s} \\ i_{dr}^{\prime s} \\ i_{or}^{\prime} \end{bmatrix}$$

$(v - s)$ (7)

Where $A = X_{LS} + X_m$ and $B = X_{Lr}^{\prime} + X_m$

$$\begin{bmatrix} i_{qs}^{s} \\ i_{ds}^{s} \\ i_{os} \\ i_{qr}^{\prime s} \\ i_{dr}^{\prime s} \\ i_{or}^{\prime} \end{bmatrix} = \begin{bmatrix} A & 0 & 0 & X_m & 0 & 0 \\ 0 & A & 0 & 0 & X_m & 0 \\ 0 & 0 & X_{LS} & 0 & 0 & 0 \\ X_m & 0 & 0 & B & 0 & 0 \\ 0 & X_m & 0 & 0 & B & 0 \\ 0 & 0 & 0 & 0 & 0 & X_{Lr}^{\prime} \end{bmatrix}^{-1} \begin{bmatrix} \psi_{qs}^{s} \\ \psi_{ds}^{s} \\ \psi_{os} \\ \psi_{qr}^{\prime s} \\ \psi_{dr}^{\prime s} \\ \psi_{or}^{\prime} \end{bmatrix}$$

(A) (8)

The developed torque and motor speed relational equations are presented in (9) and (10) respectively.

$$T_{em} = \frac{3}{2}\frac{P}{2\omega_b}\left(\psi_{ds}^{s} i_{qs}^{s} - \psi_{qs}^{s} i_{ds}^{s}\right) \quad (N.m) \quad (9)$$

$$J\frac{d\omega_{rm}}{dt} = T_{em} + T_{mech} - T_{damp} \quad (N.m) \quad (10)$$

A star connected stator winding is adopted for the analysis of single-phasing fault condition of the three phase induction motor. If phase A is disconnected with a floating neutral current, the phase A current tends to zero with the zero sequence current. Hence, $i_{as} = 0, i_{bs} + i_{cs} = 0, i_{os} = 0$. Applying the abc to qdo transformation gives rise to (11).

$$\left[i_{qdo}^{s}\right]' = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a^{s} \\ i_b^{s} \\ i_c^{s} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} 0 \\ i_b^{s} \\ i_c^{s} \end{bmatrix} \quad (11)$$

From (11), $i_{qs}^{s} = -\frac{1}{2}(i_b + i_c) \xRightarrow[i_{bs} + i_{cs}=0]{} 0$. From (7), $\psi_{qs}^{s} = (X_{LS} + X_m)\, i_{qs}^{s} + X_m i_{qr}^{\prime s} = X_m i_{qr}^{\prime s} = \psi_{mq}^{s}$. Similarly, $\psi_{qr}^{\prime s} = (X_{Lr}^{\prime} + X_m) i_{qr}^{\prime s} + X_m i_{qs}^{s} = (X_{Lr}^{\prime} + X_m) i_{qr}^{\prime s}$. $i_{qr}^{\prime s} = \frac{\psi_{qr}^{\prime s}}{(X_{Lr}^{\prime}+X_m)}$. From (1), $V_{qs}^{s} = \frac{X_m}{\omega_b}\frac{di_{qr}^{\prime s}}{dt} = \frac{1}{\omega_b}\frac{X_m}{(X_{Lr}^{\prime}+X_m)}\frac{d\psi_{qr}^{\prime s}}{dt}$. Simulations carried out using the machine modelled equations (1)-(11) under a normal supply and single phased condition are presented in figures 1-7. A fault condition was introduced at a simulation period of 2.5seconds as shown in figures 2 and 4.

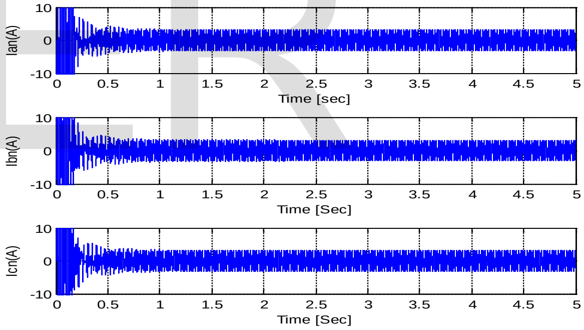

Figure 1: A plot of a balanced three phase current supply against Time.

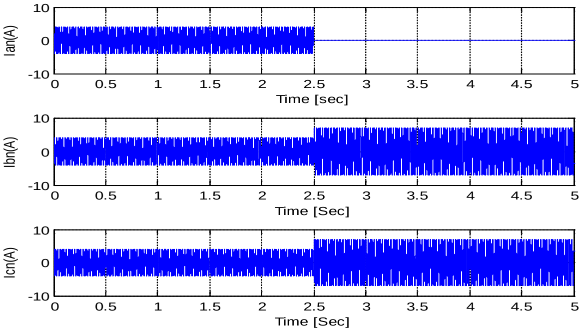

Figure 2: A plot of an unbalanced three phase current supply with phase A shorted at 2.5-5.0 sec.

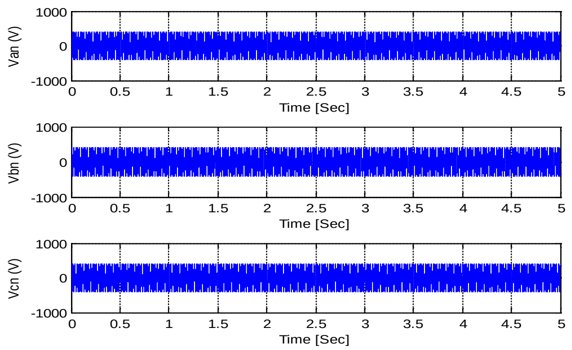

Figure 3: A plot of a balanced three phase voltage supply against time

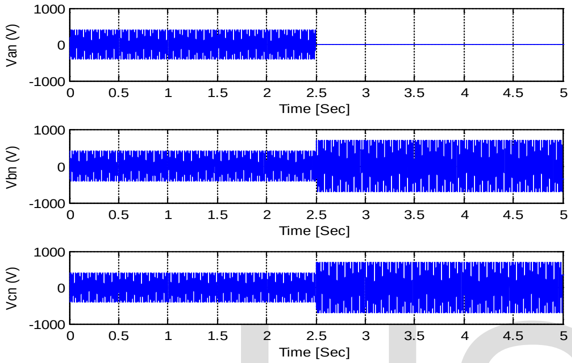

Figure 4: A plot of an unbalanced three phase voltage supply with phase A shorted at 2.5-5.0 sec.

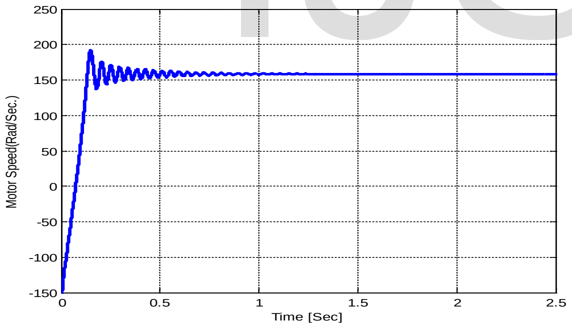

Figure 5: A plot of Motor Speed against Time.

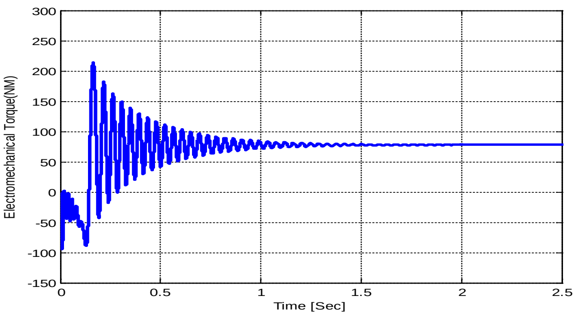

Figure 6: A plot of Motor Torque against Time.

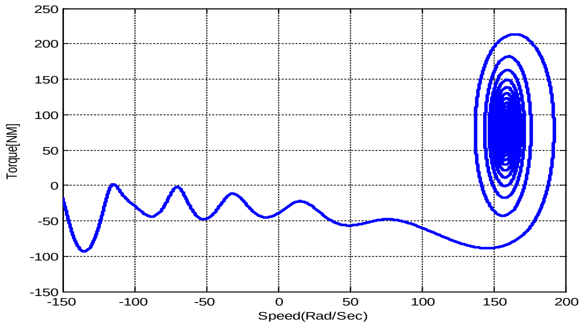

Figure 7: A plot of Motor Torque against Speed.

4.1 Experimental Design of a Three Phase Induction Motor with a Single-Phasing Fault.

The experimental design was achieved using three major sub-circuits which include: the d.c and a.c power supply to the semi-conductor devices and to the three phase induction machine, the control unit and the output unit as presented in figure 8.

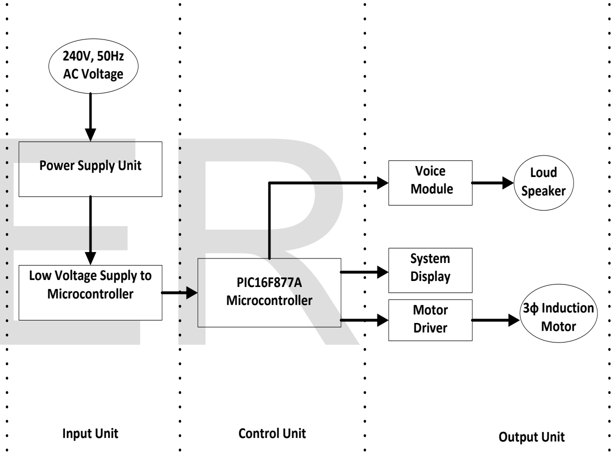

Figure 8: Block diagram of a single phasing and bi-direction protection of a three phase motor with voice notification.

The power supply unit consists of a 240/12V stepped down transformer, full bridge diode rectifiers, 2200μF, 25V capacitor, 12V and 5V voltage regulator (7812 and 7805) for biasing the microcontroller and the relay. A 100nF capacitor for filtering the ripples across the regulator. The control unit is made up of a PIC 16F877 microcontroller with 20MHz crystal oscillator for sensing the voltage drop on each of the three phase supply. The output unit is composed of an electromechanical relay, magnetic power contactor, 0.25Hp, 3ϕ, 415V, 50Hz induction motor, a Liquid Crystal Display (LCD) and a Voice Notification Module (APR 9031 Module).

4.1.1 Power Supply Unit (PSU) Design

The power supply unit is necessary for the provision of regulated dc power supply from ac mains. The power supply unit consists of a step down transformer (240/24v), the diode rectifier, capacitors for filtering and also voltage regulator. The power supply circuitry is shown in figure 9.

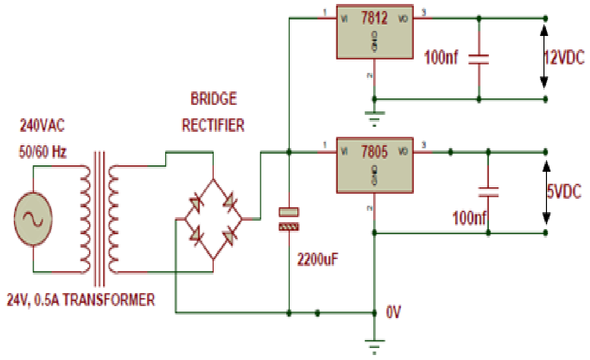

Figure 9: power supply unit

4.1.2 Control Unit

The control unit consists of PIC16F877 microcontroller and a crystal oscillator. A microcontroller is a small computer on a single integrated circuit containing a processor core, memory, and programmable input/output peripherals. For the purpose of this design, a PIC16F877A microcontroller was selected to effectively execute the control of the system. its special properties such as, flexibility, High analogue to digital converter (ADC) sample rate, RAM size, number of programmable I/O lines, programmable serial channel were harnessed. The control circuit is shown in figure 10.

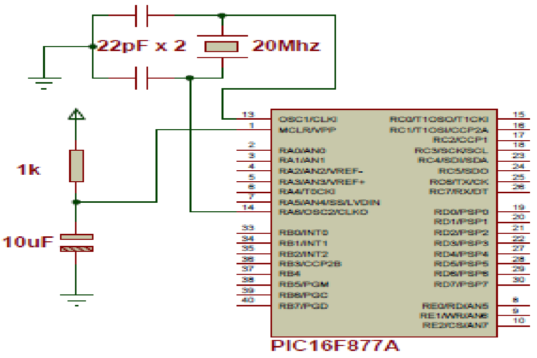

Figure 10: Control Unit configuration

4.1.3 The Output Unit

The output unit of this design presents the result of the logical operation performed by the control unit. This stage is composed of the electromechanical relay, magnetic power contactor, 0.25Hp (1/4Watts) three phase induction motor, Liquid Crystal Display Unit (LCD) and a voice notification module (APR9031 module).

a) Relay

A relay is an electrical operated switch that incorporates an electromagnet which is activated by a current or signals in one circuit usually a PIC controller to open or close another circuit (magnetic contactor). A 12V relay is used in this design for switching on and off of a power contactor switch and is also used to run 3-phase motor. The circuit for interfacing the relay to the control unit is shown in figure 11.

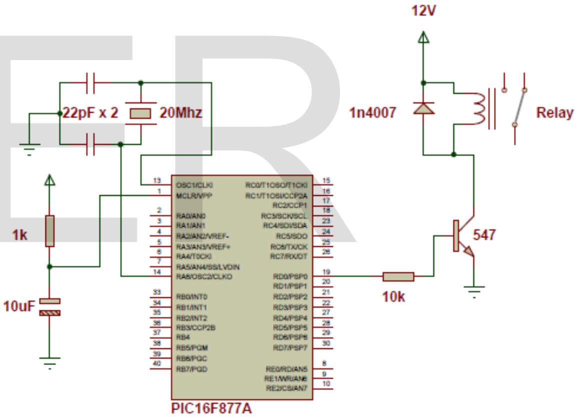

Figure 11: Interfacing a relay to the control unit

The circuit shown in figure 11 indicates that the contactor is switched on and off by the controller via the relay and bc547 transistor. To switch the relay using a transistor, a diode is applied in the circuit to prevent the transistor from been damaged by the back emf. This is because the relay is an inductive load. When a supply voltage is delivered to the coil of the relay, current flows and a magnetic field is set up which moves the armature to close one set of the contacts and opens the other set. Also when power is removed from the relay, the magnetic flux in the coil collapses and generates a fairly high voltage in the opposite direction (back emf) to the initial supply voltage.

b) Magnetic contactor

A contactor is an electrically controlled switch used for switching an electrical power circuit. It is similar to a relay except that it has higher current ratings and a few other differences. In this work, the magnetic contactor is used for switching a high current, high voltage output load (three phase motor). The power contactor was selected using a rule of thumb which states that, the current capacity of the load switching device (Contactor) should be three times larger than the normal load running current. This is to ensure that the contactor withstands the high current that the motor can draw at start up. The power contactor used for the system design is shown in figure 12

Figure 12: Magnetic Contactor

c) Liquid crystal display

A liquid-crystal display is a flat-panel display or other electronic visual display that uses the light-modulating properties of liquid crystals. It finds application in most embedded system, such as digital watches, cell phone, and television. The LCD was used to interact with the user and at every point in time to display the status of the system. The interfacing of the LCD to the device control unit is shown in figure 13.

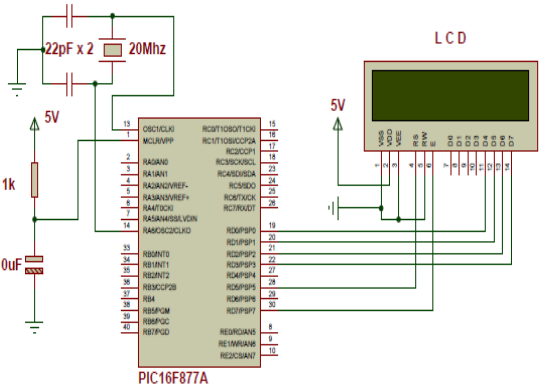

Figure 13: interfacing 16×2 liquid crystal display

d) Voice notification module

The voice notification module makes use of APR9301 module. This module is applied for relating error signal to the system operator through a loud speaker when either one of the phases is lost or when the incoming phases are reversed in sequence. The module has the feature of recording voice/sound in maximum length of 31seconds and also plays it back when enabled for playback. In this design it is used to record a notification message when there is an error in the three phase system. The interfacing circuit diagram for the voice module is shown in figure 14.

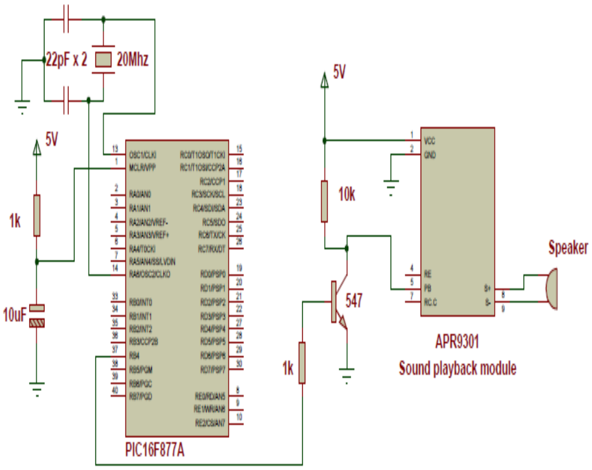

Figure 14: An interfaced circuit for sound module.

4.1.4 System Flow Chart Design

The system software design is programmed such that the microcontroller constantly reads the inputs signals from the star-connected three phase voltage divider circuits shown in figure 15. When wrong sequence is detected, the controller turns the motor off via a switching circuit. A sixty second delay is generated before another test is carried out. After sixty seconds delay, the motor is turned on if the correct sequence is detected or remains off again for sixty seconds if the wrong sequence or phase failure still persists. If after 180 seconds (3min), the error persists, the controller ends the loop that executes the check and permanently shut down the motor. An error message notification is sent via a load speaker. The process is repeated in a continuous loop to keep the system running as long as power is maintained in the device. The system program flow chart is shown in figure 16.

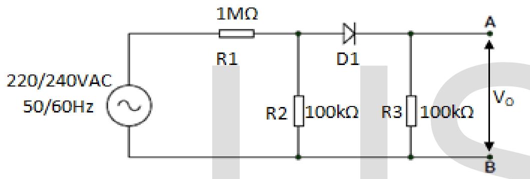

Figure 15: Single-phase equivalent circuit of three phase voltage divider.

4.1.5 System Control Operation

The system consists of the power supply unit for the generation of 5V and 12V. The whole system is controlled by a PIC16F877 microcontroller. The 220V from the source is reduced to 2.1V by a star connected resistor network using the three phase voltage divider. This is to allow the analog ports of the microcontroller read the voltage value since its inputs range from 0-5V. The single phase equivalent circuit of the three phase voltage divider circuit is shown in figure 15. This circuit consists of three resistors in parallel and with one diode in series with one of the resistors. The resistor values are calculated using equation (12). The microcontroller reads the three analog input voltages to check for phase sequence. It triggers the relay to create a contact in the magnetic contactor thereby causing the motor to turn on. Conversely, when a phase failure occurs that is when they are not in sequence, the microcontroller sends a signal to the relay. The relay opens the contacts of the magnetic contactor and shuts down the motor. At the same time, a voice notification is sent to the operator that a phase failure has occurred.

$$R_{eq} = \frac{R_2 \times (D_r + R_3)}{R_2 + (D_r + R_3)} \quad (12)$$

Where: $R_2 = 100K\Omega$, $R_3 = 10K\Omega$

D_r is the diode resistance $= 655k\Omega$

$$R_{eq} = \frac{100 \times (655+10)}{100 + (655+10)} = 10K\Omega$$

$$V_{out} = \frac{R_2}{R_1 + R_2} \times V_{in} = \frac{10k}{100k + 10k} \times 220 = 2.1V$$

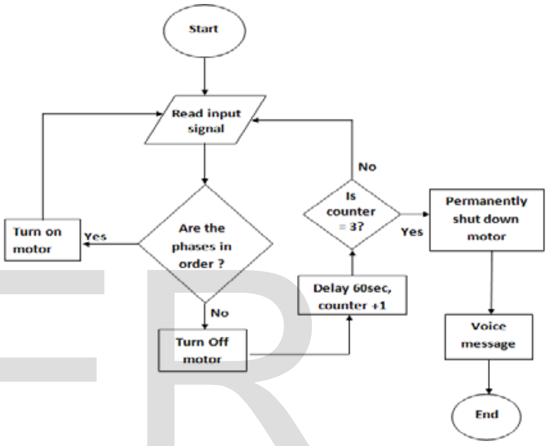

Figure 16: PIC Flow Chart Algorithm

Figure 17 shows the complete circuit design for the Single Phasing Protection of a Three Phase Motor with Voice Notification System.

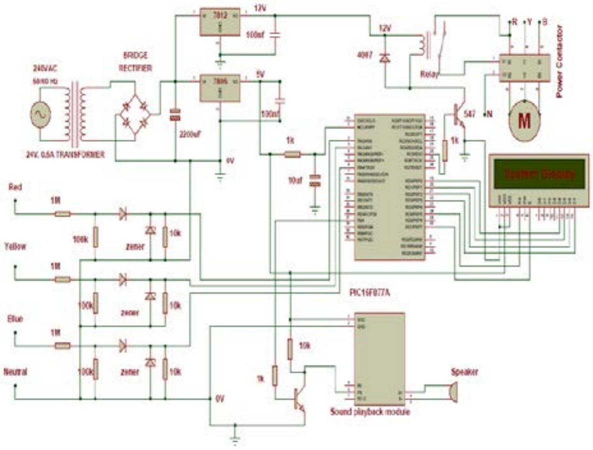

Figure 17: Control circuit design of Single Phasing Protection of a Three Phase Motor with Voice Notification System.

4.1.6 3-Phase Motor Test Results and Discussion

Test was conducted by connecting the motor power cables (stator terminal) to a direct a.c mains supply and observations were made on the motor operation in a good working condition (balanced system) and under a partial short-circuit condition (unbalanced system). A multi-meter was used to measure the voltage level of the three phases at normal operating condition and also at a short-circuit condition. The resulting tables 1-4 were obtained from the multi-meter readings.

Table 1: A balanced Three Phase Voltage Supply.

Time(s)	V_{red} (Volts)	V_{blue} (Volts)	V_{yellow} (Volts)
0.15	220.00	220.00	220.00
0.17	220.00	220.00	220.00
0.19	220.00	220.00	220.00
0.21	220.00	220.00	220.00
0.23	220.00	220.00	220.00
0.25	220.00	220.00	220.00
0.27	220.00	220.00	220.00
0.30	220.00	220.00	220.00
0.31	220.00	220.00	220.00
0.33	220.00	220.00	220.00
0.45	220.00	220.00	220.00

Table 2: An unbalanced Three Phase Voltage Supply with a shorted yellow phase.

Time(s)	V_{red} (Volts)	V_{blue} (Volts)	V_{yellow} (Volts)
0.15	220.00	220.00	185.45
0.17	220.00	220.00	160.07
0.19	220.00	220.00	148.90
0.21	220.00	220.00	132.87
0.23	220.00	220.00	101.52
0.25	220.00	220.00	85.32
0.27	220.00	220.00	66.41
0.30	220.00	220.00	44.52
0.31	220.00	220.00	21.82
0.33	220.00	220.00	10.42
0.45	220.00	220.00	0.00

Table 3: An unbalanced Three Phase Voltage Supply with a shorted blue phase.

Time(s)	V_{red} (Volts)	V_{blue} (Volts)	V_{yellow} (Volts)
0.15	220.00	180.24	220.00
0.17	220.00	169.77	220.00
0.19	220.00	147.92	220.00
0.21	220.00	134.84	220.00
0.23	220.00	119.42	220.00
0.25	220.00	56.74	220.00
0.27	220.00	42.51	220.00
0.30	220.00	68.19	220.00
0.31	220.00	88.06	220.00
0.33	220.00	0.00	220.00
0.45	220.00	0.00	220.00

Table 4: An unbalanced Three Phase Voltage Supply with a shorted red phase.

Time(s)	V_{red} (Volts)	V_{blue} (Volts)	V_{yellow} (Volts)
0.15	169.50	220.00	220.00
0.17	140.82	220.00	220.00
0.19	139.29	220.00	220.00

0.21	121.62	220.00	220.00
0.23	110.62	220.00	220.00
0.25	101.23	220.00	220.00
0.27	91.33	220.00	220.00
0.30	0.00	220.00	220.00
0.31	9.89	220.00	220.00
0.33	0.00	220.00	220.00
0.45	5.20	220.00	220.00

The experimental set up for the single phasing and bi-directional protection of a three phase motor with automatic shutdown and voice notification system is presented in Figure 18.

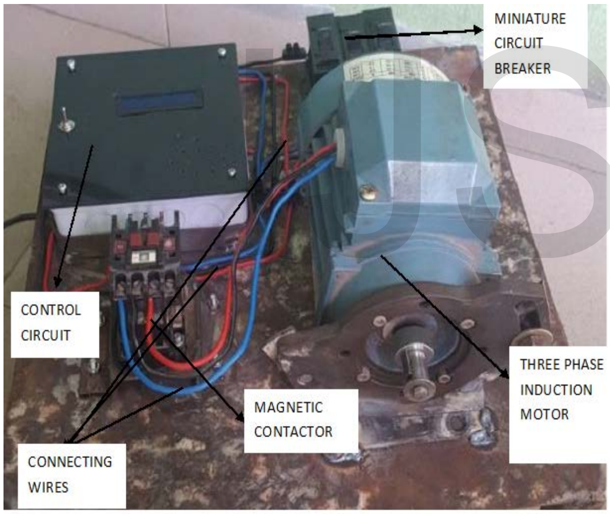

Figure 18: Complete Experimental Work for the Prototype Design.

5.1 Conclusion

A bidirectional single phasing protection of a three phase induction motor was analyzed under a balanced and unbalanced voltage condition. The characteristic effect of high current at a short-circuited condition was presented. Figures 1 and 3 indicate the current supply and voltage supply to the stator terminal of the induction motor under a balanced condition. Figures 2 and 4 represent the current supply and voltage supply for an unbalanced three phase voltage supply. At a simulation period of 2.5seconds, a short-circuit fault was applied across phase A supply. It is observed that the voltage and current magnitude rises beyond the permissible supply value. The prototype design showed that it is possible to detect the short-circuit fault at a quicker time through the voice notification alarm and LCD display. This scheme also ensures that when the phases are in correct sequence the machine remains on and runs smoothly but when there is a transition such that the phases are not in sequence, the motor shuts down. This process was achieved using a PIC16F877A microcontroller and magnetic contactor. The system architecture was able to run excellently while interacting with respective components.

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