

A Smart Industrial Protection System for Three-Phase Equipment Using Data Analytics for Real Time Fault Detection

Syed Saad Ali¹, Shujaat Ali², Aamir Khan¹, Afzaal Faridi¹, Sajid Ali¹, and Shoaib Ali³

¹Department of Electrical Engineering, Nazeer Hussain University, Karachi, Pakistan

²School of Electrical and Information Engineering, Tianjin University, Tianjin, China

³HR Department, Iqra University, Karachi, Pakistan

Correspondence Author: Syed Saad Ali (saad.ali@nhu.edu.pk)

Abstract

In this study, a smart protection system was designed for three-phase equipment's with real-time fault detection and data analytics capabilities is presented. The proposed system integrates all protection functions of over/under voltage, phase sequence, phase failure detection, voltage imbalance monitoring and earth leakage protection under a single intelligent framework to provide enhanced safety and reliability for industrial motors in comparison to the currently existing protection systems which operate independently and do not offer much monitoring capabilities. Electrical parameters are monitored continuously and the motor is automatically switched off if the parameters change in an abnormal manner to avoid overheating, insulation failure, loss of efficiency, and equipment damage. One key feature in this work is the combination of protection hardware with Python-based data analytics for processing numerical and graphical fault data in real time under various operating conditions, utilizing Jupyter Notebook. The proposed approach offers better accuracy of fault detection, quicker response to abnormal conditions, better visualization of fault behavior, and better support for predictive maintenance and decision making during operation when compared to benchmark conventional relay-based systems. According to experimental research, the developed system has a considerable effect on reducing the risk of a motor failure and enhances the reliability of the system and industrial safety. Moreover, the study points out the possible incorporation of artificial intelligence techniques in the future for intelligent fault prediction in the fields of industrial control and automation.

Index Terms: Phase Failure, Voltage Imbalances, Motor Protection, Fault Detection, and Data Analytics.

I. INTRODUCTION

The use of three-phase equipment, especially induction motors, is very important in contemporary industrial systems due to their high efficiency, reliability, and wide usage in manufacturing and automation processes. However, these systems are very vulnerable to electrical faults such as overvoltage, undervoltage, phase failure, phase reversal, and overload. These abnormalities may cause overheating, loss of insulation, performance deterioration, and eventual motor failure. Hence, an efficient protection system is necessary to guarantee safe, reliable, and consistent operation.

This paper outlines the construction and deployment of a smart three-phase equipment industrial protection system that incorporates various protective devices, such as overvoltage relays, undervoltage relays, phase failure relays, and earth leakage protection. These elements constantly check the voltage, phase sequence, and

continuity of the system, and automatically de-energize the motor when abnormal conditions occur.

Also, visual signals and alarms have been added to offer real-time status updates to increase fault awareness and improve troubleshooting efficiency. The proposed system can also be utilized as a high-tech training platform, where users can simulate and analyze actual industrial fault conditions, including single phasing, voltage imbalance, and overload. This practical methodology helps users acquire practical troubleshooting abilities with real industrial parts, including circuit breakers, contactors, relays, and control circuits.

In order to improve system analysis, data analytics were conducted in Python (Jupyter Notebook), where numerical data and system behavior under various fault conditions were assessed. This allows better understanding of fault patterns and facilitates real-time fault detection.



II. ADVANCED SAFETY, MONITORING, AND TRAINING SYSTEMS FOR THREE-PHASE INDUCTION MOTORS

The advanced safety systems for three-phase induction motors are as follows:

A. Virtual Reality-Based Condition Monitoring and Maintenance Training

The incorporation of technologies consisting of virtual reality in training has increased in recent years owing to

the splendid clinical and technological advances in this field. In truth, a digital truth application designed for schooling functions offers a singular technique that enables the training venture in assessment to standard training methods. Engineering is no exception, as numerous packages require laboratories and specialized systems that are not available to all instructional establishments. Figure 1 shows the flow of the current safety systems.

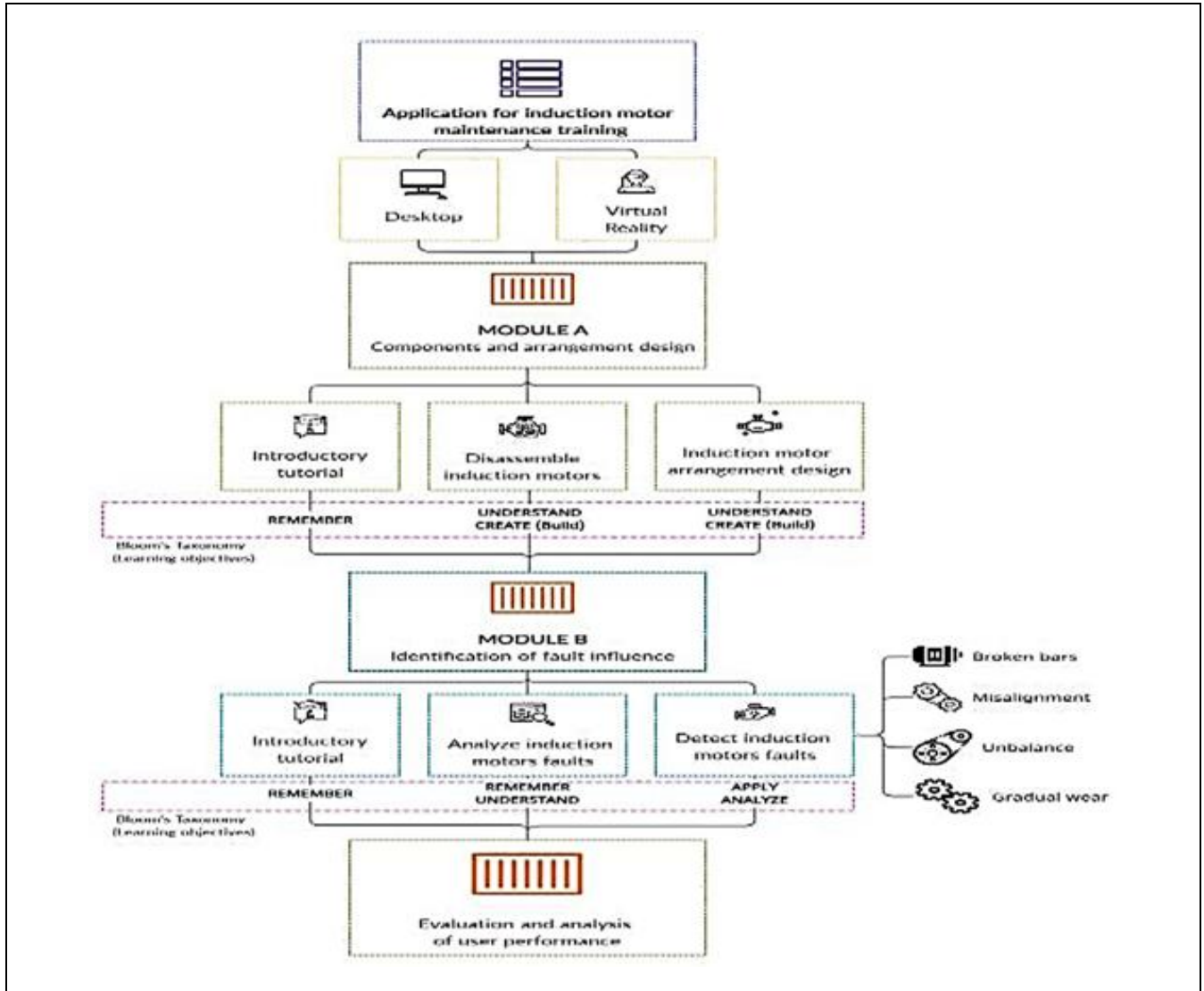


Figure 1: Condition Flow of Induction Motors [1]

B. Performance of A Programmable Logic Controller Based Electrical Motor Trainer Kit

A Programmable Logic Controller (PLC)-Based Electrical Motor Trainer Kit was developed to examine the performance of the developed trainer kit for application in Electrical Engineering.

C. Acoustic Based Fault Diagnosis of Three Phase Induction Motor

Acoustic-based fault prognosis techniques were applied to three-phase induction motors. Four actual states/operating conditions of the 3-Phase induction motor were analyzed: (1) healthy 3 phase induction motor, (2) 3 Phase induction

motor with two damaged rotor bars, and (3) three phase induction motor with a defective ring of the squirrel cage. Figure 2 shows the acoustic-based diagnosis system.

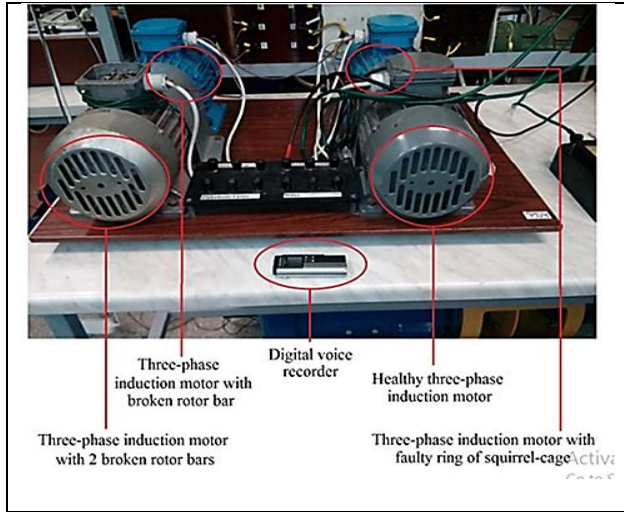


Figure 2: Fault Diagnosis System

D. Development and Acceptability of An Industrial Motor Control System Trainer

The Industrial Motor Control device/System (IMCS) trainer is an instructional equipment for understanding applied motor control systems and basic industrial/commercial automation. It assists electrical engineers, electrical technologists, and industrial personnel in enhancing their skills and knowledge.

E. Programmable Industrial Motor Control Trainer

The Programmable Motor uses as an academic tool that might help improve the coaching techniques of instructors. This device might be used for training to provide exceptional training, particularly in the area of electrical engineering and electric generation. This prompted the researcher to collect this device as a good way to deal with the inadequacy of the learning of the students using percent inside the automation field.

III. PROBLEM STATEMENT

The System Faces Several Challenges:

- Motor protection is a widespread requirement in both commercial and domestic settings. Insufficient renovation, faulty setup, and lack of sufficient protection measures can result in diverse dangers, including electric shocks, overheating, fires, mechanical injuries, and gadget failure.
- It is essential to ensure the powerful implementation of protection protocols, impart proper training to people coping with those motors, and maintain the automobiles efficiently to lessen the hazard of injuries and ensure the safety of all personnel concerned.

IV. LITERATURE REVIEW

This study presents a real-time monitoring and protection system for three-phase induction motors under fault conditions. It focuses on detecting operational abnormalities, such as voltage variations and system faults, during motor operation. The main contributions are real-time fault observation and immediate protective response,

which improve motor safety and reliability in industrial environments [1]. This study focuses on single-phasing faults, which occur when one phase of a three-phase supply is lost. The system detects this condition and disconnects the motor to prevent overheating and damage to the winding. It emphasizes the basic protective mechanisms for phase failure prevention in induction motors [2]. This study proposes a machine-learning-based approach for fault detection and predictive maintenance in induction motors. It uses electrical signal data (such as voltage and current) to train models for accurate fault classification. The innovative aspect lies in the shift from traditional relay-based protection to data-driven intelligent diagnosis. This enables early fault prediction, improves accuracy, and supports the development of smart industrial monitoring systems [3]. The System for overvoltage, undervoltage, and unbalanced conditions requires voltage monitoring and protection [4]. Undervoltage and overvoltage are quality issues that can arise from various causes [5]. The consequences of both undervoltage and overvoltage can be serious, leading to insulation failure in the case of undervoltage and overheating and burning of motor coils in the event of overvoltage [6]. To guarantee that trainees receive high-quality training in an atmosphere akin to an industrial setting, instructional materials are used in education and training, particularly in the Industrial Motor Control System [7]. The main goal of this study was to create and assess an Industrial Motor Control System (IMCS) trainer's suitability for use as a teaching tool for Electrical Engineering [8]. The developed learning materials on electrical motor control were used as a learning aid for courses on electrical power installation [9]. The Industry Motor Control Trainer provides a safety system to perform the experiment using power schemes to manage [10] creation of a Prototype Electrical Installation and Maintenance Training Device. A descriptive analysis was performed using instructors teaching electrical technology courses [11]. This scheme provides overvoltage and undervoltage protection for electrical equipment and trips the relay in response to supply changes [12]. This study presents a novel approach to life prediction for evaluating and analyzing the reliability of railway safety relays [13]. During the life tests of railway safety relays the goal of this project is to trip the relay in response to supply voltage variations in order to safeguard electrical equipment in homes and businesses against overvoltage and undervoltage. Electronic equipment is highly susceptible to voltage fluctuations, and when these fluctuations occur, the equipment is more likely to sustain damage. To safeguard the equipment under such conditions, an additional protection system is required [14]. The main objective is to protect the load during low-voltage and excessive-current conditions. The creation, organization, and assessment of a motor control trainer were the main goals of this research scheme to improve the effectiveness of the proposed system [15]. The study describes issues with a wide range of industrial applications and evaluates the current techniques for protecting medium-voltage circuits from excess load current [16]. The release of an enhanced technique for the detection of phase failure issues in polyphase induction

machines was presented at the Third International Conference on Electrical Engineering [17].

V. REMARKS

A 3-phase motor safety system that safeguards against overvoltage, undervoltage, overloading, and phase failure is critical for commercial programs to make certain the secure and efficient operation of electrical cars. Here's an overview of the components and standards that may be included into any such gadget: Voltage tracking constantly measure the voltage furnished to the motor. Overvoltage protection use overvoltage relays to detect and reply to voltage spikes above the appropriate range. Those relays can cause movements like disconnecting the motor or alerting operators. Undervoltage protection use undervoltage relays to come across voltage drops under the proper range. Those relays can provoke corrective movements, along with shutting down the motor or notifying renovation personnel. Overload safety comprise overload protection devices, which include thermal overload relays or digital overload video display units, to screen the motor's current consumption. If the present day exceeds safe tiers for an extended duration, these devices can trigger motor shutdown or shows phase failure protection which enforce phase failure relays to come across the lack of one or extra levels in the 3-phase strength deliver. Phase failure safety guarantees that the motor does not run below such situations, stopping harm and unsafe operation. Indication structures alarm systems that provide instantaneous audible and visible alerts to operators and upkeep personnel when any of the protection relay are precipitated. Automated Motor shut down the protection device to mechanically shut down the motor if any of the crucial parameters (overvoltage, undervoltage, overcurrent, or phase failure) are detected. That is a protection function to prevent motor harm and injuries.

VI. MATERIAL AND METHOD

In the design and implementation of the three-phase safety motor trainer, a protection relay was used. This system utilizes an undervoltage relay that detects when the electrical current dips below a set value. An undervoltage relay detects when the voltage drops below the preset minimum. When it does, it trips the breaker and saves the motor on undervoltage, opening the circuit and shutting down the motor connected to the circuit. The second type is the overvoltage protection relay, which detects when the current voltage exceeds a preset value. If the voltage is too high, the relay triggers the breaker. The motor was shut down. The overvoltage relays are used to prevent motor damage. In this task section, Failure Relay is a Phase voltage-balance monitoring tool designed for use with magnetic contactors to routinely prevent three-section motors from working or trying to start up under open phase conditions, thereby eliminating burnouts and consequent downtime regularly incurred by section failure. We use Earth Leakage circuit breakers to hit upon the leakage currents that are produced owing to circuit connection faults or other factors and are leaked to the earth, causing excessive shocks and deadly consequences for humans. We use overload contemporary breakers if the motor has

an overload, and its overload motor is turned into shutdown.

A. The Formula for Power of 3 Phase

$$P = \sqrt{3} \times V \times I \times PF \quad (1)$$

Where:

V=Voltage,

I= Current,

PF=Power Factor.

B. Calculations for Three Phase Motor HP Formula

$$P = \frac{\sqrt{3} \times V \times I \times \eta \times PF}{746} \quad (2)$$

Where:

V= voltage,

%EFF= Present Efficiency of Motor,

Pf= Power Factor,

I= Amperes.

C. Calculations Three Phase Kilowatts (kW) Formula

$$KW = \frac{\sqrt{3} \times V \times I \times PF}{1000} \quad (3)$$

Where:

V = Voltage,

PF = power Factor of Motor,

I = Ampere.

The Figure 3 and Figure 4 shows the MATLAB output for the designed system. In this work, MATLAB and Simulink were used to model, simulate, and analyze the proposed smart industrial protection system for three-phase equipment.

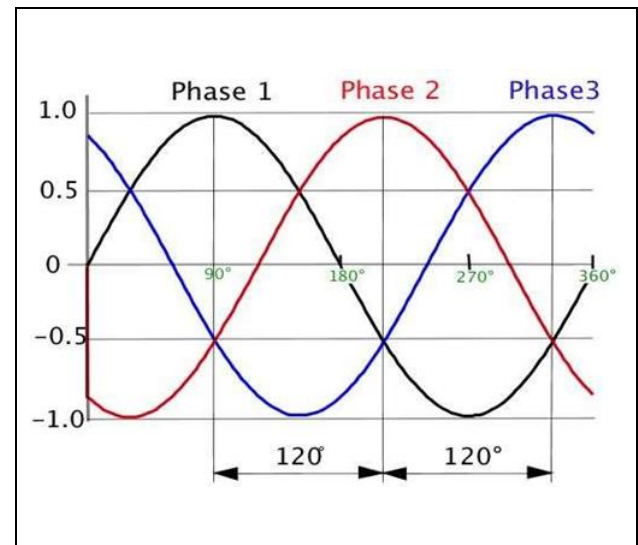


Figure 3: Three-Phase Voltage Waveforms Generated in MATLAB Simulation

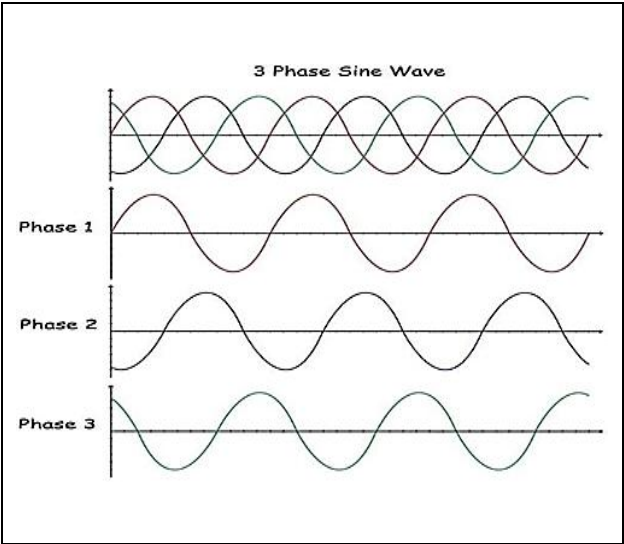


Figure 4: Three-Phase Sinusoidal Waveforms of the Proposed System

D. Flow Chart

The Figure 5 shows the process flow for the designed system.

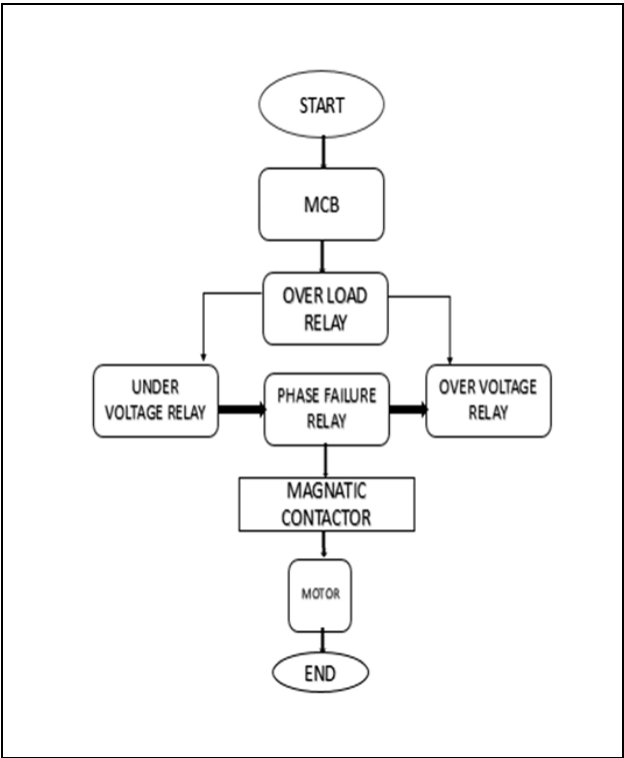


Figure 5: System Flow

E. Schematic Diagram

Figures 6, 7, and 8 show schematic diagrams of the proposed system. Schematic diagrams were designed using the Electrical Control Techniques Simulator (EKTS) software.

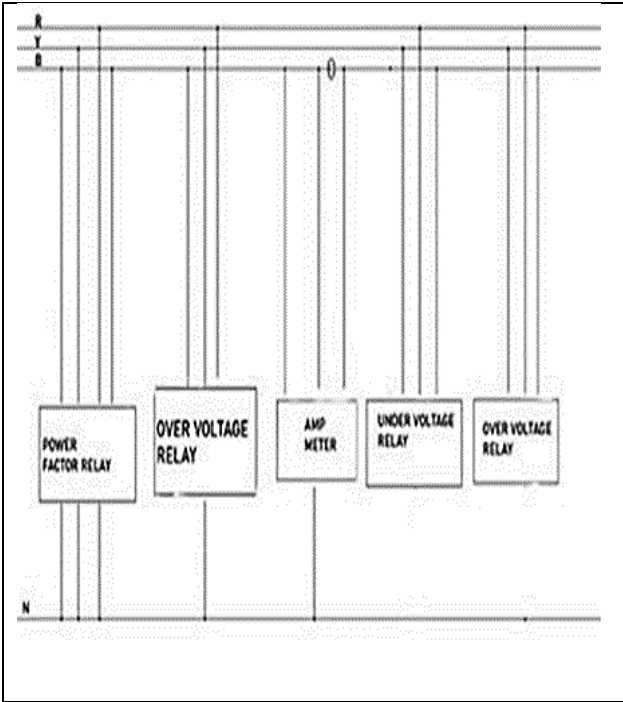


Figure 6: Measuring Instruments

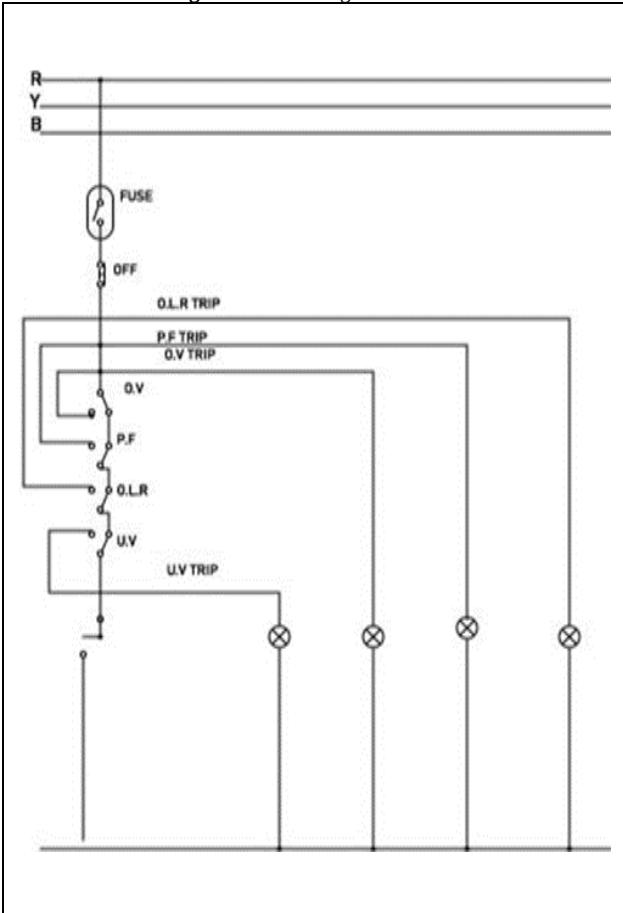


Figure 7: System Power Diagram



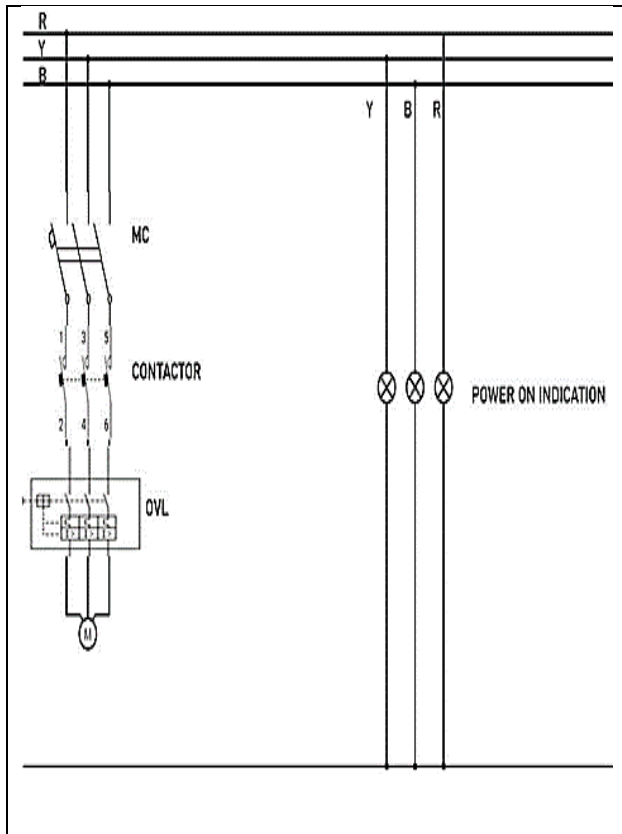


Figure 8: Overall System Configuration

F. Hardware Implementation

a) Phase Induction Motor:

A three-phase induction motor is an electromechanical strength conversion tool which converts 3-phase input electrical power into an output mechanical strength. A three-phase induction motor is composed of a stator and rotor.

b) Phase Sequence/Failure Module

Phase Sequence Monitoring of the relay module continuously monitors the sequence of the three-phase voltages in the electrical system. This ensures that the correct sequence of phase voltages (usually ABC or CBA) is maintained. If a phase sequence fault occurs, the relay module will detect it and activate an alarm or trip the circuit to prevent damage to the equipment. The SKAD 04 relay module is typically used in various applications where voltage stability is critical, such as electrical panels, industrial machinery, and power distribution systems. It operates by monitoring the three phases of the power supply and comparing their voltages. If the module detects a phase sequence reversal, it immediately cuts off the power supply to the equipment. This is important because phase-sequence reversal can cause serious damage to equipment and pose safety hazards. The SKAD 04 phase sequence/failure module is reliable and easy to install, making it an essential component of any electrical system that requires protection against phase sequence reversal and failure.



Figure 9: Phase Sequence Module

c) CT (Current Transformer) WINTOP MSQ 30

The current transformer for using ampere Meter sensing the ampere the line and read the ampere.

d) Over Voltage Relay GKT-03

Module is designed to protect electrical devices and systems from caused by voltage deviations. It works by monitoring the input voltage and triggering a response when the voltage exceeds or falls below the threshold. When the input voltage exceeds the overvoltage threshold, the relay module activates the connected protective device, which is a circuit breaker or contractor, to disconnect the power supply and prevent further damage.

e) Magnetic Contactor and Over Load

A three-phase magnetic contactor is used in motors to control the power supply to the motor. It is an electromagnetically operated switch that can handle high voltage and current levels. The contactor has three sets of contacts, one for each phase of the power supply of the motor. When the contactor is energized, the common point shifts to the normally open point. If the contactor energizes, the supply is off, and there is no point now. The normally closed contactor is used for high-voltage and high-voltage equipment operation.



Figure 10: Magnetic Contactor and Over Load

f) MCB Breaker

A three-phase Miniature Circuit Breaker (MCB) is a tool used to shield electrical circuits from overcurrent, brief circuits, and other electrical faults. It is designed to interrupt the flow of strength in the occasion of a fault to save you damage to the circuit and electrical gadget.



Figure 11: MCB Breaker

g) Earth Leakage Circuit Breaker

The ELCB works by constantly monitoring the contemporary flowing between the stay and impartial wires of the electrical circuit. If there is an imbalance between the two wires, including when a person accidentally comes into contact with an electrically charged element, the ELCB quickly breaks the circuit, disconnecting the power supply and stopping the electric shock.



Figure 12: Earth Leakage Circuit Breaker

h) Under Voltage Relay GKT 03-F

When the input voltage is less than the undervoltage threshold, the relay module activates the connected protective device, such as a circuit breaker or contractor, to disconnect the power supply and prevent further damage. Similarly, when the input voltage falls below the under voltage threshold, the relay module activates the protective device to isolate the system and protect the motor.

VII. RESULT AND DISCUSSION

The developed smart industrial protection system for three-phase equipment was successfully implemented and evaluated using both hardware setup and simulation in MATLAB / Simulink. The results demonstrate that the system effectively detects and responds to critical electrical faults, including overvoltage, undervoltage, phase failure, and voltage imbalance conditions. During testing, the protection relays operated accurately at predefined threshold limits, ensuring immediate disconnection of the motor under abnormal operating conditions. This rapid response significantly reduces the risk of overheating, insulation damage, and premature motor failure.

The integration of multiple protection mechanisms over/under voltage relay, phase sequence and failure relay, and earth leakage circuit breaker—provides a comprehensive safety framework. The system not only protects the motor but also enhances human safety by detecting leakage currents and disconnecting the supply to

prevent electric shock hazards. Experimental observations confirm that the voltage monitoring relay effectively identifies phase asymmetry and imbalance, ensuring stable and reliable motor operation.

In addition to protection performance, the developed trainer serves as an advanced educational platform. It enables students and industry trainees to simulate real-world fault conditions and perform hands-on troubleshooting using actual industrial components such as contactors, relays, and circuit breakers. This significantly improves practical skills, fault diagnosis capability, and understanding of motor control systems.

Furthermore, data collected from system operation were analyzed to observe fault patterns and system behavior under different conditions. The results highlight the potential for integrating data analytics and intelligent algorithms to enhance fault prediction and decision-making. Compared to conventional protection systems, the proposed approach offers improved reliability, real-time fault detection, and scalability toward future AI based smart industrial protection systems.

Overall, the proposed system demonstrates strong performance in ensuring equipment safety, operational reliability, and human protection, while also serving as an effective training and research platform for modern industrial applications.

a) Constraints

- Limited financial resources may restrict the acquisition of advanced equipment, technology required for effective system implementation.
- Cost-effective solutions must be adopted while ensuring system reliability, safety, and training efficiency.
- Motor defects and component failures can impact system performance and require continuous Monitoring.

b) Data Analytics

Data analytics were performed using Python in a Jupyter Notebook environment to support real-time fault detection in the proposed smart industrial protection system for three-phase equipment.

Numerical data obtained from voltage, current, and fault conditions, along with captured waveform images, were used for analysis. The primary objective of this analytics was to preprocess and evaluate system behavior under normal and faulty operating conditions, including overvoltage, under voltage, phase imbalance, and phase failure. The Figure 13 shows the data analytics interface of the designed system.



```

In [ ]: # Import required libraries
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt

# Generate time axis
t = np.linspace(0, 1, 1000)

# Generate three-phase voltages (normal condition)
Va = 230 * np.sin(2 * np.pi * 50 * t)
Vb = 230 * np.sin(2 * np.pi * 50 * t - 2*np.pi/3)
Vc = 230 * np.sin(2 * np.pi * 50 * t + 2*np.pi/3)

# Introduce faults (example: undervoltage & phase failure)
Va_fault = Va.copy()
Vb_fault = Vb.copy()
Vc_fault = Vc.copy()

# Undervoltage condition
Va_fault[400:700] = Va_fault[400:700] * 0.5

# Phase failure condition
Vc_fault[700:900] = 0

# Create DataFrame
data = pd.DataFrame({
    'Time': t,
    'Va': Va_fault,
    'Vb': Vb_fault,
    'Vc': Vc_fault
})

# Fault detection thresholds

```

Figure 13: Data Analytics

c) User Interface

The Figure 14 shows the designed system.



Figure 14: Designed System

VIII. CONCLUSION

A smart industrial protection system with real-time fault detection and data analytics for three-phase equipment was successfully designed and implemented. Incorporating critical electrical fault protection, such as overvoltage, undervoltage, single phase, phase reversal, overheating, voltage imbalance and earth leakage protection, the developed system effectively addressed the problems that are common to reduce the efficiency, reliability and operational life of three phase induction motors.

The main result of this study is that the combination of protection methods (voltage relays, phase monitoring relays, overload protection and earth leakage circuit breakers) significantly increased the reliability and safety of the motor operation under various fault conditions. The system was demonstrated in the laboratory to be able to detect abnormal operating conditions quickly and automatically turn off the motor, thus reducing the damage of the equipment and the risk of unexpected industrial downtime.

The other major contribution of the proposed work is that the data analytics for monitoring and analysis of voltage and current data is provided, which is based on Python programming language and Jupyter Notebook. The analytics framework improved the ability of the protection system to detect faults more accurately, provided fault visualization and backed up faster decision-making in the operation. The advantages these features offer for industries are in preventive maintenance, cost of maintenance and overall system performance.

Moreover, the developed prototype has also been proven as a good learning and training tool, to simulate real industrial fault scenarios and enhance the understanding of motor protection techniques and industrial safety procedures. It is a practical implementation that is used to develop skills in electrical protection systems and industrial automation.

Finally, the proposed smart protection system is an efficient, reliable and scalable solution for protecting and monitoring industrial motors. The study has practical implications, such as better equipment safety, better operational continuity, lower losses caused by faults, and assistance in implementing predictive maintenance solutions. The proposed approach also lays a solid foundation for future integration with the Internet of Things (IoT) technologies and artificial intelligence techniques for intelligent fault prediction and smart industrial automation in the context of Industry 4.0.

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protection system. Their contributions greatly assisted in improving the quality and applicability of this work.

Authors Contributions

Syed Saad Ali conceived the study, developed the research methodology, performed data analysis, and prepared the original manuscript draft along with correspondence. Shujaat Ali supervised the research, contributed to the conceptual framework, and critically reviewed and edited the manuscript. Aamir Khan and Afzaal Faridi assisted in the design and implementation of the proposed smart industrial protection system, conducted experimental validation, and contributed to result interpretation. Sajid Ali supported data processing, software implementation, and visualization of results. Shoaib Ali contributed to project coordination, documentation, and manuscript review. All authors participated in discussing the results, contributed to the final version of the manuscript, and approved it for publication.

Conflict of Interest

The author declares no conflicts of interest.

Data Availability Statement

All the data and materials provided in the manuscript.

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