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Design of a Three Phase Induction Motor Protection System

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ABSTRACT

Three-phase induction motors are widely used as industrial drives because they are rugged, reliable and economical. This paper presents the design and construction of a system for the protection of three phase induction motor from external faults such as overvoltage, under voltage and single phasing using operational amplifiers. The operational amplifier used in this work is LM 324 and was configured in the comparator mode by setting one of the inputs at a reference voltage and while varying the other input according to the mains input supply. The mains input voltage from each of the phase was stepped down to 12 VAC, regulated and divided using a potentiometer and fed to the varying input of the operational amplifier. The outputs from the operational amplifier were connected to a three input OR-gate and the output of the OR-gate was connected to the input of a Reset-Set (RS) flip-flop which energizes or de-energizes the three pole double throw relay (3PDT) to power ON or OFF the induction motor. The system was tested using a three phase variac. From the test results, the three phase induction motor only runs when the mains input voltage is between 230 VAC and 240 VAC. Any voltage below or above this from any of the phase will stop the motor from running.

1. INTRODUCTION

An induction motor is an electromechanical device that converts electrical energy to mechanical energy. Induction motors account for half of the electric power consumed in industries as they are very important part of a power system for modern industries (Schulz et al., 2003). Loss of the motor implies you can't deliver products which thus result to loss of revenue (Schulz et al., 2003). Three phase induction motors are utilized in numerous modern applications because of their cost, performance and dependability (Sudha and Anbalagan, 2009).

Electrical faults are faults in three-phase induction motor which will deliver more warmth on both stator and rotor windings. This prompts the diminishing of the life time of induction motor (Kersting, 2001). There are three factors to consider when protecting motor and they include size, significance and the load. These connect to the sort of protection framework to pick (Schulz et al., 2003).

Failures that can occur in motors include motor-induced, load-induced, environment-induced, source-induced, and operation-induced. Source-induced failures range from under/over voltage, voltage unbalance, phase failures, or phase reversal (Schulz et al., 2003). When motor voltage decreases, current increases causing damage to the motor since the kVA will not change. A voltage imbalance of 3.5% will cause a 25% increase in motor temperature.

All the failures mentioned have things in common. Most of them will cause increase in temperature of the motor as a result of overcurrent. Increased temperature in motors will cause insulation breakdown and failure of motor (Schulz et al., 2003). This paper focuses on the protection of a three phase induction from over/under voltage and single phasing faults.

2. METHODOLOGY

The modular approach was used in this work. This method involves breaking down a complex system into smaller parts called modules or skids. This is clearly shown in Figure 1.

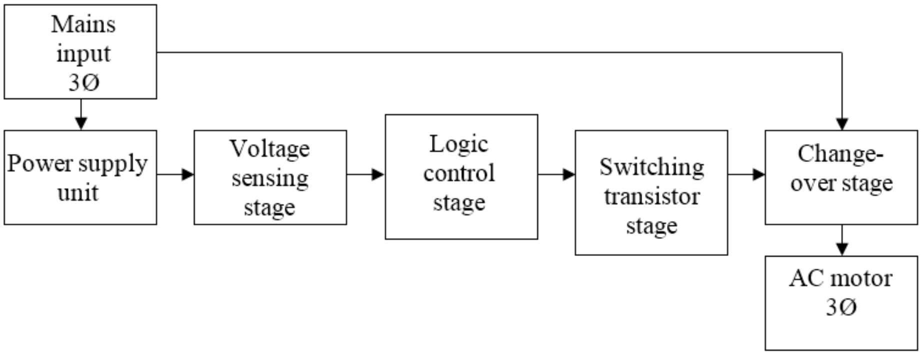

Figure 1: Block diagram of the three phase motor protection system

2.1. Power Supply Unit

The power supply unit is shown in Figure 2. This unit supplies the required voltage and current needed by the system to operate effectively. It consists of a transformer unit, rectifying unit, filter unit, and voltage regulator unit.

2.1.1. Transformer unit

It consists of an iron core step-down transformer which is used to reduce the mains input voltage from 240 VAC to 12 VAC at the same frequency.

2.1.2. Rectifying unit

It consists of a full wave bridge rectifier that is used to converts the 12 V alternating current from the output of the transformer to about 15 VDC but pulsating current.

2.1.3. Filter unit

It consists of an electrolytic capacitor whose function is to reduce the ripples present in the output voltage from the rectifier (Pyakuryal and Matin 2013). The capacitor C1 (Figure 1) was selected to offer very low impedance to the ripple frequency. The full wave bridge rectifier together with the capacitor is expected to produce a maximum value (V_m) of about 1.4 times the alternating current root mean square input (John, 2007; Rashid, 2007). So, if using a 12 VAC to supply the input of the rectifier, the output from the rectifier should be about 16.8 VDC. The capacitance of the capacitor can be calculated using Equation 1 (Jim, 2020).

$$\text{Capacitance of capacitor (C)} = \frac{0.7\ x\ I_O}{\Delta V\ X\ F} \qquad (1)$$

Where Io = output current from the transformer in amps, ΔV = peak to peak ripple voltage, F = ripple frequency which is double the line frequency for a full wave bridge rectifier (Pyakuryal and Matin, 2013).

Peak to peak ripple voltage is the difference between the maximum and the minimum voltage (John, 2007).

$$Vp\text{-}p = Vmax - Vmin \; = Vrms\sqrt{2} - (Vrms - 2V_d) \qquad (2)$$

Where Vp-p = peak to peak ripple voltage, Vmax = maximum output voltage with capacitor, V_{min} = Minimum output voltage without capacitor, Vrms = root means square voltage from transformer output, V_d = diode forward voltage drop.

$$Vp\text{-}p = 12\sqrt{2} - (12 - (2 \times 0.7)) = 6.37 \text{ Volts}$$

Therefore, capacitance of capacitor (C) = $\frac{0.7\ x\ 1}{6.37\ X\ 100}$ = 1098 μf

Any value between 1000 μf to 3300 μf is preferred because when the capacitance is high, more ripples are removed (Hart, 2011).

The DC voltage rating of the capacitor is generally selected to be double the maximum voltage i.e Vmax and is given by Equation 3 (Jim, 2020).

$$Vc = 2Vmax = 2Vrms\sqrt{2} \qquad (3)$$

Where Vc = capacitor voltage, Vmax = maximum output voltage with capacitor, Vrms = root mean square voltage from transformer output

$$Vc = 2 \times 12\sqrt{2} = 33.94 \text{ Volts}$$

2.1.4. Voltage regulator

It maintains a constant voltage across the output under various load conditions. The type of voltage regulator used is a fixed type of the AN78XX series. It has an internal reference voltage of 3 V. The output voltage is given as:

$$V_{min} = V_{out} + V_{ref} \qquad (4)$$

V_{ref} = internal reference voltage, V_{out} = output voltage of the regulator, V_{min} = minimum input voltage required for the regulator to operate.

For an 8 Volts regulator, V_{min} = 8+3 = 11 Volts

For a regulator to operate, the input voltage must be higher than the rated output voltage (Theraja and Theraja, 2003).

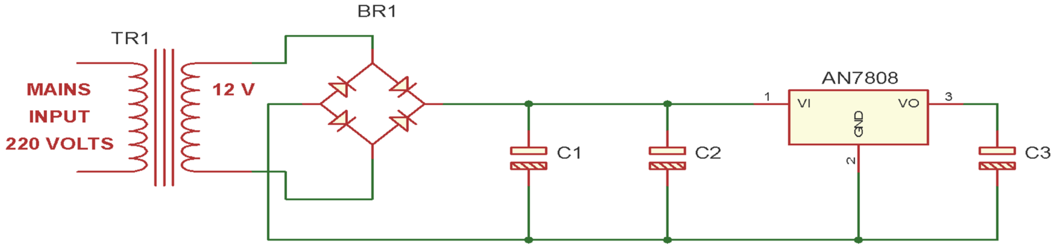

Figure 2: Power supply unit

2.2. Voltage Sensing Stage

The voltage sensing stage comprises of an operational amplifier (op-amp) LM324 used as a comparator. LM324 consists of four operational amplifiers, of which two were used in each phase to achieve the necessary control. The operational amplifier compares the voltages at its input and gives an output, which tells if they are equal or unequal. The voltage sensing stage in this system was used to sense the mains input to each phase when it drops below 200 VAC or increases above 240 VAC. Recall that the normal operating voltage is between 200 VAC and 240 VAC and any voltage below or above this indicates a fault. Considering the Red phase, the mains input supply was converted to direct current (DC) in the power supply unit and regulated to 8 VDC for the power supply needed in the circuit. The unregulated voltage varies as the mains input varies.

2.2.1. Design calculation for the undervoltage and phase failure comparator A1

From Figure 3, VR2 and R2 form a potential divider for the inverting input (V_{A1}) to reduce the unregulated voltage. At 180 VAC input, the value of V_{A1} = 3.55 VDC from Table 1. V_{A1} is calculated using voltage divider rule (Theventhira et al., 2016) as:

$$V_{A1} = \frac{VR2\ X\ V_{Unreg}}{R2 + VR2} \tag{5}$$

Where V_{A1} is the voltage drop across VR2 (variable resistor) and Vunreg is the unregulated DC voltage. From Table 1, it can be seen that Vunreg = 10.10 VDC at 180 VAC. Let R2 = 4.7 Kω (preferred value). From Equation 5, VR2 is given as:

$$VR2 = \frac{V_{A1}\ X\ R2}{V_{unreg} - V_{A1}} \tag{6}$$

$$\text{VR2} = \frac{3.55\ X\ 4700}{10.10 - 3.55} = 2547\ \Omega$$

VR2 = 2.6 kΩ preset (preferred value).

R10 and R11 form another potential divider for the reference voltage. Setting a maximum reference voltage (V_{A2}) = 4 VDC (John, 2007) and setting R10 = 10 kΩ (preferred value) and V^+ = 8 VDC, then V_{A2} is calculated using voltage divider rule (Theventhira et al., 2016) as:

$$V_{A2} = \frac{R11\ X\ V^{+}}{R11+R10} \tag{7}$$

From Equation 7, making R11 subject of formula, result in:

$$\text{R11} = \frac{V_{A2}\ X\ R10}{V^{+}-\ V_{A2}} \tag{8}$$

$$R11 = \frac{4\ X\ 10000}{8-4} = 10\ \text{k}\Omega\ \text{(preferred value).}$$

Note that the calculations done for the undervoltage and phase failure comparator unit also applies to comparator A3 and A5 in the Yellow and Blue phase.

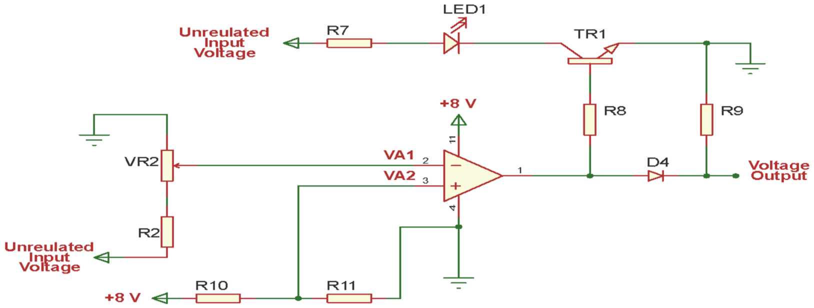

Figure 3: Undervoltage and phase failure comparator unit.

Table 1: Variation of DC voltage against mains input supply voltage

Mains input (AC)	V_{unreg} (DC)	V_{A1} (DC)	V_{B1} (DC)	State of motor
180	10.10	3.55	2.98	TURNED-OFF
185	10.38	3.64	3.10	TURNED-OFF
198	11.11	3.90	3.34	TURNED-OFF
200	11.22	4.15	3.39	TURNED-ON
205	11.50	4.28	3.49	TURNED-ON
210	11.78	4.39	3.51	TURNED-ON
215	12.06	4.50	3.62	TURNED-ON
220	12.34	4.62	3.71	TURNED-ON
225	12.62	4.75	3.82	TURNED-ON
230	12.90	4.81	3.84	TURNED-ON
235	13.18	4.93	3.94	TURNED-ON
242	13.46	5.05	4.05	TURNED-OFF
245	13.74	5.11	4.15	TURNED-OFF

The values in the table column 1 were obtained by connecting the system through a variable transformer to the means supply. The means input voltage to the system was regulated to 180 VAC with the help of the variac and the DC output voltage from bridge rectifier BR1, and the DC input to the inverting input (V_{A1}) and non-inverting input (V_{B1}) of operational amplifier A1 and A2 in Figure 6 were measure using a digital voltmeter and recorded. This process applies to all the columns in the table. It should be noted that the voltage at V_{A1} is unregulated and is the same for op-amp A3 and A5. Also, the voltage at V_{B1} is unregulated and it is the same for op-amp A4 and A6.

2.2.2. Design calculation for the overvoltage comparator A2

From Figure 4, VR1 and R1 form a potential divider for the non-inverting input (V_{B1}) to reduce the unregulated voltage. At 180 VAC input, V_{B1} = 2.98 VDC from Table 1. Then V_{B1} is calculated using voltage divider rule (Theventhira et al., 2016) as:

$$V_{B1} = \frac{VR1\ X\ V_{unreg}}{R1+VR1} \tag{9}$$

Where V_{B1} is the voltage drop across VR1 (variable resistor) and Vunreg is the unregulated DC voltage. From Table 1, it can be seen that Vunreg = 10.10 VAC at 180 VAC. Let R2 = 4.7 kΩ (preferred value). From Equation 9, VR1 is given as:

$$\text{VR1} = \frac{V_{B1}\ X\ R1}{V_{unreg} - V_{B1}} \tag{10}$$

$$VR1 = \frac{2.98\ X\ 4700}{10.10-2.98} = 1967\ \Omega$$

VR1 = 2 kΩ preset (preferred value).

R13 and R14 form another potential divider for the reference voltage. Letting a maximum reference voltage (V_{B2}) = 4 VDC and setting R13 = 10 kΩ (preferred value) and V^+ = 8 VDC, then V_{B2} is calculated using voltage divider rule (Theventhira et al., 2016) as:

$$V_{B2} = \frac{R14\ X\ V^+}{R13+R14} \tag{11}$$

From Equation 11, making R14 subject of formula, result in:

$$\text{R14} = \frac{V_{B2}\ X\ R13}{V^+ - V_{B2}} \tag{12}$$

$$R14 = \frac{4\ X\ 10000}{8-4} = 10\ \text{k}\Omega \text{ (preferred value).}$$

It should be noted that the calculations done for the overvoltage comparator also applies to comparator A4 and A6 in the Yellow and Blue phase.

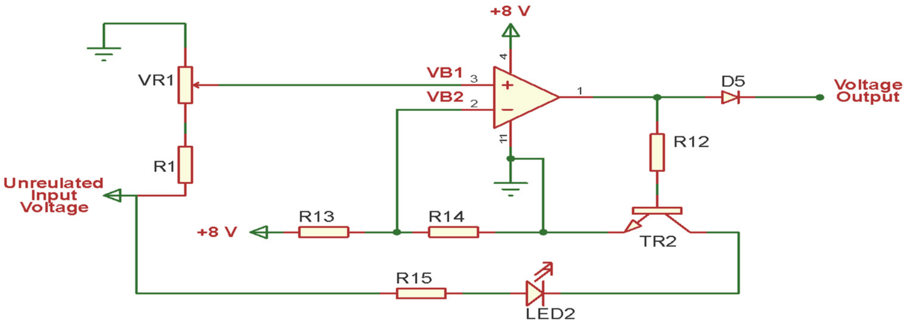

Figure 4: Overvoltage comparator unit

2.3. Switching Transistor Stage

The switching transistor TR7 in Figure 5 switches the relay, to either turn-ON or turn-OFF the three phase motor. The transistor as a switch operates in class A mode (Theraja and Theraja, 2002). The relay is switched ON when the flip-flop is in *SET* mode. Diode D14 protects the transistor from back EMF that might be generated since the relay coil presents an inductive load. In this case, R_C which is the collector resistance is the resistance of the coil, which is measured as 400 Ω for the relay type used in this project. Hence, given that:

$R_C = 400\ \Omega$ (Relay coil resistance)

$V_{BE} = 0.6$ V (silicon)

$V_{CE} = 0$ V (when transistor is switched)

$V_{in} = V^+ = 8$ VDC (from the output of flip-lop)

$H_{fe} = 400$ (from D882 data sheet)

Then, the base resistor R36 was calculated from Equations 13 to 16:

$$V^+ = I_C R_C + V_{CE} \tag{13}$$

$$V_{in} = I_B R_{36} + V_{BE}. \tag{14}$$

$$H_{fe} = I_C/I_B. \tag{15}$$

$$R_{36} = (V_{in} - V_{BE})/I_B \tag{16}$$

Where I_C = collector current, I_B = base current, $R_B = R_{36}$ = base resistor

$V_{in} = V^+$ = input voltage from output of flip-flop, R_C = collector resistor

V_{CE} = collector–emitter voltage, H_{fe} = current gain, V_{BE} = base emitter voltage

From Equation 13, $I_C = 20$ mA

From Equation 14, $I_B = 50\ \mu$A

From Equation 16, R36 = 148 kΩ

R36 = 150 kΩ (preferred value)

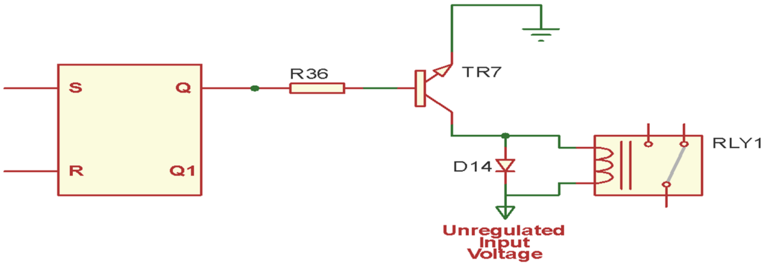

Figure 5: Voltage sensing and switching transistor stage

2.4. Change-over Stage

It comprises of a 12 VDC, 30 Amps, 3-pole double throw relay (3PDT). The relay switch mains supply to the three phase motor through the Normally-Open (N/O) contact when the coil is energised. The rating of the relay is chosen to match the capacity of the three phase motor it is going to operate. Since the maximum input power is 6 hp, the current rating of the relay can be from the equation:

$$P = IV\cos\theta \tag{17}$$

Where V = Mains input operating voltage, given as 220 VAC, I = Operating current of motor, which is unknown, Cos θ = power factor of motor given as 0.8 and P = Power rating of motor which is 6 *horse-power*

From Equation 17, making "I" subject of formula, results in:

$$I = P / V\cos\theta \tag{18}$$

But 1 hp = 746 Watts, Substituting in Equation 18, result in:

$$I = (746 \text{ x } 6) / (220\text{x } 0.8) = 25.4 \text{ Amps}$$

Therefore, a relay of a higher value (30 Amps) was chosen for this design to allow for tolerance. A motor of a higher power rating can be used with the system by changing the relay to match the power rating of the motor using Equation 18.

2.5. Mode of Operation

Figure 6 shows the complete circuit diagram of the 6 hp Three Phase Over-/Under-Voltage and phase failure protection system. This system was used to protect a three phase motor from damage arising from the following faults: Under Voltage (less than 200 VAC), Over voltage (240 VAC and above) and phase failure in any of the phase. The normal operating voltage of the motor is set between 200 VAC and 240 VAC by the system and any voltage below or above this, the motor will not operate.

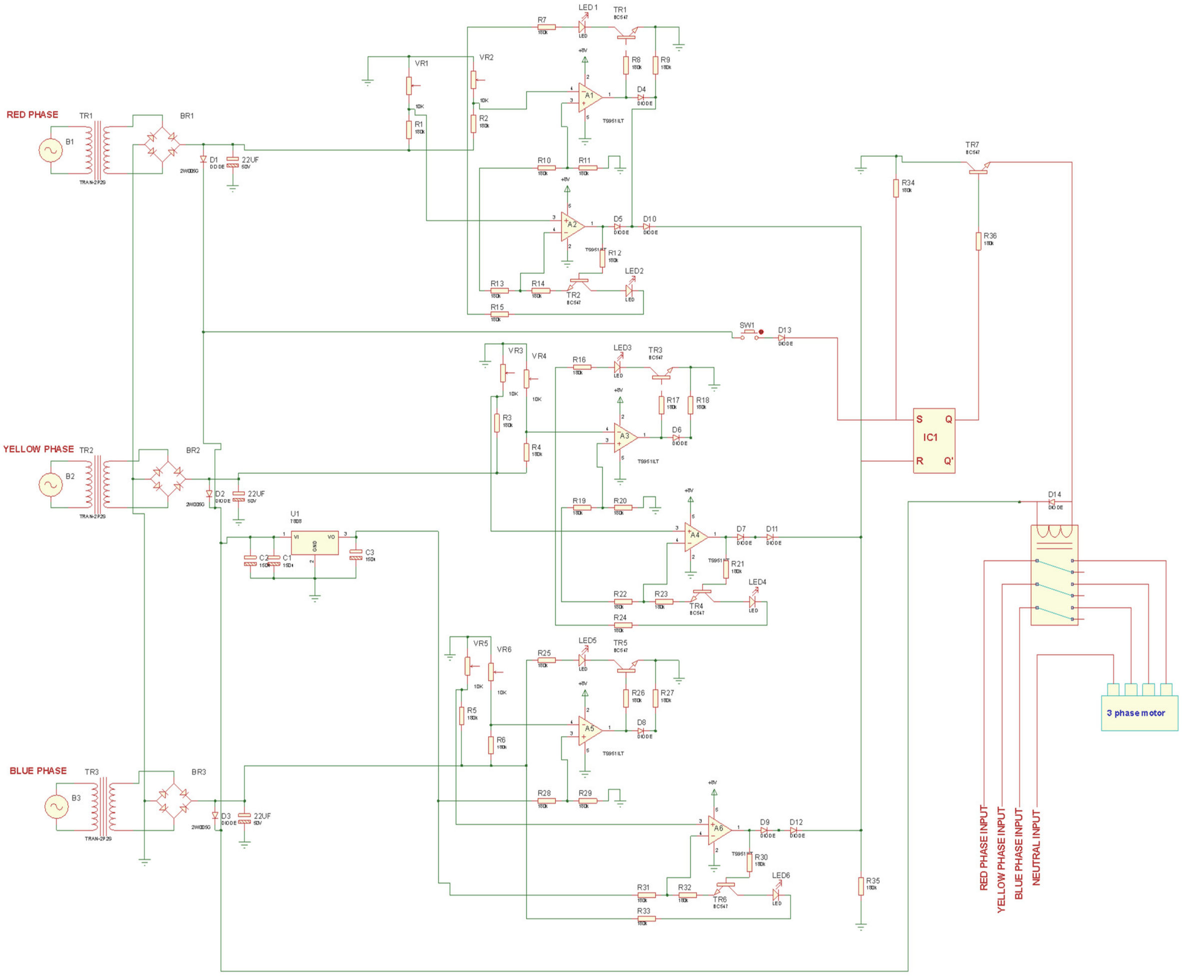

Figure 6: Complete circuit diagram of the system

Assuming the supply voltage from each phase is 220 VAC, this voltage is fed to the normally closed (N/C) terminal of a three pole double throw (3PDT) relay and the three phase motor is fed through the normally open (N/O) terminal of the relay, such that it is only when the relay is energised, that the three phase motor operates. The 220 VAC voltage is also fed to the primary of the step-down transformer (T1, T2 and T3) connected to each phase, this 220 VAC is stepped down to 12 VAC and then rectified to 12 VDC by bridge rectifier (BR1, BR2 and BR3) shown in Figure 6. The unregulated DC voltage from the bridge rectifier BR1 is connected to the series combination of resistor R1 and potentiometer VR1, and also to the series combination of resistor R2 and potentiometer VR2 for the RED phase. The unregulated DC voltage from the bridge rectifier BR2 is connected to the series combination of resistor R3 and potentiometer VR3, and also to the series combination of resistor R4 and potentiometer VR4 for the YELLOW phase. The unregulated DC voltage from the bridge rectifier BR3 is connected to the series combination of resistor R5 and potentiometer VR5, and also to the series combination of resistor R6 and potentiometer VR6 for the BLUE phase. The unregulated voltage from each phase is fed through diode D1, D2 and D3, and the cathode of each diode connected together. This is to ensure that each phase supply its own DC voltage to power the circuit. The combined unregulated supply is fed to capacitor C1 and C2 in parallel to reduce the ripples present, and to an 8 VDC voltage regulator V_{REG} to provide a constant 8 VDC irrespective of the fluctuation in AC input voltage. The voltage regulator supply voltage to operational amplifier (A1, A2, A3, A4, A5, and A6) and RS type flip-lop IC1, and is also connected to a series combination of resistor R10 and R11, and series combination of resistor R13 and R14 in the RED phase. In the YELLOW phase, it is connected to series combination of resistor R19 and R20, and to series combination of resistor R22 and R23. In the BLUE phase, it is connected to series combination of resistor R28 and R29, and series combination of resistor R31 and R32. If the mains input is between 200 VAC and 240 VAC, and reset switch SW1 closed, a positive voltage from the combined unregulated DC supply is fed to the SET input (pin 6) of IC1 and the output of IC1 goes HIGH to switch the base of transistor TR7 and the relay which is connected to the collector of transistor TR7 is energised to connect the three phase supply to the three phase motor through the normally open (N/O) terminal of the relay, and the motor starts to operate. Note that between 200 VAC and 240 VAC, the output of operational amplifier A1 to A6 is LOW.

Considering the under-voltage condition, all explanation will be done using the RED phase because all that happens in this phase applies to other phases. When the motor is operating between 200 VAC and 240 VAC, the voltage at the inverting terminal of A1 (pin 2) which is formed by the voltage divider arrangement R2 and VR2 is higher than the non-inverting input (pin 3) which is set at a reference voltage of 4 VDC through the voltage divider arrangement formed by R10 and R11, and the voltage at pin 2 of A1 varies as mains input in varies shown in Figure 6. When the mains input voltage drops below 200 VAC, the voltage at the inverting input (pin 2) of A1 drop below the non-inverting input and the output of A1 goes HIGH to drive the base of transistor T1 and LED1 is TURNED-ON indicating low-voltage. The HIGH output from A1 is used to forward bias diode D4 and D10 to *RESET* IC1 and the output of IC1 changes from non-inverting output (Q) to inverting output (Q^1) and transistor TR7 is SWITCHED-OFF and hence relay RLY1 is de-enegised. Consequently, the three phase supply is disconnected from the three phase motor to protect it from under-voltage.

For the over-voltage operation, when the motor is operating between 200 VAC and 240 VAC, the voltage at the non-inverting terminal of A2 (pin 5) which is formed by the voltage divider arrangement R1 and VR1 is less than the inverting input (pin 6) which is set at a reference voltage of 4 VDC through the voltage divider arrangement formed by R13 and R14. The voltage at pin 5 of A2 varies as mains input varies. When the mains input voltage increases above 240 VAC, the voltage at the non-inverting input (pin 5) of A2 increases above the voltage at the inverting input and the output of A2 goes HIGH to drive the base of transistor T2 and LED2 is TURNED-ON indicating over-voltage. The HIGH output from A1 is used to forward bias diode D5 and D10 to RESET IC1 and the output of IC1 changes from non-inverting output (Q) to inverting output(Q^1) and transistor TR7 is SWITCHED-OFF and hence relay RLY1 is de-enegised. The three phase supply is disconnected from the three phase motor to protect it from over-voltage. The phase failure operation is the same as the under-voltage but none of the LED will lit-up during this condition and the phase indicator on front panel will be SWITCHED-OFF. Diode D14 protects transistor TR7 from back EMF that might be generated since the relay coil presents an inductive load.

2.6. Testing

After mounting the components on a Vero-board, interconnection was made between components following the circuit diagram and soldered at specific points. A digital multimeter was used to carry out continuity and short-circuit test to ensure that all components were perfectly interconnected, and no short-circuit connection in the circuit. The circuit was them connected to a three phase supply through a Variac (variable transformer) to set the voltage at the inverting-input of op-amp A1, A3, A5 and at the non-inverting input of op-amp A2, A4, A6 shown in Figure 6 at which the output of the op-amp goes HIGH when the mains input is outside the workable range. After housing the entire system in a casing, bench test was carried out. The system was connected to a three phase supply through a Variac on each phase, and 60 Watts, 220 VAC bulb connected to the output of each phase acting as the load (three phase motor). A digital multimeter was connected across the Variac to measure the mains input voltage. For each phase, the Variac was set at 220 VAC and switch

SW1 SWITCHED-ON, and the entire 60 Watts bulbs were TURNED-ON. The Variac on the RED phase was adjusted until the mains input was just below 200 Vac, and the entire 60 Watts bulbs were TURNED-OFF indicating a low voltage supply on the RED phase, which is indicated by the low voltage LED indicator on front cover of casing on the RED phase. Again, the Variac on the RED phase was set at 220 Vac and switch SW1 SWITCHED-ON, and the three, 60 Watts bulbs were TURNED-ON. The Variac on the YELLOW phase was adjusted until the mains input was just above 240 Vac, and the entire 60 Watts bulbs were TURNED-OFF indicating an overvoltage supply on the YELLOW phase, which is indicated by the overvoltage LED indicator on front cover of casing on the YELLOW phase. Lastly, the Variac was set at 220 VAC and switch SW1 SWITCHED-ON, and the entire 60 W bulbs were TURNED-ON. The supply on the BLUE phase was removed from the mains input and the entire 60 Watts bulbs were TURNED-OFF. The indicator at the mains input of the BLUE phase on front cover was TURNED-OFF indicating a phase failure fault.

3. RESULTS AND DISCUSSION

From Table 1, it is observed that when the mains input voltage is between 180 VAC and 198 VAC, the three phase motor is turned-OFF because the voltage at the inverting input (V_{A1}) of op-amp A1 is less than the voltage at the non-inverting input (V_{A2}). Hence the output of op-amp A1 goes HIGH to forward bias the anode of diode D4 and D10 to RESET IC1. At this input voltage, the output of op-amp A2 is LOW.

Also, when the mains input voltage is between 200 VAC and 235 VAC, the three phase motor is turned-ON because the voltage at the inverting input (V_{A1}) of op-amp A1 is higher than the voltage at non-inverting input (V_{A2}), and the voltage at the non-inverting input (V_{B1}) of op-amp A2 is less than the voltage inverting input (V_{B2}). Hence the output of op-amp A1 and A2 is LOW and cannot forward bias the anode of D4and D5.

Lastly, when the mains input voltage is between 242 VAC and 245 VAC, the Three Phase Motor is turned-OFF because the voltage at the non-inverting input (V_{B1}) of op-amp A2 is higher than the voltage at the inverting input (V_{B2}). Hence the output of A2 goes HIGH to forward bias the anode of diode D5 and D10 to RESET IC1. At this input voltage, the output of op-amp A1 is LOW.

4. CONCLUSION

Induction motors form the basic part of most industrial processes and it is imperative to preserve these motor working and free from damage. To achieve this, protective schemes need to be in place to protect the motor when possible faults arise. This work presents the protection of three phase induction motor against single phasing, over/under voltage using low cost operational amplifier that requires no programming knowledge. The various tests carried out and results obtained demonstrate that the 6 hp three phase motor protection system achieved its design and construction aims. The system worked with specification and was quite satisfactory.

5. ACKNOWLEDGEMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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