


Research Article

Development of a Starter with Protective Systems for a Three-Phase Induction Motor

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Frequent burning of three-phase induction motors windings has been reported. The initial symptoms observed before the burning of the windings were an increase in operating current and a temperature rise. The induction motor protection and control system was designed, developed, and constructed to reduce the problem of burnt winding by early detection and disconnection of supply if the problem persists. It was found to be efficient, reliable, durable, and rugged. The system is a boost to Nigerian industrialists as it will reduce cases of burning of induction motors and the consequent downtime and cost. The system is cheap and easy to repair and maintain because the parts and components used in the design are available locally.

1. Introduction

Induction motors are highly reliable, rugged, and efficient machines for several industrial applications [1–3]. However, the motors are susceptible to three classes of faults: mechanical-, electrical-, and environmental-related faults. The electrical-related faults of induction motors result from phase failure, unbalanced supply voltage or current, phase sequence reversal, earthling fault, overloading, broken bars and end ring, insulation failure, and short circuits [4]. Most of these faults lead to the burning of the windings. Frequent burning of windings of induction motors has to be a serious threat to small and medium scale manufacturing industries that use the motors as prime movers for manufacturing as well as processing equipment [1]. A lot of useful time and resources are lost in trying to rewind or replace burnt motors. Rewound motors were reported to have reduced output and low efficiency that could result in long term energy and monitoring losses in [3]. Efficiency loss of between 0.5–0.7% was reported in [5]. Although the effect of rewinding on motor efficiency seems to be negligible,

consideration downtime, expertise, and extra cost are incurred in the process. Therefore, there is a need to reduce the cases of burnt windings to the barest minimum.

Two symptoms are evident before the induction motor's windings could get burnt, namely, an increase in operating current and temperature [6]. Protection against the excessive operating current can be achieved using overload relays.

Excessive temperature increases the rate of deterioration of the insulation of the motor windings, degradation of lubricant, and bearing failures [7]. Burning out of motor windings results from insulation failure, and every 10% increase in temperature reduces the insulation life by 50% [4]. In addition to the burning out of the windings, an increase in temperature could result in increased power consumption and decreased speed and efficiency. Thermal stress resulting from excessive temperature greatly contributes to the reduction of the performance and lifetime of induction motors [8]. Thus, there is a need to protect the motor against excessive temperatures. As a result, this study designed and implemented an electronic-based motor starter with the capacity to protect the motor against extreme temperatures.

2. Theoretical Model of the Effect of Temperature on Motor Windings

The protection of induction against thermal stress resulting from excessive temperature is mandatory for continuous and reliable operation. As a result, the National Electrical Manufacturers Association established permissible operating temperature limits depending on classes (Y, A, E, B, F, and H) of insulation of the stator winding [9]. Contemporary motors were reported to be produced in the F tolerance class in [10].

Class F motors are typically rated to operate with a maximum coolant temperature of 40°C and a maximum temperature rise of 100°C, resulting in a potential maximum winding temperature of 140°C [11].

Operating a motor beyond its maximum will not cause an immediate failure, rather a decrease in the life expectancy of that motor [12]. A common rule of thumb applied to insulation degradation is that, for every 10°C rise in temperature, the expected life span is halved since the winding resistance (R_T) increases with temperature [9]:

$$R_T = R_0 (1 + \alpha t), \quad (1)$$

where R_0 = resistance of material at room temperature, α = coefficient of linear expansion, and t = temperature.

Also, the power dissipated in the windings is the copper loss which is proportional to the square of the current and the winding resistance R_T given by [13]

$$P_T = I^2 R_T. \quad (2)$$

An increase of 10% in the current drawn will give an increase of 21% in the copper loss, and therefore, an increase of 21% in the temperature rise, which is 21°C for a Class F motor. This approximates to the life being reduced to a quarter of that expected. This shows that excessive temperature affects the motor's lifetime.

Furthermore, the efficiency (η) of the motor is not spared as

$$\eta = \frac{P_1}{P_2}, \quad (3)$$

where P_1 = power output and P_2 = power output (P_1) + power loss (P_L).

The combined control and protective system were developed to protect the induction motor against these problems so that its lifespan can be fully guaranteed.

3. The System Design

The system design has the following subdivisions:

- (i) The starter
- (ii) Dc power supply unit for the control circuitry
- (iii) Temperature sensing and conditioning
- (iv) Overcurrent sensing and conditioning
- (v) The forced cooling fan control unit
- (vi) Delay, shut down, and indicator units

3.1. The Starter. There are various methods of induction motor starting. These range from direct on-line, resistance, primary reactance, autotransformer, slip ring motors starting, star-delta, and so on. For this model, a 1.5 KW induction motor was used. Since the rating is smaller than 3.75 KW [14], a direct on-line starting method was adopted.

Power is supplied to the induction motor via the closure of the main contactor's contacts, as shown in Figure 1. The closure of the contacts is done by energizing the coil of the contactor coil (applying full 220 V AC across the coil).

To effectively control the motor, considering Figure 1 is introduced, the control line diagram of Figure 2 was used.

For the coil to be energized, a complete circuit has to be formed by pushing the normally open start button and connecting the normally closed stop button and the normally closed automatic stop relay contacts. On releasing the start button, the circuit is sustained by the hold-on contact of the main contractor.

This can, however, be demagnetized by pushing the stop button to break the circuit or opening the auto-stop relay contact. This will also open the hold-on contact.

3.2. The DC Power Supply Unit. The power unit consists of a step-down transformer, silicon rectifiers, electrolytic capacitance filter, three-terminal integrated circuit regulators, and a power-on indicator. Components were selected such that the output voltage gives $+12$ V, 0 V, and -12 V. The circuit diagram of the power supply is as shown in Figure 3.

3.3. The Temperature Sensing and Conditioning Unit. The temperature transducer used was a negative temperature coefficient (NTC) thermistor, whose resistive property decreases with an increase in temperature. A temperature-resistance relationship for 0–250°C was obtained for the thermistor to be used. The reason for this is that it helps to give an idea of a fixed resistor (R) to be connected in series with it to form a voltage divided network, as shown in Figure 4. The voltage (V_a) at the point of connection, according to equation (4), varies in response to temperature change:

$$V_a = \frac{R_T V_{CC}}{R_T + R}, \quad (4)$$

where R_T is the thermistor's resistance.

To further condition the signal (V_a), an instrument amplifier was used where the voltage (V_a) was fed to one input and a reference voltage (V_b) set by a variable resistor applied to the other input.

The instrument amplifier is a differential amplifier and has an output voltage which is the difference between V_a and the reference multiplied by the gain given by

$$g = 1 + \frac{2}{m}, \quad (5)$$

where "m" is the gain control resistor [9].

The circuit diagram of the temperature sensing and conditioning is as shown in Figure 4.

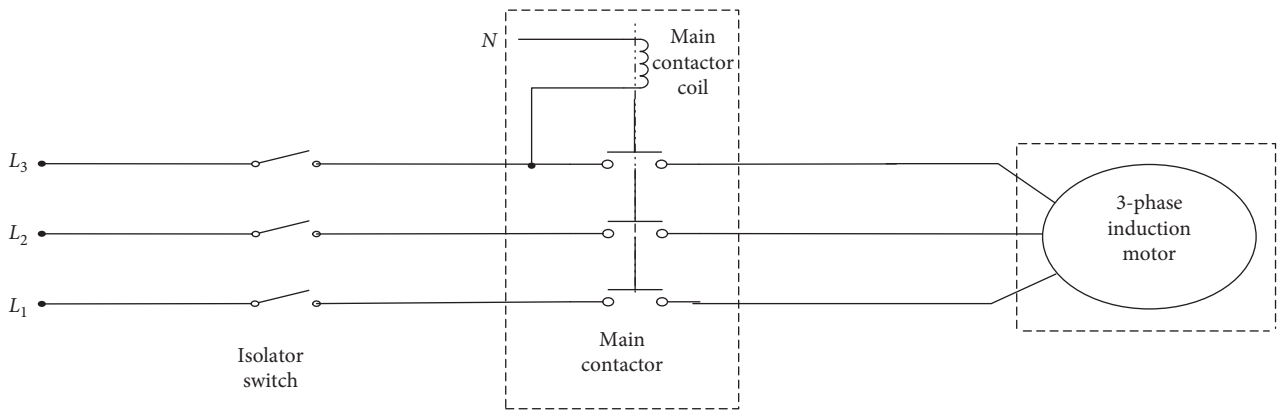


FIGURE 1: Direct on-line starter diagram for a three-phase induction motor.

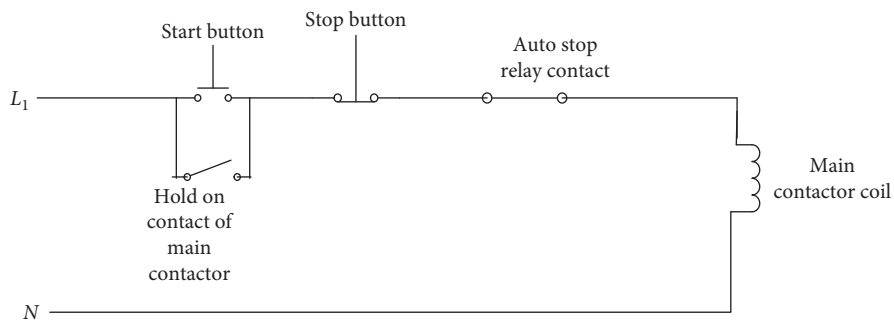


FIGURE 2: Line diagram of the induction control unit.

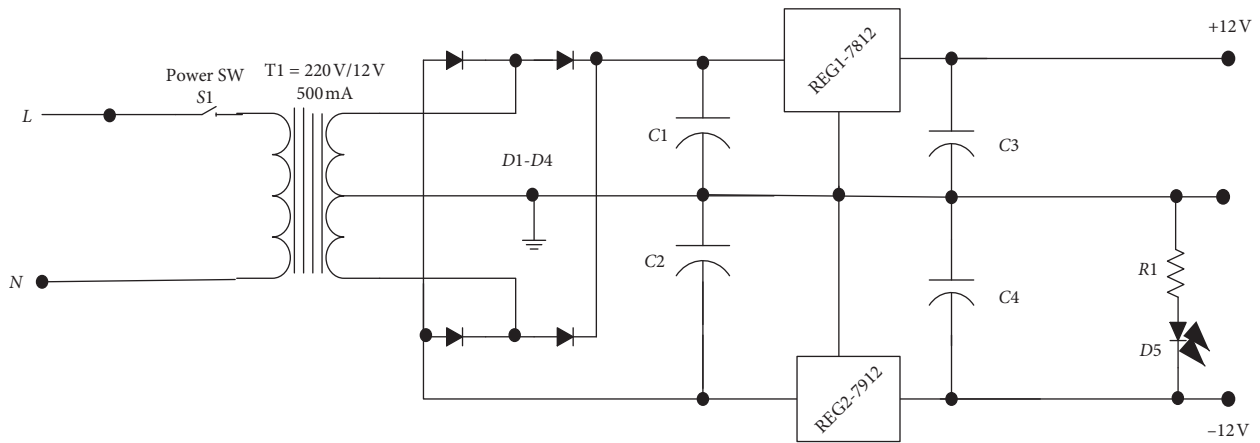


FIGURE 3: The circuit diagram of the power supply.

3.4. *Overcurrent Sensing and Conditioning Unit.* Small current transformers were connected on the cable carrying current to the motor (one per phase). The current transformer is necessary because the current flowing into the load is too high to be used directly with the control unit. So, the current transformer is serving a dual purpose of stepping down the current as well as isolation.

The output of the current transformer is proportional to the current flowing into the load (induction motor) and connected to a variable resistor used as attenuators through rectifier diodes. The signal is a pulsating DC voltage whose amplitude is proportional to the current drawn by the load.

The peak attenuated values of the pulsating dc voltage is compared with a preset reference voltage set by V_{R4} , V_{R5} , and V_{R6} using operational amplifiers IC_{7a} , IC_{7b} , and IC_{7c} as comparators.

The output of the operational amplifiers was connected using diodes to form an OR gate arrangement. The circuit configuration is as shown in Figure 5.

3.5. *Forced Cooling Fan Control Unit.* The forced cooling fan unit was used to control the speed of the fan, which is a small AC motor in proportion to the temperature of the induction

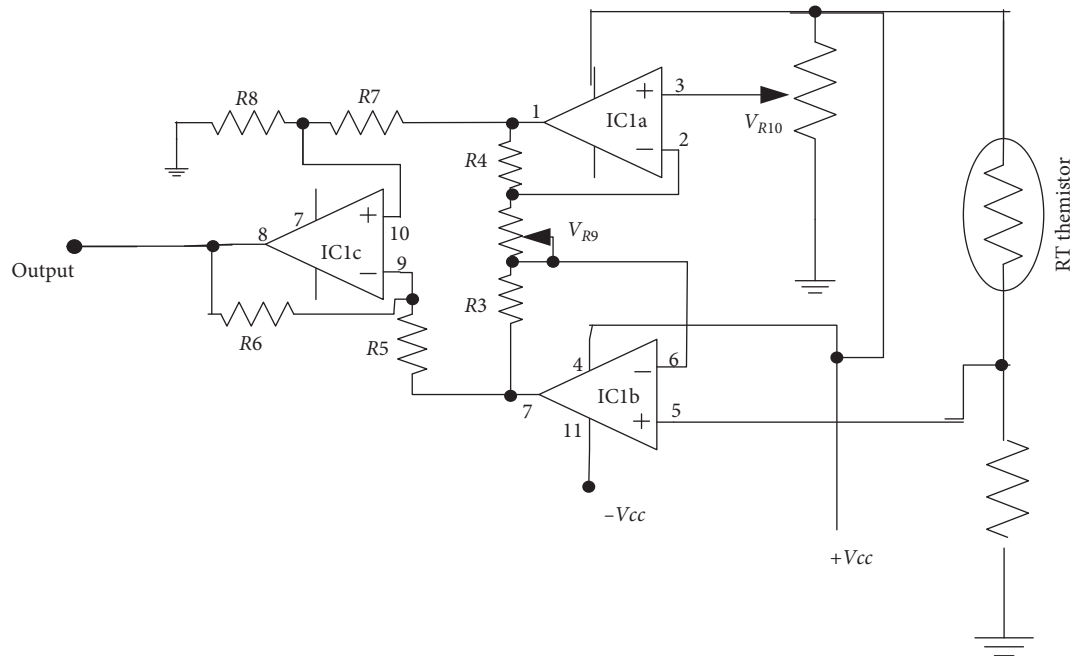


FIGURE 4: The circuit diagram of the temperature sensing and conditioning.

motor. The fan was powered via a Triac (BT136). The gate of the Triac was triggered through (IC2) a Diac-LED optocoupler (MOC3010) [10]. The light-emitting diode section was powered by a voltage controlled oscillator (VCO) configured using the monolithic 555-timer integrated circuit connected in the astable mode (free-running oscillator) with frequency (f) given in [15] as

$$f = \left[\frac{1.44}{R_{11} + R_{22}} \right] C_5. \quad (6)$$

The control voltage terminal of the 555-timer was fed with the variable voltage from the instrument amplifier. Thus, when the temperature of the motor starts rising, the speed of the forced cooling fan gets higher. Figure 6 shows the circuit diagram of this unit.

3.6. The Delay, Indicator, and Auto Shutdown Units. The output of the temperature sensing unit is connected to a comparator configured using IC1d. The output voltage is compared with a reference voltage set by V_{R3} . If the temperature of the motor goes beyond the set value, the output of the comparator goes high.

The outputs of both sensing units were connected to the delay network formed by R_{18} and C_6 through diodes D_{13} and D_{15} .

The delay circuit is necessary to cater for the starting period when the high starting current flows.

The voltage across the delay capacitor (C_6) is again compared with a fixed reference voltage set by V_{R7} .

We use the comparator configured from IC7d whose output goes high when the capacitor voltage exceeds the reference voltage.

The auto shutdown mechanism is a normally closed contact of a relay that opens when a fault condition is detected.

Either of the two fault conditions (overcurrent or over-temperature) can trigger it. Therefore, for the operator to know what led to the tripping, a bistable multivibrator was incorporated and configured using a 555-timer integrated circuit.

The triggering of the multivibrator is conditioned by both the output of the fault detector and the delay output. The gate used was the 2-input NAND Schmitt trigger (4093).

The outputs of the bistable multivibrators are “OR-ed” using diodes D_{17} and D_{18} to bias the transistor ($Q1$) to switch the relay to open the normally closed contact to shutdown the motor automatically. The circuit diagram of this section is as shown in Figure 7, while Figure 8 shows the complete circuit diagram of the system.

The arrangement of the control unit, the forced cooling fan, and the induction motor protected is shown in Figure 9.

4. Fabrication and Testing

As seen from the circuit diagram, simple and relatively available electronic discrete and integrated circuit components that are obtainable in average electronics shops were used in addition to other local materials. The low-cost electronic discrete and integrated circuit components used in implementing the system include diodes, operational amplifiers, 555-timer, capacitors, transistors, resistors, current transformers, thermistor, and others already referred to in Section 3. The system was assembled and tested, as shown in Figures 10 and 11, respectively.

To validate the functionality of the system, the motor used for testing was loaded in three stages. In the first stage, it was loaded at 50% of the full load and run for six hours in case of which neither the fan nor the overload trip responded. In the second stage, the motor was 100% loaded in case of which the external cooling fan came on after thirty-

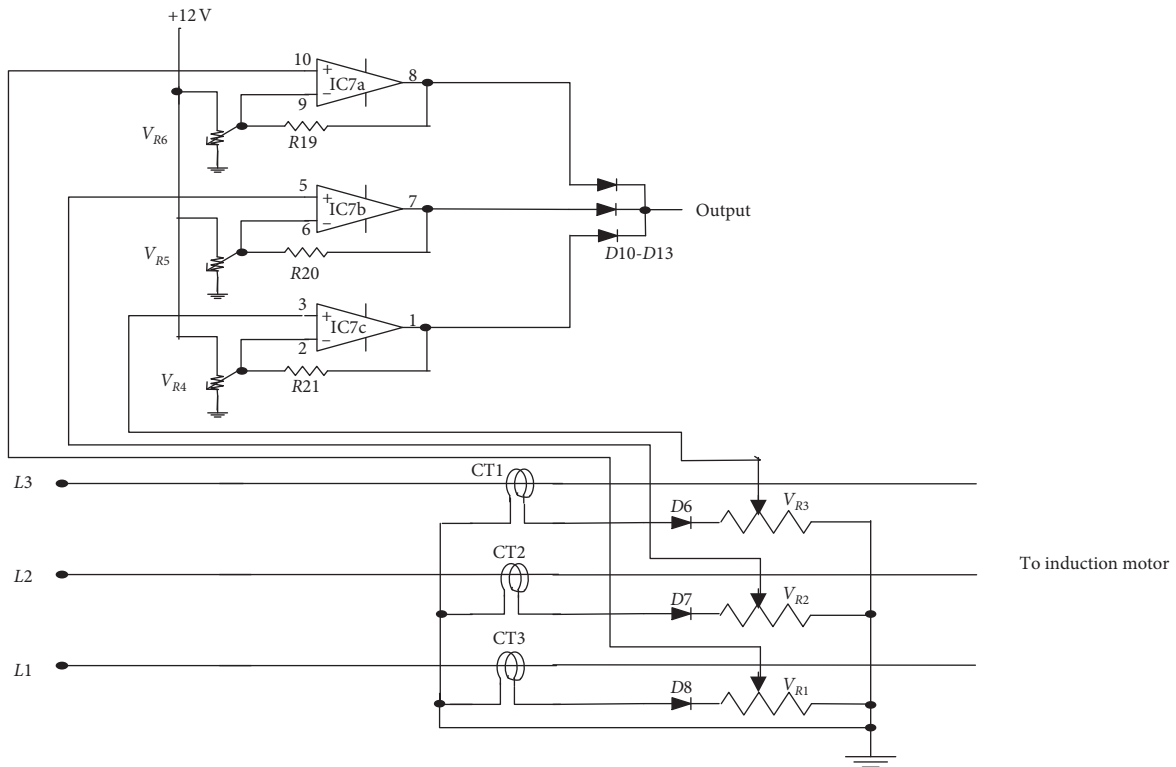


FIGURE 5: The circuit diagram of the overcurrent sensing and conditioning unit.

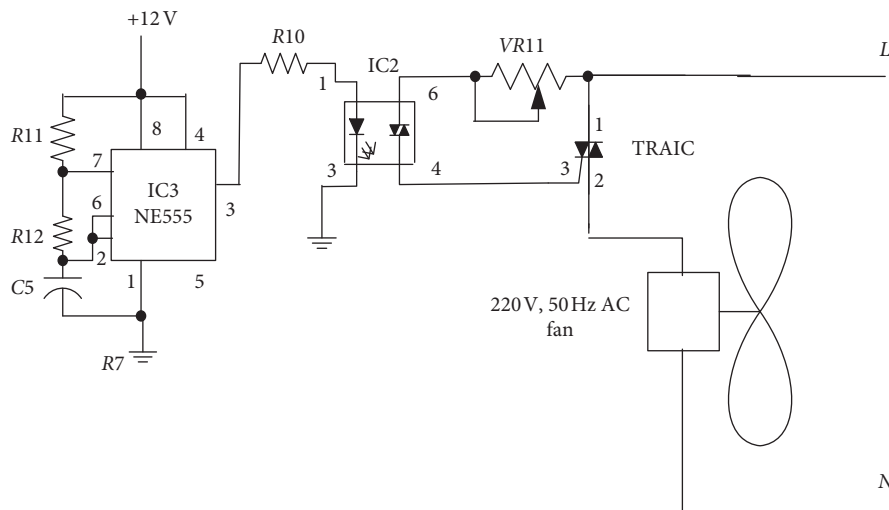


FIGURE 6: Circuit diagram of the forced cooling fan control unit.

eight minutes when the temperature became 920°C and remained on for two hours without overload trip operating. Lastly, the motor was loaded above full load capacity in case of which the overload tripped in forty-three seconds. The results show that the system can adequately protect induction motors against overcurrent and excessive temperature. The external forced cooling fan helped in keeping the motor’s temperature below normal operating temperatures,

thus preventing the insulation breakdown of the copper conductors used for the windings.

4.1. Cost Implication. The prototype used for the 1.5KW three-phase induction motor costs N6, 780:00, as of June 2020 which is quite affordable by small and medium scale industrialists and business operators.

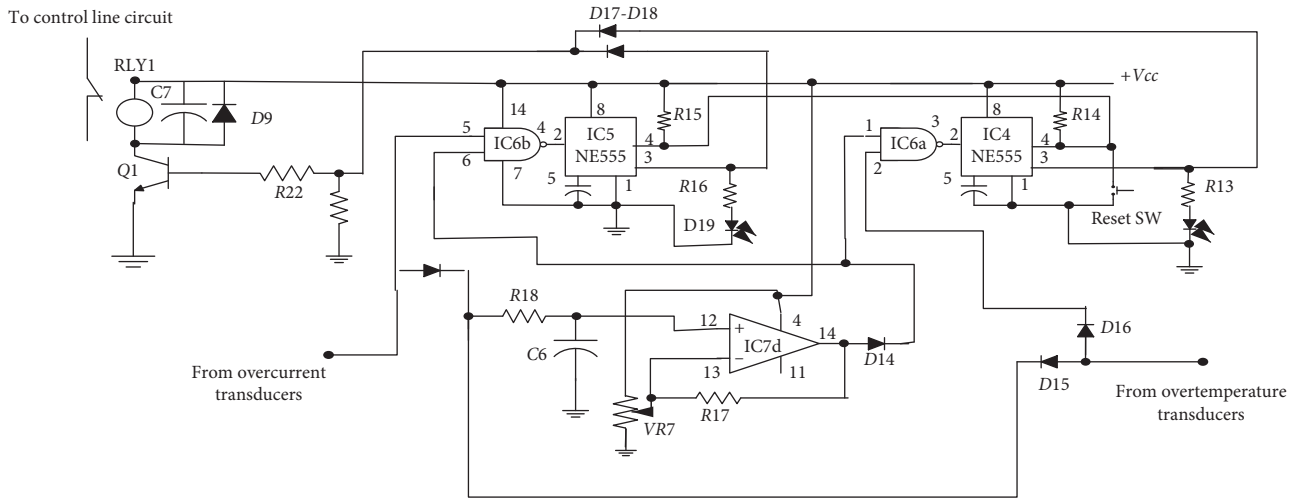


FIGURE 7: The circuit diagram of the delay, indicator, and auto shutdown units.

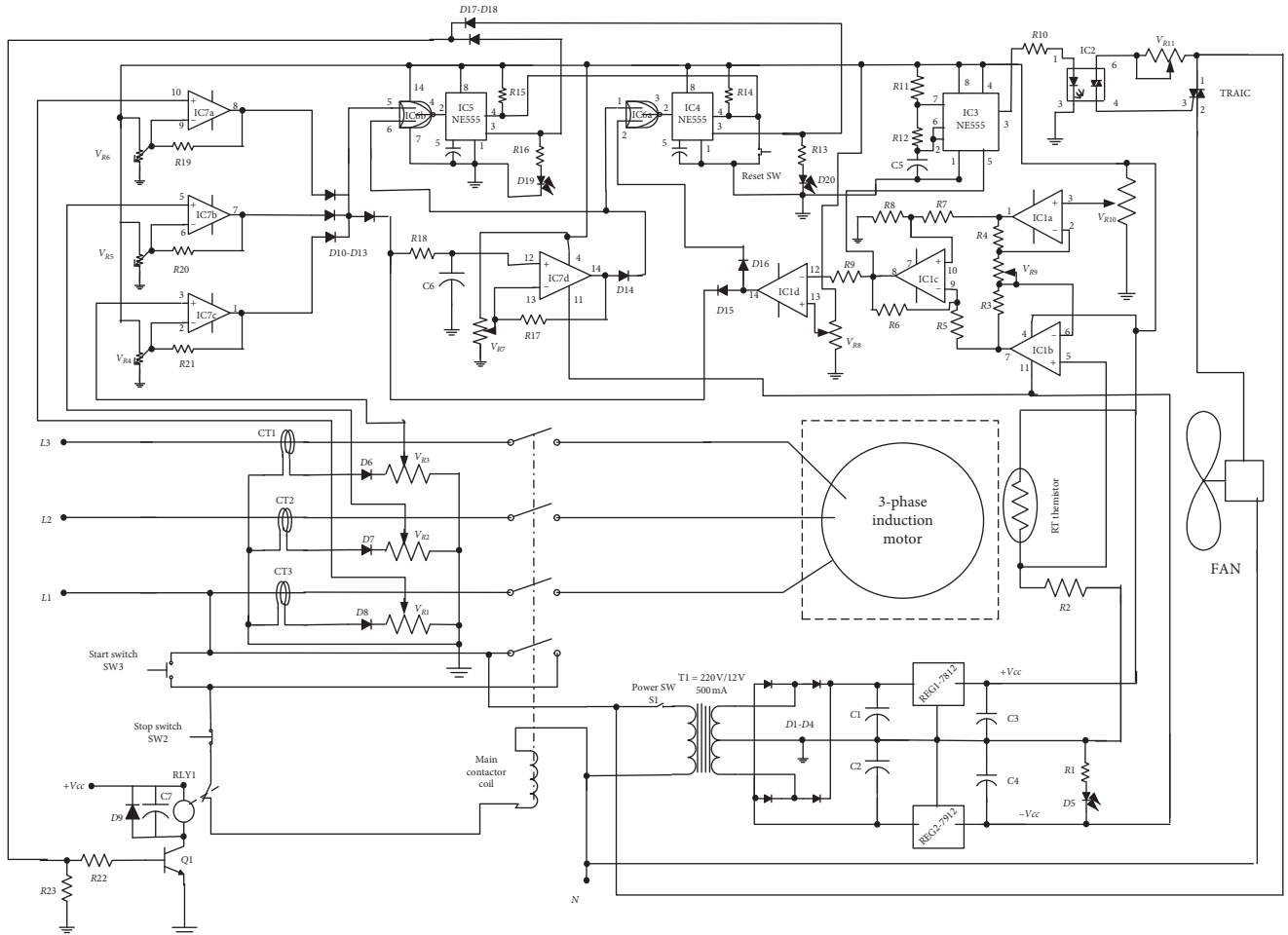


FIGURE 8: The complete circuit diagram of the system.

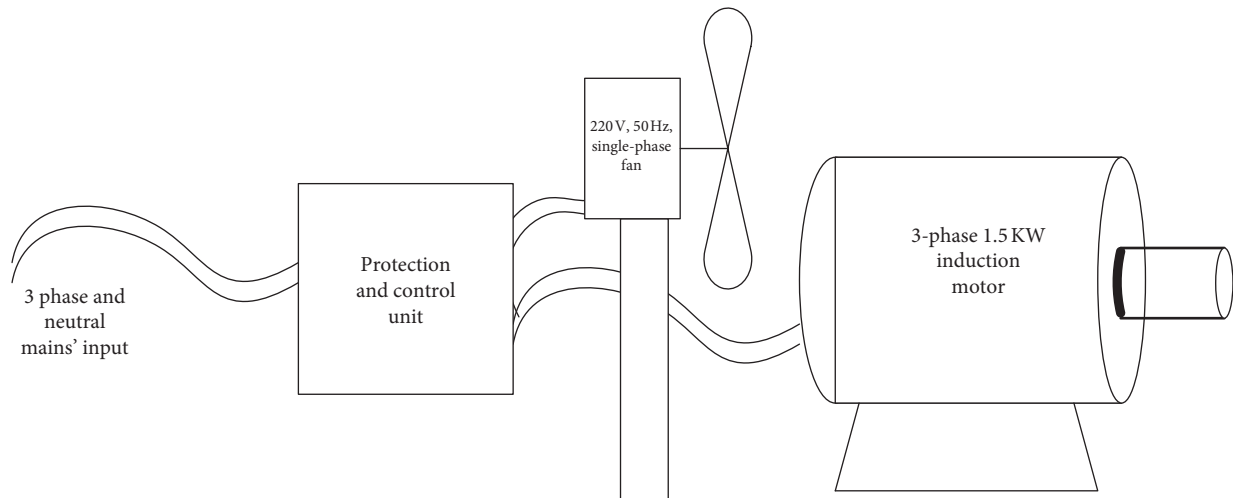


FIGURE 9: The physical arrangement of the control unit, fan, and induction motor.

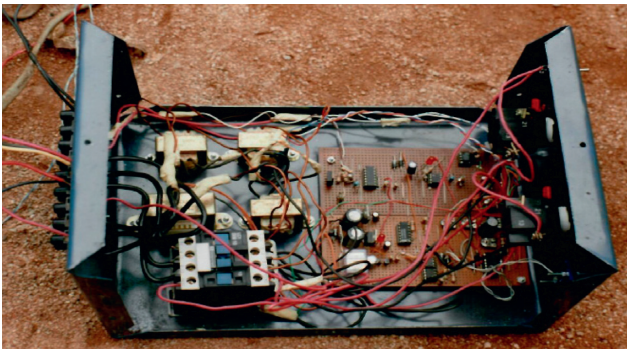


FIGURE 10: The assembled system.

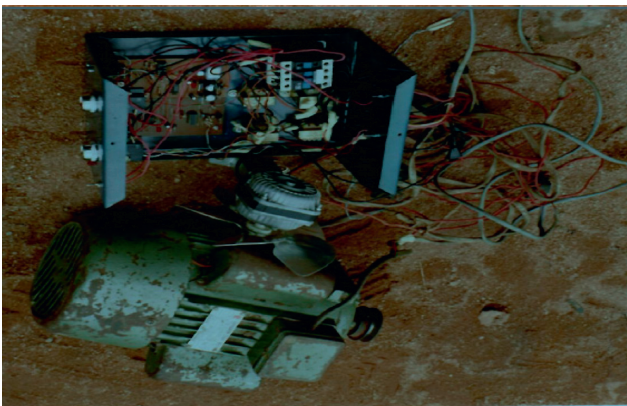


FIGURE 11: The system being tested.

5. Conclusion

The induction motor protection and control system was designed, developed, and constructed. It was found to be efficient, reliable, durable, and rugged. The system is a boost to Nigerian industrialists as it will reduce cases of burning of induction motors and the consequent downtime and cost. The system is cheap and easy to repair and maintain because spare parts and components are available locally.

Data Availability

Data are available within the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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