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Automated Control and Real-Time Monitoring of Agricultural Water Pumping Systems Using IoT

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Abstract

The agricultural sector is rapidly embracing digital transformation through the Internet of Things (IoT), enabling intelligent solutions for remote control and monitoring. This project presents the design and implementation of an automated system for real-time monitoring and control of agricultural water pumping systems using IoT technology. The system is built around an Arduino microcontroller that reads data from voltage and current sensors to assess operating conditions and detect faults.

The measured data is transmitted to the user via a SIM800L GSM module, allowing remote access and control. A mobile application was developed using the Blynk platform to provide an intuitive user interface, including pump status, timer-based operation, and real-time feedback notifications. The system offers advanced protection for a three-phase induction motor pump against common electrical faults such as overvoltage, undervoltage, overload, single phasing, phase imbalance, and reverse rotation. Laboratory tests confirmed the system's effectiveness in providing reliable protection, automation, and remote monitoring, making it suitable for agricultural applications in remote or resource-limited areas.

Keywords: Internet of Things (IoT), voltage and current sensors, SIM800L, advanced protection for a three-phase induction motor pump

الملخص:

يشهد القطاع الزراعي تحولًا رقميًا متسارعًا بفضل تقنيات إنترنت الأشياء (IoT)، التي توفر حلولًا ذكية للتحكم والمراقبة عن بُعد. يهدف هذا المشروع إلى تطوير نظام آلي لمراقبة وتشغيل أنظمة ضخ مياه الري في الوقت الحقيقي باستخدام تقنيات إنترنت الأشياء. يعتمد النظام على لوحة Arduino لقراءة البيانات من مستشعرات الجهد والتيار، وتحليلها للكشف عن حالات التشغيل غير الطبيعية.

يتم إرسال البيانات إلى المستخدم عبر وحدة GSM من نوع SIM800L، كما تم تطوير تطبيق ذكي باستخدام منصة Blynk لعرض حالة النظام والتحكم في تشغيل المضخة عن بُعد. يوفر النظام حماية متقدمة للمضخة الكهربائية (ثلاثية الأطوار) من الأعطال الشائعة مثل انخفاض أو ارتفاع الجهد، الحمل الزائد، الفقد الأحادي للطور، اختلال التوازن، والدوران العكسي. أظهرت نتائج الاختبار أن النظام يتمتع بدرجة عالية من الكفاءة في الحماية والتشغيل الآلي، مما يجعله مناسبًا للتطبيقات الزراعية في البيئات البعيدة أو قليلة الموارد

الكلمات المفتاحية: إنترنت الأشياء، مستشعرات الجهد والتيار، SIM800L, حماية متقدمة للمضخة الكهربائية.

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LIST OF ABBREVIATIONS

$\Delta\Theta_{S,R}$	The temperature rise of the stator or the rotor (Cº)
$P_{S,R}$	The weighting factor for the short time constant of the stator or the rotor (winding conductors)
I	The measured phase current, typically the highest phase current
I_N	The rated current of the protected machine
$\Delta\theta_{NS,NR}$	The temperature rise (ºC) with the rated current under sustained load, the stator or the rotor
$\tau_{1S,1R}$	The short heating / cooling time constant of the stator or the rotor (winding conductors)
$\tau_{2S,2R}$	The long heating / cooling time constant of the stator or the rotor (stator or rotor body)
t	The time
Θ_A	The thermal level describing motor parts having fast heat absorption, that is, "hot spot" behavior
Θ_B	The thermal background history level describing motor parts having slow heat absorption, for example stator body
I	The measured phase current
τ	The selected time constant
p	The selected weighting factor for the thermal history
Θ_p	The calculated thermal level when the current goes below the rated current setting, for example after a startup
NEMA	National Electrical Manufacturer Association
IEC	International Electrotechnical Commission
VUF	voltage unbalance factor
LVUR	Line voltage unbalance rate
V_{avg}	Average line voltage magnitude
CVUF	The complex voltage unbalance factor
V_1	Positive Sequence Voltage Phasor
V_2	Negative Sequence Voltage Phasor.
OVU	Overvoltage Unbalance
UVU	Under-Voltage Unbalance
AU	Angle Unbalance

BOV	Balanced Over Voltage
BUB	Balanced Under Voltage
RVU	Rated Voltage Unbalance
L	Inductance of The Line
δ	The Phase Angle Difference Between Voltages
$V_{vv,avg}$	Average of the Instantaneous Product
AC	Alternating Current
ADC	Analog to Digital Converter
DC	Direct Current
GSM	Global System for Mobile Communications
IDE	Integrated Development Environment
PCB	Printed Circuit Board
SMS	Short Message Service
V_{CC}	Voltage Common Collector
V_{Ar}	Arduino 5V power.
I_{rms}	input current range.
N_{Turns}	turns ratio.

General Introduction

Nowadays, Agriculture plays one of the fundamental pillars of Algeria's national economy, serving a vital role in achieving food security, especially in the context of the arid and semi-arid climate. Since water is a key element in agricultural activity, irrigation systems represent the backbone upon which sustainable agriculture depends. However, these systems - particularly in remote areas- often suffer from operational and maintenance issues due to reliance on traditional methods, which leads to decreased efficiency and increased resource consumption.

In this context, integrating Internet of Things (IoT) technologies with water pumping systems not only improves operational efficiency but also enables real-time remote monitoring, reducing the need for manual intervention and allowing for timely and informed decision-making based on accurate data.

This thesis aims to design and implement a smart system for real-time control and monitoring of agricultural water pumps, using the Arduino platform and IoT technologies. The system relies on sensors to measure voltage and current, along with wireless communication modules, to automatically detect faults such as phase reversal, overload, voltage imbalance, or dry running. It also enables the user to monitor and control the pump remotely via a mobile application or SMS messages.

Chapter One presents the general framework of the agricultural sector, the importance of irrigation and pumps, and the role of IoT technologies in enhancing and modernizing this field. Chapter Two explores the electrical faults that affect electric motors and discusses the necessary protection methods to ensure their safe and efficient operation. Chapter Three focuses on the practical design of a smart electronic board that handles protection, monitoring, and control, integrated with a mobile application to provide a user-friendly and efficient interface for farmers and operators.

Through this work, we aim to deliver an effective and integrated technical solution that contributes to improving the efficiency of water resource utilization, facilitating irrigation management, and minimizing costly failures.

Chapter 1

Overview of Agricultural Irrigation Systems and the Role of IoT in Pumping Efficiency

1.1 Introduction

Agriculture is one of the fundamental pillars of Algeria's national economy, especially with regard to food security and arid climatic conditions. Efficient management of irrigation systems is therefore increasingly important to ensure the sustainability of water resources and increase the efficiency of production. This chapter covers the importance of agriculture in Algeria, the roles of irrigation and water pumps, and increasingly the role of including Internet of Things (IoT) technologies for real-time monitoring and improved operation of these systems.

1.2 The Importance of Agriculture in Algeria

Agriculture is the second-largest economic sector in Algeria after oil and gas, contributing 12.4% to the Gross Domestic Product (GDP), with an estimated value of around 25 billion USD annually. The agricultural sector also employs approximately 2.6 million people, representing over 24% of the national workforce. Furthermore, the agricultural sector covers about 73% of the country's food needs, making it a fundamental pillar for achieving food security and reducing reliance on imports [1].

El Oued is considered the leading Saharan province in agricultural production, to the extent that it has ranked among the top nationally in the production of various types of crops, particularly early-season crops [2]. Notably, in recent years, El Oued has held the first place among potato-producing provinces at the national level, contributing more than 40% of the national potato production, which represents 50% of the province's local plant-based agricultural output [3].

1.3 Importance of Irrigation

Irrigation plays a vital role in enhancing agricultural productivity and ensuring food security, especially in arid regions. It helps overcome the uncertainties of rainfall, increases cultivated areas, and supports the use of high-yield crop varieties and fertilizers, thus stabilizing and intensifying production. To meet these goals, various irrigation techniques are used, including surface, sprinkler, and micro-irrigation. While choosing or switching between methods can be complex, water-saving benefits generally increase with more advanced systems. However, the success of any technique depends on local conditions, management practices, and careful evaluation of the existing system.

Figure 1.1: Irrigation by basins

Figure 1.2: Sprinkler irrigation

Figure 1.3: Central Pivot Irrigation System

1.4 The Role of Water Pumps in Agriculture

Water pumps play a pivotal role in modern agriculture by ensuring the efficient distribution of water across farmlands, thereby enhancing productivity and supporting sustainable farming practices. Their importance cannot be overstated, especially in regions where water availability is inconsistent or where large-scale irrigation is necessary to maintain crop health.

Water pumps are primarily used to extract water from various sources, such as rivers, lakes, wells, and underground reservoirs, and deliver it to agricultural fields. They ensure that crops receive the right amount of water at the right time, which is crucial for their growth and yield. Additionally, water pumps help in maintaining soil moisture levels, preventing soil degradation and ensuring that nutrients are adequately distributed in the soil. By facilitating effective irrigation, water pumps mitigate the risks associated with droughts and irregular rainfall patterns.

1.5 Components of Irrigation Systems

1.5.1 The Pumps

In agricultural water systems, pumps are essential for efficiently transporting and distributing water to support various agricultural activities. They convert mechanical energy into hydraulic energy, typically powered by electrical sources, although alternative power options such as diesel engines are also used. The primary functions of these pumps include:

- Water conveyance: Transporting water from sources such as wells, rivers, or lakes to storage tanks or directly to fields for irrigation.
- Water distribution: Distributing water within irrigation systems to ensure even coverage across agricultural fields.

Several types of pumps are commonly used in agricultural irrigation systems, each suited to specific applications:

1.5.1.1 Centrifugal Pump

Centrifugal pumps utilize a rotating impeller to impart kinetic energy to the water, converting it into pressure energy as the water exits the pump

These pumps are widely used for moving water from sources like reservoirs, lakes, streams, and shallow wells. They are also employed as booster pumps in irrigation pipelines. Centrifugal pumps are suitable for systems requiring the movement of large volumes of water at relatively low pressures [4].

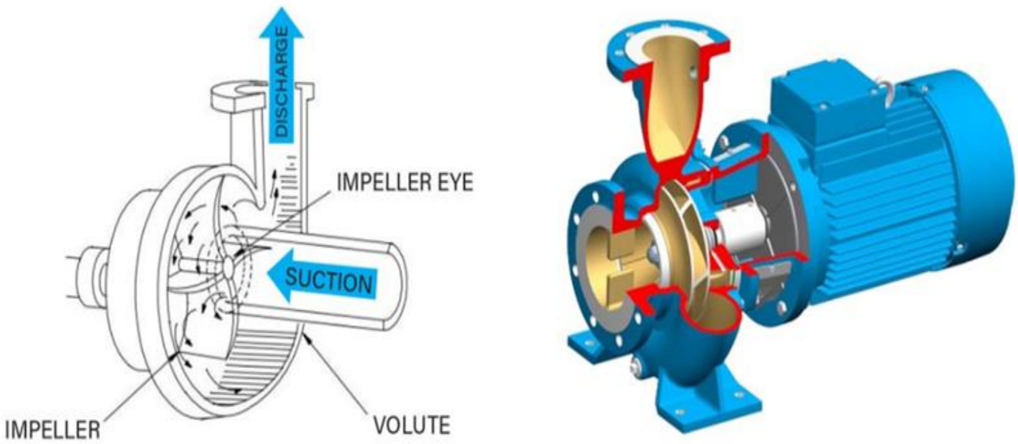


Figure 1.4: Centrifugal pumps.

1.5.1.2 Submersible pumps

Submersible pumps are designed to operate while fully submerged in water. They push water to the surface by converting rotational energy into kinetic energy, which is then transformed into pressure energy

Ideal for deep well applications, submersible pumps are commonly used to extract groundwater for irrigation purposes. Their design minimizes the risk of cavitation and makes them efficient for pumping water from significant depths [4].

Figure 1.5: Submersible pumps**.**

1.5.2 Induction Motors

Induction motors are the top pick for agricultural water pumps because they offer high efficiency, sturdy construction, and are adaptable to varying loads, all while requiring minimal maintenance. Their durability in moisture-heavy environments and compatibility with variable speed drives ensure they perform reliably even under tough conditions.

Figure 1.6: Induction motor.

1.5.3 Control and protection system

1.5.3.1 Importance of Control and Protection

Providing electrical protection for irrigation pumps is an essential process to ensure efficient operation and avoid costly breakdowns or accidents. Whether they are operating in wells or surface water supplies, proper electrical protection system installation is critical. Inadequately protected pumps may suffer irreversible damage due to overvoltage, mechanical obstructions, or dry running (operating without water).

Exposure of unprotected irrigation pumps, whether submerged within a well or running at surface level, to various risks likely to cause significant failures include:

Overvoltage capable of accelerating damage to internal components.

Dry running that can lead to dangerous overheating.

Blockages or improper sizing that can lead to **electrical overload**.

These conditions not only threaten the pump with damage but also cause more hazardous failures such as short circuits or fires, which jeopardize not only your safety but also your installation [5].

Basic knowledge of the risks of electromechanical systems, combined with the correct selection of protection devices such as circuit breakers, relays, and monitoring sensors, is crucial to ensuring system reliability and minimizing the risk of failures

1.5.3.2 Protection devices

Classic irrigation systems utilize advanced electrical components to ensure efficiency and precision in water application.

- ✓ **Thermal Magnetic Circuit Breaker**

The thermal-magnetic circuit breaker is a key component in electrical systems that is responsible for protecting them against overloads and short circuits, which is what "circuit breaker" means. Its main function is to interrupt the flow of electric current when an abnormal situation is detected in the circuit, which explains "circuit breaker how it works" [8].

This prevents possible damage to cables, electrical equipment and even prevents fire hazards.

It is recommended to use D-curve circuit breakers in industrial and agricultural applications, as they provide a fast response and high inrush current tolerance, ensuring reliable protection in demanding environments.

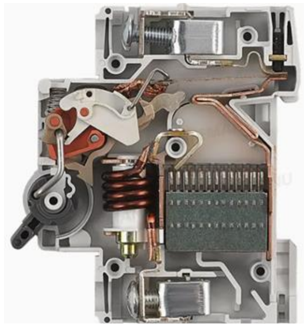


Figure 1.7: thermal magnetic circuit breaker.

✓ **Thermal Overload Relay**

Thermal overload relays are designed to provide electromechanical protection to motors against overloading from drawing excessive input currents from the main circuit. These electronic components can provide great protection against permanent electrical damages during electrical anomalies like phase failure and over voltages [9].

The thermal overload relay serves as a crucial protective device in electrical systems, primarily used to safeguard motors from overheating and potential damage due to excessive current. It operates based on the principle of thermal sensing, monitoring the heat generated by the motor during operation.

When the motor draws excessive current over an extended period, indicating a potential overload, the thermal overload relay responds by tripping and disconnecting the power supply to the motor. This prevents the motor from overheating, reducing the risk of damage and enhancing operational safety.

Figure 1.8: Thermal Overload Relay

✓ **Phase Sequence Relays**

Phase monitoring relays are protection relays that sense and react to three-phase system faults such as **phase loss**, **phase reversal**, **voltage imbalance**, **overvoltage**, and **undervoltage**. They are essential in motor-driven applications such as submersible and surface pumps, where these electrical faults will lead to overheating, mechanical stress, or even motor failure. These relays ensure dependable operation and equipment longevity by disconnecting the pump during unfavorable electrical conditions [10].

Figure 1.9: Phase Sequence Relays

✓ **Contactor:**

A contactor is an electromechanical switch used for controlling an electrical circuit. It differs from a relay in terms of its capacity to handle higher current and voltage levels.

Contactors are commonly used to remotely control power circuits, providing a safe and efficient means of starting and stopping motors, lighting systems, and other electrical loads [11].

Figure 1.10: Three Phase Contactor.

1.6 Challenges Associated with Monitoring and Operation of Pumping Systems

Traditional water pumping systems face numerous technical and operational challenges that negatively affect their efficiency, reliability, and operational cost. These challenges can be categorized into three main areas:

1.6.1 Efficiency

Many pumps operate outside their Best Efficiency Point (BEP), leading to reduced operational efficiency, increased wear, noise, and significant energy loss. To achieve optimal efficiency, it is essential to properly select pumps according to system characteristics and apply control technologies such as Variable Frequency Drives (VFDs), which allow for adjusting pump speed based on flow and pressure demands [12].

1.6.2 Energy Consumption

Pumps represent one of the largest energy consumers in industrial and agricultural applications. Inefficient operation leads to excessive energy waste and increased operational costs. To address this issue, the International Energy Agency recommends the use of high-efficiency motors and improvements in system design to achieve optimal performance with minimal energy consumption [13].

1.6.3 Maintenance Challenges

Maintenance remains a key challenge, as most traditional pumping systems rely on reactive maintenance, which involves fixing issues only after they occur, resulting in unexpected downtimes and higher costs. In contrast, predictive maintenance, which is based on data collected from monitoring equipment, enables early detection of faults and reduces system downtime [14].

In this context, Internet of Things (IoT) technologies have become essential tools for remote pump monitoring and real-time data analytics. Among the most critical components are voltage and current sensors, which monitor the electrical behavior of the pump. These sensors help detect issues such as voltage drops or overloads, allowing for early intervention. The collected data is transmitted to cloud platforms or control systems, enabling instantaneous decision-making that minimizes failure risks and improves overall performance [15].

1.7 The Internet of Things (IoT) in Agricultural Water Pumping

1.7.1 Internet of Things

In 1999, Kevin Ashton of Procter & Gamble tabled the term "Internet of Things" for the very first time. In simple words, the IoT is a network of objects that are embedded with sensors, software, and other related technologies mainly for connecting, exchanging, and transferring data with other devices and systems via the internet. These devices may range from simple household objects to complex business and industrial tools and technologies.

We can say that it is an ecosystem where humans, objects/devices, and the internet interact with each other, intersect with each other and gives birth to IoT as seen in figure 1.11 below [16].

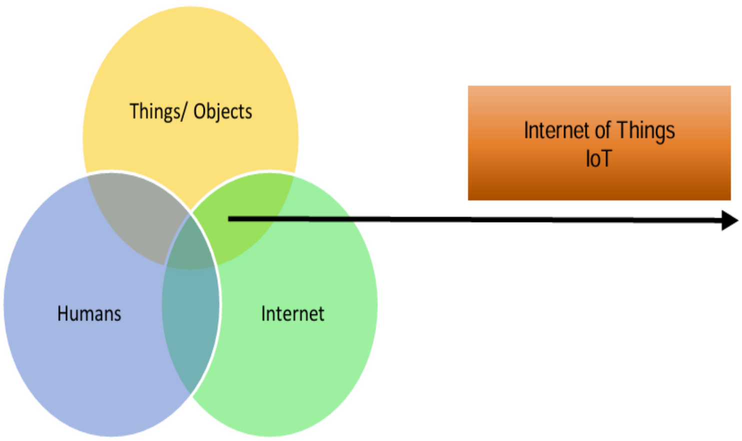


Figure 1.11: simple illustration of IoT.

1.7.2 IoT applications

The IoT provides a wide range of applications to enhance people's daily lives and activities. Figure 1.8 shows potential examples of IoT applications [17].

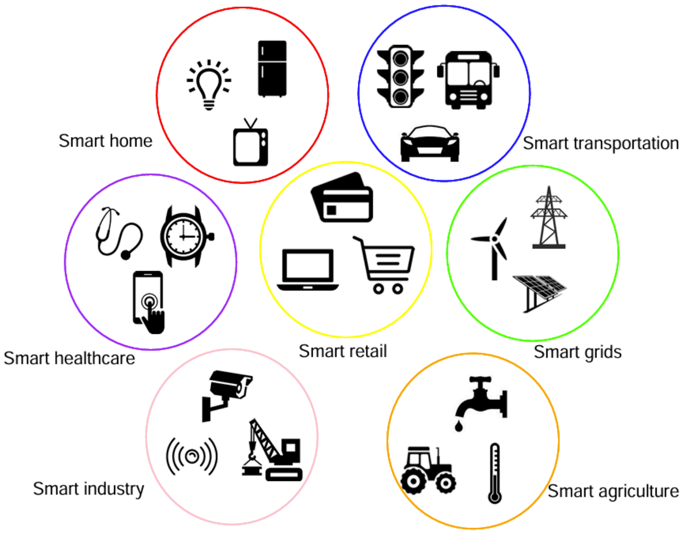


Figure 1.12: IoT applications.

Smart home encompasses a collection of smart devices (e.g., smart lock, baby monitor, fire detector) deployed at home and locally communicate over wireless channels. Home devices can be remotely accessed through a home gateway.

Smart healthcare enables collection, transmission and storage of patient's physiological information. For instance, patients heart rate can be collected by medical sensors and transmitted to hospital server for diagnosis and tracking purposes.

Smart industry known as industrial IoT (IIoT) uses machine-to-machine technology to automate the process of manufacturing with insignificant cant human intervention. The IIoT aims to better control the production process, data, and issues to provide efficient and reliable final products.

Smart agriculture allows remote control of temperature, humidity, irrigation, soil moisture and micro-climate conditions to provide high production/quality and prevent financial losses. In an intelligent farming system, sensors can be attached to animals to track livestock behaviors and health conditions.

1.7.3 Uses of IoT technologies for remote monitoring and control in the field of agricultural systems

The IoT has revolutionized agricultural systems by enabling remote monitoring and control of various critical parameters. Here are some notable applications [18]:

1.7.3.1 Soil and Environmental Monitoring

IoT sensors are used to monitor soil properties such as moisture, temperature, and pH, sending data directly to intelligent analysis systems to make precise decisions on irrigation and fertilization, improving resource efficiency and crop quality.

1.7.3.2 Smart Irrigation Systems

Smart irrigation systems rely on sensor data to automatically activate pumps and valves when needed, reducing water consumption and enhancing irrigation efficiency with minimal human intervention.

1.7.3.3 Precise Climate and Environmental Monitoring

Smart weather stations enable farmers to track climate variables such as temperature, humidity, and wind speed, assisting in better agricultural planning and mitigating climate-related risks.

1.7.3.4 Plant Health Monitoring and Early Disease Detection

IoT-connected cameras and optical sensors are used to monitor plant health and detect diseases early, allowing for swift intervention and reducing pesticide use and costs.

Figure 1.13: IoT technologies for monitoring in the field of agricultural

1.7.4 The Role of IoT in Monitoring and Controlling irrigation system

The IoT has revolutionized various sectors, and irrigation system applications are no exception. By connecting devices and systems, IoT enables real-time data collection, analysis, and automation. In the context of irrigation system, IoT plays a crucial role in enhancing monitoring and control processes.

Pumps are essential components in agricultural water pumping systems. Therefore, its efficiency and reliability are essential factors to ensure the smooth operation of the irrigation system.

1.7.5 Benefits of IoT in Monitoring irrigation system [19]

1.7.5.1 Real-time Monitoring

IoT enables real-time monitoring of pumps and valves, providing instant feedback on their status and performance. This allows for immediate corrective actions, reducing downtime and preventing damage.

By analyzing data trends, IoT systems can predict when maintenance is needed, preventing unexpected failures and extending the lifespan of pumps and valves. This predictive maintenance approach is more cost effective than traditional reactive maintenance.

1.7.5.2 Improved Efficiency and Performance

IoT systems optimize the operation of pumps and valves, improving their efficiency and performance. This leads to energy savings, reduced operational costs, and better overall productivity.

1.8 Conclusion

This chapter has highlighted the strategic importance of agriculture in Algeria, particularly under arid climatic conditions, and emphasized the central role of irrigation systems in ensuring food security and sustainable productivity. It detailed the structure and function of agricultural water pumping systems, focusing on the essential roles of pumps, induction motors, and control and protection devices. Furthermore, it examined the major operational challenges faced by traditional systems, including inefficiency, excessive energy consumption, and inadequate maintenance practices.

To overcome these issues, the IoT was introduced as a key enabler for modernizing irrigation systems. By leveraging real-time monitoring, data-driven control, and predictive maintenance, IoT enhances system reliability, performance, and resource efficiency.

This foundational understanding sets the stage for the next chapter, which will examine the most significant electrical and mechanical faults affecting the motor-pump system. It will also explore how effective protection mechanisms and smart technologies can prevent these faults, ensuring the durability and optimal performance of agricultural pumping systems.

Chapter 2

Electric Motor Protection in Pumping Systems

2.1 Introduction

Electric motors are exposed to many kinds of disturbances and stress. Part of the disturbances is due to imposed external conditions such as over- and undervoltage, unbalanced system voltages and supply interruptions. Other possible causes of external disturbances are dirt in the motor, cooling system and bearing failures or increase of ambient temperature and humidity. Stress factors due to abnormal use of the motor drive itself are frequent successive startups, stall and overload situations including mechanical stress. The above stress and disturbances deteriorate the winding insulation of the motor mechanically and by increased thermal ageing rate, which may eventually lead to an insulation failure.

The purpose of the motor protection is to limit the effects of the disturbances and stress factors to a safe level, for example, by limiting overvoltage's or by preventing too frequent startup attempts. If, however, a motor failure takes place, the purpose of the protection is to disconnect the motor from the supplying network in due time [20].

2.2 The Role of Electric Motors in Pumps

At the heart of nearly every industrial pump lies an electric motor, silently converting electrical energy into mechanical energy. This transformation is crucial as it's this mechanical energy that is utilized to drive the pump. However, the interaction between the electric motor and the pump is not just limited to energy transformation; it also influences the pump's operational characteristics.

Electric motors are intrinsically linked to the action of the pump, dictating crucial operational factors such as flow rate and pressure. The power output, rotational speed, and torque provided by the motor directly affect how effectively the pump operates. As such, the electric motor is a critical component that not only powers the pump but also determines its performance characteristics.

Let's explore how electric motors function within some of the common types of pumps [21]:

2.2.1 Centrifugal Pumps

In these pumps, the electric motor powers the impeller, a disc with curved blades. As the motor rotates the impeller, it generates centrifugal force, moving the fluid from the center of the pump to its periphery.

2.2.2 Positive Displacement Pumps

In a positive displacement pump, the electric motor powers a mechanism (like a gear, rotor, or piston) that traps a fixed volume of fluid and moves it to the discharge pipe. Here, the motor's speed and torque significantly influence the flow rate and pressure.

2.2.3 Submersible Pumps

For these pumps, the electric motor is encased in a waterproof housing and directly coupled to the pump body. It drives the pump impeller or mechanism, moving fluid from lower to higher elevations.

2.2.4 Diaphragm Pumps

In diaphragm pumps, the electric motor powers a reciprocating mechanism that moves the diaphragm, creating a suction effect that draws the fluid into the pump chamber on one stroke, and then pushing it out on the other stroke.

2.3 The Role of Motor Protection in Maintaining the Performance of Pumping Systems

Every year, more than 20% of electric motors installed burnout around the world. This is in spite of protection systems being provided. This proves inadequacy of selected protection systems. In most cases, the reasons for pumping system failure are other than the pumping system itself. These include improper selection of pump, improper handling of the system, and improper selection of protective devices. The protective device for the motor is the heart of the total system. Great care is needed while making an appropriate selection of the same, Incorrect selection of protective devices can lead to the notion that these are not fulfilling their intended functions [6].

2.4 Types of Required Protection

2.4.1 Thermal Behavior and Thermal Protection

2.4.1.1 Thermal Model

The thermal behavior of the stator and the rotor during startups and during constant overload situations differs significantly from each other. Due to this fact, the dynamics of the motor heating and cooling is typically modeled separately for the stator and for the rotor. Implementing the thermal overload protection in this way, it can be set to follow the thermal state of the motor optimally, and good and accurate protection against both short and long-time overload conditions can be accomplished, which allows the full use of the available capacity.

The protection operates according to the model that is the most critical one in the prevailing operating conditions. Thus, the thermal model for the stator and for the rotor can be written as [22]:

$$\Delta\Theta_S = (P_S.(I/I_N)^2.\Delta\theta_{NS}).\left(1 - e^{-t/\tau_{1S}}\right) + ((1 - P_S).(I/I_N)^2.\Delta\theta_{NS}).\left(1 - e^{-t/\tau_{2S}}\right) \quad (2.1)$$

$$\Delta\Theta_R = (P_R.(I/I_N)^2.\Delta\theta_{NR}).\left(1 - e^{-t/\tau_{1R}}\right) + ((1 - P_R).(I/I_N)^2.\Delta\theta_{NR}).\left(1 - e^{-t/\tau_{2R}}\right) \quad (2.2)$$

The estimated temperature of the stator and the rotor can then be obtained by adding the prevailing ambient temperature to the calculated temperature rises. For the ambient temperature, either a constant maximum value can be given as a setting value or it can be measured by the IED with the related functionality.

The model must also take into account the fact that a running motor heats up and cools down according to the same time constant but in a standstill the long time constant for cooling can be much longer than that for heating, depending on the cooling system. This is important especially in providing adequate protection against too frequent starting.

The values of $\tau_1, \tau_2, \Delta\theta_N, I_N$ and P are set according to the motor type in question. The time constants and weighting factors for the stator and the rotor can also be extracted from the thermal limit curve of the ma chine by assuming that the heating is proportional to the square of the load current. The value of the rated temperature rise depends on the insulation class of the machine, and it is obtained by subtracting the assumed ambient temperature from the highest allowed temperature.

Table 2.1 shows the temperature limits for insulation classes B, F and H.

Definition	Insulation Class		
	B	F	H
Highest "hot spot" temperature (C°)	130	155	180
Highest operating temperature (C°)	120	145	165
Highest operating temperature when short-time ambient temperature does not exceed 40 (C°)	80	105	125

With typical squirrel gage induction machines, the maximum temperature is according to class F, but the maximum temperature rise according to class B. The purpose of this is to obtain additional thermal margin, and to extend the lifetime of the insulation. Also, a typical squirrel gage rotor of an induction machine is not insulated, so the temperature rise can usually be higher than in the stator without increasing the risk of damage. However, a rotor temperature of 250 C° must not be exceeded.

However, adequate thermal modeling can also be accomplished by using a single-time-constant model but treating the normal loading and overload situations in a different way. In this kind of modeling, the thermal behavior has two different thermal characteristic curves; one describing short and long-time overloads, that is, modeling the motor "hot spot" behavior, and the other keeping track of the thermal background, that is, modeling the motor parts with a slower heat absorption, such as the stator body. Equations (2.3), (2.4) and (2.5) represent this kind of modeling. Equations (2.3)and (2.4) are valid when the measured motor current exceeds the rated current I_N [22]:

$$\Theta_A = \left(\frac{I}{1{,}05.I_N}\right)^2.\left(1-e^{-t/\tau}\right).100\% \tag{2.3}$$

$$\Theta_B = \left(\frac{I}{1{,}05.I_N}\right)^2.\left(1-e^{-t/\tau}\right).p\% \tag{2.4}$$

When an overload situation ends, that is, the measured current becomes lower than the rated current, the thermal level describing the "hot spot" behavior is taken down to the thermal background level in a relatively short period. This constitutes the thermal behavior modeling of the motor when the hot spot temperature will cool down due to the effect of the other parts of the motor, after which Equation (2.5) is valid.

$$\Theta_B = \left(\left(\frac{I}{1{,}05.I_N}\right)^2.p-\Theta\right)\left(1-e^{-t/\tau}\right)+\Theta_p\% \tag{2.5}$$

Figure 2.1 illustrates the behavior of the single-time-constant modeling in accordance with Equations (2.3), (2.4) and (2.5). A thermal level of 0% corresponds to the ambient temperature, and 100% the maximum allowed temperature.

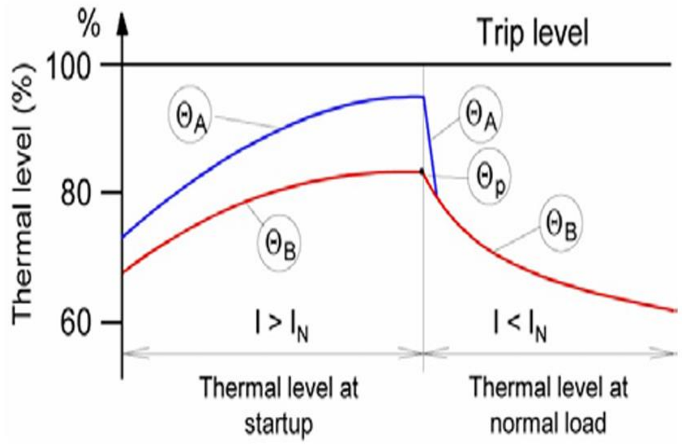


Figure 2.1: The behavior of the single-time-constant thermal model [22].

The purpose of the single-time-constant modeling is not to try to model the protected motor as accurately as possible. Typically, its accuracy is sufficient for supervising the thermal state of the motor and in this way allowing the normal use of the motor drive for which it is designed to with a suitable margin. The parameters of the model are then selected based on this assumption, and they are typically easily derived from the basic data of the motor.

2.4.1.2 Frequent Startup Supervision

To preserve the motor's lifespan, it is essential to maintain a sufficient time interval between consecutive startups. Each motor has a specified maximum number of permissible startups per hour, known as the starting frequency, which must not be exceeded.

During repeated startups, the rotor experiences rapid temperature fluctuations, while the stator's temperature changes more gradually. Under normal load conditions, the rotor remains cooler than the stator. If the motor runs for a while after starting, the rotor has adequate time to cool before the next stop. In such cases, the decision to restart depends primarily on the stator temperature, which becomes the limiting factor.

However, if the motor starts from a cold state and fails shortly after, the rotor temperature becomes the critical factor in determining whether a restart is safe. Conversely, if the motor was initially hot, the stator temperature once again becomes the limiting constraint. This thermal behavior -modeled using a dual time-constant approach for both rotor and stator- is illustrated in Figure 2.2.

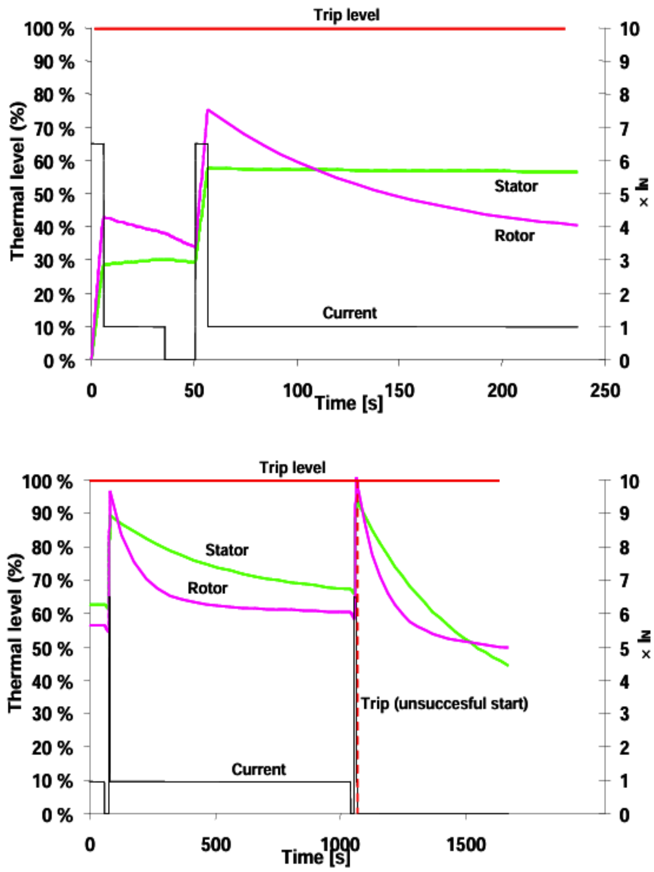


Figure 2.2: Temperatures of the rotor and stator according to the two-time-constant model when two startups have been done from cold condition (top) and when one successful startup and one unsuccessful startup have been done from hot condition (bottom) [22].

Supervision of successive startups can be done by using a simple counter-function: a certain amount of starting seconds is allowed in certain period. The disadvantage of this method is that it does not assort stalled or undervoltage startups from normal ones. Figure 2.3 shows an example of this kind of counter-function, the setting values of which are the sum of the allowed starting seconds and the countdown rate.

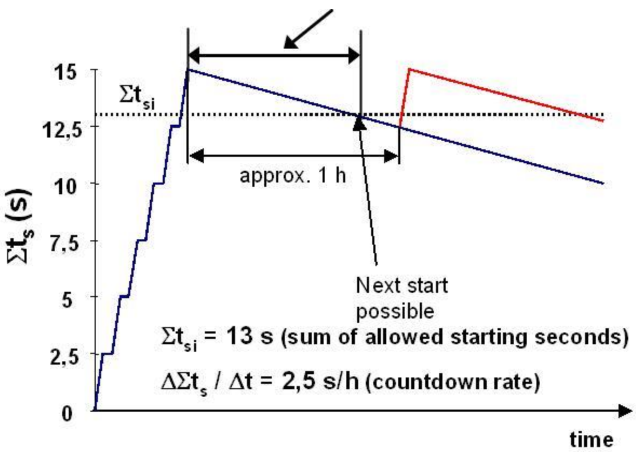


Figure 2.3: Operation and setting of a restart inhibit counter when six consecutive startups are performed. The starting time is 2.5 s, and no more than 6 starts per hour are allowed [21].

A better and more accurate way to protect the motor against too frequent starting is to make use of the thermal model and to determine and set a restart inhibit temperature limit: if the estimated rotor or stator temperature exceeds this limit, a further restart attempt is inhibited. For example, a restart inhibit level for the example of Figure 2.2 could be set at 55%, which is based on the estimated 45% increase in thermal level for a single startup [22].

2.4.1.3 Overload Protection

A slight overload may not lead to immediate motor failure, but over time, it can significantly reduce the motor's expected lifespan. On the other hand, a continuous overload often indicates a disturbance or malfunction in the process where the motor is being used.

To address this, a two-stage overload protection strategy is recommended. The first stage, known as the warning stage, alerts the operator when the motor's rated load, with an allowable margin, is exceeded. This is typically implemented through a pre-warning temperature threshold in the thermal model, providing the operator time to identify and resolve the source of the overload.

If the overload persists or increase -typically by 10 to 15%- the second stage is triggered. This is the tripping stage, which will disconnect the motor feeder if the overload is not resolved within a certain time frame. According to the thermal model, tripping occurs once the estimated thermal level surpasses 100%.

Figure 2.4 illustrates an example of the motor's thermal response under a constant cyclic overload. The curves are based on simulations using the two-time-constant model for both the stator and the rotor. In this scenario, the pre-warning level is crossed, prompting a notification to the operator. The issue is then addressed in time, preventing the motor from tripping.

The figure also highlights that effective overload protection ideally requires the two-time-constant thermal model to accurately reflect the thermal dynamics of both the rotor and the stator. This ensures optimal utilization of the motor's capacity. However, adequate protection can also be achieved using a single-time-constant model, provided it is properly configured to allow normal motor operation with an appropriate safety margin [23].

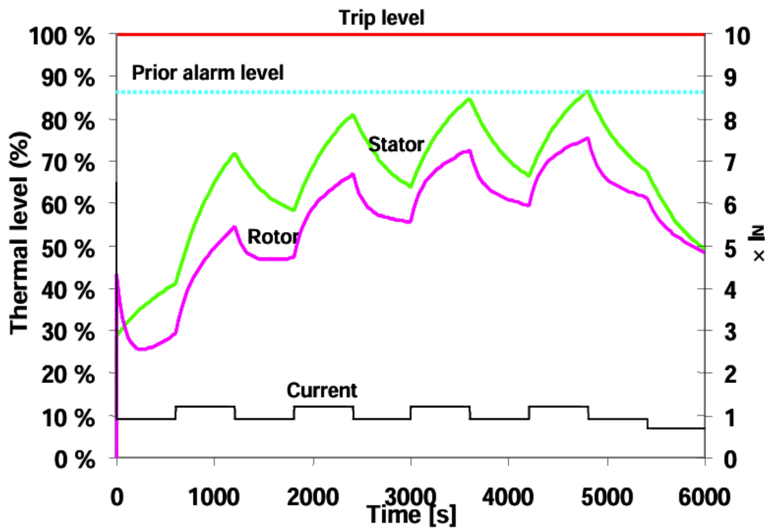


Figure 2.4: Temperatures of the rotor and the stator according to the two-time-constant model when the motor is running in constant cyclic overload. Pre-warning level is set to 90% [23].

The ambient temperature has a high impact on the motor loadability as shown in Table 2.2 For this to be fully utilized, the protection scheme must be equipped with a sensor for measuring the ambient temperature, which is then used for compensating the thermal model. Alternatively, the ambient temperature can be taken into account when selecting the start current setting of the protection.

Table 2.2: Effect of ambient temperature on the loadability of the motor [23].

Ambient temperature	Allowed output
C°	% of rated output
30	107
40	100
45	96
50	92
55	87
60	82*
70	65*
80	55*

(*) Output power and lubrication according to the contract.

2.4.2 Unbalance Protection

In a balanced sinusoidal supply system, the three phases to neutral voltages are equal in magnitude and are phase displaced from each other by 120 degrees. Any differences that exist in the three voltage magnitudes and/or a shift in the phase separation from 120 degrees are said to be unbalanced supply. Causes of voltage unbalance include unequal impedances of three-phase transmission and distribution system lines, large and/or unequal distribution of single-phase loads, phase to phase loads and unbalanced three-phase loads. When a balanced three-phase load is connected to an unbalanced supply system the currents drawn by the load also become unbalanced. The level of voltage unbalance is calculated using unbalance index term known as voltage unbalance factor (VUF), which is generally expressed in percentage [24].

2.4.2.1 Voltage Unbalance Factor

Voltage unbalance factor is a measure of level of voltage unbalance in the system. There are various definitions of voltage unbalance factors but, out of these, National Electrical Manufacturer Association (NEMA) and International Electrotechnical Commission (IEC) definitions are well accepted and widely used definitions. All the definitions given by different sources are being given below:

2.4.2.1.1 NEMA Definition

The voltage unbalance factor in percentage (VUF) at the terminal of a machine as given by the National Electrical Manufacturer Association (NEMA) Motor and Generator Standard (NEMA MGI) used in most studies is given by [25].

Voltage unbalance factor (VUF) or Line voltage unbalance rate (LVUR) is given by:

$$\text{VUF or LVUR} = \frac{maximum \text{ Voltage from average line Voltage magnitude}}{\text{average line Voltage magnitude}} \times 100$$

$$= \frac{Max\left[\left|V_{ab} - V_{avg}\right|, \left|V_{bc} - V_{avg}\right|, \left|V_{ca} - V_{avg}\right|\right]}{V_{avg}} \times 100 \qquad (2.6)$$

Where $V_{avg} = \frac{V_{ab}+V_{bc}+V_{ca}}{3}$

NEMA recommends that motors can be used safely up to one percent of VUF. If VUF exceeds one percent then, one should derate the motor as per NEMA derating curve (Figure 2.5); above 5 % unbalance motor operation is not recommended.

2.4.2.1.2 IEEE Definition

As per IEEE standard 141, VUF is defined as the same way as NEEMA, only differences is that the phase voltages have been taken instead of line voltages and it is also called Phase unbalance voltage rate (PVUR) [26]. So as per IEEE definition

$$\text{VUF or LVUR} = \frac{maximum \text{ Voltage deviation from average phase Voltage magnitude}}{\text{average phase Voltage magnitude}}$$

$$= \frac{Max[|V_a - V_{avg}|, |V_b - V_{avg}|, |V_c - V_{avg}|]}{V_{avg}} \times 100 \qquad (2.7)$$

Where $V_{avg} = \frac{V_a+V_b+V_c}{3}$

IEEE definition cannot be used for angle unbalanced; therefore, this definition is seldom used by researcher and field engineers.

2.4.2.1.3 IEC Definition

The voltage unbalance factor (VUF) is defined by International Electrotechnical Commission (IEC) as the ratio of negative-sequence voltage component to the positive-sequence voltage component [25].

$$\text{VUF in percentage} = \frac{V_2}{V_1} \times 100 \qquad (2.8)$$

Where V_2 is negative sequence voltage component magnitude and V_1 is positive sequence voltage component magnitude. This definition is popular among researchers.

2.4.2.1.4 Complex Voltage Unbalance Factor (CVUF)

An extension of VUF is the complex voltage unbalance factor (CVUF) that is defined as the ratio of negative-sequence voltage phasor to positive sequence voltage phasor. The CVUF is a complex quantity having the magnitude and angle. Appropriately, complex voltage unbalance factor (CVUF) can be written as

$$\text{CVUF in percentage} = \frac{V_2}{V_1} \times 100 \qquad (2.9)$$

Whereas V_1 is positive sequence voltage phasor and V_2 is negative sequence voltage phasor.

2.4.2.2 Classification of Unbalancing [26]

There may be different types of unbalances in a supply system with a possibility of voltage variations above and below the rated value. Thus, voltage unbalance can be classified into overvoltage unbalance (OVU), under-voltage unbalance (UVU) and angle unbalance (AU).

OVU is a condition when the three phase voltages are not equal to each other, in addition positive sequence component is greater than the rated value while UVU is a condition where the three phase voltages are not equal to each other and in addition the positive-sequence component is lesser than the rated value.

Angle voltage unbalancing AU is the condition when magnitudes of all voltages are not equal to 120 degrees. OVU, UVU, and phase angle unbalance are further classified as single phase, two phases and three phase unbalances.

Some other authors have used the term balanced over voltage (BOV) and balanced under voltage (BUB), but these term falls under the definition over voltage and under voltage, so these terms are not required as these are not unbalance, these are simply under voltage and over voltage.

2.4.2.3 Impact of Voltage Unbalance on Induction Motor

Even though the unbalanced voltage applied to the motor is small, large unbalanced motor current can flow because of relatively low negative sequence impedance. The large unbalanced current makes difficult problems in induction motor applications, such as a heating problem, increased losses, and vibrations, acoustic noises, shortening of the life, and decreased rotating torque. So, this section can be classified as follows:

2.4.2.3.1 Impact on Losses, Efficiency, Heat Generation and Life Expectancy

As the voltage unbalance increases, the losses increase identically, this will result to increase in the temperature. Temperature increment curve is somewhat above the motor loss curve because; heated resistance has more value than the less heated resistance (Figure 2.5). Due to excess loss, the efficiency will decrease as value of unbalance increases. If the positive sequence voltage is kept constant, efficiency diereses on increase value of VUF [26]. Approximate formula to find temperature rise based upon experiments has been given as:

Percentage increase in temperature rise will be two times the square of the VUF. It has been well established fact that every increase of 10 degree will result half of the insulation life [25].

2.4.2.3.2 Impacts on Torque, Vibrations and Noise:

The value of steady state torque is reduced due to negative torque produced by negative sequence current. Unbalanced supply creates the rotating field elliptical instead of circular [27], magnitude of torque pulsation become increased that may result mechanical damage of bearings. Due to torque pulsation, vibrations and noise is increased which is proportional to the voltage unbalance factor.

Increase in motor losses and heating
VS Voltage Unbalance

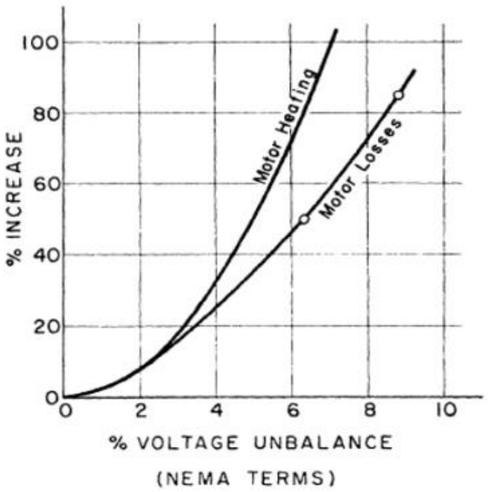


Figure 2.5: Increment of loss and heat

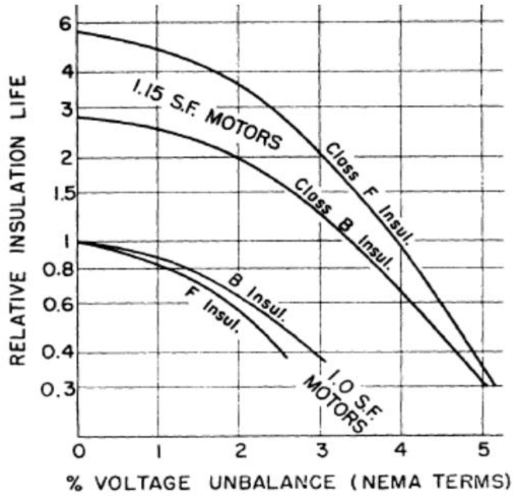


Figure 2.6: Life expectancy

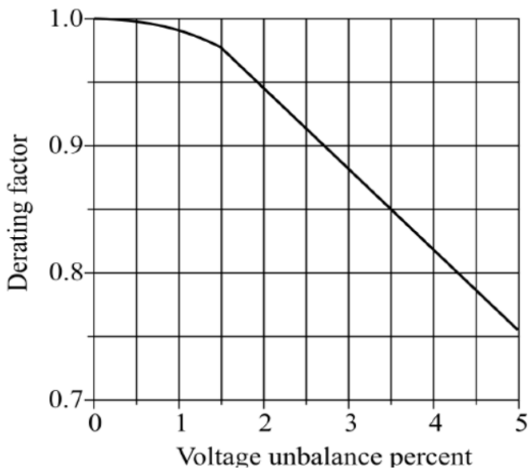


Figure 2.7: NEEMA derating curve

2.4.2.3.3 Impact on Power Factor

With increment of VUF, power factor may increases or decreases. The power factor mainly depends upon the value of positive sequence voltage. Power factor increases at UVU case and decreases in the OVU case. Negative sequence voltage has little impact on the power factor [28].

2.4.3 Overvoltage and Undervoltage

Overvoltage and undervoltage are two common electrical phenomena that can have adverse effects on electronic devices, electrical systems, and overall power supply stability. These voltage fluctuations, occurring either above or below the standard voltage levels, can result in significant damage, malfunctions, and safety hazards. Therefore, implementing effective overvoltage and undervoltage protection mechanisms is essential to safeguarding equipment, ensuring uninterrupted operation, and preventing potential risks [29].

2.4.3.1 Definition of Over Voltage

An Overvoltage can be described as an increase in the r.m.s. value of the voltage up to a level between 1.1 pu to 1.8 pu at power frequency for intervals ranging from a half cycle to a minute as shown in Figure 2.8.

Where

$$pu = \frac{Actual\ value}{\text{Base value}} \tag{2.10}$$

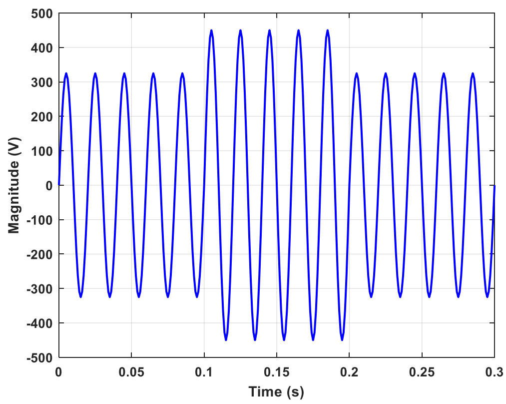


Figure 2.8: Overvoltage waveform

Overvoltage is less common than undervoltage, but it can occur as a result of system fault. A single line to ground fault can cause overvoltage, which raises the voltage of the other phases. It can also occur as a result of huge industrial loads being disconnected or capacitor banks being switched on. Overvoltage has more severe and devastating consequences. Due to overheating produced by excessive voltage, it may cause electrical equipment to fail. The electrical loads, electronic devices and circuits, and electrical and electronic equipment connected to the supply mains can all be damaged by this overvoltage. The energization of the capacitor bank is the primary source of overvoltage. It can also be caused by a sudden reduction in load. There is a sudden fall in current due to the disconnection of the load, which causes the voltage to rise [29].

$$v = L\frac{di}{dt} \tag{2.11}$$

Where L is the inductance of the line.

Furthermore, Overvoltage may be classified by their duration as shown in Table 2.3.

Table 2.3: Classification of overvoltage according to IEEE 1159.

Type of voltage	duration	Magnitude
Instantaneous	0.5-30 cycles	1.1-1.8 pu
Momentary	30 cycles- 3 sec	1.1-1.4 pu
Temporary	3 sec- 1 min	1.1-1.2 pu

2.4.3.2 Causes of Over Voltage

Over voltages on power systems are due to various causes. External and internal over voltages are the two main types of over voltages that can occur in a power system.

2.4.3.2.1 External Over Voltage

These Over voltages are caused by atmospheric disturbances, primarily lightning. These over voltages appear as a unidirectional impulse, whose the highest possible amplitude has no direct relationship with the operating voltage of the system [29].

These are several factors that create the external voltages.

- Direct lightning strokes.
- lightning discharge taking place near the line (commonly known as 'side stroke') Electromagnetically induces over voltages.
- Changing in atmospheric conditions along the line length will induce Voltages.
- the presence of charge clouds nearby Electrostatically induces over voltages.
- frictional effects of small particles such as dust or dry snow in the atmosphere or due to change in the altitude of the line Electrostatically induces overvoltage

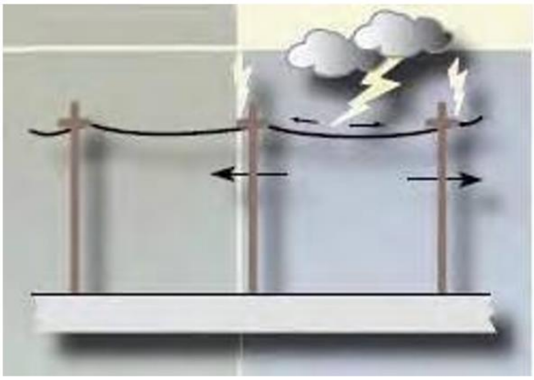


Figure 2.9: Over Voltage due to Direct Lightning Stroke on overhead line

Figure 2.10: Over Voltage due to indirect Lightning Stroke on ground

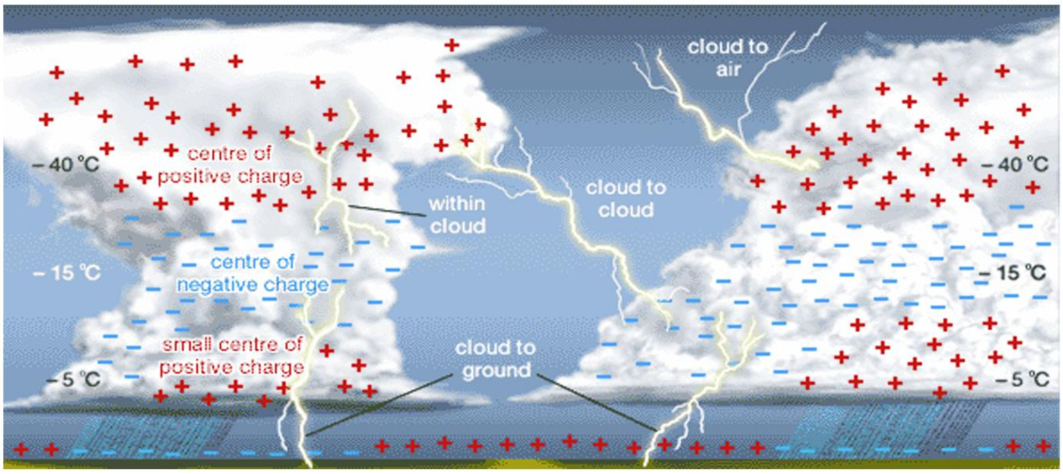


Figure 2.11: Over Voltage due to Presence of Charged Cloud

2.4.3.2.2 Internal Over Voltage

Overvoltage's typically arise due to variations in the network's operating conditions. These internal overvoltages can be categorized into two types: switching overvoltages (high-frequency transient surges) and temporary overvoltages (power-frequency steady-state surges).

Switching overvoltages, also known as high-frequency transient surges, occur during changes in the network's state caused by switching operations or fault events. These overvoltages are often oscillatory, resembling a damped sinusoidal waveform. Their frequencies can range from a few hundred Hz to several kHz. Common causes include switching operations involving unloaded transformers or high-voltage reactors, which generate these transient spikes.

Temporary overvoltages, on the other hand, are steady-state voltage surges at the power system's fundamental frequency. They typically arise when a load is disconnected, especially on long transmission lines. To evaluate these surges, the overvoltage factor - defined as the ratio between the peak of the overvoltage and the rated peak phase voltage- is used. This factor is also known as the amplitude factor. A thorough analysis of overvoltages includes examining their magnitude, waveform shape, duration, and how frequently they occur within the system.

2.4.3.3 Definition of undervoltage

An undervoltage is a condition in which the voltage level root mean square (r.m.s) value at the supply frequency is in the range of 0.1 p.u. to 0.9 p.u. and lasts for a time period of half cycle to one minute. When large loads are switched on, such as an induction motor, the lagging current draws 6-10 times the full load rated, causing a fall in voltage across the system's impedance [6].

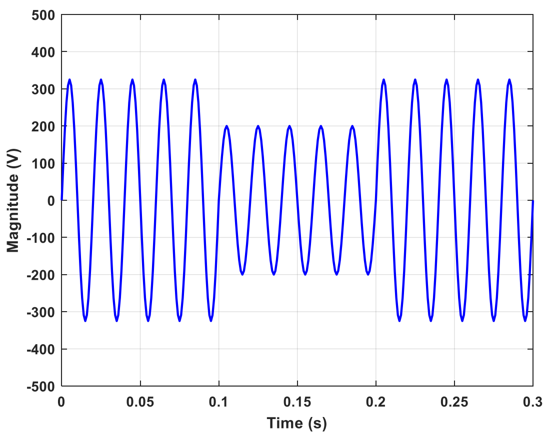


Figure 2.12: Undervoltage waveform

Furthermore, Undervoltage may be classified by their duration as shown in Table 2.4

Table 2.4: classification of undervoltage

Type of voltage	duration	Magnitude
Instantaneous	0.5-30 cycles	0.1-0.9 pu
Momentary	30 cycles- 3 sec	0.1-0.9 pu
Temporary	3 sec- 1 min	0.1-0.9 pu

2.4.3.4 Causes of Under Voltage

There are various causes for which undervoltage is created in system voltage.

- Closing and Opening of Circuit Breakers: When a phase's circuit breaker opens unexpectedly, the line it feeds is temporally disconnected. Other feeder lines from the same substation system will operate as a voltage regulator.

- Due to Fault: A power plant operation can be affected by undervoltage due to a failure. The magnitude of undervoltage in each phase might be equal or uneven, depending on whether the fault is symmetrical or unsymmetrical in form.
- Equipment Failure: Insulation failure, temperature, short circuits, and other factors that cause electrical equipment to fail.
- Pollution: When there is a storm in the coastal regions and the electrical lines are covered in salt, a flashover occurs. Faults occur because this salt buildup functions as an excellent conductor of electricity.
- Construction Activity: In most urban locations, all electricity lines are undergrounded; however, digging for foundation work can damage underground cable and produce undervoltage.

2.4.3.5 The Effect of Under Voltage on the Performance of Electric Motors

When electric motors are subjected to voltages, below the nameplate rating, some of the characteristics will change slightly and others will change more dramatically. A basic point is; to drive a fixed mechanical load connected to the shaft, a motor must draw a fixed amount of power from the power line. The amount of power the motor draws is roughly related to the voltage times current (amps). Thus, when voltage gets low, the current must get higher to provide the same amount of power. The fact that current gets higher is not alarming unless it exceeds the nameplate current rating of the motor. When amps go above the nameplate rating, it is safe to assume that the buildup of heat within the motor will become damaging if it is left unchecked. If a motor is lightly loaded and the voltage drops, the current will increase in roughly the same proportion that the voltage decreases [30].

For example, a 10% voltage decrease would cause a 10% amperage increase. This would not be damaging if the motor current stays below the nameplate value. However, if a motor is heavily loaded and a voltage reduction occurs, the current would go up from a fairly high value to a new value which might be in excess of the full load rated amps. This could be damaging. It can be safely said that low voltage in itself is not a problem unless the motor amperage is pushed beyond the nameplate rating.

Aside from the possibility of over-temperature and shortened life created by low voltage, some other important items need to be understood. The first is that the starting torque, pull-up torque, and pull-out torque of induction motors, all change based on the applied voltage squared. Thus, a 10% reduction from nameplate voltage (100% to 90%, 230 volts to 207 volts) would reduce the starting torque, pull-up torque, and pull-out torque by a factor of 0.9×0.9. The resulting values would be 81% of the full voltage values. At 80% voltage, the result would be 0.9×0.9, or a value of 64% of the full voltage value. In this case, it is easy to see why it would be difficult to start "hard-to-start" loads if the voltage happens to be low. Similarly, the motor's pull-out torque would be much lower than it would be under normal voltage conditions. To summarize the situation, low voltage can cause high currents and overheating which will subsequently shorten motor life. Low voltage can also reduce the motor's ability to get started and its values of pull-up and pull-out torque. On lightly loaded motors with easy-to-start loads, reducing the voltage will not have any appreciable effect except that it might help reduce the light load losses and improve the efficiency under this condition. This is the principle that is used in the so-called Nola devices that are sold as efficiency improving add-on equipment to motors.

2.4.3.6 The Effect of Over Voltage on the Performance of Electric Motors

One of the basic things that people assume is, since low voltage increases the amperage draw on motors, then by the same reasoning, high voltage would tend to reduce the amperage draw and heating of the motor. This is not the case. High voltage on a motor tends to push the magnetic portion of the motor into saturation. This causes the motor to draw excessive current in an effort to magnetize the iron beyond the point to which it can easily be magnetized. This generally means that the motors will tolerate a certain change in voltage above the design voltage but extremes above the designed voltage will cause the amperage to go up with a corresponding increase in heating and a shortening of motor life. For example, older motors were rated at 220/440 and had a tolerance band of plus/minus 10%. Thus, the voltage range that they can tolerate on the high voltage connections would be 396 to 484. Even though this is the so-called tolerance band, the best performance would occur at the rated voltage. The extreme ends, either high or low, would be putting unnecessary stress on the motor [30].

Generally speaking, these tolerance bands are in existence not to set a standard that can be used all the time but rather to set a range that can be used to accommodate the normal hour-to-hour swings in plant voltage. Operation on a continuous basis at either the high extreme or the low extreme will shorten the life of the motor

Overall, it is definitely in the equipment's best interest to have the utility company change the taps on incoming transformers to optimize the voltage on the plant floor to something that is very close to the equipment ratings. In older plants, some compromises may have to be made because of the differences in the standards on old motors (220/440) and the newer "T" frame standards (230/460), but a voltage in the middle of these two voltages, something like 225 or 450 volts, will generally result in the best overall performance. High voltage will always tend to reduce power factor and increase the losses in the system which results in higher operating costs for the equipment and the system [30].

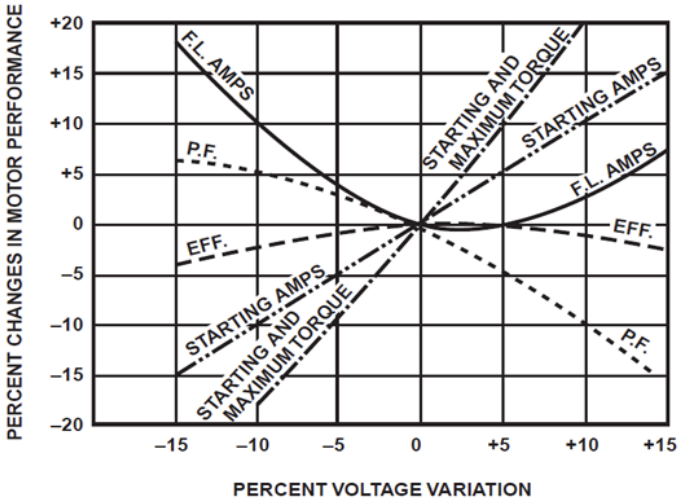


Figure 2.13: Effect of voltage variation on "T" frame motors**.**

Figure 2.9 is commonly used to depict the typical impact of both high and low voltage on the performance of "T" frame motors. While it serves well to demonstrate general trends, it's important to note that the graph reflects the behavior of a single motor, and actual performance can vary significantly depending on the specific motor design.

Some general guidelines might be useful:

- Small motors tend to be more sensitive to over-voltage and saturation than large motors.
- Single phase motors tend to be more sensitive to over-voltage than three phase motors.
- U-frame motors are less sensitive to over-voltage than "T" frames.
- Premium efficiency Super-E motors are less sensitive to over-voltage than standard efficiency motors.
- Two pole and four pole motors tend to be less sensitive to high voltage than six pole and eight pole designs.
- Over-voltage can drive up amperage and temperature even on lightly loaded motors. Thus, motor life can be shortened by high voltage.
- Full load efficiency drops with either high or low voltage.
- Power factor improves with lower voltage and drops sharply with high voltage.
- Inrush current goes up with higher voltage.

2.4.4 phase reversal

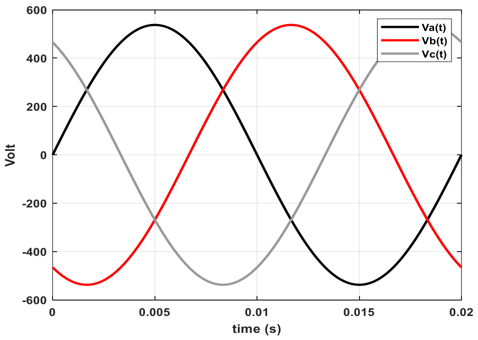
In the fields of engineering, phase rotation -also known as phase sequence- is a basic concept that supports the functionality of various three-phase electrical systems, which are core in industrial, commercial, and residential settings. Proper phase rotation alignment and verification is essential not only to allow for the correct operation of these devices, but also to confirm system synchronization and efficiency [31].

2.4.4.1 Phase Rotation in electrical systems?

Phase rotation, also known as phase sequence, is a fundamental concept in the operation of three-phase electrical systems. It determines the order -commonly labeled as "ABC" or "ACB"- in which the phase voltages reach their peak values. This sequence is essential for the correct operation of three-phase equipment.

In such systems, the phase sequence governs the rotation direction of motors and the functioning of various industrial machines. For instance, a motor connected to an ABC sequence will rotate in one direction, while the same motor will rotate in the opposite direction if the sequence is ACB. This is particularly critical in applications requiring precise directional control, such as conveyor systems, automated production lines, and robotic mechanisms. Therefore, verifying the phase sequence is crucial during equipment installation and routine maintenance procedures.

Figures 10.A through 11.B illustrate various aspects of a balanced three-phase system: the voltage waveforms and phasor diagrams of both the positive and negative sequences. In a balanced system, the phases are separated by 120º in both sequences. The positive sequence (Figure 14.B) corresponds to a clockwise A-B-C rotation, while the negative sequence (Figure 15.B) corresponds to a counterclockwise A-B-C rotation.



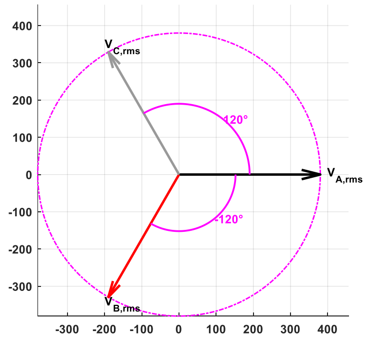
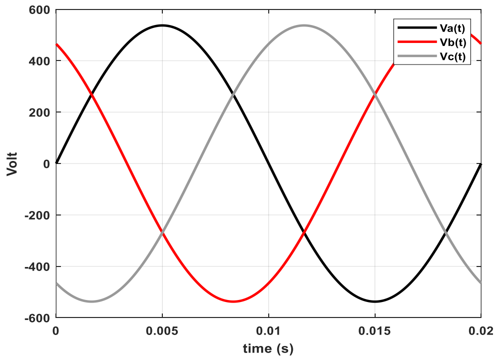


Figure 2.14.A: Positive sequence of a balanced three-phase system.

Fig 2.14.B: Phasor diagram of a balanced three-phase system in positive sequence.



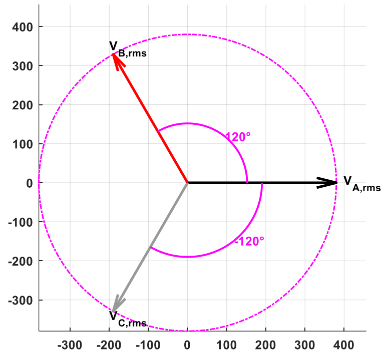


Figure 2.15.A: Negative sequence of a balanced three-phase system.

Figure 2.15.B: Phasor diagram of a balanced three-phase system in negative sequence.

2.4.4.2 Determining Phase Rotation

The AC voltage equation can be written as follows:

$$V_x(t) = V_{max}\cos(wt - \theta_x) \tag{2.12}$$

where, x, w, and θ are the phase of the voltage, the radian frequency, and the phase shift. The phase angle difference between voltages (δ), for example the voltages of phase $V_a(t)$ and phase V_b can be obtained using equation 4.

$$V_a(t) = V_{max}\cos(wt - \theta_a) \tag{2.13}$$

$$V_b(t) = V_{max}\cos(wt - \theta_b) \tag{2.14}$$

$$\delta = |\theta_a - \theta_b| \tag{2.15}$$

An alternative way to get the voltage angle difference between phases, if the data of the voltages as a function of time are known. is to use the following formula:

$$V_{a,rms} = \sqrt{\frac{1}{T}\int_0^T v_a^2(t)dt} \tag{2.16}$$

$$V_{b,rms} = \sqrt{\frac{1}{T}\int_0^T v_b^2(t)dt} \qquad (2.17)$$

$V_{vv,avg}$ It is the **average of the instantaneous product** between two voltage signals: V_a(t) and $V_b(t)$, over a time period T. It is calculated using the following integral:

$$V_{vv,avg} = \frac{1}{T}\int_0^T V_a(t).V_b(t)dt \qquad (2.18)$$

So, we finally get:

$$\cos(\delta) = \frac{V_{vv,avg}}{V_{a,rms}.V_{b,rms}}$$

and therefore:

$$\delta = \cos^{-1}(\frac{V_{vv,avg}}{V_{a,rms}.V_{b,rms}}) \qquad (2.19)$$

By using trigonometry, equation 2.18 can be drawn in Figure 2.16

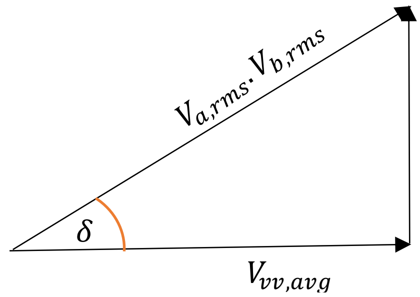


Figure 2.16: The Trigonometric for The Angle Difference between Phases.

2.4.4.3 Effects of Phase Reversal on the Pump

- **Reversed rotation** causes the motor and impeller to spin in the opposite direction, which may lead to reversed water flow or complete flow interruption depending on the pump design.
- **Hydraulic performance degradation**, as the pump fails to build adequate pressure or head, accompanied by unusual vibrations, noise, or weak flow.
- **Potential mechanical damage**, including impeller wear, seal leakage, and bearing failure.

- **Cavitation risk** due to pressure imbalance inside the pump, leading to internal component erosion and reduced efficiency.

2.4.5 Dry running protection

For protection against dry running a sensing prod is used. It is positioned inside the bore, slightly above the level of the pump. When the water level on the bore drops lower than then the sensing prod, it is expected to trip the starter. However, this does not happen because of many problems like:

1- Corrosion of the prod after a certain period due to moist atmosphere leading to loss of sensitivity.
2- Incorrect dry-run signal due to formation of water film around the prod.
3- Incorrect continuity signal resulting from a humid and moist atmosphere around the prod, due to water yield from the top even if the water level is very low.
4- Failure of water level guard due to the absence of proper earthing on the control panel.
5- Difficulty in taking out the pump for servicing due to –
   a- Loosening of the prod from the terminals of breaking of the cable
   b- Prod getting stuck in the lining.
6- Installation of a water level guard is not possible without removing the pump set completely. In short, this prod fails to function as a water level guard in most installations. Hence, it is not advisable to depend upon a device which employs a prod for its dry running protection.

Because of these limitations, normally the water level guard is by – passed immediately after commissioning of the pump and the pump is virtually denied dry running protection.

It is possible to offer protection against dry running by sensing the motor current which changes during dry running conditions or by sensing the motor current which changes during dry running conditions or by sensing the RPM of the motor and the water pressure which also change during dry running conditions. If suitable devices are used to sense the motor current or the motor RPM and water pressure, then it is possible to provide reliable protection against dry running. Sensing the water level in the borewell is also possible with capacitance-based water level guards or an ultrasonic level detector [6].

2.6 Conclusion

This chapter has detailed the various electrical faults and abnormal conditions that affect the performance and efficiency of electric motors, such as thermal overload, voltage unbalance, under- and overvoltage, and phase sequence reversal. The negative impacts of these factors on motor lifespan and reliability were highlighted, along with the importance of thermal modeling and different protection mechanisms.

However, despite the availability of theoretical knowledge and conventional protection techniques, a fundamental problem remains: How can these concepts be translated into a practical and intelligent system capable of early fault detection, autonomous response, and real-time user notification, especially in environments where manual monitoring is impractical - such as remote agricultural sites or continuously operating industrial systems?

This challenge forms the foundation of the next chapter, which focuses on the design and implementation of a smart electronic protection board for electric motors using an Arduino microcontroller, combined with an IoT-based monitoring and control system. This solution aims to provide a practical and responsive approach to ensuring motor safety and operational continuity.

Chapter 3

Implementing a Smart Water Pump Protection Monitoring System Using Arduino Uno

3.1 Introduction

This chapter will examine the testing of the off-the-shelf smart board and its reliability in protecting the pump from electrical faults that could lead to its shutdown. It will also address remote control via the IoT. The main motivation behind this endeavor is the challenges farmers face in maintaining irrigation systems. They are forced to travel long, regular distances due to the distance between their fields and their homes. Agriculture relies on irrigation, so monitoring the situation is essential to ensure that crops receive sufficient water. To operate irrigation systems and facilitate the distribution of prepared water, farmers must travel to their fields daily, regardless of the distance. This daily journey is time-consuming, costly, and physically demanding.

This chapter presents a smart water pumping system that uses a SIM800L GSM module and an Arduino Uno controller to solve these problems. Farmers no longer need to visit their irrigation pumps daily thanks to this IoT-based technology, which enables them to control and monitor them from their mobile phones. By reducing costs and time, this approach enhances agricultural productivity and efficiency [32].

3.2 System Architecture

The proposed smart water pump monitoring and protection system is designed around an Arduino Uno microcontroller, which serves as the central processing unit for sensor data acquisition and control logic. The architecture integrates three current sensors (SCT-013) and three voltage sensors (ZMPT101B), each corresponding to a phase of the three-phase power supply feeding the induction motor. These sensors continuously measure the electrical parameters—current and voltage—and send analog signals to the Arduino for real-time processing.

To enable remote monitoring, the system employs a SIM800L GSM module, which sends SMS notifications to the farmer's mobile phone whenever a fault or significant status change is detected. This functionality eliminates the need for physical presence at the irrigation site. In the event of electrical faults such as overvoltage, undervoltage, overload, or phase failure, and phase reversal, the Arduino processes the sensor data and triggers protective actions using relays. These relays are connected to an electrical control cabinet that includes a contactor and the main induction motor. The relays can disconnect the motor from the power supply to prevent damage and ensure system safety. The system is shown in Figure 3.1.

This modular architecture ensures that the system is both scalable and adaptable, making it suitable for various agricultural settings where reliability and autonomy are critical.

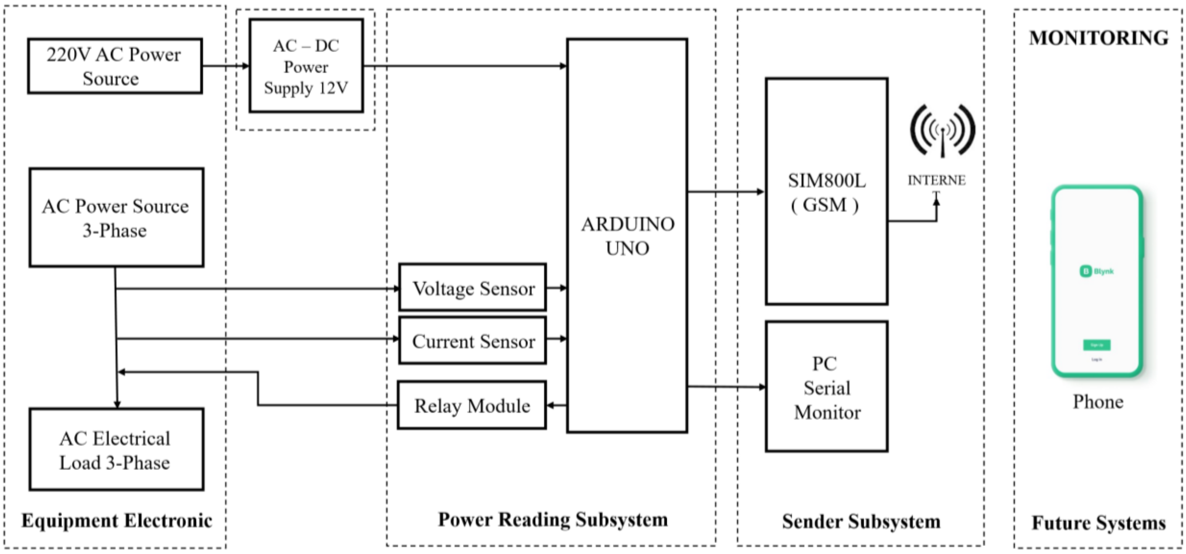


Figure 3.1: The diagram block system

3.3 Hardware Components and Functional Roles

This section is based on the stages of implementation and installation of voltage and current sensors:

3.3.1 Current Sensor (SCT-013)

The SCT013 is a non-invasive current transformer based on the operation of clipping the alternating current around a conductor. Such a module provides an analog voltage output proportional to the current entering the conductor. It is this kind of analog output which Arduino reads for further processing; hence, it finds a perfect application in energy measurement [32].

3.3.1.1 Key Technical Specifications (SCT-013)

- Input Current Range: 0 to 100 A
- Output Signal: 0 to 50 mA
- Core Material: Ferrite
- Conductor Opening: 13 x 13 mm
- Operating Temperature: -25 to +70 °C
- Non-linearity: ±3% (within 10%–120% of rated input current)
- Turns Ratio: 1:2000
- Dielectric Strength: 3.5 kV AC between output and outer shell for 1 minute at 5 mA, 50 Hz

Figure 3.2: SCT-013 current sensor.

3.3.1.2 Current transformer sensor

In a current transformer, the secondary winding has many turns, whereas the primary winding may consist of just one turn (a single wire passing through the core) As shown in the figure(3.2) [33].

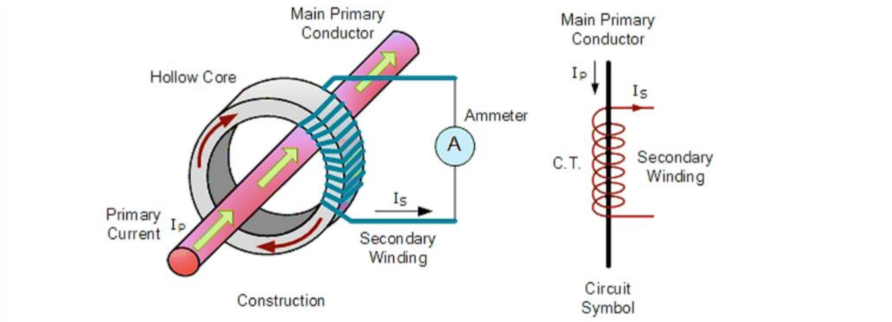


Figure 3.3: Current transformer schematic drawing .

A current transformer is used to reduce the high current in the primary winding to a much lower current in the secondary winding. The transformation is based on the turns ratio of the primary and secondary windings:

$$\frac{N_2}{N_1} = \frac{I_1}{I_2} \rightarrow N_1 = 1\,, \qquad I_2 = \frac{I_1}{N_2} \tag{3.1}$$

Where:

- N1 and N2 are the number of turns in the primary and secondary windings.
- I1 is the current in the primary winding (high current).
- I2 is the current in the secondary winding (low current, used for measurement).

3.3.1.3 Shifting circuits

Giving the fact that the Arduino platform operates with positive 5V DC, and the SCT sensor creates an analog waveform during readings, the voltage divider of the shield will split the 5V value to create a new 2.5V reference voltage. Analog values that vary between 2.5V and 5V DC will be interpreted as the positive signal or HIGH, while the values between 2.5V and 0 V will be interpreted as the negative signal or LOW in digital conversion figure(3.3). The Arduino 10 bits ADC will scale positive analog values to binary digital signal, so the scaling will be positive from 512 to 1024 and negative whatever value is under 512 - the mid value for reference [34].

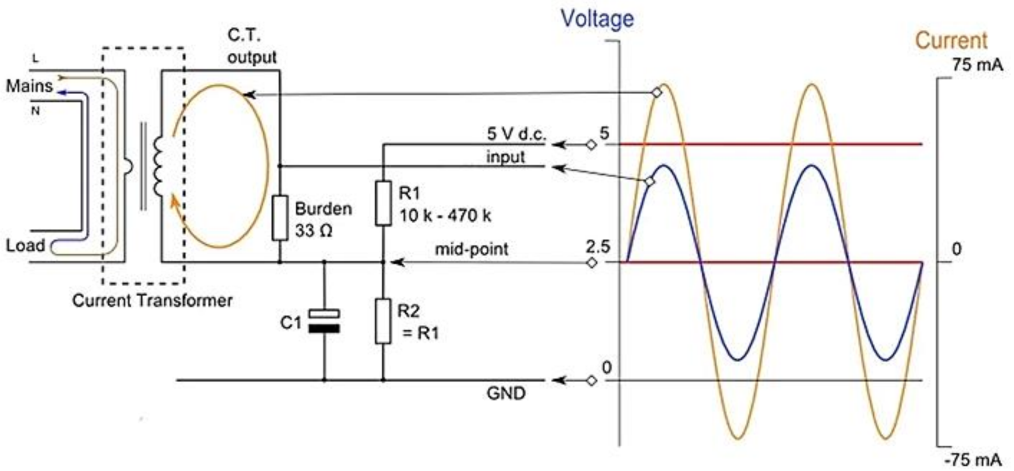


Figure 3.4: Voltage divider schematic to reduce the analog signal read by the Arduino.

To get 2.5 V DC, we used the voltage divider formula as shown in the schematic diagram:

$$v_{out} = \left(\frac{R_1}{(R_1 + R_2)}\right) . V_{IN} \tag{3.2}$$

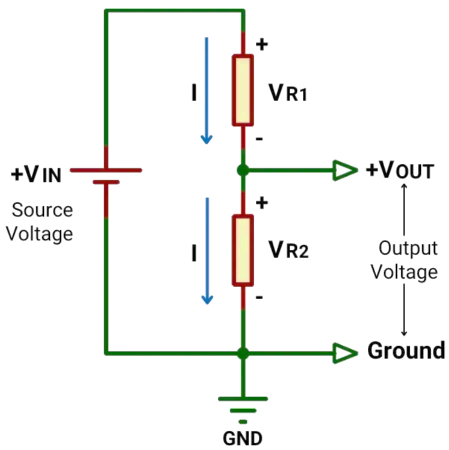


Figure 3.5: resistive voltage divider.

where Vout is the output voltage, Vin is the input voltage, R1 and R2 are the dividing resistors.

Thus we have:

$$v_{out} = \left(\frac{10}{(10+10)}\right).5 = 2{,}5v \quad (3.3)$$

3.3.1.4 Resistance calculation burden (RB)

To accurately measure the induced current, a burden resistor is connected in parallel with the secondary winding of the current transformer. The burden resistor creates a voltage drop proportional to the secondary current, which can be measured using an analog or digital sensor, for example, the analog input pins of the Arduino . In this application note, the measured secondary current is converted into an RMS current value using appropriate calibration ratios and calculations.

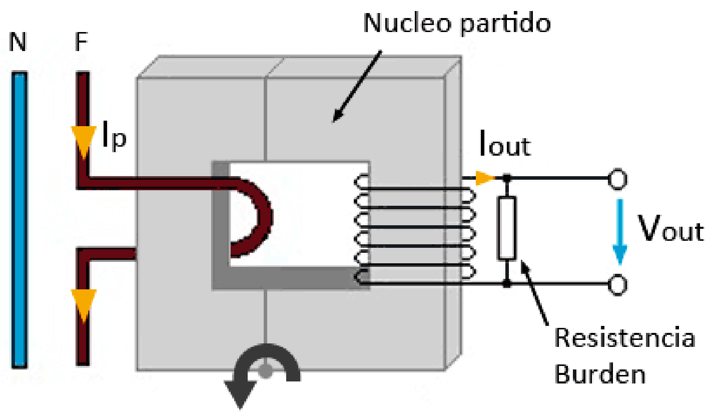


Figure 3.6: Current transformer.

- Primary winding peak current (I_P):

$$I_p = I_{rms} \times \sqrt{2} = 100 \times \sqrt{2} = 141.4A \quad (3.4)$$

- Secondary winding peak current (I_S):

$$I_s = \frac{I_p}{N_{Turns}} = \frac{141.4}{2000} = 0.0707A \quad (3.5)$$

- Ideal burden resistor (R_{Burden}):

$$R_B = \frac{V_{Ar}}{2 \times I_s} = \frac{5}{2 \times 0.0707} = 35.36\Omega \quad (3.6)$$

V_{Ar} : Arduino 5V power.

I_{rms} : input current range.

N_{Turns} : turns ratio.

For this application note and the current transformer used, the ideal load resistance is 35.36 Ω, you can use a commercially available resistance value, e.g., connecting two resistors in parallel or series gives you a resistance of approximately 40 Ω.

3.3.1.5 LM358P Operational Amplifier

The LM358P is an integrated circuit consisting of two independent operational amplifiers. It is specifically designed to operate with a single power supply over a wide voltage range. This op-amp features high gain with internal frequency compensation. Additionally, it can function with split or distributed power supplies, and the supply current consumption remains independent of the supply voltage magnitude [35].

Figure 3.7: LM358P Operational Amplifier.

3.3.1.6 Current Sensor Design (SCT-013)

This represents the design of the electronic circuit shown in the picture, which reads the SCT-013 current sensor.

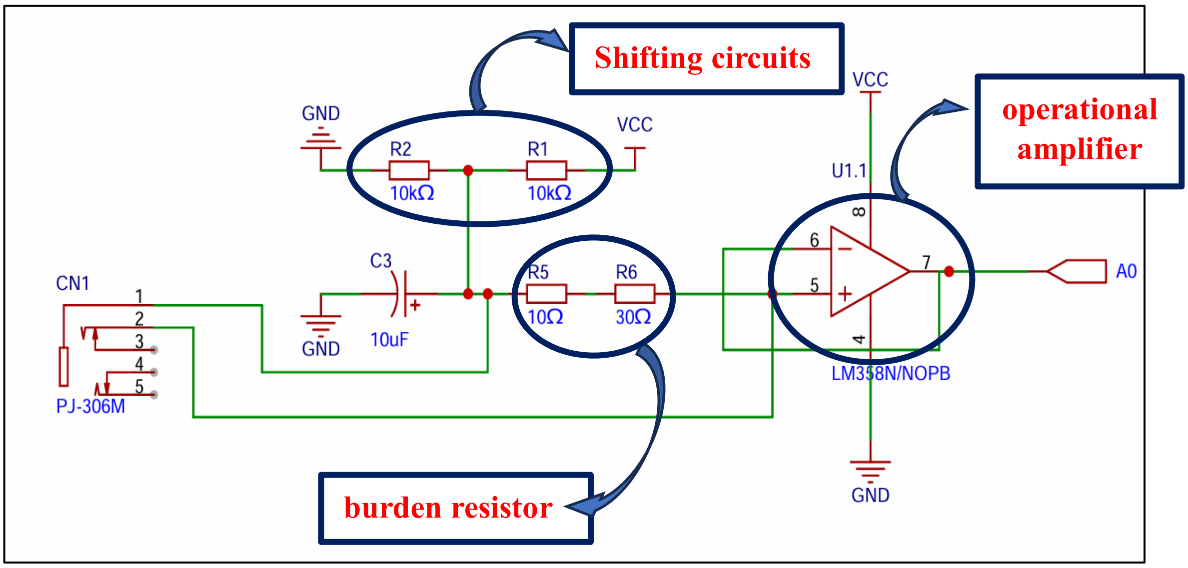


Figure 3.8: Current sensor design.

3.3.2 Voltage Sensor (ZMPT101B)

The ZMPT101B is a high-precision voltage sensor capable of converting an AC voltage signal into an Arduino-readable analog signal that will be proportional. An integrated operational amplifier is used in it, thus providing conditioning of the signal to measure the voltage correctly. Very suitable for energy monitoring systems[36].

Key Technical Specifications

- Transformer: ZMPT101B
- Supply Voltage: 5 to 30 VDC
- Input Voltage Range: 0 to 250 VAC
- Nominal Input Current: 2 mA
- Nominal Output Current : 2 mA
- Voltage Isolation : 4000 V
- Accuracy: ±1%

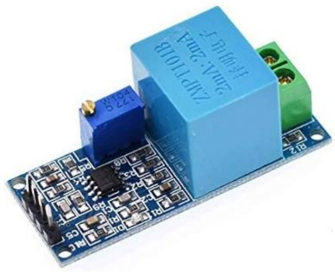


Figure 3.9: Voltage sensor ZMPT101b.

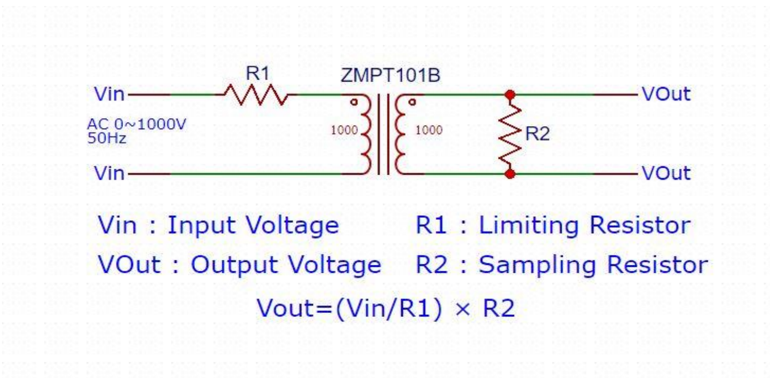


Figure 3.10: Voltage sensor schematic Diagram.

3.3.3 Relay

It behaves like an electromechanical switch that may drive a high-powered device-like lamp or motor-with a low-powered control signal from Arduino. If a controlling signal is given out from Arduino, it will close its switch and current will flow through the device connected to it, hence turning it on or off [36].

Figure 3.11: Relay shapes and symbols.

Two relays were used:

- **Automatic motor stop relay**: Used to automatically stop the motor in case of an electrical fault.
- **Remote start/stop relay:** Used to stop/start the motor remotely.

3.3.4 GMS module (SIM800L)

SIM800L GSM/GPRS module is a miniature GSM modem, which can be incorporated right into an amazing range of IOT projects. You can use this module to perform nearly anything a normal cell phone can; SMS text messages, Make or receive telephone calls, connecting to net via GPRS, TCP/IP, and greater! To top it off, the module supports quad-band GSM/GPRS community, which means it really works quite tons anywhere inside the world [37].

Figure 3.12: SIM800L GSM/GPRS module.

3.3.5 Arduino Uno

Based on the ATmega328P microcontroller, the Arduino UNO is a popular open-source microcontroller board.3 It is a component of the Arduino hardware platform and is renowned for being user-friendly, adaptable, and simple. The ATmega328P microcontroller is an 8-bit AVR microarchitecture chip that has EEPROM, SRAM, and flash memory for data retention and program storage.

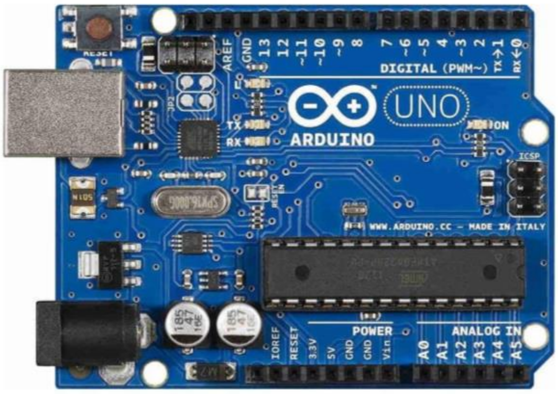


Figure 3.13: Arduino UNO.

3.3.6 Breadboard Prototype

This stage design demonstrates a simple Arduino Uno-to-PC power monitoring configuration. To detect the voltage and current from a motor load, the Arduino interfaces with a ZMPT101B voltage sensor and an SCT-013 current sensor. The Arduino receives analog inputs from the sensors and processes them before sending the data to the PC for monitoring. The motor is supplied by an AC source. To facilitate testing and prototyping, the complete circuit is constructed on a breadboard.

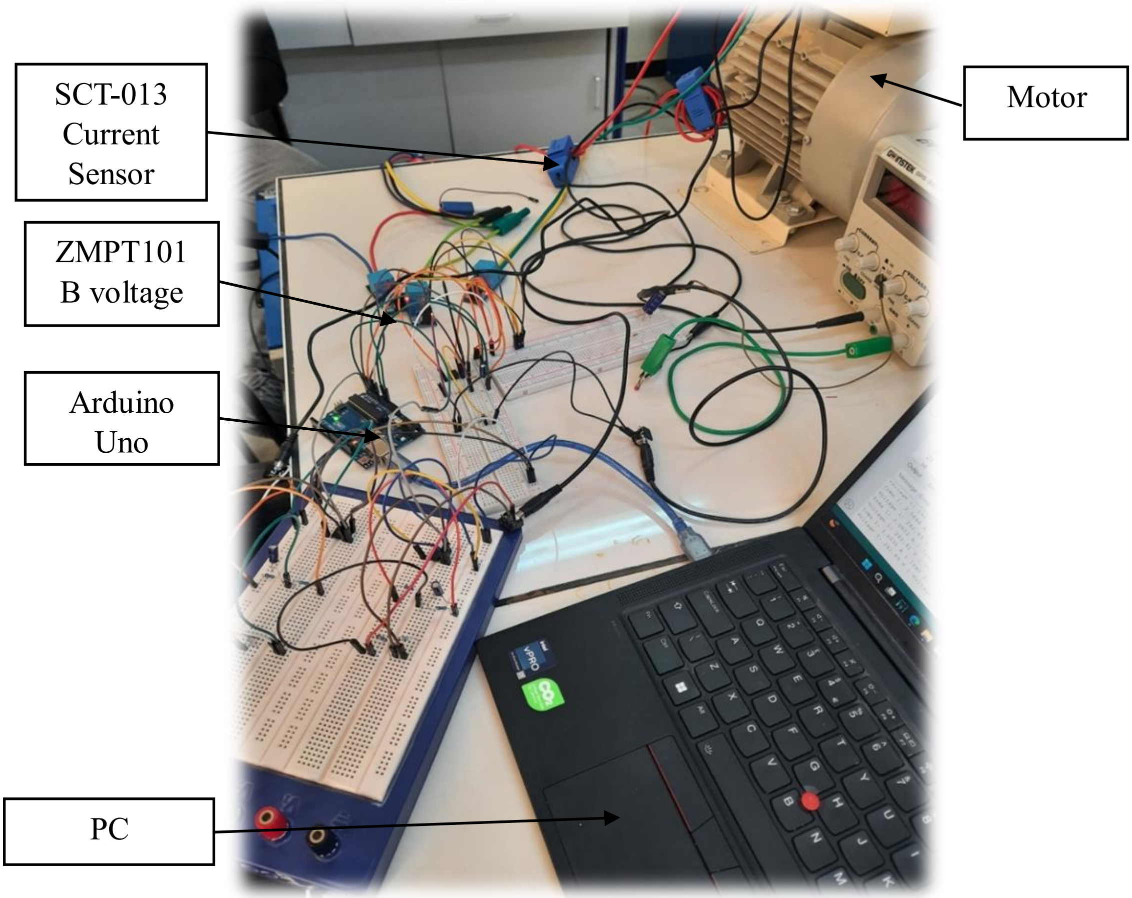


Figure 3.14: Design the first circuit on the breadboard.

3.3.7 Circuit diagram

This circuit was designed using EasyEDA Schematic Editor, an advanced tool for creating and designing electronic circuit diagrams. It allows users to add components, arrange them, and connect them with wires in an intuitive environment.

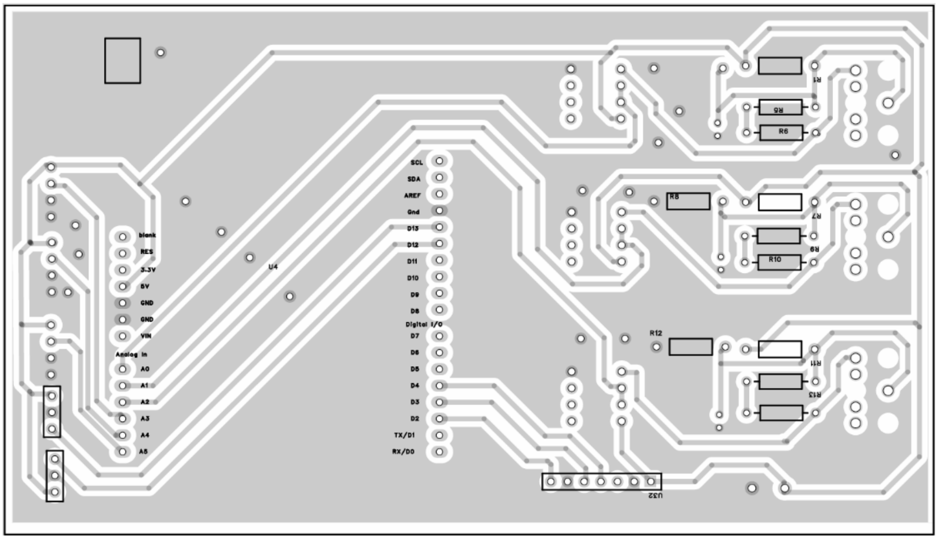


Figure 3.15: Circuit schematic of the sensor**.**

Before beginning the PCB manufacturing process, we first create a detailed 3D model of the integrated circuit and all its components, ensuring they reflect their actual dimensions.

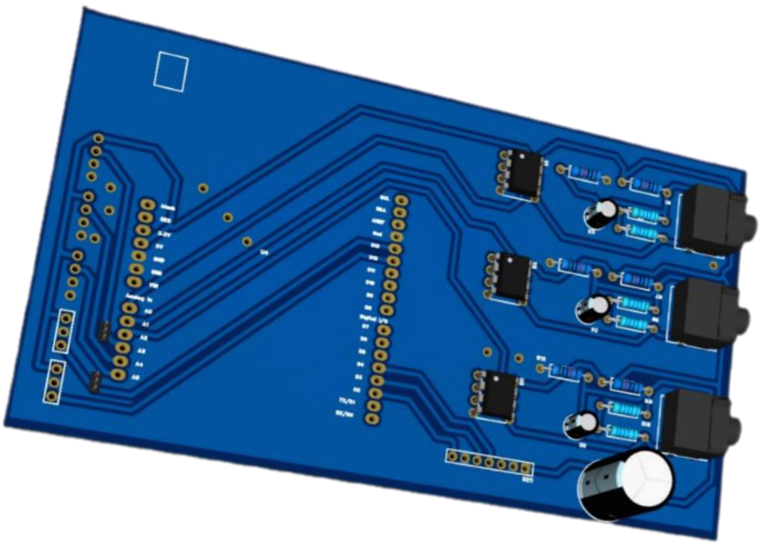


Figure 3.16: 3D PCB Design.

3.3.8 Final PCB manufacturing

This part of the circuit board displays the fully assembled components, where each electronic element has been accurately positioned and securely soldered to ensure reliable electrical connections.

Figure 3.17: Final design and manufacture of printed circuit board.

of the three-phase power supply and compares the values against predetermined criteria.

3.4 Real-Time Measurement of Electrical Quantities

The Arduino IDE is a programming environment. Some code is used to calculate electrical quantities such as voltage and current. This is also known as root mean square (RMS). The effective current (RMS) can be calculated based on current sensor readings at any given time. The value given by measuring devices such as an AC ammeter is the RMS current. RMS current is calculated using the following formula:

$$I_{RMS} = I_{max}\sqrt{\frac{1}{\pi}\int_{0}^{\pi} sin(t)^2\, dt} \quad (3.7)$$

RMS voltage is the standard value shown on measuring devices such as multimeters. It is particularly useful in AC systems, where the voltage varies continuously over time.

The formula below is used to calculate RMS voltage:

$$V_{RMS} = V_{max}\sqrt{\frac{1}{\pi}\int_0^{\pi} sin(t)^2\, dt} \tag{3.8}$$

3.5 IoT-Based Remote Monitoring and Control

The Internet of Things (IoT) service goes through three fundamental stages, devices, cloud server, and Android application :

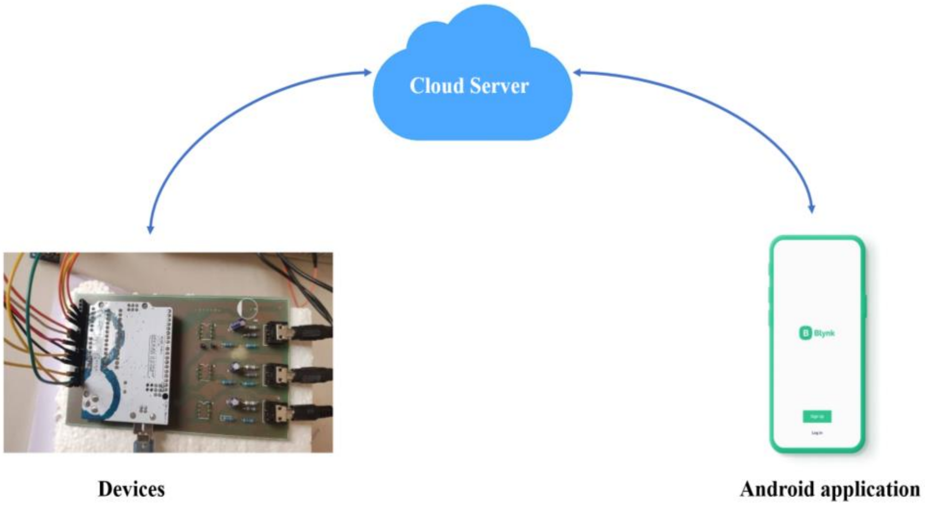


Figure 3.18: IOT Server and wireless control and device.

- **Devices:** An electronic circuit collects data during the monitoring process using internal sensors, such as current and voltage measurements. This data is then sent via an internet-connected chip to a cloud server. The device also receives commands from the cloud server.
- **Cloud Server:** The cloud server acts as an intermediary between the device and the Android application or user. This server performs a range of vital tasks that ensure smooth and efficient communication between the various components of the system.
- **User Interface:** An online Android application that allows users to remotely control the device. The application sends and receives commands from a cloud server. This application is specifically designed to meet user needs. It detects electrical faults (overload, voltage drop, overvoltage, imbalance, reverse circuit), and provides on/off buttons for direct control via the cloud server.

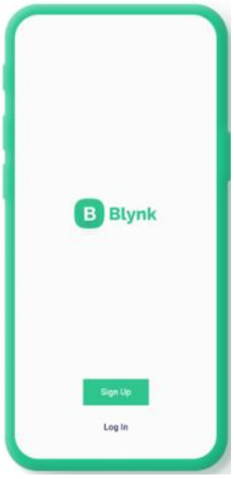


Figure 3.19: user interface(Android Application).

3.5.1 Creating New Templates and Adding New Device

Through Mobile App You may set up the entire Blynk IoT project through Blynk IoT Mobile App

- **Download Blynk IoT and install it from the App Store or Play Store**

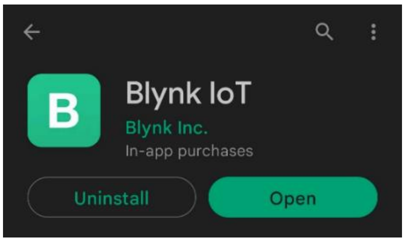


Figure 3.20: Install the BLYNK app.

- **Create a new template as follows:**

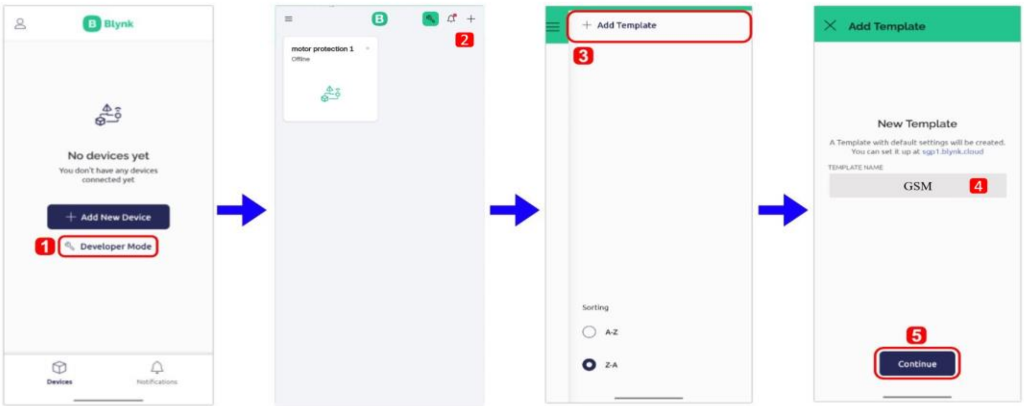


Figure 3.21: Create a new template.

- **After creating a new template**

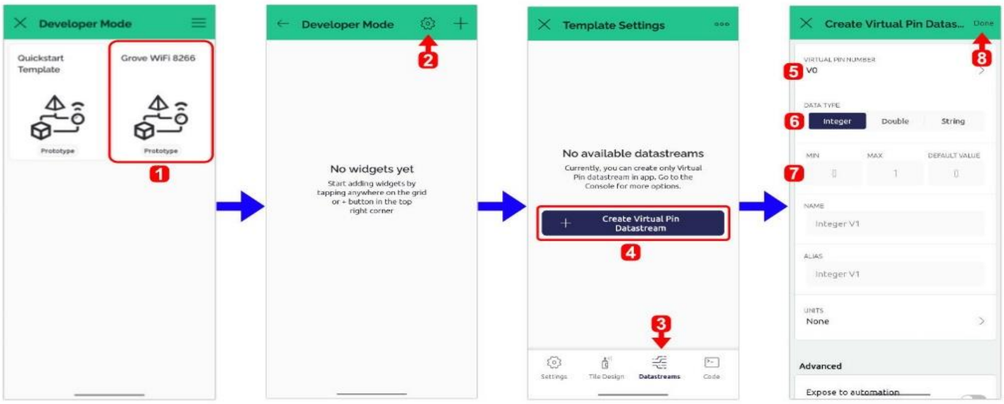


Figure 3.22: Create a new template.

- **Set up tools to set pin for data flow:**

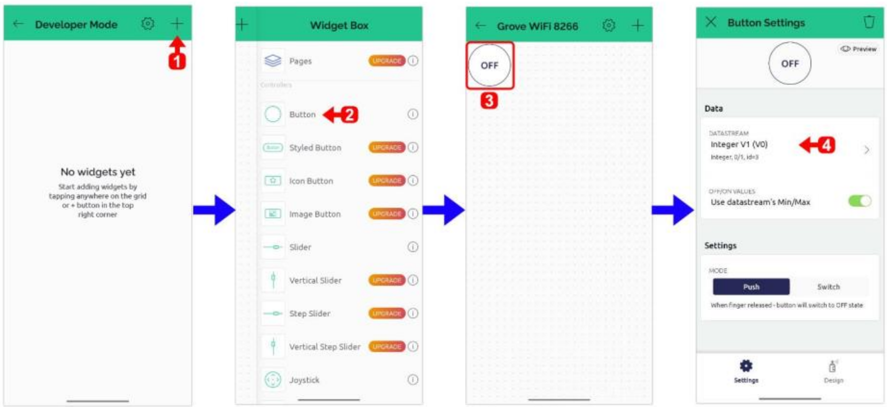


Figure 3.23: To create new data streams for virtual pins.

- **User interface at the end**

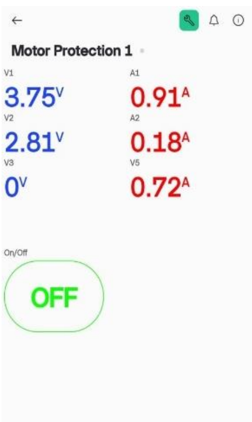


Figure 3.24: User Interface.

3.5.2 Getting the Auth Token

You can only authenticate via the web browser version.

- In a web browser, go to https://blynk.io/ and log in to your account.
- Go to "Search" and select "Your Device."

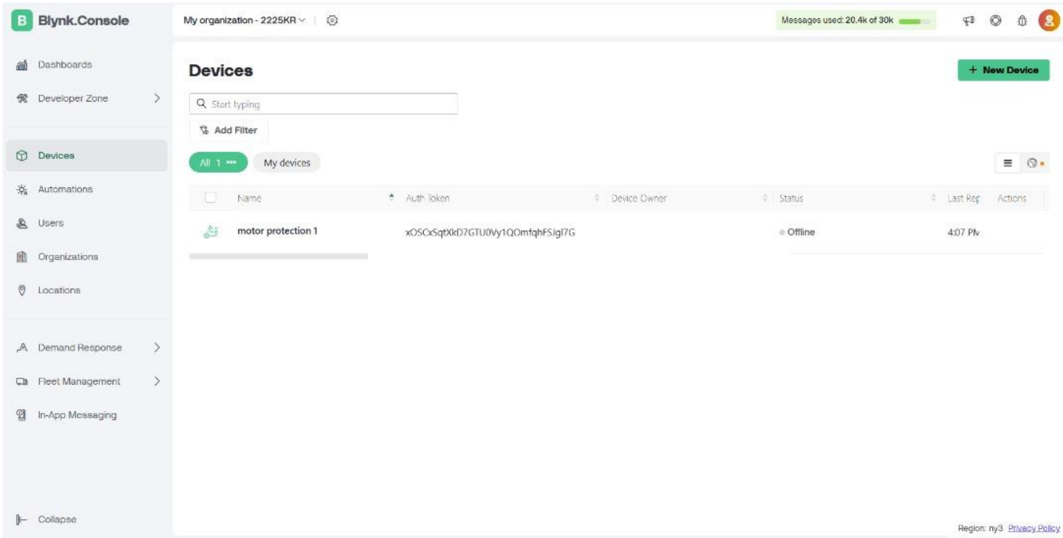


Figure 3.25: BLYNK Web Browser.

You can see your Auth Token and other information about your project under "Device Info":

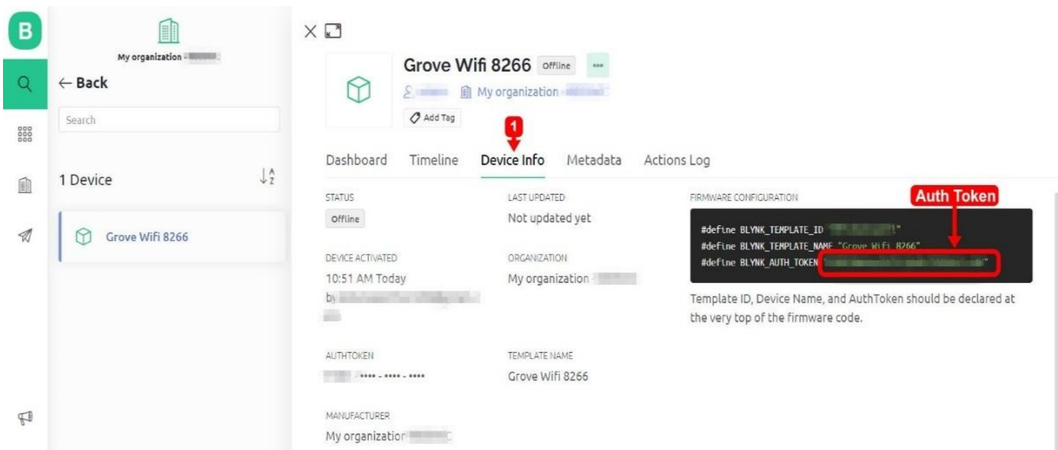


Figure 3.26: Device Info.

Ultimate web browser user interface:

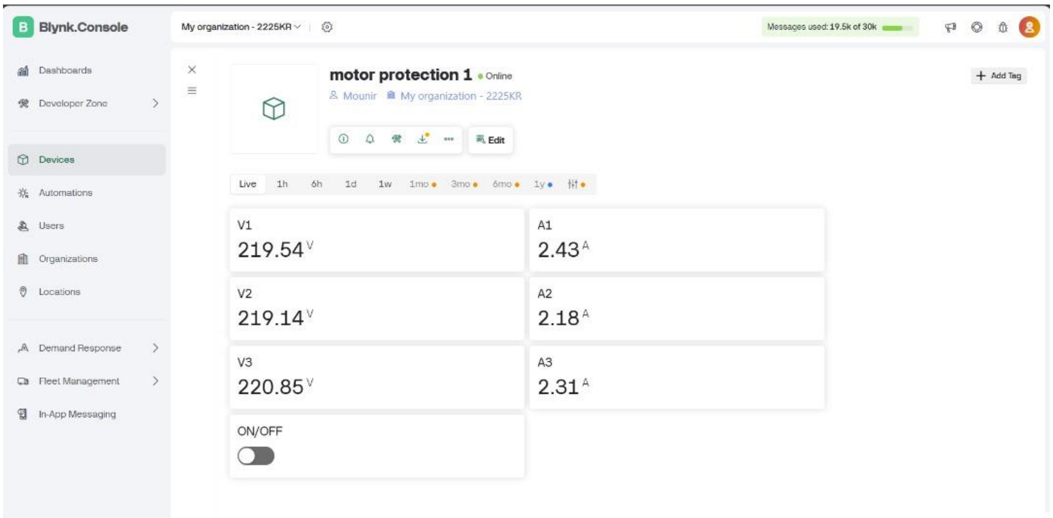


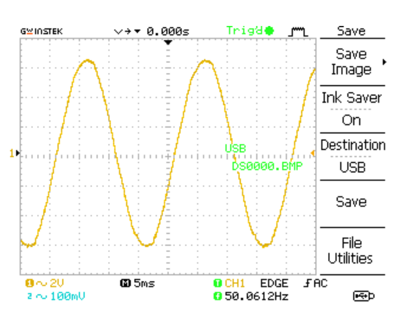
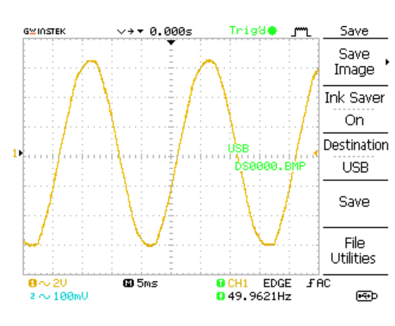
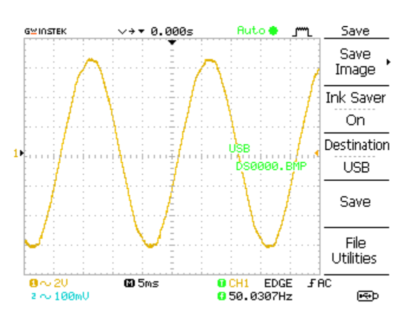
Figure 3.27: Web browser user interface.

3.6 The results and discussion

Voltage balance is critical in power distribution networks due to its impact on electrical loads. Here, we present a field study on motor operation under various power grid conditions, pre-fault detection, and telephone alerts in the event of a pump failure. The pumps operate with voltage balance and an intelligent protection system that extends their lifespan.The following the table (1) shows the signal of a balanced three-phase power system using an oscilloscope. The system test will address the following:

- unbalanced.
- Over Voltage.
- Under Voltage.
- Overload.

Table 3.1: Three-phase 220V balanced system using an electric Oscilloscope.

		
Ph1	**Ph2**	**Ph3**

This work involved the application of the reading system to the BLYNK app under natural conditions. Figure 3.28 observations show that the multimeter and phone readings in the BLYNK app are accurate. This allows us to draw the conclusion that the system can be relied upon and functions effectively in practice.

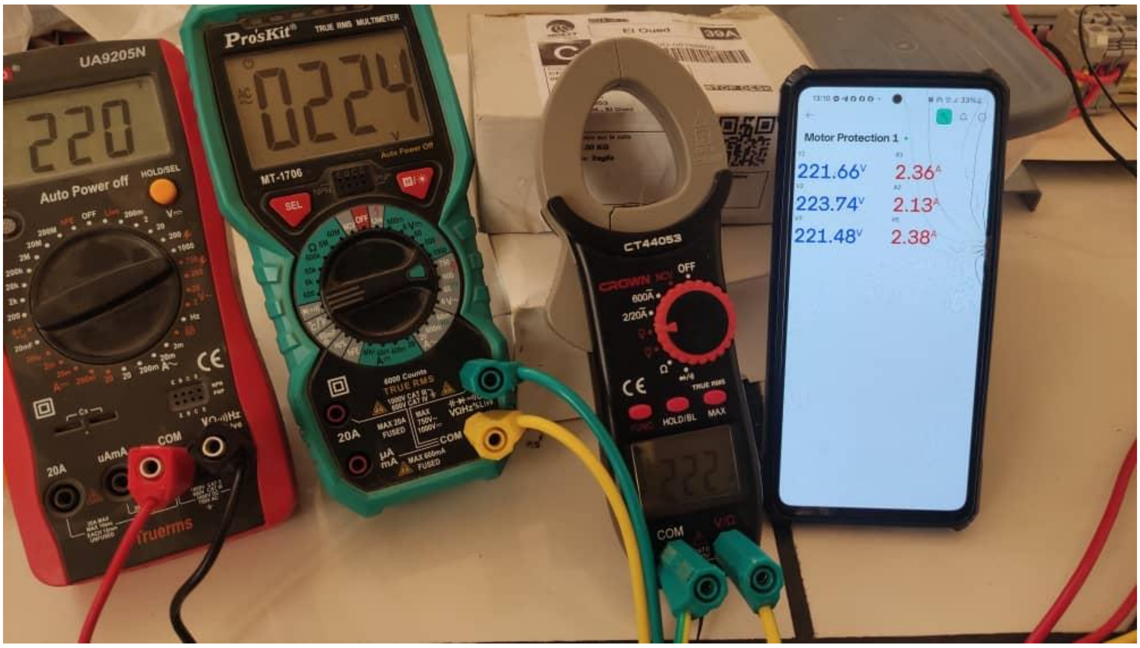


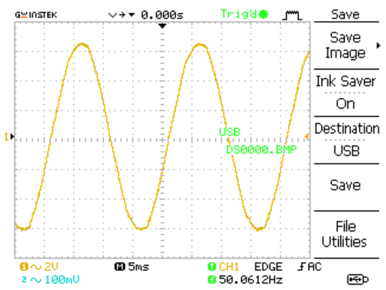
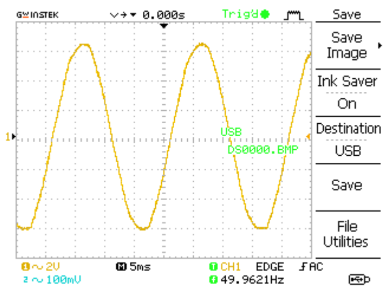
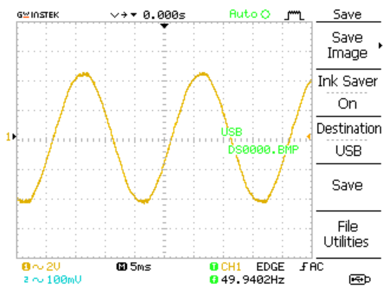
Figure 3.28: System reading on the BLYNK app.

3.6.1 Unbalanced

The operation of a three-phase motor operating at 220 V per phase was tested. The effective voltage (Vrms) was accurately measured using a ZMPT101B sensor connected to an Arduino board. To protect the system from any electrical failures, control logic was implemented in the Arduino IDE that stops the motor immediately upon detecting a phase imbalance via a relay that automatically triggers a motor failure. When this occurs, the SIM800L communication module sends an immediate alert via SMS.

The smart motor monitoring system was tested on a three-phase motor connected to a standard 220 V per phase power supply. To verify performance, an oscilloscope was used to plot the three-phase signals shown in Table (3.2), allowing for waveform and synchronization monitoring. The third-phase voltage (Ph3) dropped significantly, as shown in the results, triggering the built-in protection mechanism and allowing the fault to be identified and the motor to be stopped immediately. This rapid response demonstrates the system's effectiveness in monitoring motor status and responding quickly to problems.

Table 3.2: 220V three phase unbalanced system using oscilloscope.

		
Ph1	**Ph2**	**Ph3**

The figure 3.29 shows an alert status in the BLYNK app on Unbalanced.

Figure 3.29: Unbalanced fault alert.

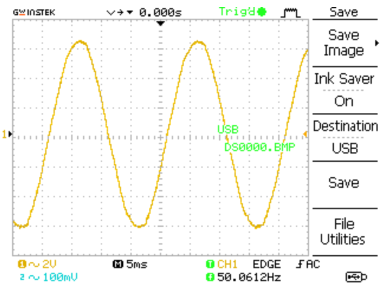
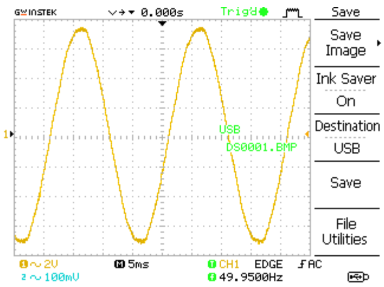
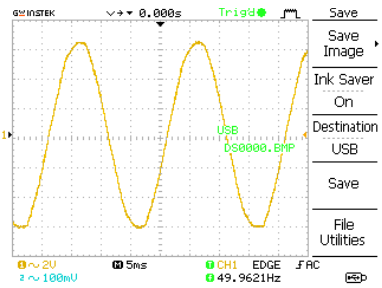
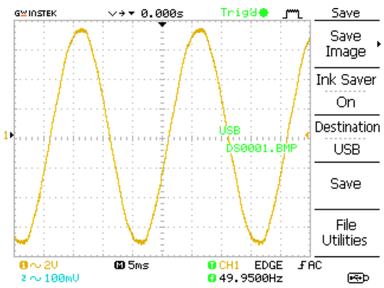
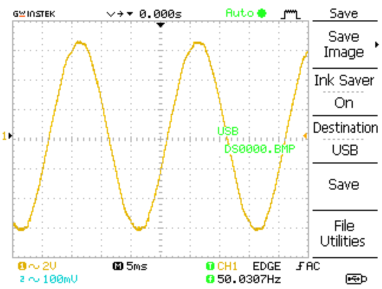
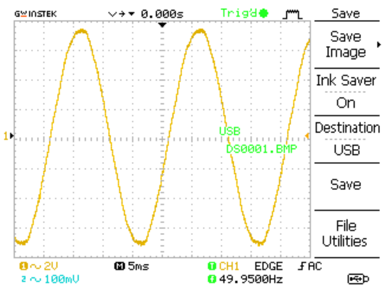
3.6.2 Over Voltage

Using a ZMPT101B sensor connected to an Arduino board, the effective voltage (Vrms) was accurately measured while the motor was operating at a three-phase voltage of 220 V per phase. An oscilloscope was used to track the waveform of the three-phase voltage system on a typical 220 V power supply to check phase synchronization and operational safety, as shown in Table (3).

The motor was powered up, and the voltage (Vrms) reading was tracked using the Arduino IDE via the serial monitor after programming it. The Arduino was configured to automatically shut down when the voltage exceeds the 242 V threshold as a precaution against overvoltage. Once this condition is identified, the SIM800L communication module immediately notifies the specified alarm phone number via a text message.

The voltage was intentionally increased to 250 V to test the effectiveness of the smart motor monitoring system. The system responded as expected, detecting the overvoltage, stopping the motor, and documenting the voltage change through an oscilloscope plot of the signal, as shown in Table (3). As shown in the attached picture, the mobile phone alert is also shown, which records the system functions and quick response to emergencies.

Table 3.3: Oscillation results for 220V three-phase balanced system and 250V overvoltage.

<table>
<tr><th></th><th>220V Three-phase balanced system</th><th>Over Voltage 250V</th></tr>
<tr><td>Ph1</td><td>
</td><td>
</td></tr>
<tr><td>Ph2</td><td>
</td><td>
</td></tr>
<tr><td>Ph3</td><td>
</td><td>
</td></tr>
</table>

The figure 3.30 shows the alarm status of the BLYNK application in case of overvoltage.

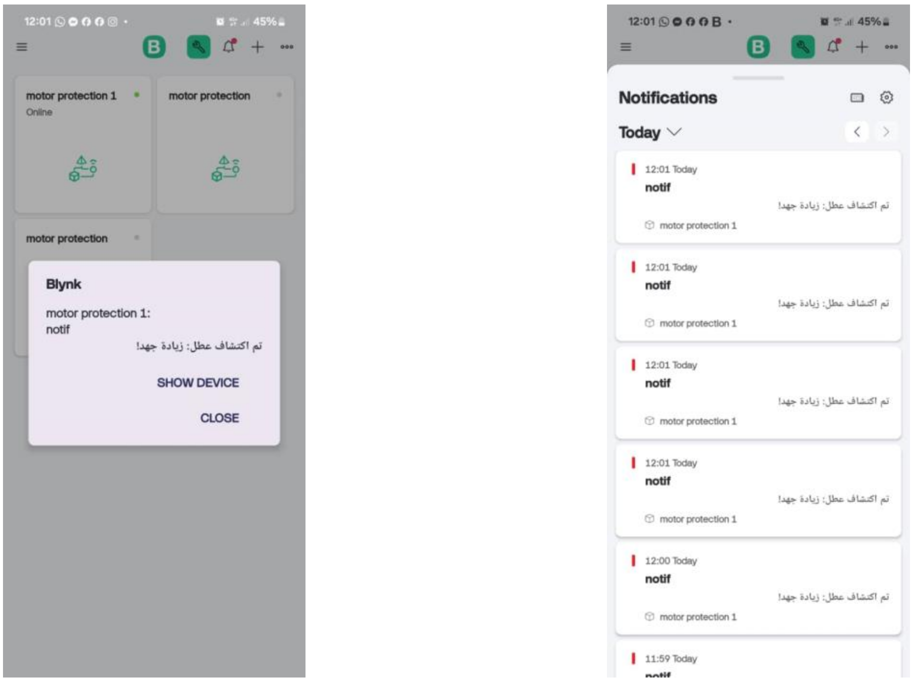


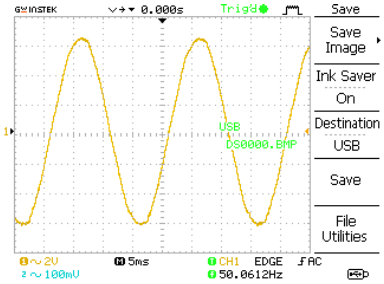
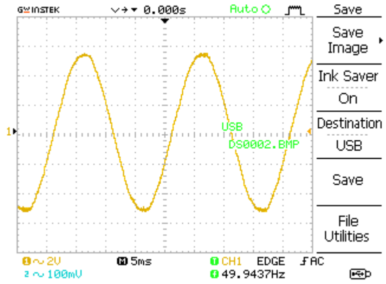
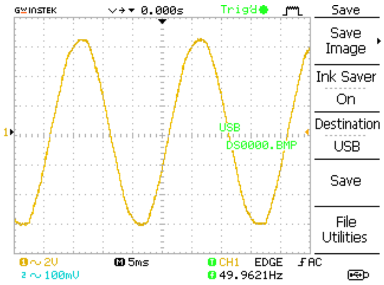
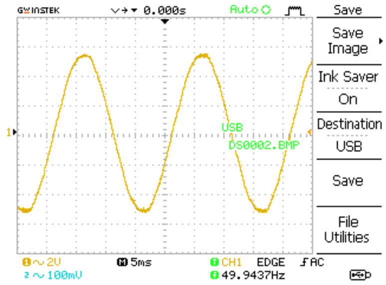
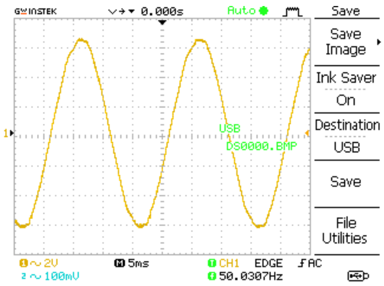
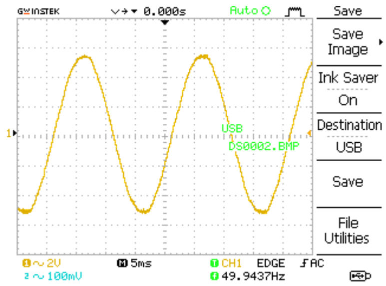
Figure 3.30: Overvoltage fault alert.

3.6.3 Under Voltage

We tested the ZMPT101B sensor connected to an Arduino board. The effective voltage (Vrms) was accurately measured while the motor was operating at a three-phase voltage of 220 V per phase. An oscilloscope was used to track the waveform of the three-phase voltage system on a typical 220 V power supply to check phase synchronization and operational safety, as shown in Table (4).

The motor was powered up, and we tracked the voltage (Vrms) reading using the Arduino IDE via the serial monitor after programming it. The Arduino was configured to automatically shut down when the voltage exceeds 190 V as a precaution against low voltage. Once this condition is identified, the SIM800L communication module immediately notifies the specified alarm phone number via a text message.The voltage was intentionally lowered to below 190 V to test the effectiveness of the smart motor monitoring system. The system responded as expected, detecting the overvoltage, stopping the motor, and documenting the voltage change through an oscilloscope plot of the signal, as shown in Table (4). As shown in the attached image, the mobile phone alert is also shown.

Table 3.4: Oscillation results for 220V three-phase balanced system and Under Voltage 185V.

	220V Three-phase balanced system	**Under Voltage 185V**
Ph1		
Ph2		
Ph3		

The figure shows the alarm status of the BLYNK application in case of Under Voltage.

Figure 3.31: Under Voltage fault alert.

3.6.4 Overload

In the lab, we operated a three-phase motor at 220V. To ensure voltage stability throughout the motor's operation, we tested a 100A/50mA SCT-013 current sensor connected to an Arduino board to measure effective current (Irms). The Irms reading was tracked using the Arduino IDE via the serial monitor after programming. The Arduino UNO and the relay were set to automatically shut down in the event of an overcurrent as a precautionOnce this condition was identified, the SIM800L communication module immediately reported the specified alarm via BLYNK. This experiment was tested by reducing the programming current to 2.5A, as the motor current reaches 3.4A under normal conditions. Upon detecting a current exceeding the programmed value of 2.5A, the motor was immediately stopped via a fault relay, activating the built-in protection mechanism and allowing the fault to be identified and the motor to be stopped immediately. This rapid response demonstrates the system's effectiveness in monitoring motor status and responding quickly to problems.

Figure 3.32: Overload fault alert.

3.6.4 Dry running

In the laboratory, a test was conducted to simulate a dry run condition, one of the common faults that can cause damage to the pump due to the absence of water during operation. To detect this fault, the threshold current value in the program was set to 2.2 A, where readings below this limit are considered an indication of dry running.

To avoid false alarms caused by temporary current fluctuations, the system was programmed to delay the response by 10 seconds after the fault condition persists. During the experiment, the system responded correctly, detecting the fault automatically after the delay period, sending a notification via the Blynk platform, and cutting off power to the pump.

This test demonstrates the system's effectiveness in accurately detecting dry run conditions, minimizing potential mechanical damage, and ensuring stability by avoiding false alerts.

Figure 3.33: Dry running fault alert.

3.7 Discussion of the results of the figures and tables

Table (3.2) and Figure(3.29): Our conclusion is that the system has a voltage unbalanced fault. The suggested monitoring system identifies a voltage unbalanced fault in the motor, automatically shuts down the system, and sends a notification to your phone that reads: "Fault detected: Unbalanced".

Table (3.3) and Figure (3.30): Our conclusion is that the system is experiencing an overvoltage fault. The suggested monitoring system detects the overvoltage condition in the motor, automatically disables the system, and sends a notification to your phone that reads: "Fault detected: Over Voltage."

Table (3.4) and Figure (3.31): Our conclusion is that the system is experiencing an undervoltage fault. The suggested monitoring system identifies an undervoltage fault in the motor, automatically disables the system, and sends a notification to your phone that reads: "Fault detected: Under Voltage."

Figure (3.32): The system shows an overload fault. The suggested monitoring system identifies a motor overload, automatically deactivates the system, and sends a notification to your phone that reads: "Fault detected: Overcurrent."

3.8 Conclusion

In the previous chapter, we covered practical work, where we developed a smart protection system for pumps. The experimental work, conducted in the university laboratory, achieved impressive and excellent results. We relied on current and voltage readings to create a smart system that protects against all faults and provides alert messages when the system fails.

The system architecture, as described in this chapter, includes essential components such as current and voltage sensors, relays, and a robust protection algorithm programmed into an Arduino Uno microcontroller. These components work seamlessly to ensure reliable operation of the three-phase induction motor, while providing immediate feedback and alerts to the user via SMS notifications. One of the system's most important features is its integration with the Internet of Things (IoT), which enhances the ability to track data at any time using a mobile phone and connect multiple users to the system through data entry. We aim to improve the system's protection architecture and enhance our ability to solve environmental problems in the field of electronics.

General conclusion

In this research, we designed, implemented, and tested an intelligent system for the protection and monitoring of agricultural irrigation water pumping systems in real-time using Internet of Things (IoT) technologies. Given the increasing importance of modern irrigation systems, especially in remote and arid areas like southern Algeria, the integration of smart monitoring solutions has become essential to ensure operational efficiency, energy conservation, and system reliability .

We began our work by studying the role of agriculture in Algeria and the urgent need for effective water resource management. We also reviewed the types of pumps and electric motors, and the common electrical faults that affect these systems such as voltage spikes or drops, overload, phase imbalance, and phase reversal .

The proposed solution is a system based on an Arduino board integrated with current and voltage sensors (SCT-013 and ZMPT101B), a GSM communication module (SIM800L), and a smartphone application (Blynk) for remote control and receiving alerts. Laboratory tests have demonstrated the system's ability to accurately detect and respond to electrical faults, ensuring the pump is protected from damage and reducing unexpected downtimes .

In conclusion, the developed system has proven effective in enhancing automation, safety, and management of agricultural irrigation pumps. Its low cost, ease of expansion, and suitability for remote agricultural environments make it a practical solution for farmers and stakeholders looking to modernize irrigation systems and improve water use efficiency.

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