INTERNATIONAL JOURNAL of SMART GRID
H. K. Khan et al., Vol.7, No.2, June, 2023

Design and Performance Evaluation of Numerical Relay for Three-Phase Induction Motor Protection

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Received: 27.03.2023 Accepted:24.06.2023

Abstract-In today's automated world, the three-phase induction motor is important electrical equipment. These motors are extensively used in industrial driving because they are simple to build, dependable, inexpensive, and simple to use. The performance of an induction motor is very important for maintaining the production process in the industry. This paper proposes a protection scheme for the motor against various types of electrical faults that affect its performance and efficiency. In conventional protection systems, one module is used for each fault, but in the proposed protection scheme, it is possible to protect three faults with one module. For this purpose, the current and voltage values of induction motors were measured using current and voltage transformers. Here, Arduino Uno automatically selects the IDMT characteristic according to the type and magnitude of the fault. The proposed scheme is simulated by Proteus software, followed by hardware implementation, and the performance evaluation of the protection system is done in the laboratory.When over-voltage, overload, and single-phase faults are detected while the motor is running, according to the algorithm, the Arduino-controlled operation system is immediately activated, and all necessary parameters are displayed on the LCD. The simulation results and the obtained experimental results were very similar.

Keywords: Arduino Uno, Electromagnetic Relay, Induction Motor, IDMT.

1. Introduction

Everyday living necessitates the use of automobile protection. Under voltage, overvoltage, overheating, single phasing, and phase reversal are all common difficulties with three-phase induction motors. In our work, a variable resistance is chosen because when the supply voltage is lower than the rated voltage; the voltage drop across the resistance is greater, protecting the motor from this failure. Classical protection solutions for three-phase IMs are a rapidly evolving technology for fault detection. The equipment employed in this work has mechanical parts, and their reflexes are quite rapid when compared to other devices [1-4].

The mechanical components of the equipment can improve the system's dependability and efficiency. The cost of traditional relays has lately been reduced in terms of economics. In modern protection systems, the potential transformer is linked in parallel with the three-phase power supply, while the current transformer is linked in series with the three-phase power supply. The potential transformer and current transformer in this protective system are responsible for continually monitoring the voltage and current, respectively. When a three-phase supply is provided, the operation of CT and PT is continually monitored. When a defect occurs, such as an overvoltage, under-voltage, overload, phase reversal, unbalanced voltage, or single-phasing, the sensor unit activates. Some preset values are placed on the microcontroller, and with the assistance of these settings, the microcontroller compares the reference value [5-10].

1.1 Importance of Motor Reliability and Protection

Three-phase induction motor protection entails safeguarding against single phasing, phase reversal, over voltage, under-voltage, and over load. Because of this electrical defect, the winding of the motor becomes heated, causing the insulation to break and so reducing the motor's life. This failure occurs in an induction motor owing to a change in the characteristics of the induction motor. When a three-phase induction motor works constantly, it must be protected from certain expected problems. Three-phase induction motors are normally directly linked through the supply; if the supply voltage sags and swells owing to a fault, the motor's performance suffers, and in certain cases, the winding is burnt out [11-15].

Also, a balanced three-phase supply system is important for obtaining On-load constant rotor speed and torque from a three-phase induction motor.

Regardless of shaft load, the rotor will always settle at a speed 'ω_t' smaller than the supply frequency 'ω_e'. This difference in speed is referred to as the slip speed 'ω_{sp}.' The relationship between 'ωe', and 'ω_{sp}' is given as follows,

$$\omega_{sp} = \omega_e - \omega_t \quad (1)$$

If ω_j is the mechanical rotor speed,

$$\omega_t = \frac{P}{2}\omega_j (2)$$

The rotor is considered to be symmetrical, with three-phase windings dispersed in space by a 120° angle, several effective rotations N_r, and a resistance of r_r. The voltage equations for the stator and rotor are as follows: For the stator:

$$V_{abcs} = r_s I_{abcs} + p\lambda_{abcs} \; (3)$$

$$V_{abcr} = r_r I_{abcr} + p\lambda_{abcr} \quad (4)$$

Here, $V_{as}, V_{bs} and V_{cs}$ are three balanced voltages that are rotated at the supply frequency [16-19].

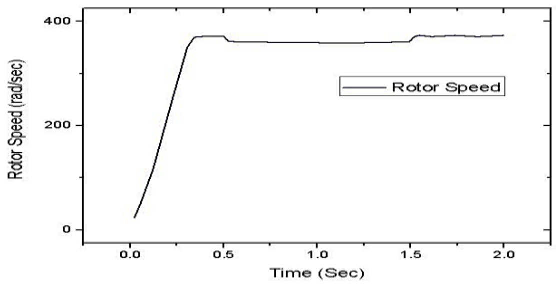

Fig. 1. On load characteristic for rotor speed [20].

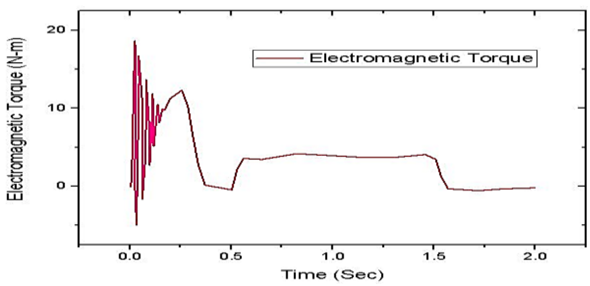

Fig. 2. On load characteristic of torque [21].

1.2 Literature Review

Zebin Yang and his team solved a problem of insufficient accuracy in the traditional analytical model by proposing an optimized dynamic model based on a fixed-pole rotor structure designed by the research group, which comprehensively considers the effect of suspension winding, torque winding, and rotor winding [22-24]. Magno Ayala and his colleagues offer an experimental stability investigation of modified predictive current controllers used in an asymmetrical six-phase induction machine to measure the limits of stability. The experimental findings were provided to validate the theoretical analysis results in terms of sampling frequency and rotor speed stability ranges [25-26]. Minghao Zhou and his colleagues suggested a sensor-less induction motor speed control solution based on full-order terminal sliding-mode control theory. The speed control system was made up of three feedback control loops: speed, flux, and current. The controllers in these three feedback loops were developed with full-order terminal sliding-mode to improve robustness and dynamic performance, minimize singularity, and reduce chattering [27-28]. B. Prathap Reddy and his colleagues concentrated on modeling and enhanced control of the PPMIM drives in all possible pole-phase combinations. The dynamic mathematical modeling of the PPMIM in the real phase variable domain is detailed [29-30]. Marko Hinkkanen and his colleagues investigated the stability of volts-per-hertz (V/Hz) control for induction motors. The electromagnetic torque and the back-electromotive force were nonlinearly connected to the dynamics of the induction motor model's electrical and mechanical subsystems [31-32].

1.3 Objective

The primary purpose of this research is to improve the performance of a three-phase induction motor protection system. It will be accomplished by creating an IDMT over current and overvoltage relay. The primary goals of this work are to become acquainted with the characteristics of Inverse Define Minimum Time (IDMT) over current and overvoltage relays, to build hardware with complete input or output peripherals according to the proposed design, and to evaluate the performance of the proposed system technically and physically.

2. System Design

Basically, two major types of errors, electrical and mechanical, are crucial; they can break down the induction motors. If these faults are not considered, then the motor's operating life is reduced. Many problems persist with induction motors in the industry due to different faults that cause motors to stop, which leads to production losses as well as financial losses. Hence, detection and protection systems are required to prevent motor defects.

In Fig. 3, the functional block diagram of the proposed protection system has been shown. Here, three 220V/12V, single-phase step-down transformers are used to measure the three-phase supply voltage. And their outputs are connected to the input of the signal conditioning circuit.

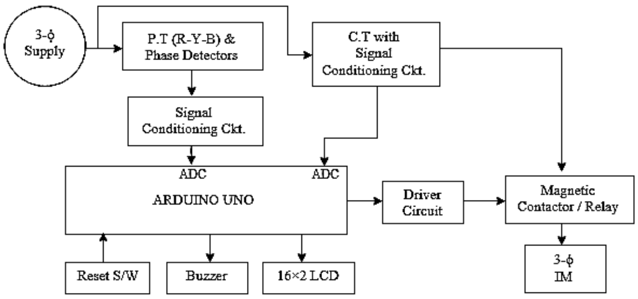

Fig. 3. Block diagram of the proposed motor protection system.

Here, the signal conditioner circuits basically convert the AC signal to its equivalent DC signal, and the potentiometer used in the circuit can be calibrated as per the requirements of the input signal value. The step-down transformers used here also work for phase detection. A 20-ampere AC CT module is used to measure motor current, which is connected in series with the relay or magnetic contactor, induction motor, and power supply system. The outputs of all the signal conditioning circuits are connected to the ADC pin of the Arduino Uno. The driver circuit shown in the figure is primarily designed to operate high-current rating relays or magnetic contactors. This protection system also has a 16×2 LCD and a Buzzer. When a fault occurs in the system, the Arduino Uno will generate a control signal according to the given algorithm, the motor will be stopped, and the buzzer will make a sound. All parameter values and fault types will be displayed on the LCD.

Figure 4 shows the simulation circuit drawn on Proteus. Here, the possible output is determined by simulation in software before hardware implementation. In TR1, TR2, and TR3, there are three 220/12-volt step-down transformers used as PT. Here, the signal conditioning circuit is basically made up of rectifier diodes, filtering capacitors, and potentiometers. The outputs of the signal conditioning circuits of all CT and PT modules are connected to the ADC pins of the Arduino Uno from A0 to A3, respectively. Pins 0 to 5 of the Arduino Uno are used to operate the LCD, PIN 7 is used to operate the buzzer, and PINs 8 to 10 are used to operate the opto-isolated relay module. As the value of the input voltage of the PT module decreases and increases, the output voltage of the conditioning circuit decreases and increases proportionally. Similarly, as the input current value of the CT module decreases and increases, the output voltage value of the signal conditioning circuit decreases and increases at a proportional rate. Arduino Uno has a 10-bit built-in ADC, so its step size is 4.88 mV. As the analog voltage at the input of the ADC increases or decreases, its step size also increases or decreases. When a phase-missing, over voltage, or over current fault occurs in the system, the number of step sizes of the corresponding ADC is less or greater than a predefined value, which indicates a fault, has occurred. Arduino Uno determines

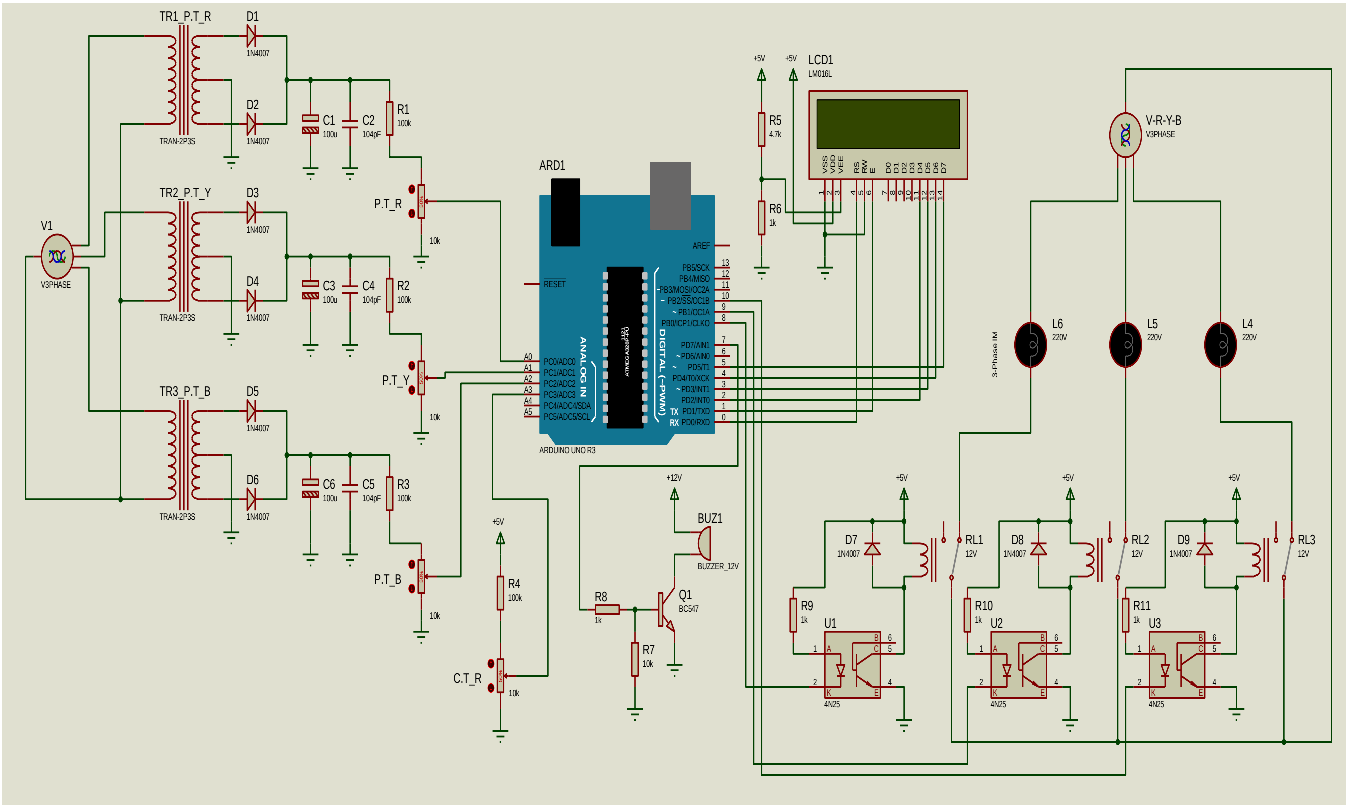

Fig. 4. Proteus simulation circuit for proposed IM protection system.

the nature and magnitude of the fault depending on the step size of the corresponding ADC and generates the required control signal according to the given algorithm. As a result, the relay module becomes inactive and disconnects the motor from the supply line. The proposed protection system indicates voltage above 242 volts as high voltage, current above 6 amps as overload load, and voltage difference below 100 volts as phase missing or voltage unbalance fault. All parameter values are displayed on the LCD in normal and faulty conditions, and a buzzer sounds as a warning signal in the case of fault.

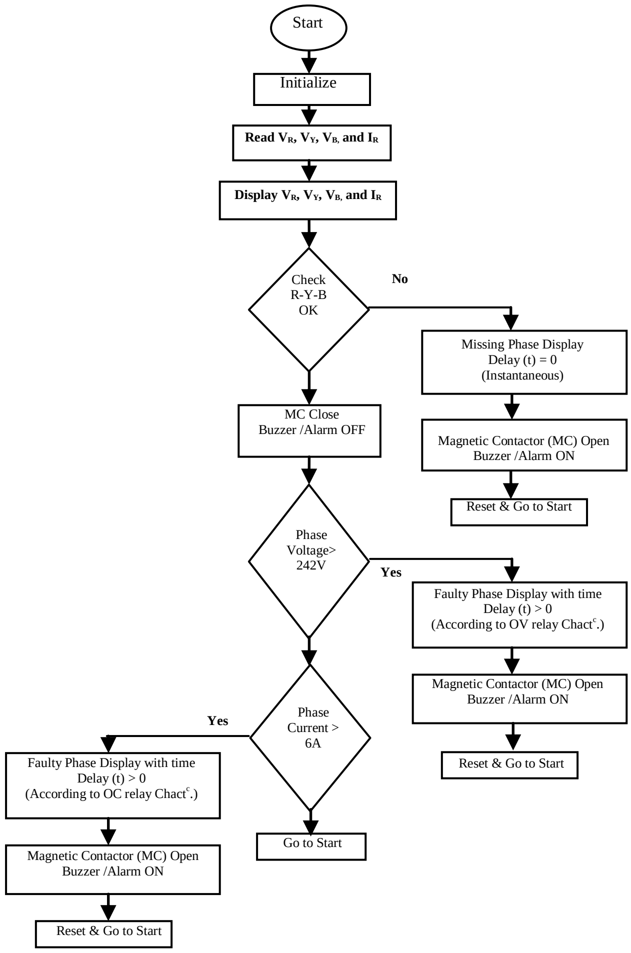

Fig. 5. System flow chart.

3. Hardware Setup and Results

The following components were used in this work: NPN transistor, potentiometer, step-down transformer, CT module, buzzer, display, rectifier diodes, capacitors, relay, positive regulated IC (LM7805), and Arduino Uno. Following the achievement of the desired result through Proteus simulation, the proposed circuit is practically built in the laboratory. Figure 6 depicts a practical implementation of a numerical relay-based three-phase induction motor protection circuit.

Fig. 6. Complete prototype on working condition.

3.1 Over Voltage Fault

A three-phase variac is used in the laboratory for this test, with an output of 0 to 300 volts. According to the proposed algorithm, the nominal voltage of a phase-to-neutral system is 220V, and the minimum range of the overvoltage is 110% of the rated voltage or the nominal voltage. So, over voltage relay operating time [33].

$$t = \frac{0.5}{\log\left(\frac{Vs}{1.1\times 220}\right)}\text{, Second} \qquad (5)$$

When the supply voltage is increased to greater than 242 volts, the proposed protection system detects an overvoltage fault. Relay operating time decreases with respect to the supply voltage magnitude increasing, which indicates the IDMT characteristic. The experimental values are shown in Table 1, and Fig. 7 shows the graphical representation of Table 1.

Table 1.Experimental results for over voltage fault.

S.L	Supply Voltage (V)	Relay Operating Time (Sec)
1	270	04.58
2	267	05.09
3	264	05.75
4	261	06.62
5	259	07.37
6	257	08.34
7	256	08.89
8	253	11.26
9	251	13.70
10	250	15.39
11	249	17.54
12	248	20.42
13	247	24.45
14	245	40.58

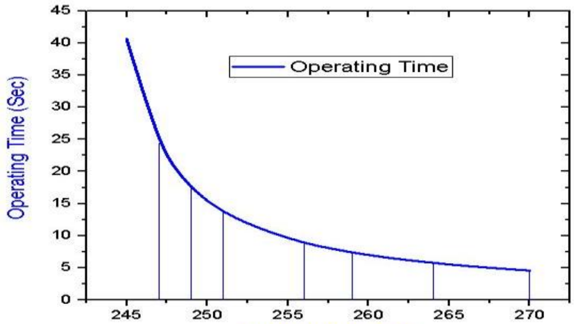

Fig. 7. Graphical representation of over voltage fault.

Fig.8. When the B-phase voltage is 256 V.

3.2 Single Phasing Fault

According to the proposed algorithm, when any phase-to-phase voltage difference is greater than 100 volts or any phase-to-neutral voltage is less than 100 volts, the proposed protection system detects a phase-missing fault. At that time, the relay switched off immediately. As a result, the motor is disconnected from the supply system.

Fig.9. When the Y-phase is missing or unbalanced.

3.3 Over Load Fault

A three-phase squirrel-cage induction motor and belt-coupled electrodynamometer have been used in the laboratory for this test. The motor rating was 1 kW, 400 volts, 1.77 A (Y), 50 Hz, and drew 4.35 A at the delta connection. That's why 5A is set as the rated current. An overload fault has been created by increasing the electrodynamometer's excitation. According to the proposed algorithm, the standard inverse characteristic has been selected with a time-setting multiplier of 0.17 seconds, and the pickup current is 120% of the rated current. When the CT module measures above 6 A of line current, the proposed system detects an overload fault. Relay operating time decreases with respect to the overload current increasing, which indicates the IDMT characteristic. The experimental values are shown in Table 2, and Fig. 10 shows the graphical representation of Table 2.

Plug Setting Multiplier (PSM):

$$\text{PSM} = \frac{\text{Fault Current}}{\text{Pick -up Current}} \tag{6}$$

In this research work, the relay curve is selected as standard or normal inverse type,

So, over current relay operating time,

$$t = \frac{0.14 \times \text{TSM}}{(\text{PSM}^{\,0.02} - 1)} \text{ sec} \tag{7}$$

Table 2. Experimental results for over load fault.

S.L	IM current (A)	Relay Operating Time (Sec)
1	10.16	02.25
2	09.67	02.48
3	08.89	03.02
4	08.50	03.41
5	08.30	03.65
6	07.81	04.50
7	07.13	06.89
8	06.84	09.11
9	06.35	21.11
10	06.25	29.14
11	06.15	47.45
12	06.05	131.09

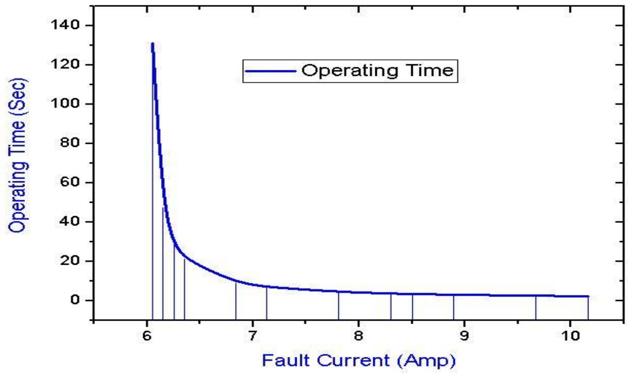

Fig.10. Graphical representation of over load fault.

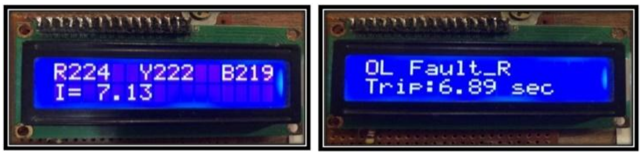

Fig.11. When the Induction motor is overloaded.

4. Conclusion

In this study, an IDMT relay-based three-phase induction motor fault detection and protection system has been successfully developed. The system works with any motor design with a high degree of accuracy. The method is very sensitive and fast, and it detects faults while running and before starting. The proposed scheme can protect a three-phase induction motor from over voltage, single-phasing, and over load to provide smooth running of the motor and improve its lifetime and efficiency. In this research work, the 10A relay module, the 20A precision CT module, and the Chinese Arduino Uno board have been used. So for the implemented project to be used in an industrial environment, several protection features must be added. For example, ESD protection systems, EMI protection systems, advanced cooling systems, etc. For high-power rating motor protection, it is essential to increase the current rating of the CT and use a high-current rating magnetic contactor instead of a relay module. In the future, an IoT-based real-time data logging system can be integrated.

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