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Protection Method against Induction Motor Single-Phasing Fault

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Abstract—***This paper proposes a protection scheme for three phase induction motors against single-phasing faults. Dynamic model of the induction motor in the stationary reference frame was adopted and modified to reflect single-phasing fault. A simulation algorithm was proposed, which can help determine the impact of single-phasing on any three phase induction motor. A case study simulation was carried-out with sudden single-phasing using MATLAB/SIMULINK software. A single-phasing protection by means of contactors was reviewed before an enhanced single-phasing protection was designed. A prototype of the enhanced protection method was implemented by the use of ac to dc converter, PIC16F877A and DC relays. The latter, in additional to offering protection against single-phasing, also protects the motor from under-voltage, over-voltage and voltage unbalance.***

Index Term---Single-phasing, Three-phase induction motor, PIC16F877A, ADC, contactor

I. INTRODUCTION

Single-phasing is the condition that results when one phase of a three phase motor is suddenly open-circuited during operation [1]. Single-phasing can occur as a result of blown fuse, loose connection and partial failure of switchgears; this is a fault condition. One potential threat of a single-phased induction motor is overheating, which consequently leads to insulation damage. When a three-phase induction motor in operation is suddenly single-phased, it continues to operate but draws excessive current in the other two remaining phases. A single-phased induction motor, by itself, does not have a starting torque, thus when an attempt is made to power it on from rest, it will only produce a humming sound. Leading standard organizations have concluded that 30 percent of motor failures are attributed to insulation failure and 60 percent of these are caused by overheating [2]. It is also known that thermal overloading and single-phasing make up to 44% of malfunction case [3, 4]. Maintenance experts agree that excessive heat causes rapid deterioration of motor winding insulation. The common rule is that insulation life is reduced by half for every 10°C of additional heat to the windings [2]. Several studies have been done on protection against single-phasing, under voltage, over voltage and voltage unbalance [3, 5, 6].

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II. DYNAMIC MODEL OF THREE PHASE INDUCTION MOTOR IN THE STATIONARY REFERENCE FRAME

Three-phase induction motor is usually simulated either in the qd0 stationary reference frame or in the qd0 synchronously rotating reference frame. The stationary reference is, for convenience, chosen for this simulation. The stationary reference is realized from the arbitrary qd0 reference frame by equating the axis speed, ω, to zero. The equivalent circuit and equations of the induction motor derived in [1] is shown below:

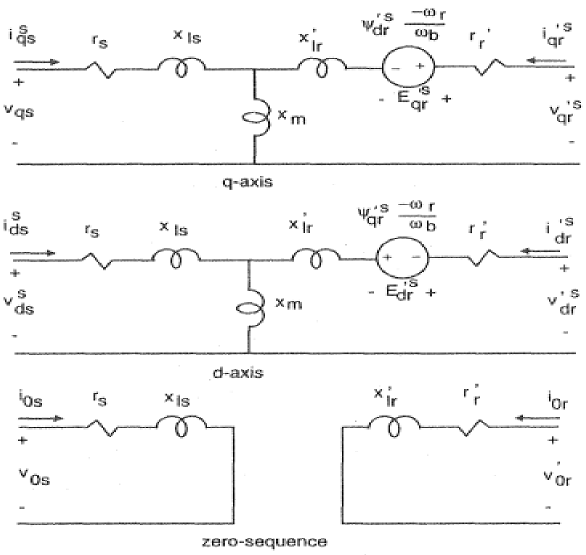

Figure 1: Equivalent Circuit of an Induction Motor in the Stationary Reference Frame [1]

The machine model equations are derives as follows

$$\left.\begin{aligned}
v_{qs}^{s} &= \frac{p}{w_b}\psi_{qs}^{s} + r_s i_{qs}^{s}\\
v_{ds}^{s} &= \frac{p}{w_b}\psi_{ds}^{s} + r_s i_{ds}^{s}\\
v_{0s} &= \frac{p}{w_b}\Psi_{0s} + r_s i_{0s}\\
v_{qr}^{\prime s} &= \frac{p}{w_b}\Psi_{qr}^{\prime s} - \frac{w_r}{w_b}\Psi_{dr}^{\prime s} + r_r^{\prime} i_{qr}^{\prime s}\\
v_{dr}^{\prime s} &= \frac{p}{w_b}\Psi_{dr}^{\prime s} + \frac{W_r}{w_b}\Psi_{qr}^{\prime s} + r_r^{\prime} i_{dr}^{\prime s}\\
v_{0r}^{\prime} &= \frac{p}{w_b}\Psi_{0r}^{\prime} + r_r^{\prime} i_{0r}^{\prime}
\end{aligned}\right\} \qquad (1)$$

Where operator p represents the differential operator d/dt, and the superscript "s" denote the stationary reference frame. The flux linkage equations are:

$$\begin{bmatrix} \psi_{qs}^{s} \\ \psi_{ds}^{s} \\ \psi_{0s} \\ \psi'^{s}_{qr} \\ \psi'^{s}_{dr} \\ \psi'_{0r} \end{bmatrix} = \begin{bmatrix} x_{ls}+x_m & 0 & 0 & x_m & 0 & 0 \\ 0 & x_{ls}+x_m & 0 & 0 & x_m & 0 \\ 0 & 0 & x_{ls} & 0 & 0 & 0 \\ x_m & 0 & 0 & x'_{lr}+x_m & 0 & 0 \\ 0 & x_m & 0 & 0 & x'_{lr}+x_m & 0 \\ 0 & 0 & 0 & 0 & 0 & x'_{lr} \end{bmatrix} \begin{bmatrix} i_{qs}^{s} \\ i_{ds}^{s} \\ i_{0s} \\ i'^{s}_{qr} \\ i'^{s}_{dr} \\ i'_{0r} \end{bmatrix} \quad (2)$$

From equation (2)

$$\begin{bmatrix} i_{qs}^{s} \\ i_{ds}^{s} \\ i_{0s} \\ i'^{s}_{qr} \\ i'^{s}_{dr} \\ i'_{0r} \end{bmatrix} = \begin{bmatrix} x_{ls}+x_m & 0 & 0 & x_m & 0 & 0 \\ 0 & x_{ls}+x_m & 0 & 0 & x_m & 0 \\ 0 & 0 & x_{ls} & 0 & 0 & 0 \\ x_m & 0 & 0 & x'_{lr}+x_m & 0 & 0 \\ 0 & x_m & 0 & 0 & x'_{lr}+x_m & 0 \\ 0 & 0 & 0 & 0 & 0 & x'_{lr} \end{bmatrix}^{-1} \begin{bmatrix} \psi_{qs}^{s} \\ \psi_{ds}^{s} \\ \psi_{0s} \\ \psi'^{s}_{qr} \\ \psi'^{s}_{dr} \\ \psi'_{0r} \end{bmatrix} \quad (3)$$

The developed torque is:

$$T_{em} = \frac{3}{2}\frac{P}{2\omega_b}(\psi_{ds}^{s} i_{qs}^{s} - \psi_{qs}^{s} i_{ds}^{s}) Nm \quad (4)$$

The relationship between torque and speed is given below as:

$$\frac{2J}{P}\frac{d\omega_r}{dt} = T_{em} + T_{mech} - T_{damp} N.m \quad (5)$$

III. MODELLING OF THREE-PHASE INDUCTION MOTOR WITH SUDDEN SINGLE-PHASING FAULT

Star connected stator winding is adopted for the analysis of single-phasing fault condition of the three phase induction motor. Assuming the neutral is floating and that the ‘a’ phase is suddenly disconnected. This simply implies that the zero sequence current is equal to zero and the ‘a’ phase current is also equal to zero.

Therefore, $i_{as} = 0, i_{bs} + i_{cs} = 0, i_{0s} = 0.$

Applying the transformation between *abc* and stationary *qd0*

$$[i_{qd0}^{s}] = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a^s \\ i_b^s \\ i_c^s \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} 1 \\ i_b^s \\ i_c^s \end{bmatrix} \quad (6)$$

$$i_q^s = -\frac{1}{2}(i_b + i_c) \quad (6a)$$

$$\Rightarrow i_q^s = 0$$

(6b)

From equation (2),

$$\psi_{qs}^{s} = (x_{ls} + x_m) i_{qs}^{s} + x_m i'^{s}_{qr} = x_m i'^{s}_{qr}$$

$$\Rightarrow \psi_{qs}^{s} = x_m i'^{s}_{qr} = \psi_{mq}^{s}$$

(7)

From equation (1), $v_{qs}^{s} = \frac{p}{\omega_b}\psi_{qs}^{s} + r_s i_{qs}^{s}$,

substituting $i_{qs}^{s} = 0$ and $\psi_{qs}^{s} + x_m i'^{s}_{qr}$ yields

$$v_{qs}^{s} = \frac{x_m}{\omega_b}\frac{di'^{s}_{qr}}{dt}$$

(8)

Also, $\psi'^{s}_{qr} = x_m i_{qs}^{s} + (x'_{lr} + x_m) i'^{s}_{qr} = (x'_{lr} + x_m) i'^{s}_{qr}$

Simplifying $i'^{s}_{qr} = \dfrac{\psi'^{s}_{qr}}{(x'_{lr} + x_m)}$

(9)

Substituting equation (9) into (8), we obtain

$$v_{qs}^{s} = \frac{1}{\omega_b}\frac{x_m}{(x'_{lr} + x_m)}\frac{d\psi'^{s}_{qr}}{dt}$$

(10)

$$[V_{abc}^{s}] = [T_{qd0}^{s}]^{-1}[V_{qd0}^{s}]$$

$$[V_{abc}^{s}] = \begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \end{bmatrix}\begin{bmatrix} v_{qs}^{s} \\ v_{ds}^{s} \\ v_{0s} \end{bmatrix}$$

From which we realize that $v_a^s = v_{qs}^s + v_{0s}$, it is known that since the neutral is isolated, the zero sequence component of the voltage is zero. Therefore, $v_a^s = v_{qs}^s$. When phase ‘a’ losses connection to voltage supply, the open circuit voltage across coil ‘a’ is given by equation (10).

$$v_a^s = v_{qs}^s \quad (11)$$

The simulation of induction motor with sudden single phasing is realized by simulating normal operations of the induction motor and suddenly introducing fault by modifying the equations with that proved in this section.

IV. SIMULATION ALGORITHM

The simulation algorithm is detailed below:

(a) Start induction motor simulation with rated value using equations (1) to (5).

(b) Introduce fault to the system at the moment when i_a=0 by disconnecting the phase-a supply voltage and replacing it with open circuit voltage, which is equal to v_{qs}^{s}. At the same time we modify the equations of the motor with equations (6) to (11).

(c) End the simulation at the desired time and observe the effect of single-phasing on stator phase currents, torque, and speed.

V. SIMULATION RESULTS

In order to drive the point home, a simulation was performed with the above algorithm and a fault condition was introduced at a simulation time of 2 seconds. Below are the results:

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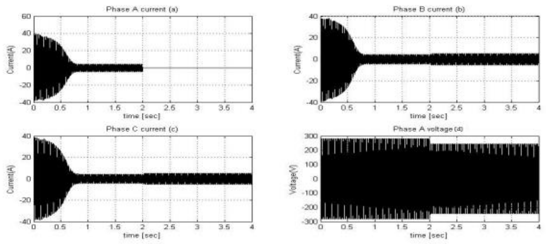

Figure 2: a, b, c and d, showing Currents in the phase a, b and c and Voltage across the Phase a Coil respectively.

From figure (2) we observe the increase in current in phase b and c after the fault occurred

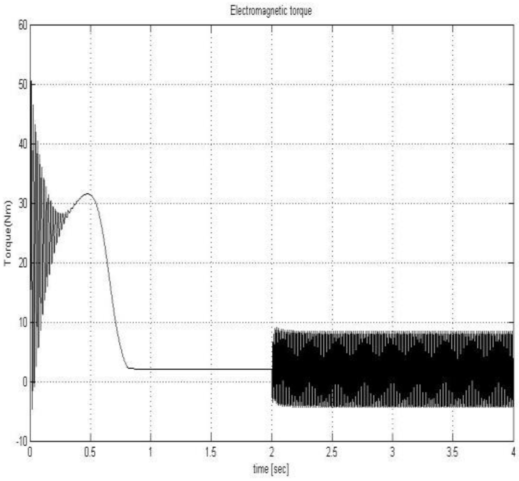

Figure 3: Electromagnetic Torque

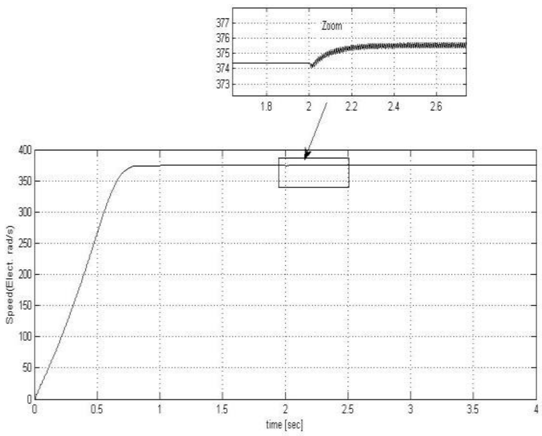

Figure 4: Rotor Speed in elect. rad/s

VI. CONVENTIONAL PROTECTION AGAINST SINGLE-PHASING

Most protective circuits against single-phasing are electronic in nature and may not easily be available to lab and workshop supervisor. The figure below shows a simple protective circuit which can easily be implemented and added to most motor starters, but for simplicity, we incorporated it to DOL. It involves the use of three contactors (K_1, K_2 and K_3) whose coils are connected to each of the motor phase supply. The contacts of these contactors are placed in series at the starter circuit to realize a logical AND, such that any phase that fails will automatically disconnect the motor from the supply. In order to simplify analysis and ensure good connections, electric motor connection circuits are usually divided into two circuits – the *power circuit* and the *control or starter circuit*. At first, the motor is OFF because the contactor contacts k_4 are normally open and not yet been energized. When the start button is pressed (the start button is a normally opened push button or monostable button), line 1 (L1) gets to the coil of the contactor and it becomes energized and closes the contactor contacts; but the push button moves back to its open state. In order to ensure that the contactor remains energized after the first push, one of the contactor contacts is connected in parallel with the start button, and this contact retains its connection by ensuring that the coil is still energized after the operator pressed the push button; that is why this parallel connection is called retaining contact.

If the operator presses the stop button or power is interrupted, it de-energizes the coil of the contactor and there is no way it will get energized again because the retaining contact gets disconnected when the coil was de-energized. The advantage of this is that the motor does not suddenly start once power is restored.

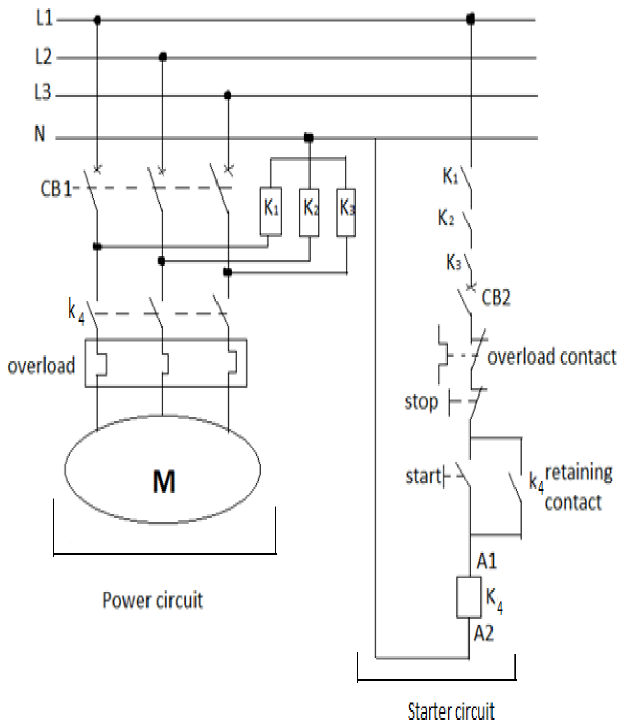

Figure 5: A Simple Circuit showing Motor Protection against Single-Phasing

The disadvantage of this protective approach is that it offers protection to the machine only against single-phasing. It, however, does not offer protection to the machine against excessive voltage, under voltage and voltage imbalance.

VII. VOLTAGE MONITOR CIRCUIT AGAINST SINGLE-PHASING

This new approach involves converting the 3 phase ac voltages into proportionate dc values and which are then controlled as dc. The block diagram for this approach is shown below in figure 6.

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(a) AC to DC Converter

The three AC to DC converters were used, one for each phase to achieve AC to DC voltages conversion. The circuit used for each phase is shown in figure 7. The zener diode is used to ensure that the voltage does not exceed 5.1V. The circuit below is repeated for phase B and C. Three proportionate dc are realised (Vdc_A, Vdc_B and Vdc_C respectively for phase A, B and C) and are sent to the analog to digital converter pin of the microcontroller.

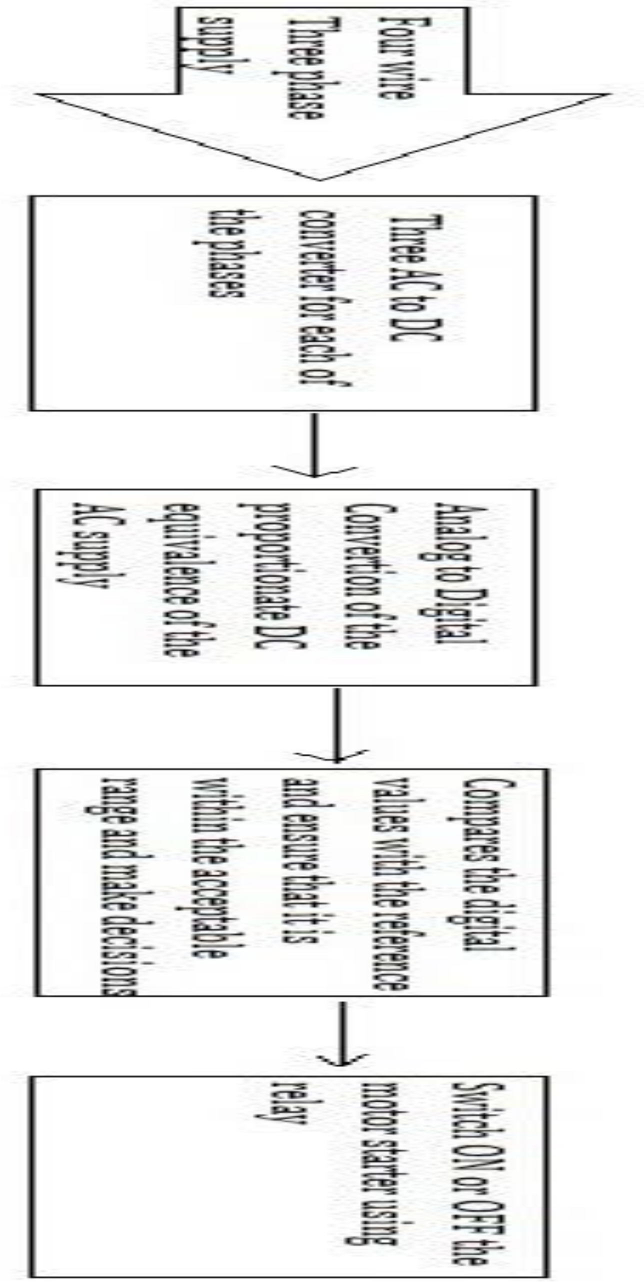

Figure 6: Block Diagram of Voltage Monitor Circuit

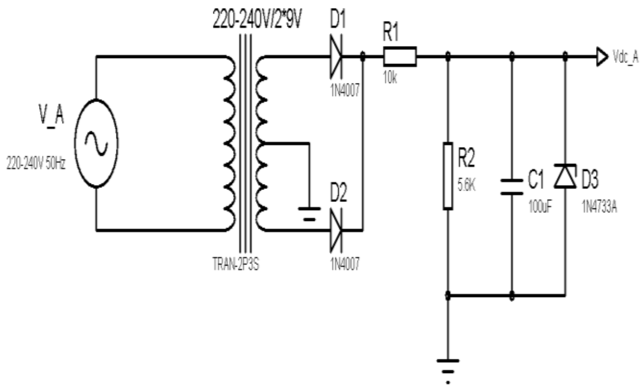

Figure 7: AC to DC Converter

The relationship between the input AC voltage value and the proportionate dc is fairly linear in the range of 100 to 300V AC, and is sufficient for the monitoring of the AC value from the DC value. The graph below shows this relationship:

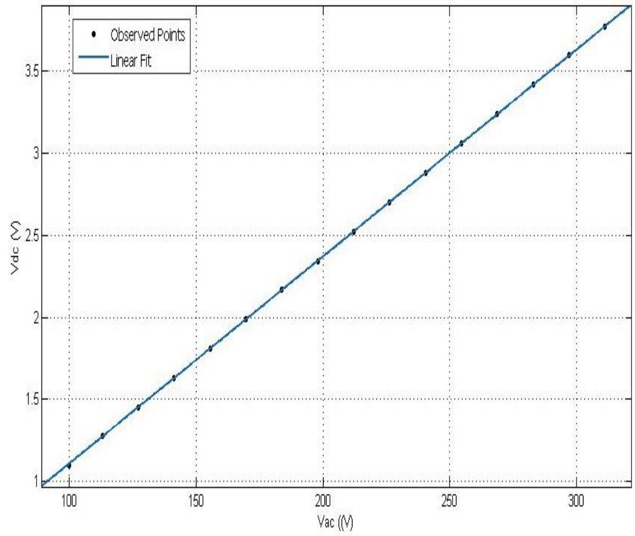

Figure 8: Graphical relationship between Vac and Vdc

The mathematical relationship is given by:

$$Vdc = 0.01264 * Vac - 0.1572 \qquad (12)$$

(b) Analog to Digital Converter

The PIC 16F877A has an in-built analog to digital converter and details of which can be found in the datasheet and is available for free download at [7], which is the official Microchip website. The DC equivalents of the phases are converted to digital form using a 10 bit ADC (Analog to Digital Converter) which has a resolution of 5/1023 volts DC on a range of 0-5Volts DC.

For a 10-bit ADC with an analog range of 0-5V, the relationship between the digital value and the analog dc input is given by:

$$ADC_{value} = \frac{1023 * V_{dc}}{5} \qquad (13)$$

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$$\xrightarrow{yields} ADC_{value} = 2.586 * V_{ac} - 32.16 \tag{14}$$

$$V_{ac} = 0.3867\, ADC_{value} + 12.436 \tag{15}$$

Graphically it is shown as

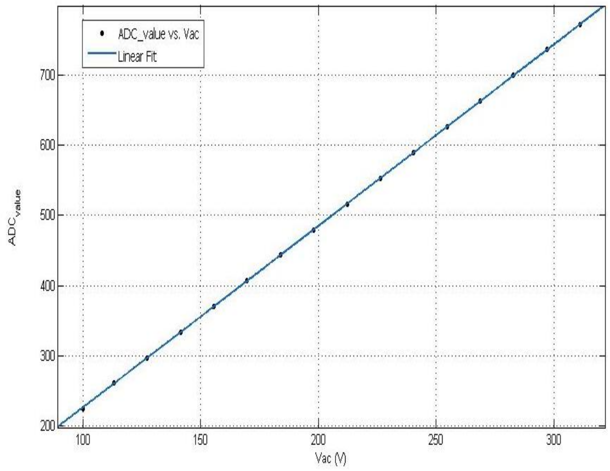

Figure 9: Graphical relationship between Vac and ADC value

VIII. COMPARISON AND DECISION MAKING

The resulting 10-bit digital values are converted to their previous AC values in software using equation (15) and compared with two other digital values which corresponds to lower voltage limit and upper voltage limit of the three phase electric motor; differences in AC voltages of the three phases are also examined and if all three 10-bit digital values fall within the acceptable range (this actually involves logical AND) then the starter relay is switched ON else it is OFF. This section and the previous were implemented in software using C program and compiled with MicroC.

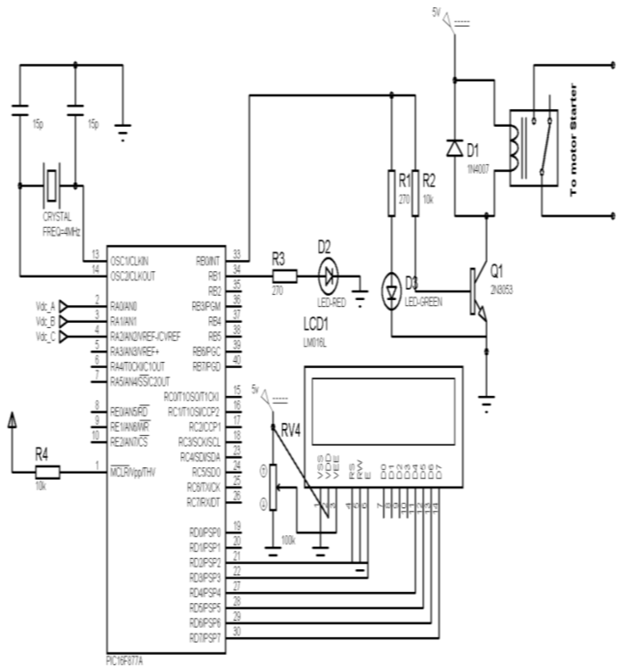

Figure 10: Voltage Monitor Circuit for Three Phase Motor

The advantage of using this protective approach over the previous one that made use of contactors are its sensitivity to voltage variations, protection against voltage unbalance, under-voltage and excessive voltage, and lastly its lower cost. There are lots more to be done with this simple approach – one may decide to add manual knob for setting the tolerable voltage limits and so on; we are keeping as simple as this so that the concept is not lost.

IX. CONCLUSION AND RECOMMENDATIONS

This paper has highlighted that single-phasing constituent a large percentage to motor damage and there is need for protection against this fault condition. Two protections methods to single-phasing were examined in this paper: the first being the conventional approach using contactors and the second method that employ voltage monitor circuit. The second method offers more protection against single-phasing and is equally very sensitive to voltage variation and is thus recommended.

APPENDIX: C PROGRAM

```
/*Date: March, 2014, Three phase Voltage monitor program
#define START PORTB.RB0
#define SWITCH_OFF PORTB.RB1
void main()
{
unsigned int Va,Vb,Vc=0;
TRISB = 0; // portB is output
PORTB=0;
// Configure A/D converter.
ADCON1 = 0x80; //Vref=+5V and 0V, right justified
Delay_ms(1000);
  for(;;) // Endless loop
  {
  Va = Adc_Read(0); // Read from channel 0 (AN0)
  Va = 0.3867*Va+12.436;//convert to normal voltage values
  Vb = Adc_Read(1);// Read from channel 0 (AN1)
  Vb = 0.3867*Vb+12.436;
  Vc = Adc_Read(2);// Read from channel 0 (AN2)
  Vc = 0.3867*Vc+12.436;
     if
(Va<=245&Va>=210&Vb<=245&Vb>=210&Vc<=245&Vc>=210\
     &abs(Va-Vb)<=10&abs(Va-Vc)<=10&abs(Vc-Vb)<=10){
     START=1;
     SWITCH_OFF=0;
     }
     else{
     START=0;
     SWITCH_OFF=1;
     }
  delay_ms(1000);
  }
}
```

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Engr. Cosmas U. Ogbuka, is currently concluding his Ph.D research in Power Devices in the Department of Electrical Engineering, University of Nigeria, Nsukka where he also works as a Lecturer. He obtained his M.Eng (with Distinction in 2009) and B.Eng (with First Class Honours in 2004). He is a registered engineer with the Council for the Regulation of Engineering in Nigeria (COREN) and a member of the Nigerian Society of Engineers (NSE). He has widely published both locally and internationally.

Ogbonnaya Bassey, graduated in 2013 from the Department of Electrical Engineering, University of Nigeria, Nsukka with a First Class Honours, emerging as the Best Graduating Student. He is presently undertaking the compulsory one year National Youths Service. He is a research-oriented individual with a promising academic future.