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Development and implementation of a maintenance plan and a remote control system for pumps in industrial electrical systems

Realized by

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ملخص

يركز هذا المشروع النهائي على تطوير وتنفيذ خطة صيانة تنبؤية مدمجة مع نظام تحكم عن بُعد مخصص للمضخات الغاطسة المستخدمة في الأنظمة الكهربائية الصناعية. تبدأ الدراسة بعرض شامل للتقنيات المستخدمة في أنظمة الضخ واستراتيجيات الصيانة، مع التأكيد على الدور الحاسم لتشغيل المضخات بشكل موثوق في مختلف القطاعات الصناعية. بناءً على ذلك، تم اقتراح استراتيجية صيانة محسنة تدمج بين الصيانة الوقائية والتنبؤية بهدف تقليل التوقفات غير المخططة. يعتمد النظام على متحكم دقيق من نوع أردوينو، مزود بمستشعرات كهربائية وحرارية، ومربوط بوحدة الاتصال GSM SIM800L لتمكين المراقبة والتحكم في الوقت الحقيقي. تم تصميم النظام خصيصًا للمضخات الغاطسة، واختباره من خلال نموذج أولي وظيفي. وقد أظهرت النتائج فعالية النظام، وقابليته للتوسع، وكفاءته من حيث التكلفة. يمثل هذا العمل أساسًا واعدًا لدمج حلول صيانة ذكية قائمة على إنترنت الأشياء في البيئات الصناعية.

الكلمات المفتاحية :

المضخات الغاطسة – الصيانة الوقائية – أردوينو – GSM SIM800L – المراقبة عن بُعد – التحكم عن بُعد – المستشعرات الكهربائية – إنترنت الأشياء الصناعي – نموذج أولي وظيفي – الموثوقية – الأتمتة الصناعية.

Abstract

This graduation project focuses on the development and implementation of a predictive maintenance plan combined with a remote control system for submersible pumps used in industrial electrical systems. The study begins with a comprehensive overview of pumping technologies and maintenance strategies, highlighting the critical role of reliable pump operation in various industries. Building on this, an optimized maintenance strategy is proposed, integrating preventive and predictive approaches to reduce unplanned downtime. The system's core is based on an Arduino microcontroller, equipped with electrical and thermal sensors and connected via the SIM800L GSM module for real-time monitoring and control. The implementation is tailored to submersible pumps and tested through a functional prototype. The results demonstrate the effectiveness, scalability, and cost-efficiency of the system. This work provides a promising foundation for integrating IoT-based smart maintenance solutions in industrial environments.

Keywords : Submersible Pumps – Preventive Maintenance – Arduino – GSM SIM800L Module – Remote Monitoring – Remote Control – Electrical Sensors – Industrial IoT – Functional Prototype – Reliability – Industrial Automation.

Résumé

Ce projet de fin d'études porte sur le développement et la mise en œuvre d'un plan de maintenance prédictive, combiné à un système de commande à distance, destiné aux pompes submersibles utilisées dans les installations électriques industrielles. L'étude débute par un état de l'art complet des technologies de pompage et des stratégies de maintenance, en soulignant le rôle essentiel d'un fonctionnement fiable des pompes dans divers secteurs. Sur cette base, une stratégie de maintenance optimisée est proposée, intégrant des approches préventives et prédictives afin de réduire les arrêts non planifiés. Le cœur du système repose sur un micro-

contrôleur Arduino, équipé de capteurs électriques et thermiques, et connecté via le module GSM SIM800L pour assurer la surveillance et le contrôle en temps réel. L'implémentation est adaptée aux pompes submersibles et validée par un prototype fonctionnel. Les résultats obtenus démontrent l'efficacité, l'évolutivité et la rentabilité du système. Ce travail constitue ainsi une base prometteuse pour l'intégration de solutions de maintenance intelligente basées sur l'IoT dans les environnements industriels.

Mots clés : Pompes submersibles – Maintenance préventive – Arduino – Module GSM SIM800L – Télésurveillance – Télécommande – Capteurs électriques – IoT industriel – Prototype fonctionnel – Fiabilité – Automatisation industrielle.

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الإهداء

إلى والديّ الكريمين،
...يا من زرعتما في قلبي الإيمان، وفي عقلي الحكمة، وفي طريقي الصبر
...يا من تحملتما الكثير من أجلي، وكان عطاؤكما بلا حدود، ودعاؤكما نوراً يهدي خطواتي
أهديكما هذا العمل عربون شكر لا يفي قدركما، واعترافاً بجميل لا يُرد
فأنتما الأصل، والدافع، والغاية

إلى أساتذتي الأفاضل،
منارة العلم ومشاعل الفكر،
لكم كل الامتنان على ما بذلتموه من جهد، وما منحتمونا من علم وتوجيه

وإلى أصدقائي الأعزاء،
رفقاء الدرب ومصدر السند في كل المواقف،
...كنتم العون في لحظات التعب، والفرح في لحظات النجاح
لكم مكانة خاصة في القلب لا تقدر بثمن
عمار تجيني

إهداء

...إلى من كان لهم الفضل، بعد الله، في كل خطوة خطوتها
إلى والديّ العزيزين، سندي ونبراسي، اللذين لم يبخلا عليّ بدعائهما، وصبرهما، وحبهما اللا
مشروط، فكانا الدافع الأول، والدعامة الأقوى في هذا الطريق
إلى أساتذتي الكرام، الذين غرسوا فيّ بذور العلم، ووجهوني بإخلاص، وكانوا القدوة في درب
المعرفة
إلى من ساندوني في لحظات التعب، وشجعوني في أوقات الضعف، وآمنوا بي رغم العثرات،
فكانوا نوراً يبديد ظلمة الشك
..إلى كل من ترك في قلبي أثراً جميلاً، ولو بكلمة، أو بسمه، أو دعاء صادق
...أهدي هذا العمل المتواضع إلى كل من كان جزءاً من هذا النجاح
شكراً من القلب، وامتناناً لا يزول.
عبد النور خلفاوي

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List of Acronyms

- **AFNOR** : Association Française de Normalisation
- **ADC** : Analog to Digital Converter
- **AMDEC** : Analyse des Modes de Défaillance, de leurs Effets et de leur Criticité
- **FTA** : Fault Tree Analysis
- **FAST** : Function Analysis System Technique
- **SADT** : Structured Analysis and Design Technique
- **IoT** : Internet of Things
- **GSM** : Global System for Mobile Communications
- **SIM800L** : GSM Module for Serial Communication
- **UNO** : Arduino UNO Microcontroller Board
- **PCB** : Printed Circuit Board
- **LED** : Light Emitting Diode
- **LCD** : Liquid Crystal Display
- **Vcc** : Voltage Common Collector (Power Supply Voltage)
- **GND** : Ground (Electrical Ground)
- **PWM** : Pulse Width Modulation
- **°C** : Degree Celsius
- **SMS** : Short Message Service

General Introduction

In the era of Industry 4.0, the reliability and availability of industrial equipment are essential for maintaining operational continuity and reducing costly downtimes. Among the critical components in many industrial sectors, pumps particularly submersible pumps play a vital role in ensuring the efficient transport of fluids. However, these systems are often subject to wear, electrical faults, and environmental stress, making effective maintenance strategies indispensable.

This graduation project addresses these challenges by developing a comprehensive solution that combines an optimized maintenance plan with a remote control and monitoring system for submersible pumps used in industrial electrical environments. The work begins with a theoretical foundation, examining pump types, functions, and traditional maintenance methods. From this foundation, an optimized strategy is proposed that emphasizes predictive maintenance supported by sensor data.

The practical realization of this strategy is achieved through an Arduino-based system equipped with voltage, current, and temperature sensors. Communication with the user is facilitated by a GSM module (SIM800L), allowing real-time control and fault notification via SMS. This approach ensures early detection of anomalies, minimizes unplanned downtimes, and provides a cost-effective and scalable alternative to conventional systems.

This project serves as both a practical solution for pump control and supervision and a solid base for future enhancements involving IoT platforms, SCADA integration, or web-based interfaces.

This thesis is structured into four chapters as follows :

- Chapter 1 :** presents a state of the art review of pumping systems, with particular emphasis on submersible pumps. It also introduces the fundamentals of industrial maintenance, including its objectives, hierarchical levels, and strategic approaches.
- Chapter 2 :** focuses on the functional analysis of the submersible pump, the identification of potential failure modes, and the design of a structured preventive maintenance plan using reliability and safety analysis tools.
- Chapter 3 :** details the electronic components selected for the development of the monitoring system (Arduino UNO board, sensors, GSM module, relay, breadboard, etc.), and presents the technical specifications of each element.
- Chapter 4 :** outlines the practical implementation of the system, from the electrical schematic to the printed circuit board design (using EasyEDA), through to programming, functional testing, and analysis of the results under various simulated scenarios (operating state, shutdown, and alarm conditions).

Chapter 1

Overview of Pumping Systems and Industrial Maintenance

1.1 Introduction

Pumping systems are essential components in a wide range of industrial applications, particularly in sectors such as agriculture, oil and gas, and wastewater treatment, where fluid and water management is critical. These systems ensure the transportation, distribution, and control of liquids within industrial processes.

This chapter provides a comprehensive overview of pumping systems, highlighting their fundamental roles within hydraulic circuits, their operating principles, and the various pump categories with a focus on positive displacement pumps and centrifugal (turbo) pumps. Special emphasis is placed on submersible pumps, which are commonly used in harsh environments and require dedicated design and maintenance strategies.

In parallel, the chapter introduces key concepts of industrial maintenance, outlining its objectives, classification (corrective, preventive, predictive, and proactive), and levels of intervention. Attention is given to the evolution of maintenance practices, particularly the shift toward more intelligent and anticipatory approaches enabled by advancements in monitoring technologies.

This integrated view of pumping systems and maintenance methodologies sets the foundation for understanding how to ensure operational reliability, minimize equipment downtime, and extend the lifespan of industrial assets.

1.2 Overview of Pumps

Water is fundamental to human life, and throughout history, mankind has developed and refined systems to transport this vital resource from sources such as wells and rivers to residential and industrial areas. In early civilizations, water was transported manually using natural or crafted containers, a method that demanded significant physical effort, especially over long distances and large volumes. The basic principles of fluid transport including those underpinning pump operation were first explored during the Greco-Roman period. However, their practical application remained limited until the emergence of structured human settlements and the increasing need for reliable water supply systems. This context marked the conceptual birth of the pump. In modern hydraulic systems, pumps play a pivotal role, comparable to that of

the heart in the human circulatory system. They generate the flow of hydraulic fluid within pipelines, allowing energy transmission to actuators or hydraulic motors. A pump is therefore essential to any hydraulic circuit, as it provides the mechanical energy required for fluid motion.

More formally, a pump is defined as a mechanical device that imparts hydraulic energy to a fluid, enabling its movement from one location to another under specific flow and pressure conditions[1] [2].

1.2.1 Definition

The term “pump” (derived from the Italian *pompa*) refers to a mechanical device that transfers a fluid from a low-pressure region to a high-pressure region. The primary purpose of a pump is therefore to increase the pressure of the conveyed fluid. From a physical standpoint, a pump converts mechanical energy typically supplied by a motor into hydraulic energy.

This transformation occurs as the fluid passes through the pump, gaining energy in the form of increased pressure and velocity. The total energy imparted to the fluid includes kinetic, potential, and pressure energy components. Thus, a pump effectively generates a pressure differential between its inlet and outlet.

Pumps are vital components in industrial installations, particularly in the oil and gas sector. Their failure can cause significant downtime and reduced productivity, which is why their selection, sizing, and maintenance are of critical importance. Proper pump operation requires both careful engineering design and ongoing maintenance by skilled personnel to ensure long-term reliability and performance.

The energy required for pump operation depends on several parameters, including :

- **Fluid properties** : density, dynamic viscosity.
- **Flow characteristics** : pressure, velocity, volumetric flow rate, and head.
- **System characteristics** : pipeline length, internal diameter, and surface roughness [3] [4].

1.2.2 Role and Functions of a Pump

A pump is a machine that imparts energy to a liquid, enabling it to move from one point to another whether to a higher elevation or to a zone of higher pressure. Pumps are commonly used to :

- Transfer fluid from a lower-level reservoir to a higher-level one.
- Transport liquid from a region of lower pressure to a region of higher pressure.
- Increase the volume flow rate within a pipeline system.

Through these roles, pumps serve as critical enablers in fluid handling applications across various sectors, including water distribution, industrial processing, and energy production.

1.2.3 Principle of Pump Operation

The fundamental operating principle of a pump is based on the generation of a pressure differential between the suction (inlet) and discharge (outlet) zones. This pressure difference is produced by the pump’s active component such as a piston, impeller, or diaphragm which

continuously acts on the fluid. From a physical standpoint, the pump transforms the mechanical energy delivered by its driving motor into hydraulic energy, enabling the fluid to move against gravitational and frictional forces. This energy conversion process is what allows the fluid to flow from a lower-pressure area to a higher-pressure one, ensuring continuous transport throughout the hydraulic circuit [5].

1.2.4 Classification of Pumps

Pumps are generally classified into two major categories based on the principle of fluid displacement and the mechanical behavior of their internal components :

- **Positive Displacement Pumps**, which deliver a fixed volume of fluid per cycle by confining and forcing it through the system.
- **Dynamic Pumps** (also called turbopumps), which impart velocity to the fluid and convert it into pressure.

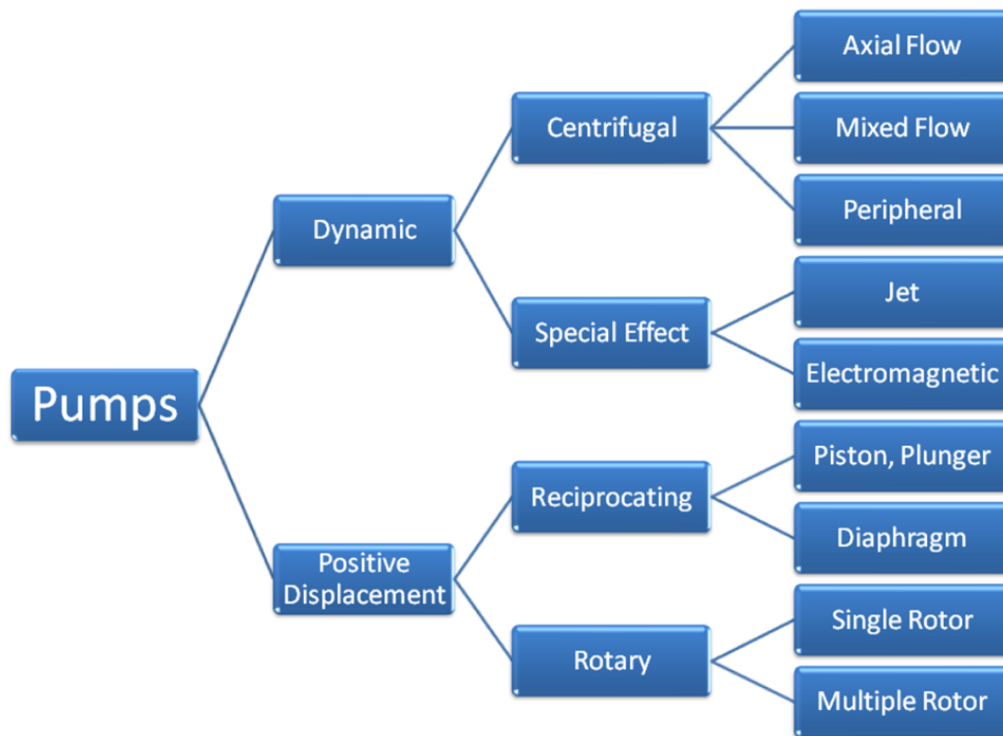


FIGURE 1.1 – General Classification of Pumps Based on Displacement Mode and Operating Principle

Positive displacement pumps are subdivided into reciprocating (such as piston and diaphragm pumps) and rotary types (single or multiple rotor designs). These are typically used in applications requiring high pressure and precision.

Dynamic pumps, on the other hand, are further classified into centrifugal (based on flow direction : axial, radial, or mixed) and special effect pumps (such as jet or electromagnetic types). They are best suited for high-flow, low-viscosity fluids in continuous operation systems.

1.2.4.1 Positive Displacement Pumps

Positive displacement pumps are a class of pumps in which mechanical energy is converted into pressure energy by means of periodic fluid displacement. This displacement is achieved through the mechanical action of components such as pistons, screws, gears, or vanes, which transfer fluid from the suction side to the discharge side in a controlled manner.

These pumps are commonly used in applications that require precise volumetric flow, high pressure, or the handling of viscous or shear-sensitive fluids. Due to their operational characteristics, positive displacement pumps are generally self-priming, capable of handling fluids with entrained gases, and maintain consistent flow regardless of system pressure.

Positive displacement pumps are broadly divided into two main categories :

- Rotary pumps.
- Reciprocating pumps.

Operating Principle

Positive displacement pumps operate based on a cyclic mechanism, in which a fixed volume of fluid is enclosed within a chamber and subsequently displaced towards the outlet. This action results in a continuous transfer of fluid between the suction and discharge ports. Compared to centrifugal pumps, positive displacement pumps :

- Typically achieve higher discharge pressures.
- Offer consistent flow rates, even at varying system pressures.
- Submersible pumps operate with high efficiency, often reaching up to 90% under optimal conditions.

Although their flow rate is generally lower and more pulsating in nature, these pumps are ideal for precision fluid transfer applications and can handle a wide range of viscosities [6].

Rotary Positive Displacement Pumps

Rotary positive displacement pumps utilize a rotating mechanism to transfer fluid from the suction side to the discharge side. The internal rotor(s) move continuously within a fixed casing, capturing and displacing a fixed volume of fluid during each rotation. This configuration allows for smooth and uniform flow, even at varying pressures or with viscous fluids.

These pumps are commonly employed in applications requiring steady, low-pulsation flow, and they perform well with both low- and high-viscosity fluids.

The main types of rotary positive displacement pumps include :

- Gear pumps.
- Vane pumps.
- Lobe pumps.
- Screw pumps.
- Peristaltic pumps.
- Impeller and blade pumps.

Each type has a specific mechanical configuration suited to different operational requirements, as illustrated in Figure 1.2.

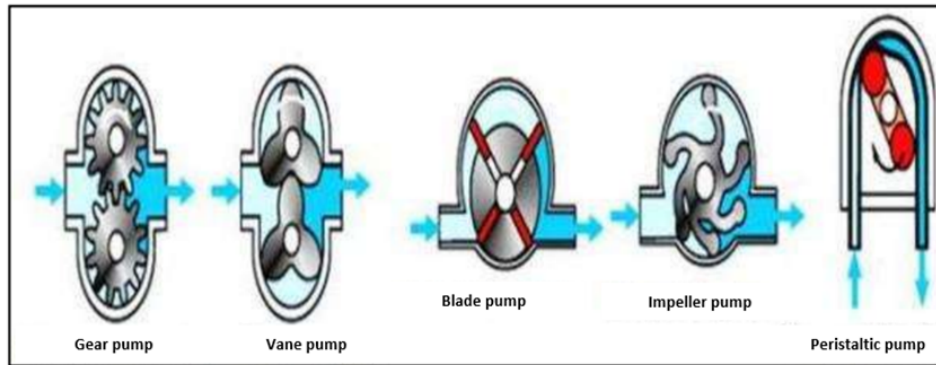


FIGURE 1.2 – Types of Rotary Positive Displacement Pumps [7]

Reciprocating Positive Displacement Pumps

Reciprocating positive displacement pumps operate based on the linear back-and-forth motion of a piston, plunger, or diaphragm within a chamber. This reciprocating motion generates alternating suction and discharge phases that enable the fluid to move through the system.

The suction stroke draws fluid into the chamber through an inlet valve, while the discharge stroke forces it out through an outlet valve. These pumps are ideal for high-pressure and low-flow applications, and they provide precise volumetric control of the fluid.

The main types of reciprocating positive displacement pumps include :

- Piston pumps.
- Diaphragm pumps.

Their operating cycle is illustrated in Figure 1.3, showing the phases of suction, compression, and discharge.

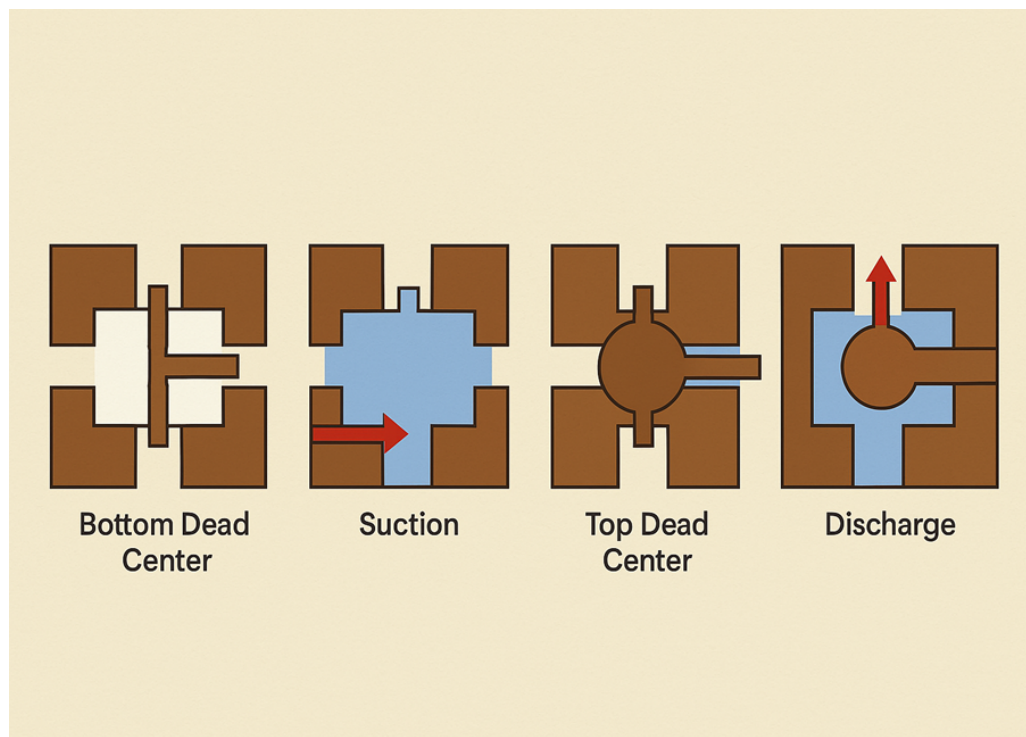


FIGURE 1.3 – Operating Cycle of Reciprocating Positive Displacement Pumps [7]

1.2.4.2 Turbopumps

Turbopumps, a subclass of dynamic pumps, are widely used in industrial systems due to their compact design, continuous flow capabilities, and mechanical simplicity. They operate using a rotary motion without articulated joints, which allows for easy coupling with electric motors or internal combustion engines.

Compared to positive displacement pumps, turbopumps are approximately eight times smaller in size. Their design can be further optimized using a vertical axis, significantly reducing both infrastructure and maintenance costs.

Turbopumps are generally classified into three main types :

- Centrifugal pumps.
- Radial (propeller) pumps.
- Mixed-flow (semi-axial) pumps [6].

Operating Principle

The operation of a turbopump typically involves three key stages :

1. **Suction :**

Fluid is drawn into the impeller via the suction pipe and directed through the diffuser, guiding it smoothly to the impeller eye. As fluid velocity increases, pressure at the center of the impeller decreases, sustaining continuous suction [7].

2. **Acceleration :**

The impeller imparts kinetic energy to the fluid. As it exits the impeller, the fluid enters the volute, where the gradually expanding cross-sectional area begins the conversion of velocity into pressure.

3. **Discharge :**

In the final stage, the diffuser slows the fluid further, completing the transformation of kinetic energy into hydraulic pressure.

This energy conversion process is central to the turbopump's ability to handle large flow rates efficiently and continuously.

Advantages and Disadvantages of Turbopumps

a) **Advantages :**

- Simple mechanical construction with minimal maintenance requirements.
- Moderate initial cost and low long-term maintenance expenses.
- Compatible with a wide range of materials, making them suitable for corrosive or abrasive fluids.
- Compact and lightweight, ideal for space-limited installations.
- High operating efficiency.
- Continuous, smooth fluid delivery.
- Resistant to damage from discharge circuit blockages.

b) **Disadvantages :**

- Not self-priming (requires initial priming).
- Poor performance with high-viscosity fluids.
- Requires precise balancing to reduce vibration and wear [7].

Different Types of Turbopumps

Turbopumps can be classified according to the impeller geometry and the direction of fluid flow relative to the impeller. The main types include :

- Centrifugal Pumps.
- Axial Flow Pumps.
- Mixed Flow Pumps.

- Centrifugal Pumps

Centrifugal pumps are the most commonly used type of turbopumps, operating based on the centrifugal force principle. These pumps use a rotating impeller with curved blades, which imparts velocity to the fluid and subsequently converts it into pressure.

The impeller is enclosed within a pump casing (volute) that contains two main openings :

- **Axial inlet** : located at the center (the eye of the impeller), allowing the fluid to enter the pump.
- **Radial outlet** : located tangentially to the impeller, enabling the fluid to exit the pump after gaining energy.

As the impeller rotates, it draws fluid into its center and accelerates it radially outward using centrifugal force. The high-velocity fluid then enters the volute casing, where its kinetic energy is converted into pressure energy before being discharged.

This mechanism makes centrifugal pumps ideal for high flow rate and low-to-moderate pressure applications, such as water supply systems, irrigation, and industrial circulation processes [8].

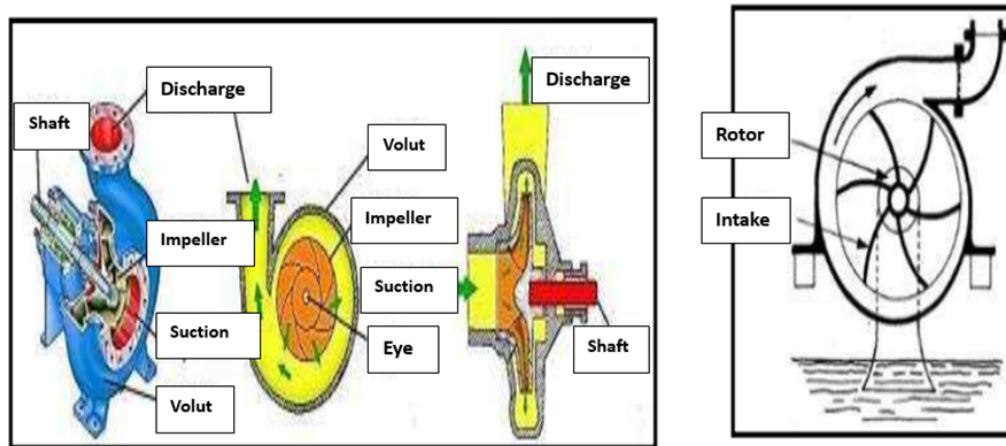


FIGURE 1.4 – Schematic Representation of a Centrifugal Pump [9]

- Axial or Propeller Pumps

Axial flow pumps, also referred to as propeller pumps, are characterized by a flow direction that remains parallel to the pump shaft throughout the entire operation, both at the inlet and the outlet. Unlike centrifugal pumps, which rely on centrifugal force, axial pumps generate pressure primarily through the lifting action of the impeller blades, similar to the function of a boat propeller.

These pumps are best suited for applications involving :

- High flow rates.

- Low head (elevation height).

Typical uses include irrigation systems, cooling water circulation, and flood control.

The impeller imparts velocity to the fluid, causing it to move axially along a cylindrical path, with particles following a helical trajectory. This smooth, linear flow minimizes energy loss and allows efficient handling of large volumes of water with relatively low energy input. [7] [9].

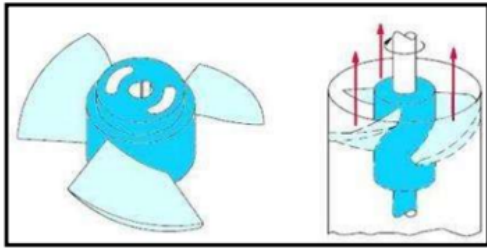


FIGURE 1.5 – Axial Impeller [8]

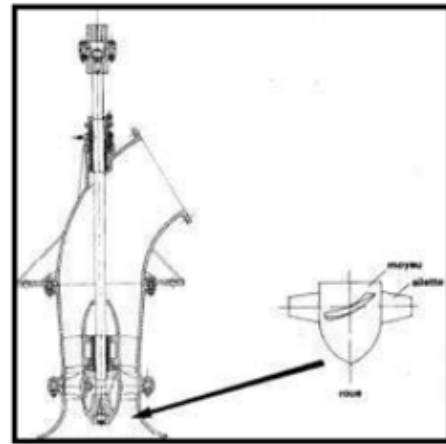


FIGURE 1.6 – Axial Rotary Pump [10]

- Mixed-Flow (Helico-Centrifugal) Pumps

Mixed-flow pumps, also referred to as helico-centrifugal pumps, combine the operating principles of both centrifugal and axial pumps. In these systems, the fluid enters the impeller axially but is discharged at an angle between radial and axial directions, creating a spiral (helical) trajectory.

The impeller is composed of double-curved blades whose geometry is designed to :

- Generate centrifugal force that imparts pressure to the fluid.
- Induce axial lift through the blade inclination, enhancing suction.

This dual-action mechanism allows mixed-flow pumps to achieve a balanced compromise between flow rate and pressure, making them particularly suitable for :

- Moderate head heights.
- Large volume transfers, such as in agricultural irrigation, drainage systems, and water treatment.

Their efficiency is generally higher than axial pumps for medium-head applications, while still maintaining a compact design [7].

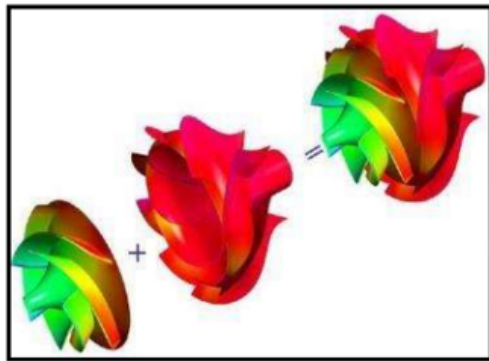


FIGURE 1.7 – Helico-Centrifugal Impeller [8]

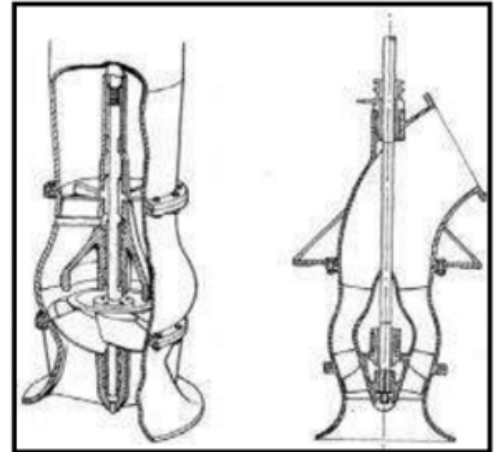


FIGURE 1.8 – Helico-Centrifugal Pump [8]

1.2.4.3 Centrifugal Pumps

A centrifugal pump is a rotary device designed to move liquid by imparting kinetic energy through a rotating impeller (sometimes mistakenly referred to as a turbine). It is the most commonly used type of industrial pump. The fluid enters axially, is accelerated radially by the rotating impeller, and is then discharged tangentially into the volute casing [10].

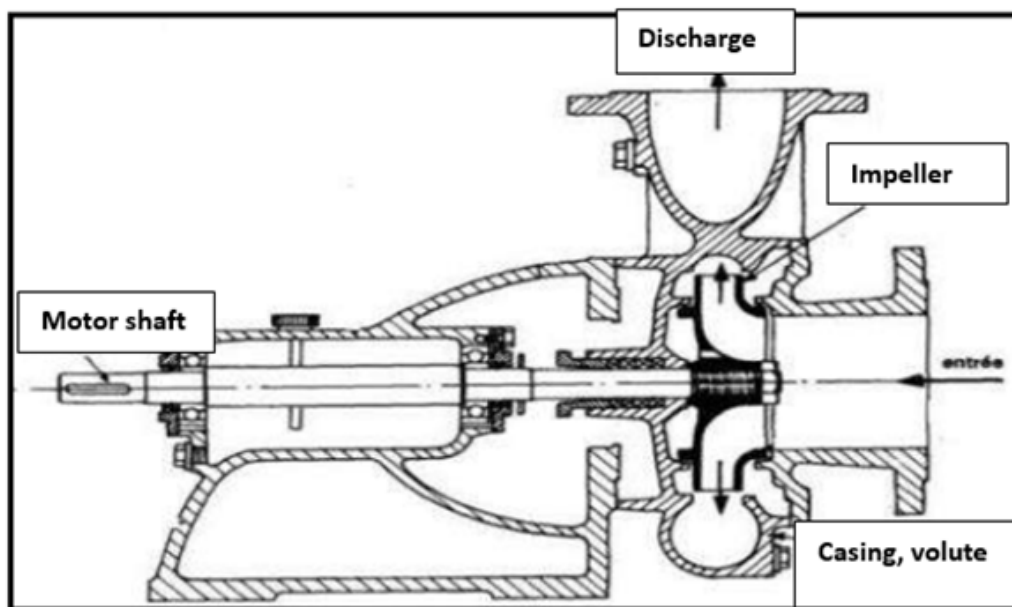


FIGURE 1.9 – Centrifugal Pump [11]

Applications

Centrifugal pumps are widely used in industrial applications due to their broad operational range, simplicity, and low cost. However, there are specific applications where they are unsuitable, such as :

- Pumping highly viscous fluids.
- Handling fluids sensitive to excessive turbulence.

- Applications requiring precise metering, where performance may deviate under non-optimal conditions [11].

Components of a Centrifugal Pump

A centrifugal pump essentially consists of three major parts :

- **The Distributor** : Located upstream of the impeller, it ensures that the fluid enters the impeller smoothly and with the correct orientation. In single-stage pumps, it often appears as a simple inlet pipe.
- **The Rotor (Impeller)** : This rotating component features radial or curved vanes. It converts mechanical energy into kinetic energy by accelerating the fluid.
- **The Collector** : This fixed component collects the fluid discharged from the impeller and redirects it toward the outlet. It is composed of :
 - **The Diffuser** : Reduces the flow velocity and converts kinetic energy into pressure energy.
 - **The Volute** : A spiral-shaped casing that helps equalize pressure and stabilize flow before exit.

This structural breakdown is clearly illustrated in Figure 1.10, which labels each component for better visual understanding.

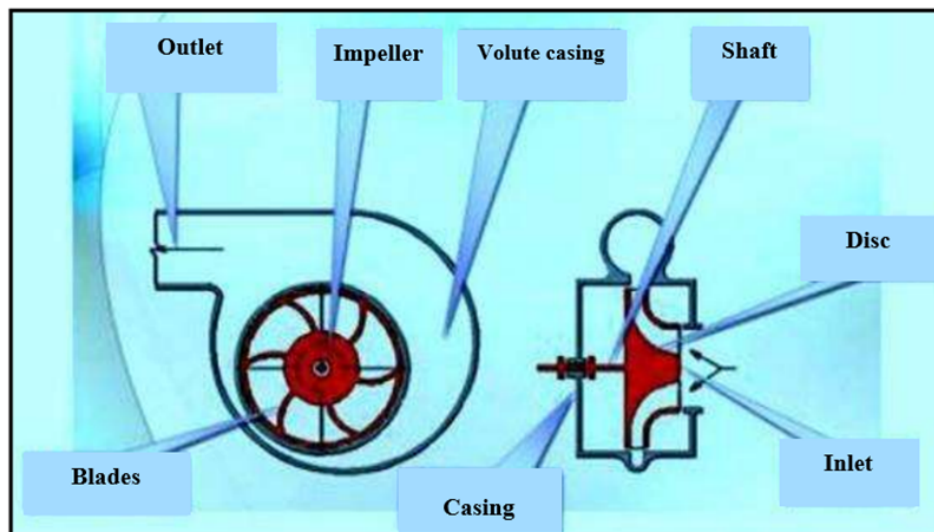


FIGURE 1.10 – Components of a Centrifugal Pump [11]

Operating Principle of a Centrifugal Pump

A centrifugal pump, in its basic form, consists of an impeller with radial vanes rotating within a casing (pump body). Its operating principle relies on the centrifugal force generated by the impeller's rotation to impart energy to the pumped liquid. The liquid enters the pump through the suction inlet and moves toward the center of the rotating impeller (rotor). From there, it is radially propelled outward by centrifugal force. The fluid's velocity is then converted into pressure as it passes through the diffuser [12].

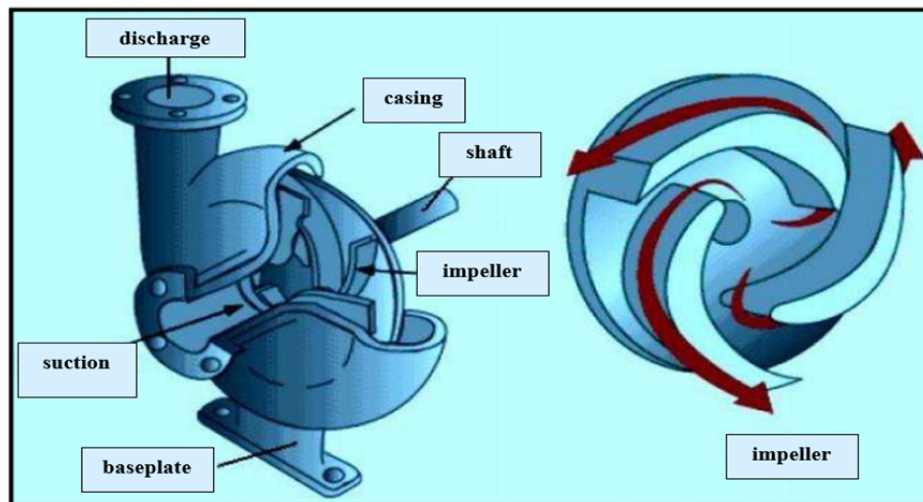


FIGURE 1.11 – Operating Principle of a Centrifugal Pump [13]

The impeller is the main component in radial or semi-axial centrifugal pumps, consisting of two flanges connected by a certain number of blades. In axial pumps, the flanges are absent.

Classification of Centrifugal Pumps :

Centrifugal pumps can be classified in several ways, particularly based on the following criteria :

1) Shape of the Impeller Blades :

- **Radial centrifugal pumps** : In these pumps, the water streamlines are contained within planes perpendicular to the pump's axis.
- **Axial centrifugal pumps** : In these pumps, the water streamlines are aligned with the pump's axis.
- **Semi-axial (helico-centrifugal) pumps** : The water streamlines in these pumps follow surfaces whose meridional section is inclined relative to the pump axis, meaning they are semi-helical (neither purely axial nor purely radial).

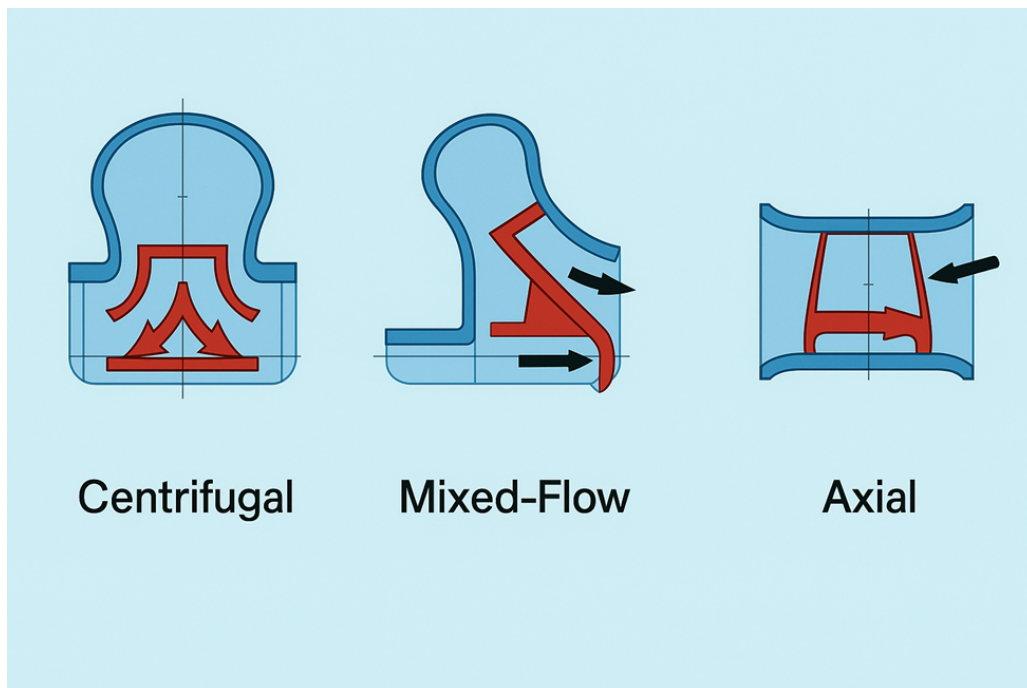


FIGURE 1.12 – Different types of pumps based on fluid trajectory [11]

2) Shape of the Pump Casing :

- **Volute pumps** : These pumps have a casing designed to maintain equal flow velocities around the impeller and to gradually decrease the water velocity at the outlet section.
- **Diffuser pumps (circular or turbine-type)** : These pumps feature a casing with a constant cross-section, concentric to the impeller. The impeller in this case is surrounded by stationary blades that direct the flow and reduce the water velocity, thereby converting kinetic energy into pressure energy.

3) Number of Impellers :

- **Single-stage pumps (monocellular pumps)** : When a pump consists of only one stage, it is referred to as a single-stage (monocellular) pump. It is composed of an impeller and a volute or pump casing, which serves as the pump's diffuser [13].

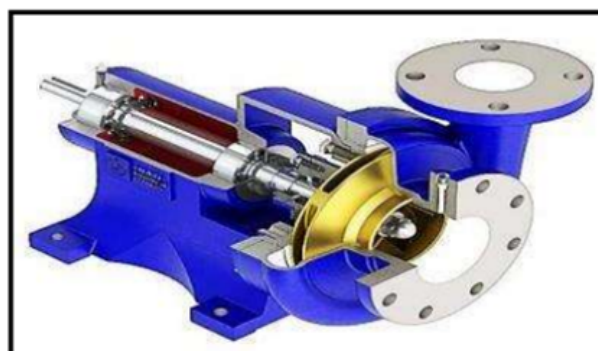


FIGURE 1.13 – Single-Stage Pump [14]

- **Multistage pumps** : These pumps are used when a high discharge pressure is required. Theoretically, a pump with a large-diameter impeller could be used; however, it is generally more cost-effective to use multistage pumps (comprising multiple stages), which consist of single-stage pumps mounted in series on a common drive shaft.



FIGURE 1.14 – Multistage Pump [14]

4) **Axis Orientation** : Pumps are classified based on the orientation of their axis as either horizontal-axis pumps or vertical-axis pumps :

- **Horizontal-Axis Pumps** : This is the most common configuration, generally used for surface pumps. It simplifies maintenance and disassembly.

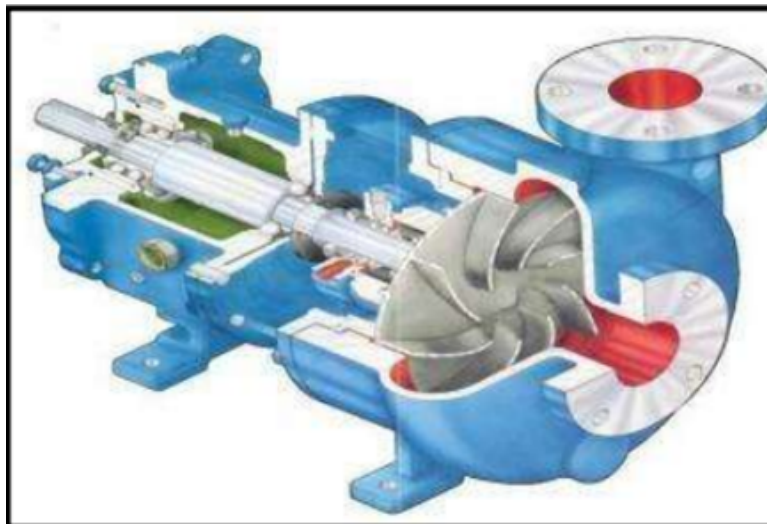


FIGURE 1.15 – Horizontal-Axis Pump [14]

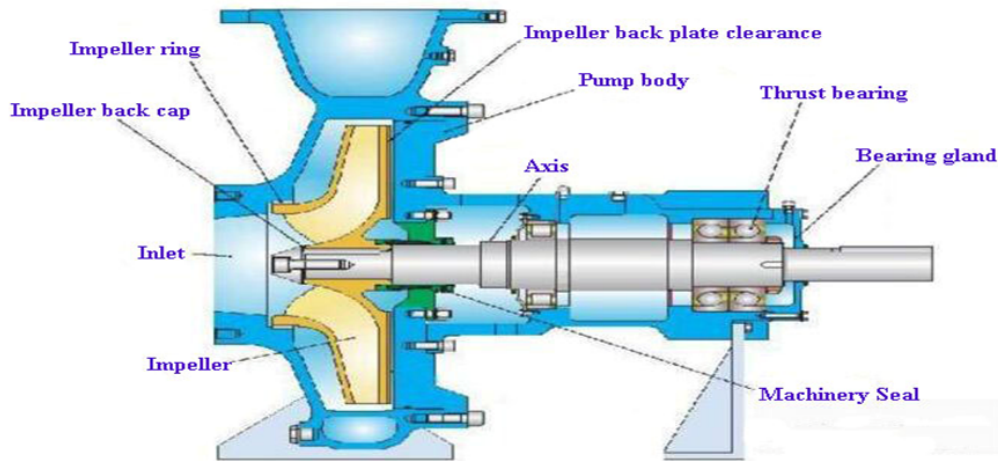


FIGURE 1.16 – Horizontal-Shaft Pump [14]

- **Vertical-Axis Pumps :** These vertical pumps are either submerged or immersed and are specifically designed for deep-well applications [14]. They can be driven by a motor located at the surface or by a submerged motor.



FIGURE 1.17 – Vertical-Axis Pump [15]

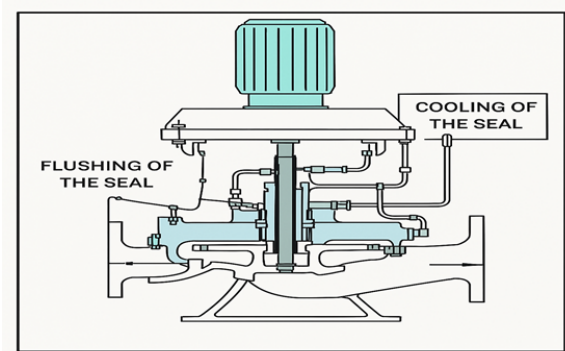


FIGURE 1.18 – Vertical-Shaft Pump [15]

5) Coupling Methods :

- Chain coupling.
- Gear coupling.
- Flange coupling.
- Belt coupling.

6) Drive Mechanisms :

- Electric motor.
- Diesel or gasoline engine.
- Steam or gas turbine.

1.2.5 SUBMERSIBLE PUMPS

1.2.5.1 Definition

A submersible pump is a compact and sealed unit comprising a hydraulic section and an electric motor, specifically designed to operate while fully submerged in the fluid it is intended to pump. This configuration enables direct installation into a pit or well.

The pump is typically connected to the discharge piping via a specialized coupling system that facilitates easy installation, lowering, and retrieval. Alternatively, it may be attached to a flexible discharge hose or pipeline depending on the application.

The power supply is delivered through one or more insulated flexible cables, with lengths tailored to the specific installation depth and requirements [15].

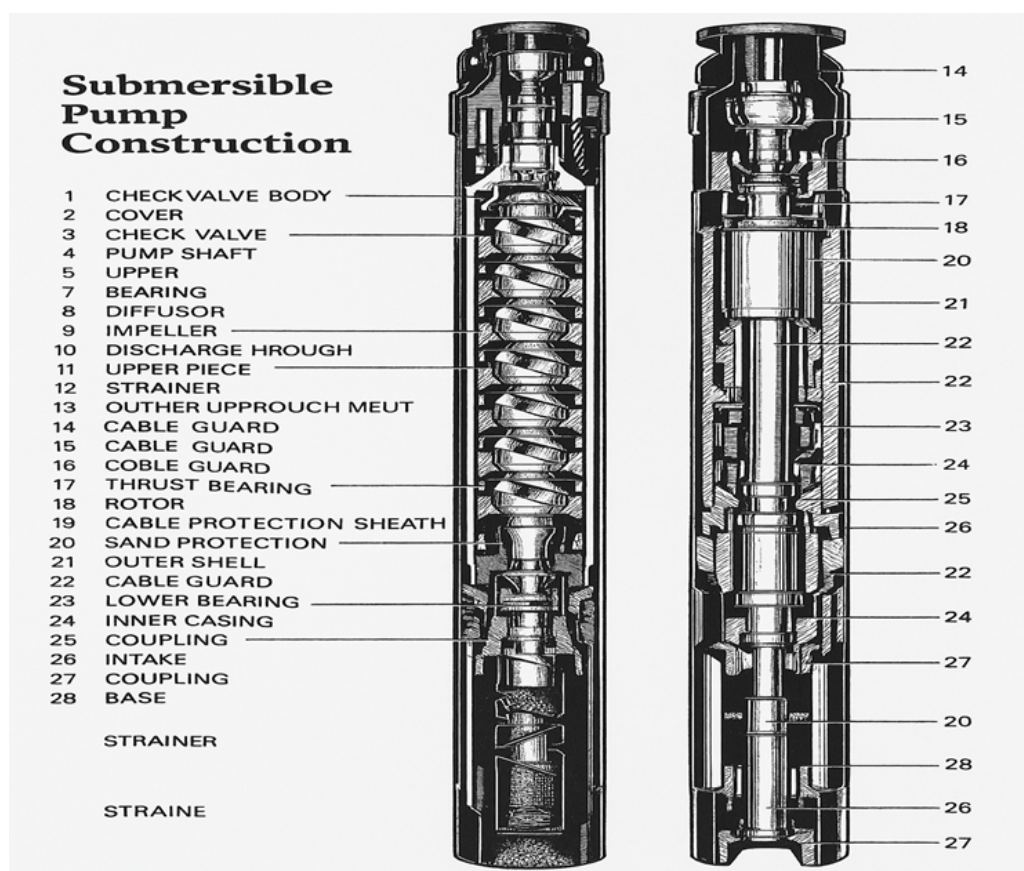


FIGURE 1.19 – Submersible Electro-Pump Units [16]

1.2.5.2 Classification of Submersible Pumps

Submersible pumps can be categorized according to various criteria, primarily based on the configuration of the motor and pump, the depth of application, and the intended use :

Vertically Oriented Submersible Pumps

This configuration includes two main elements : a submerged hydraulic pump located within the borehole, and a surface-mounted motor that delivers the driving power. The pump is actuated via a long vertical shaft, which can be installed either inside or outside the discharge column.

- **Internal shaft configuration** : The shaft is housed within the discharge pipe and is supported by plain bearings, which are lubricated and cooled by the pumped water.
- **External shaft configuration** : Lubrication is managed through a dedicated auxiliary circuit. This type is suitable for medium to shallow wells (typically between 15 and 80 meters). However, for deeper installations, mechanical limitations such as shaft torsion and vibration restrict its viability.

Submersible Electro-Pump Units

In this advanced setup, both the electric motor and the pump are fully submerged within the borehole. This technology allows for greater depth and compact design but comes at a higher cost. The entire unit is suspended within the well using the discharge pipe, with the power cable secured along the pipeline. Motor operation and monitoring are handled via a surface-mounted control panel [16].

Submersible Pump Units

These are high-flow, low-pressure electro-pump units used in wastewater management and drainage applications. The pump and motor operate in either partial or full immersion and are typically placed in specially designed pits.

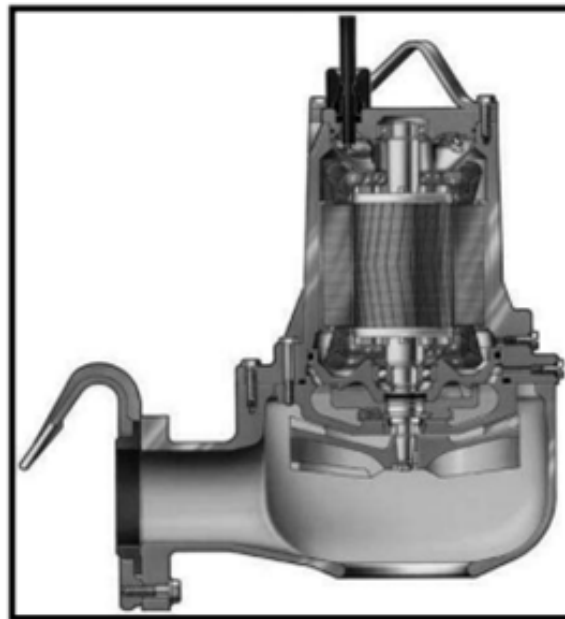


FIGURE 1.20 – A Modern Submersible Pump [17]

Some submersible pumps can be installed in a dry configuration, similar to conventional pumps. This allows for uninterrupted operation even in the event of a dry-pit flooding. Submersible pumps are suitable for a wide range of applications and specific requirements. Additionally, there are specially designed pumps for particular uses. A submersible pump consists of a sealed motor and a hydraulics system adapted to the application.

Submersible borehole pumps can be equipped with either radial or semi-axial impellers. Furthermore, they can have multiple impellers or stages, making them multistage pumps. The stages are typically arranged in series to increase discharge pressure. However, in special cases, mixed configurations (series-parallel) may be used. Manufacturers offer a specific number of stages for

each pump model, with the pump assembly customized according to client requirements. The number of stages is calculated based on the pressure required for the project.

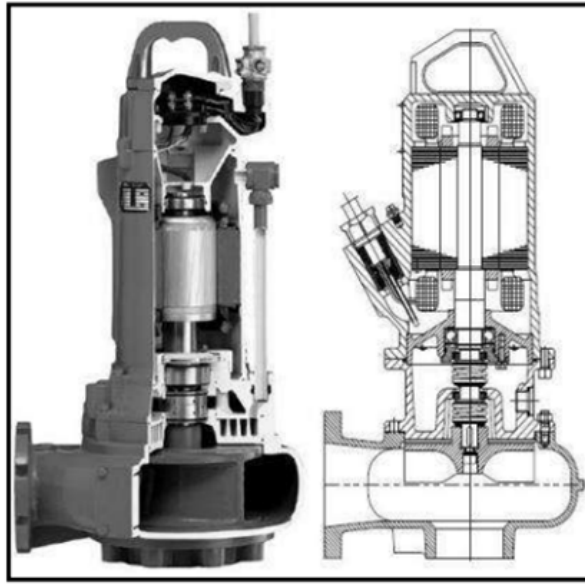


FIGURE 1.21 – Submersible Pump Unit with Single-Channel Impeller [17]

1.3 General Overview of Maintenance

Maintenance plays a vital role in ensuring the performance, reliability, and longevity of industrial systems, particularly for critical equipment such as submersible pumps. By minimizing the risk of failures and optimizing operational efficiency, maintenance contributes directly to reducing downtime and operating costs especially in harsh environments where equipment is exposed to challenging conditions.

This section introduces the foundational concepts of industrial maintenance, including its objectives, challenges, and classification into corrective, preventive, and predictive strategies. It also outlines the historical evolution of maintenance practices, highlighting the shift toward more modern and proactive approaches, made possible by technological advances in condition monitoring and diagnostics.

Particular attention is given to the relevance of maintenance in the context of submersible pumps, which are widely used in sectors such as agriculture, water supply, and wastewater treatment. Ensuring their continuous and efficient operation is essential for maintaining the productivity and sustainability of these systems.

1.3.1 Definition of Maintenance

According to the **ISO 9000 :2015** standard, maintenance is defined as :

“The combination of all technical, administrative, and managerial actions during the life cycle of an asset, intended to retain it in or restore it to a state in which it can perform the required function.” [17]

Likewise, the **AFNOR** standard describes maintenance as :

“The set of technical, administrative, and managerial activities undertaken to maintain or restore an asset, equipment, or system to a condition in which it is capable of performing a required function.” [18]

These definitions emphasize three fundamental aspects :

- **Maintenance** : A proactive process involving continuous monitoring and intervention to ensure the asset remains operational and reliable.
- **Restoration** : Corrective measures taken to repair malfunctions or failures, thereby returning the equipment to its optimal working condition.
- **Specified condition and required function** : A reference to the performance standards and operational criteria that define acceptable functioning of the asset.

This conceptual foundation underlines the dual nature of maintenance : preserving functionality and intervening to recover it when degraded.

1.3.2 Maintenance Objectives

The primary goal of maintenance is to minimize failures and ensure that equipment and production systems operate under optimal conditions. To achieve this, maintenance strategies are designed to meet both financial and operational objectives, as illustrated in Figure 1.22.

a) Financial Objectives :

- Reduce maintenance costs by limiting interventions to what is strictly necessary.
- Maximize profitability by improving equipment availability and minimizing downtime.
- Optimize maintenance investments according to the equipment's age, criticality, and usage conditions.

b) Operational Objectives :

- Ensure proper functioning of machines and systems in real time.
- Guarantee high availability and readiness of equipment.
- Prevent and eliminate failures before they lead to breakdowns.
- Extend the service life of assets by reducing wear and degradation.
- Sustain high performance levels and maintain production continuity.

These dual objectives highlight the strategic role of maintenance in both operational efficiency and cost control.

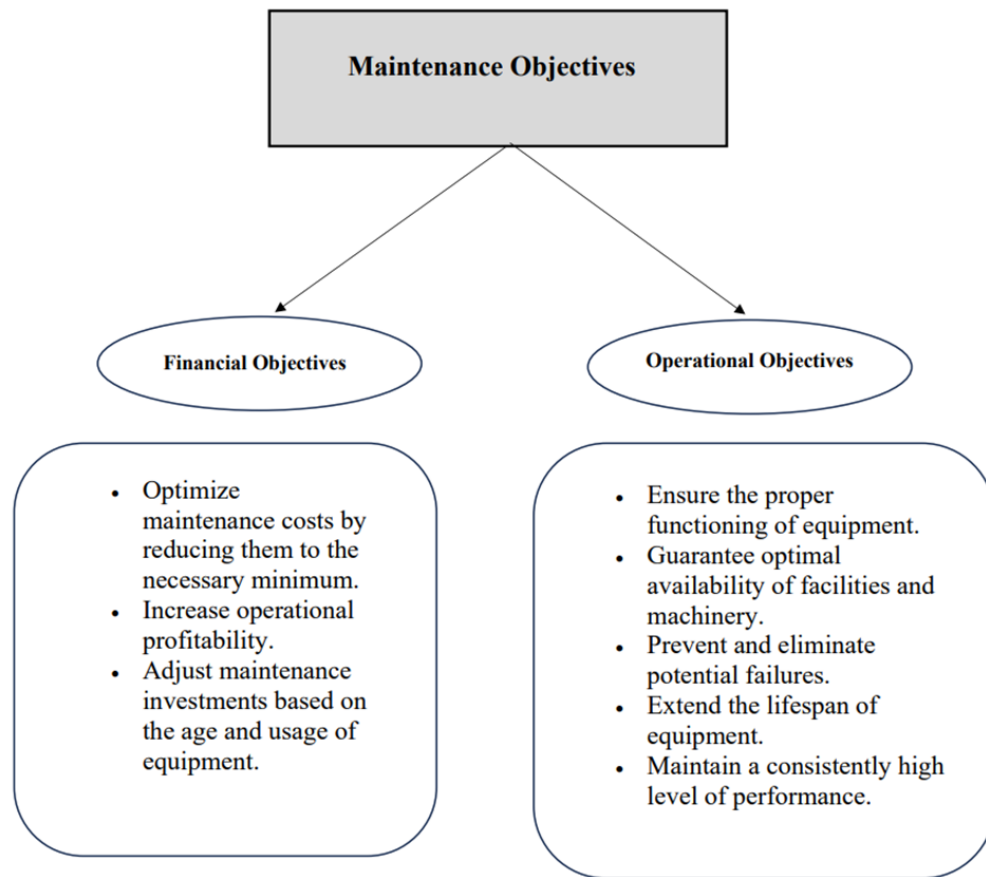


FIGURE 1.22 – Maintenance Objectives [19]

1.3.3 Types of Maintenance

Maintenance is primarily classified into two main types [19] :

1.3.3.1 Corrective Maintenance

According to the AFNOR standard (X 60-010), "Corrective maintenance refers to all maintenance actions performed after the detection of a failure, with the objective of restoring an asset to a state in which it can perform its required functions" [20]. This type of maintenance is subdivided into two main categories :

Curative Corrective Maintenance

Curative corrective maintenance involves definitive repair actions aimed at completely resolving the failure. It focuses on restoring the equipment to its original operational condition by eliminating the root cause of the malfunction. This approach is generally preferred when immediate and complete restoration is feasible and necessary for operational continuity.

Palliative Corrective Maintenance

Palliative corrective maintenance consists of temporary or partial interventions that enable the equipment to operate under minimal acceptable conditions. These actions, such as quick fixes or temporary bypasses, are typically implemented when permanent repairs cannot be immediately carried out due to time, resource, or operational constraints. The objective is to maintain service

continuity until a complete intervention is possible.

1.3.3.2 Preventive Maintenance

According to the AFNOR standard (X 60-010), "Preventive maintenance is maintenance carried out with the intention of reducing the probability of asset failure or the degradation of service quality" [17]. It is a proactive approach designed to ensure the continuous and efficient operation of equipment.

The primary objectives of preventive maintenance include :

- Prolonging the service life of assets.
- Reducing the risk of unexpected failures during operation.
- Minimizing equipment downtime during maintenance interventions.
- Improving the working environment and safety for operational personnel.
- Lowering the overall cost of maintenance over time.

Preventive maintenance is generally categorized into three main types :

Systematic Preventive Maintenance

As defined by the AFNOR standard (X 60-010), systematic preventive maintenance refers to "maintenance performed at predetermined intervals based on time or usage units." This type is implemented regardless of the current condition of the asset and follows a fixed schedule (e.g., every 500 hours of operation or every 6 months).

Conditional Preventive Maintenance

According to AFNOR, conditional preventive maintenance is "maintenance triggered by a pre-determined event, such as self-diagnostics, sensor feedback, or measurement results." This approach relies on monitoring the condition of the equipment and performing maintenance only when specific indicators suggest it is necessary.

Predictive Preventive Maintenance

Predictive preventive maintenance involves scheduling interventions in advance based on forecasts derived from operating time, equipment condition, or usage patterns. Unlike systematic maintenance, this strategy aims to optimize both performance and availability by anticipating failures before they occur.

This approach minimizes unnecessary interventions and helps to prevent serious malfunctions while maximizing the asset's operational efficiency.

Proactive Maintenance

Proactive maintenance represents an advanced form of predictive maintenance. It not only focuses on preventing failures but also aims to identify and eliminate the root causes of potential breakdowns before they manifest.

This methodology relies heavily on data analysis and intelligent decision-making tools to detect warning signs and initiate corrective actions early. It is typically supported by :

- Continuous monitoring of equipment (via sensors, IoT devices, etc.).
- Real-time and historical data analysis.
- Early detection of abnormal patterns and deviations from expected behavior.

The primary objectives of proactive maintenance include :

- Anticipating failures by diagnosing and addressing underlying causes in advance.
- Increasing equipment reliability to ensure smooth and uninterrupted operations.
- Reducing maintenance costs by limiting emergency repairs and unplanned outages.
- Prolonging asset lifespan by minimizing premature deterioration.
- Maximizing system availability through timely and well-targeted interventions.
- Enhancing workplace safety by avoiding sudden and hazardous equipment failures.

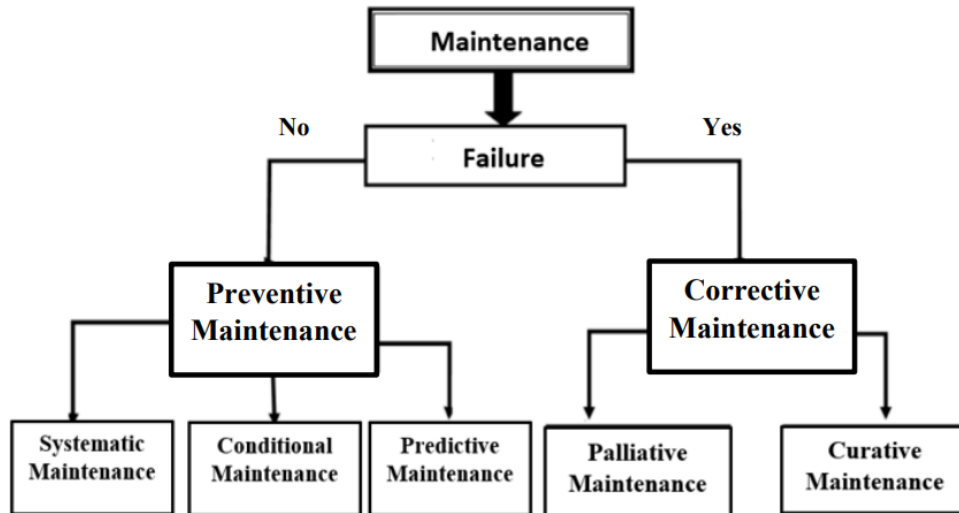


FIGURE 1.23 – Types of Maintenance

1.3.4 Maintenance Operations

Inspections

Inspections are routine monitoring activities typically performed at high frequency, intended to detect early signs of equipment deterioration. These inspections usually do not require tools or production shutdowns. Their primary objective is to ensure daily operational surveillance and prevent minor faults from escalating into major breakdowns [21].

Typical inspection tasks include :

- Lubrication checks (verification, refilling, and oil replacement).
- Monitoring key process parameters (pressure, temperature, vibration, etc.).
- Sensory inspections (visual leaks, unusual smells, abnormal noises).
- Simple corrective actions (minor repairs and adjustments).
- Acoustic analysis (detecting pump cavitation or hydraulic shocks using specialized head-sets).

Preventive Maintenance Checks

These are systematic interventions conducted at fixed intervals according to a predefined checklist. They may require partial or complete disassembly of components and can involve temporary equipment shutdowns. The goal is to detect wear or degradation before failure occurs, thus ensuring long-term operational continuity [21].

Troubleshooting

Troubleshooting refers to immediate interventions on malfunctioning equipment to restore functionality in the shortest time possible. This type of intervention is often applied in critical production environments where planned shutdowns are not feasible. It typically involves diagnosis, temporary repair, or bypass techniques to resume operations quickly [21].

Repairs

Repairs are definitive corrective actions performed after a failure has occurred. They may follow a temporary fix (e.g., after troubleshooting) or be planned as part of a preventive maintenance strategy (systematic or condition-based). Repairs aim to fully restore the equipment's functionality and reliability [21].

Overhauls

Overhauls are comprehensive maintenance interventions carried out after a predefined number of operating cycles or service hours. These activities involve detailed inspections, testing, and major replacements or reconditioning of components. The objective is to avoid critical failures and extend equipment lifespan [21].

Inspections and Compliance Checks

These operations involve verifying the conformity of equipment and processes with established standards, regulations, or internal specifications. Depending on the results, they may lead to :

- Data collection for maintenance planning.
- Decision-making on future maintenance interventions.
- Immediate corrective or preventive actions.

Compliance checks thus contribute to improving equipment reliability and aligning operations with regulatory or safety requirements [21].

1.3.5 Maintenance Levels

The concept of maintenance levels allows for the classification of maintenance tasks based on their complexity, required expertise, tools, and intervention location. This hierarchical structuring enables efficient resource allocation, ensures proper task execution, and facilitates the optimization of maintenance strategies [22]. The five standardized maintenance levels are described as follows :

The different maintenance levels are as follows :

Level 1 : Operator-Level Maintenance

This level is performed on-site by the machine operator and involves basic tasks such as :

- Minor adjustments.
- Visual inspections.
- Cleaning and lubrication.
- Replacement of easily accessible consumables (e.g., filters, fuses).

These tasks do not require specialized tools or deep technical knowledge.

Level 2 :Technician-Level Maintenance (Basic)

Conducted on-site by qualified maintenance technicians, this level includes :

- Simple diagnostics and troubleshooting.

- Standard part replacements (e.g., relays, switches).
- Resetting circuit breakers or safety devices.
- Minor preventive operations based on predefined procedures.

It requires basic tools and limited technical expertise.

Level 3 : Intermediate Maintenance

This level is carried out either on-site or in a dedicated workshop by specialized technicians and includes :

- Fault identification and in-depth diagnostics.
- Advanced corrective maintenance procedures.
- Scheduled preventive interventions involving disassembly and testing.
- Use of technical documentation and precision tools.

Level 4 : Advanced Maintenance

Performed in a specialized workshop by a team with advanced technical expertise, this level involves :

- Complex preventive or corrective maintenance.
- Calibration and verification of precision instruments.
- Testing and validation of system functionality after intervention.
- Use of specialized diagnostic equipment and adherence to rigorous standards.

It typically applies to critical equipment or high-value assets.

Level 5 : Overhaul and Refurbishment

This level includes complete renovation, reconstruction, or major repair operations. It is entrusted to :

- The equipment manufacturer (OEM), or
- An authorized refurbishing entity with equivalent manufacturing capabilities.

These tasks may involve :

- Full disassembly and reassembly of components.
- Structural repair or reengineering.
- Replacement of obsolete subsystems.

Due to their complexity and importance, these interventions must be conducted by highly skilled personnel using certified facilities and methodologies to ensure reliability and safety compliance.

Maintenance Level	Performed By	Typical Tasks	Required Resources
Level 1 : Operator-Level	Machine operator (non-specialist)	Basic checks, cleaning, lubrication, consumables replacement	Basic tools, visual inspection
Level 2 : Technician-Level (Basic)	Qualified on-site maintenance technician	Standard part replacement, simple troubleshooting, resetting breakers	Hand tools, simple diagnostic equipment
Level 3 : Intermediate	Specialized technician (on-site/workshop)	Diagnosis, disassembly, repairs, advanced preventive tasks	Technical manuals, diagnostic tools, workshop equipment
Level 4 : Advanced	Expert technical team (specialized workshop)	Calibration, complex repairs, system validation, component testing	Precision instruments, calibration tools, specialized environment
Level 5 : Overhaul & Refurbishment	OEM or certified refurbishing entity	Complete overhaul, reconstruction, structural repair	OEM-grade tools, full workshop capabilities, certified procedures

TABLE 1.1 – Overview of Maintenance Levels and Associated Requirements

1.4 State of the Art on Remote Monitoring Systems for Submersible Pump Maintenance

1.4.1 Introduction

Remote monitoring of industrial equipment has become a strategic element in modern maintenance practices. In the case of submersible pumps, which are often located in hard-to-reach areas, the ability to remotely track critical parameters allows for early fault detection and reduced intervention costs. The advancement of electronic and communication technologies has enabled the development of compact, cost-effective, and efficient remote monitoring systems.

1.4.2 Technologies Used in Monitoring Systems

The development of remote monitoring systems relies on the coherent integration of several complementary technologies. These technologies enable the measurement, processing, transmission, and real-time interpretation of data, with the primary objective of ensuring the proper functioning of monitored equipment and detecting any anomalies that may lead to failure.

a) Microcontrollers

Microcontrollers form the core of the monitoring system. In this project, the **Arduino UNO** was chosen due to its ease of use, wide support community, and ability to interface with various sensors. It collects data from the sensors (current, voltage, temperature), compares them with predefined thresholds, and triggers alerts via the communication module when necessary.

b) Sensors

Sensors are essential components for monitoring physical and electrical parameters. Each sensor plays a specific role in tracking the operating condition of the pump :

- The current sensor (ACS712) detects overcurrents, which often indicate mechanical blockage or overload.
- The voltage sensor (ZMPT101B) monitors the stability of the power supply, which is critical for proper motor operation.
- The temperature sensor (DS18B20) is used to detect abnormal heating that may result from prolonged operation, insufficient cooling, or electrical faults.

These sensors provide real-time data that are essential for anticipating failures and planning maintenance interventions.

c) GSM Communication Module

The collected data are transmitted using the **SIM800L GSM module**, which utilizes the mobile network to send SMS alerts to operators or maintenance personnel. This technological choice is particularly relevant for remote locations where Internet access (Wi-Fi or 4G) is not guaranteed.

Unlike systems based on IoT platforms or web interfaces, SMS communication ensures robustness and autonomy while remaining simple to implement. Moreover, the operating cost is limited to the SIM card subscription, making the system accessible to low-budget facilities.

d) Power Supply and Protection Systems

The embedded system is powered by a stabilized low-voltage power source that supplies the Arduino, sensors, and GSM module. Electrical protection components (such as diodes, fuses, and decoupling capacitors) may also be integrated to ensure the safety and durability of the circuit, particularly in cases of overvoltage or short circuits.

e) Embedded Software

Finally, the system is driven by an embedded program written in the Arduino language (C/C++), which performs the following operations :

- Periodic sensor readings.
- Comparison of measured values with safety thresholds.
- Generation and transmission of alert messages in case of anomalies.

This software plays a key role in ensuring the autonomous operation of the system, without the need for human interaction during normal functioning.

1.4.3 Existing Works and Similar Prototypes

Numerous academic studies and experimental projects have explored the use of Arduino and GSM modules for the monitoring of electromechanical systems. These projects demonstrate that a simple system based on sensors and an Arduino board can provide essential information on equipment status via SMS alerts. Examples include :

- Monitoring of generators with overheating or overload detection.
- Water level monitoring and pump control in agricultural boreholes.
- Diagnostics of electric motors through SMS alerts when thresholds are exceeded.

1.4.4 Limitations of Conventional Systems

Conventional systems have several drawbacks :

- Lack of connectivity in remote areas makes monitoring difficult without GSM.
- High cost of industrial solutions using PLCs and SCADA systems.
- Limited flexibility for small-scale or local installations.
- Interfaces often designed for complex systems, making them less accessible to field technicians.

1.4.5 Positioning of the Developed Prototype

The system developed in this project offers a simple, affordable, and functional alternative to conventional monitoring solutions. It is characterized by :

- The exclusive use of low-cost components (Arduino, sensors, SIM800L),
- Transmission of essential data via SMS, without the need for Internet access or graphical interfaces,
- A design tailored for remote locations with limited network availability,
- Coherent integration into a preventive maintenance approach, through the transmission of relevant electrical information (voltage, current, temperature).

This type of solution enables technicians to receive key information remotely and to plan interventions without systematic travel, thereby improving the responsiveness and reliability of the maintenance system.

1.5 Conclusion

This chapter has presented a comprehensive overview of the role and significance of pumps in industrial systems, with a particular emphasis on submersible pumps, which are tailored to meet stringent technical and environmental requirements. The wide variety of pump types, their operating principles, and application domains highlights the necessity of informed selection and tailored maintenance strategies.

From a maintenance perspective, ensuring that equipment remains in optimal working condition is not merely a technical requirement—it is a strategic priority. The evolution from basic corrective maintenance to more advanced predictive and proactive approaches reflects a growing emphasis on efficient and intelligent asset management.

Incorporating these maintenance methodologies into the operation of pumping systems is essential to :

- Guarantee service continuity,
- Enhance overall system performance,
- Reduce long-term operational and maintenance costs.

Ultimately, effective maintenance strategies directly contribute to the reliability, safety, and sustainability of industrial operations.

Chapter 2

Design and Deployment of an Optimized Maintenance Strategy : Application to Submersible Pumps

2.1 Introduction

Industrial systems depend heavily on critical equipment such as submersible pumps, whose availability and reliability are vital for ensuring operational continuity. However, due to their operation under harsh environmental and mechanical conditions (such as submersion, mechanical stress, and flow fluctuations), these pumps are subject to frequent failures, which can lead to significant operational and financial consequences. Traditional reactive maintenance, which intervenes only after failures occur, has proven insufficient in reducing production downtime and associated costs.

This chapter aims to develop an optimized maintenance plan for submersible pumps by integrating a proactive strategy based on risk analysis and predictive monitoring with a systematic approach that includes both scheduled and condition-based maintenance actions.

To achieve this objective, the methodology is structured into three main phases :

1. **Functional analysis**, using tools such as the Octopus Diagram, SADT, and FAST, to identify system requirements and technical interactions.
2. **Failure mode and risk analysis**, leveraging tools such as FMECA, Ishikawa diagrams, and Pareto charts, to prioritize failure risks and guide critical maintenance decisions.
3. **Implementation of a maintenance plan**, including both preventive and corrective maintenance procedures.

This structured approach establishes a solid foundation for the following chapter, which addresses the design and implementation of a remote control system, thus bridging theoretical insights with practical industrial applications.

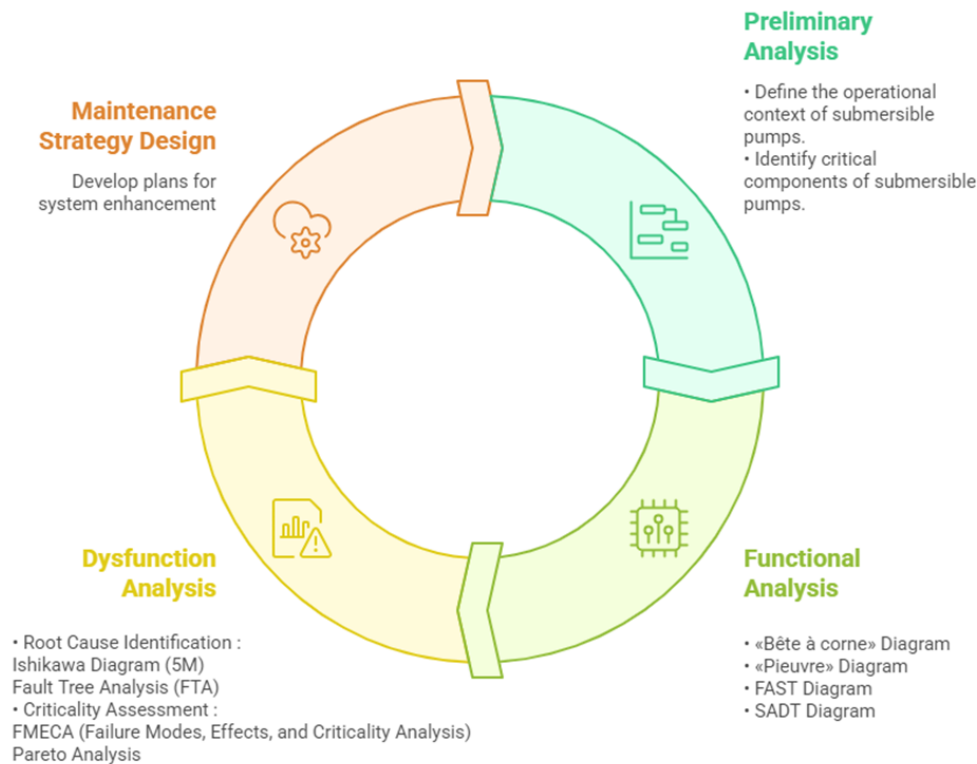


FIGURE 2.1 – Analysis Procedure

2.2 Technical Overview of Submersible Pumps

This section introduces the main system under study : **the submersible pump**, which is commonly used to extract water from wells or aquifers and deliver it to storage tanks or distribution systems. A detailed overview of its key components will be presented, followed by an analysis of its operation based on functional analysis tools and methodologies.

2.2.1 Structural and Functional Description of Submersible Pumps

Submersible pumps are electromechanical devices specifically designed to operate entirely while submerged in liquid. They are typically installed in deep boreholes or wells and are tasked with transporting water from underground sources to the surface.

Each pump unit consists of a hermetically sealed electric motor coupled directly to a hydraulic stage. The motor, located beneath the impeller assembly, drives the rotation of the impellers, which generate kinetic energy to lift the water through a delivery pipe.

One of the main advantages of submersible pumps is that they do not require priming, as they operate fully immersed in the fluid. This design reduces the risk of cavitation and improves

efficiency.

To ensure operational safety and longevity, these pumps are generally equipped with :

- **Non-return (check) valves**, to prevent backflow.
- **Temperature and water level sensors**, for environmental monitoring.
- **Dry-run protection**, to avoid damage during low water conditions.

Pump selection is typically based on multiple parameters, including the depth of installation, required flow rate, total dynamic head, and water quality (clean, sandy, or containing solids).

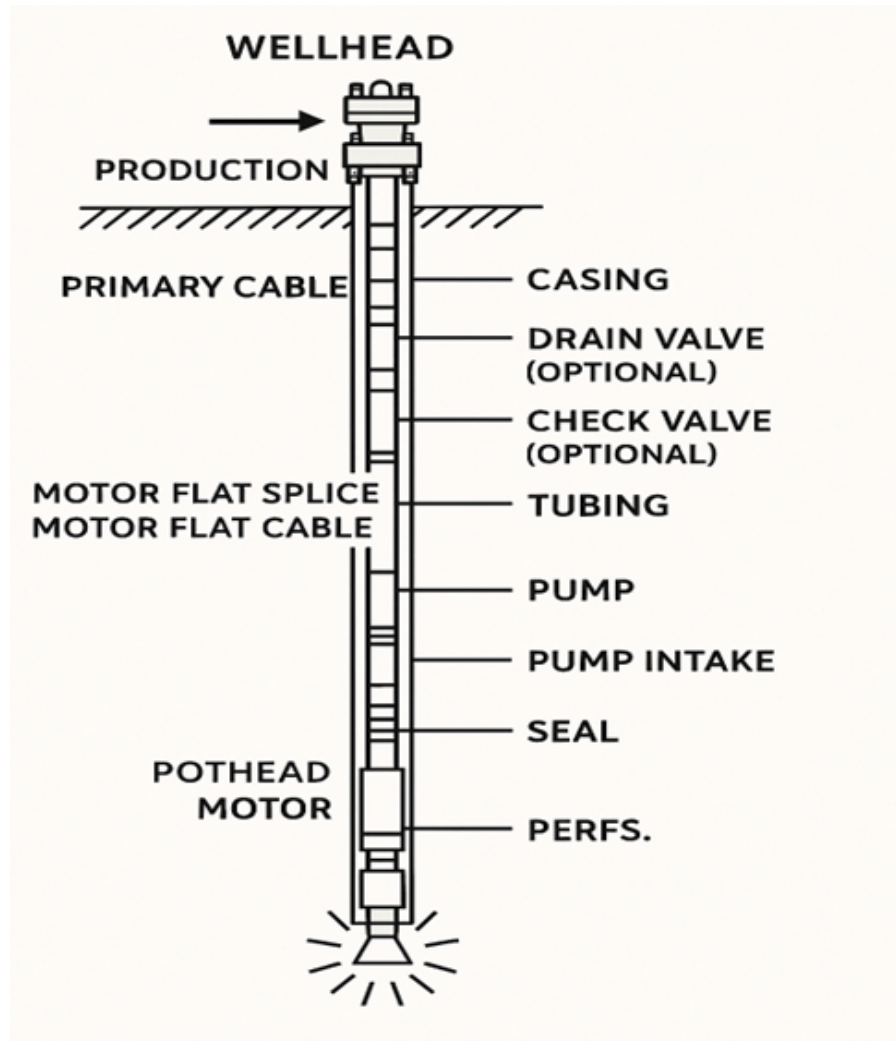


FIGURE 2.2 – Schematic Overview of a Submersible Pump Installed in a Borehole [16]

2.2.2 Description of the Main Components of a Submersible Pump

This section presents the key components that constitute a typical submersible pump, focusing on both its hydraulic and mechanical assemblies. Each element plays a vital role in the efficient and reliable operation of the system :

- **Impeller (Turbine) :**
The impeller is the primary rotating component that transmits kinetic energy to the fluid through its blades (vanes). It is responsible for increasing the fluid's velocity as it exits the suction chamber.
- **Diffuser :**
Acting as the stationary casing of the pump, the diffuser collects the high-velocity fluid

- discharged by the impeller and converts a portion of this velocity into pressure. In multistage pumps, it also redirects the fluid toward the next impeller stage.
- **Suction Chamber :**
The suction chamber, often integrated with the pump casing, directs the incoming fluid toward the impeller inlet while maintaining uniform velocity distribution, thus minimizing turbulence and hydraulic losses.
 - **Drive Shaft :**
The drive shaft is the main mechanical axis of the pump, typically fabricated from steel or stainless steel. It transmits torque from the motor to the impellers and is dynamically balanced to minimize vibrations. Keyways along the shaft secure the rotating components in place.
 - **Keyways :**
Keyways ensure a secure rotational connection between the drive shaft and the impellers or spacers, maintaining mechanical integrity during high-speed operation.
 - **Wear Rings :**
Wear rings are precision-fitted components that separate the rotating and stationary parts of the pump. They help maintain hydraulic efficiency by minimizing internal leakage between low-pressure and high-pressure zones and protecting the casing from abrasion.
 - **Spacers :**
Spacers are rigid cylindrical elements installed between impellers in multistage pumps. They ensure consistent axial spacing and alignment of the rotating components.
 - **Coupling :**
The coupling connects the pump shaft to the motor shaft. Typically made from stainless steel, it allows for easy disconnection during maintenance operations and absorbs minor misalignments.
 - **Non-Return Valve (Check Valve) :**
This valve ensures unidirectional flow of the fluid, preventing backflow into the system when the pump is stopped. It is often installed at the pump outlet for system protection [23].

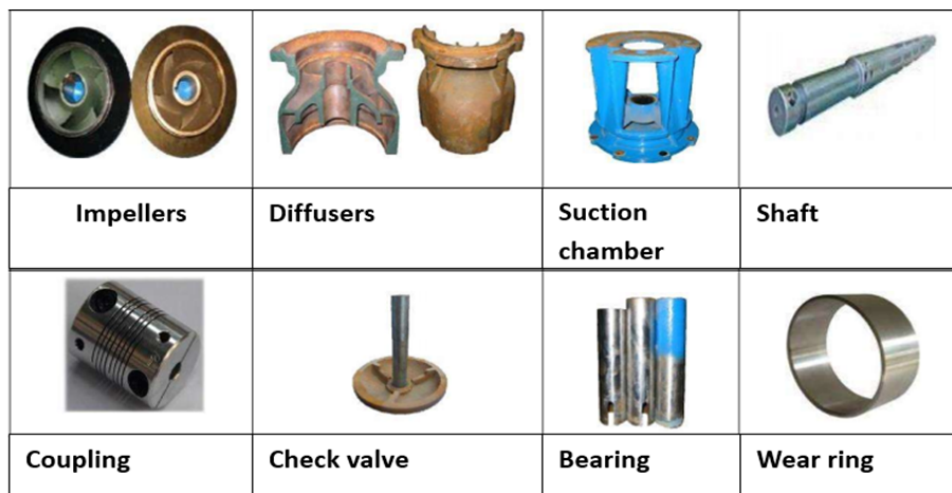


FIGURE 2.3 – The key Components of a Submersible Pump

2.3 Functional Analysis of the Submersible Pump

This section applies the principles of functional analysis to the system under study, namely the submersible pump. The goal is to formally define the functional needs and expectations that the system must satisfy, thereby providing a structured foundation for the subsequent design and maintenance phases.

2.3.1 Identification of System Requirements Using the Horned Beast Diagram

The **Horned Beast Diagram** (Diagramme de la Bête à Cornes) is a widely used tool in functional analysis. It helps to identify the fundamental requirements and motivations behind the existence of a technical system by answering three guiding questions :

Questions	Answers
Who is the system intended for ?	The water distribution network
What does the system act upon ?	Underground water
Why does the system exist ?	To extract and deliver water under pressure

TABLE 2.1 – Functional requirements identified through the Horned Beast Diagram

2.3.2 System Need Identification Using the Horned Beast Diagram

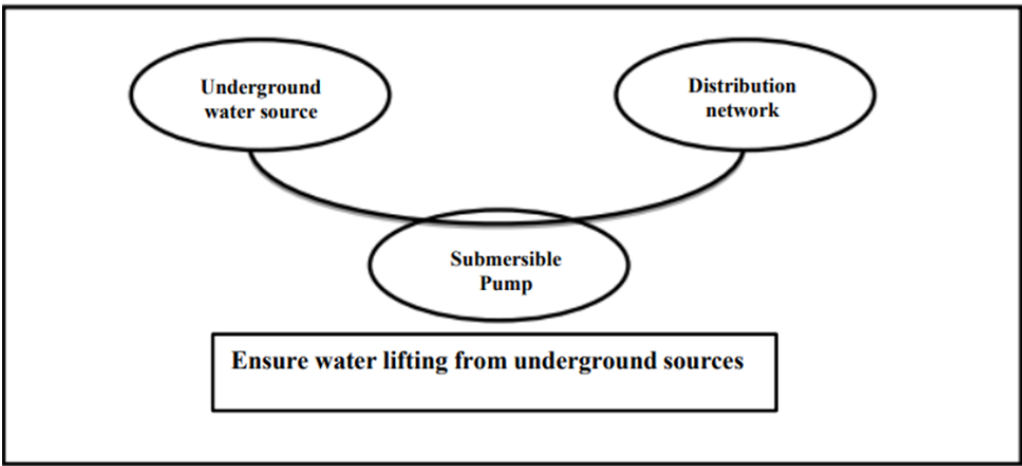


FIGURE 2.4 – Horned Beast Diagram of the Submersible Pump

2.3.3 Octopus diagram of the Submersible Pump

The **Octopus Diagram** is a functional analysis tool used to identify and categorize the external interactions and service functions of a technical system. In the context of the submersible pump, it illustrates the various physical and functional relationships between the pump and its surrounding environment. As shown in Figure 2.5, the submersible pump interacts with several

external entities such as the storage tank, electrical network, operator, and environmental conditions, each corresponding to a specific function to be fulfilled by the system.

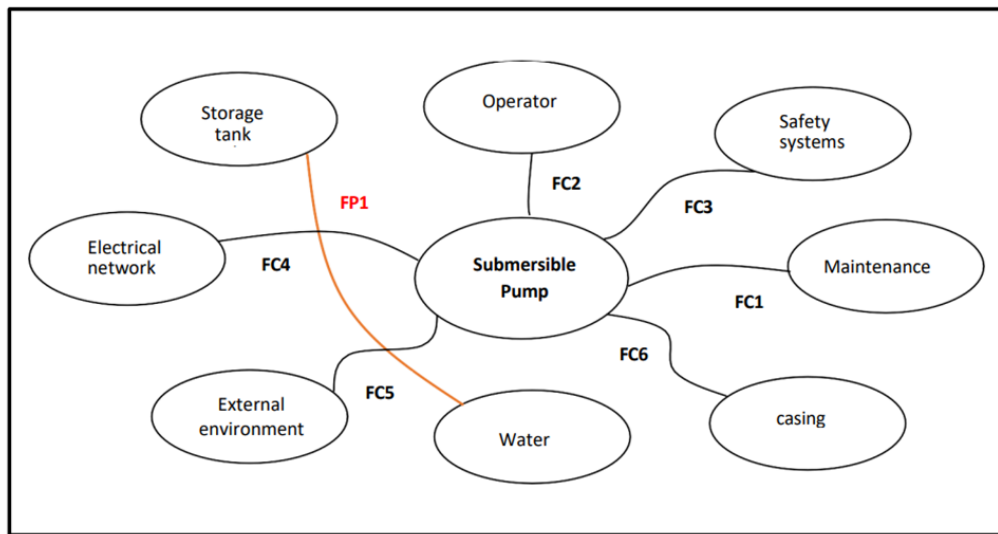


FIGURE 2.5 – Octopus Diagram of the Submersible Pump

Functions	Designations
FP1	Transfer and pump the water from the source to the storage tank
FC1	Ensure pump maintenance
FC2	Be regulated and integrated into the system by the operator
FC3	Ensure safety
FC4	Be powered by electricity
FC5	Exchange heat with the external environment
FC6	Be hermetic and resistant to external conditions

TABLE 2.2 – The service function of the submersible pump

2.3.4 FAST Diagram of the Submersible Pump

The **FAST (Function Analysis System Technique) diagram** is used to break down the technical functions of the submersible pump in a logical and hierarchical manner. It answers essential questions such as : “Why does the system exist?”, “How does it achieve its purpose?”, and “When does each function occur?”

As illustrated in Figure 2.6, the primary goal (*Why*) is to increase the water pressure and deliver water from the well to the surface. This is achieved through a sequence of intermediate functions such as :

- Driving the pump mechanism.
- Converting electrical energy into mechanical energy.
- Converting mechanical energy into hydraulic energy.
- Transmitting and increasing pressure via the diffuser.

The right side of the diagram also identifies the physical components responsible for each function, such as the electric motor, hydrodynamic coupling, and diffuser.

This structured approach helps visualize both functional logic and system architecture, ensuring a deeper understanding of the operational dynamics of the submersible pump.

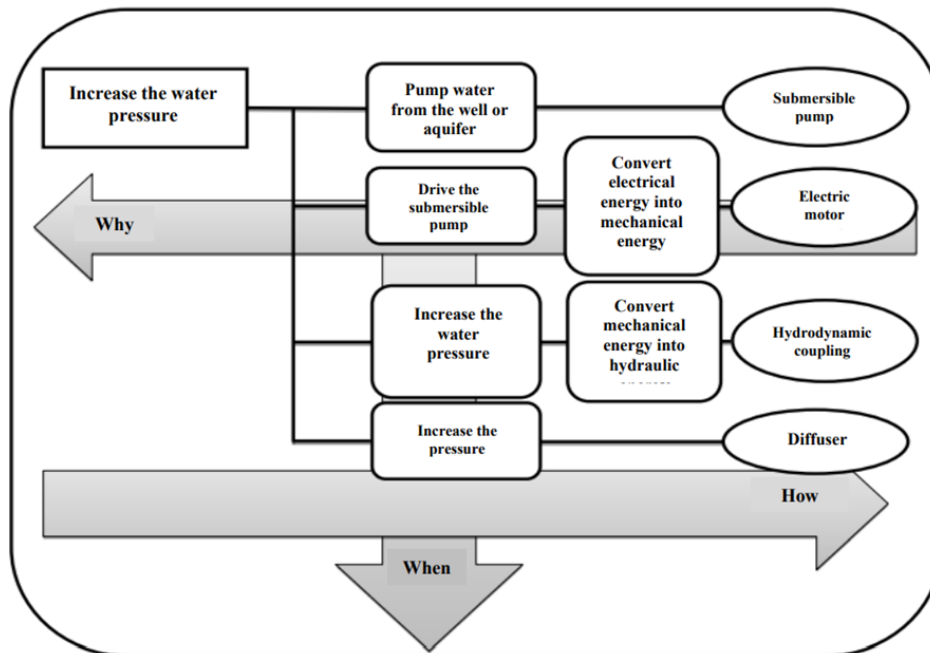


FIGURE 2.6 – FAST Diagram of the Submersible Pump

2.3.5 Structural Analysis of the Pump Using the SADT Method

2.3.5.1 SADT Diagram – Level A-0 : Submersible Pump System

The A-0 level of the **SADT (Structured Analysis and Design Technique)** method provides a high-level overview of the core function performed by the submersible pump system.

As illustrated in Figure 2.7, the central function of the system is to transfer and pump water from the source to a storage tank. This operation requires the following elements :

- **Inputs :**
 - Inlet water (typically at low pressure).
- **Controls :**
 - The user (initiating operation or controlling the system).
 - Electrical energy (power source needed for operation).
- **Mechanism (Resources) :**
 - The submersible pump (physical component that performs the operation).
- **Outputs :**
 - Outlet water (at higher pressure or elevated position).

This level of decomposition offers a clear understanding of the main transformation performed by the system (from input to output), and sets the stage for a more detailed functional breakdown at the next level (A0).

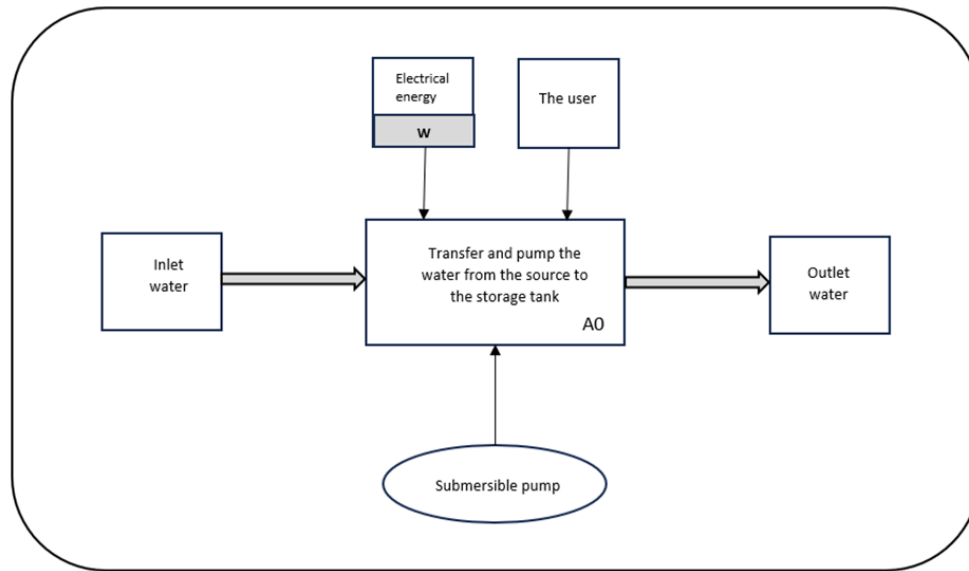


FIGURE 2.7 – SADT Diagram – Level A-0 of Submersible Pump System

2.3.5.2 SADT A0 Level – Detailed Functional Decomposition

Level A0 of the SADT method offers a more granular breakdown of the submersible pump's operation, illustrating the internal processes and functional interactions that enable water lifting from underground sources. This decomposition is presented in Figure 2.8.

The main functions performed by the system include :

- **A1 – Suction of the water** : The inlet water is drawn into the system through the impeller, initiating the pumping process.
- **A2 – Conversion of electrical energy into mechanical energy** : Performed by the electric motor, this function powers the shaft and impellers.
- **A3 – Application of centrifugal force to the water** : The impeller imparts kinetic energy to the water, increasing its velocity and pressure.
- **A4 – Discharge of water to the storage tank** : Pressurized water is directed through the discharge pipe toward the storage unit.
- **A5 – Dissipation of heat** : Heat generated during the process is exchanged with the casing and surrounding environment to prevent overheating.

Each function is associated with corresponding resources :

- **Energy input** : Electrical energy (W)
- **Control** : The user or system operator
- **Mechanisms** : Electric motor, impellers, casing, and discharge pipe.

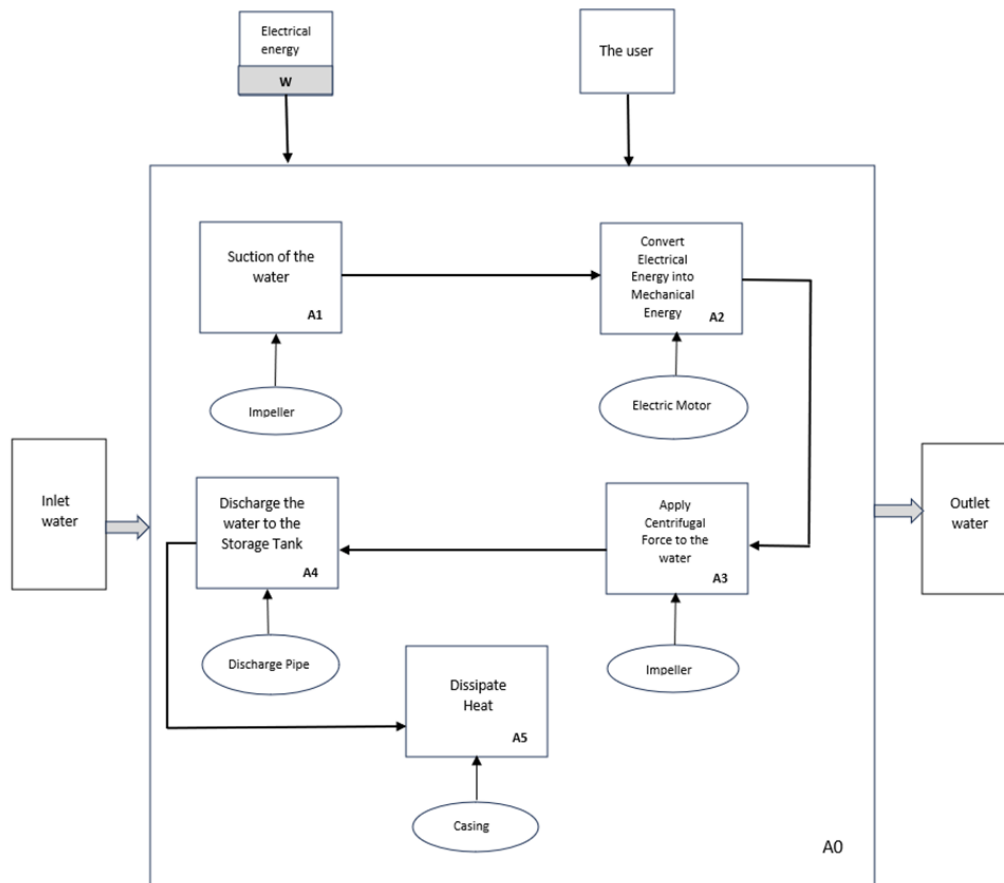


FIGURE 2.8 – SADT Diagram Level A-0 of Submersible Pump System

The functional analysis presented in the previous section systematically identified the roles, interactions, and technical requirements of submersible pumps. These findings serve as a solid foundation for the next phase of the study : failure and risk analysis, which aims to anticipate system vulnerabilities and ensure operational reliability.

2.4 Analysis of Failures and Risks

While functional analysis defines how a system should ideally operate, real-world conditions often lead to deviations, faults, and unexpected breakdowns. Submersible pumps, operating under harsh environmental and mechanical constraints, are especially prone to malfunctions that can disrupt performance and lead to costly downtime.

This section aims to systematically evaluate the most significant failure scenarios by :

- Identifying potential failure modes through techniques such as Failure Mode, Effects, and Criticality Analysis (FMECA), the Ishikawa (fishbone) diagram, and Fault Tree Analysis (FTA).
- Assessing the criticality of each identified failure mode using quantitative tools, particularly the Pareto chart, to prioritize maintenance actions and guide decision-making.

Through this structured approach, the objective is to highlight the most probable and impactful faults, their root causes, and their consequences, laying the groundwork for the development of an optimized, risk-based maintenance plan.

2.4.1 Identification of Failure Causes

2.4.1.1 Ishikawa Diagram

The **Ishikawa diagram**, also known as the fishbone diagram or cause-and-effect diagram, is a qualitative analysis tool used to identify and categorize the root causes of failures observed in the submersible pump system. It visually maps out the different factors contributing to a specific problem by grouping them into major categories such as :

- Technical causes.
- Human factors.
- Environmental influences.
- Material or equipment-related issues.
- Operational or procedural flaws.

By organizing these elements in a structured way, the Ishikawa diagram facilitates a comprehensive understanding of the underlying mechanisms that may lead to malfunction or performance degradation.

This approach supports the implementation of effective corrective and preventive actions by highlighting the key areas requiring attention, thereby improving both the reliability and availability of the pumping system.

The diagram shown in Figure 2.9 represents the Ishikawa cause-and-effect analysis.

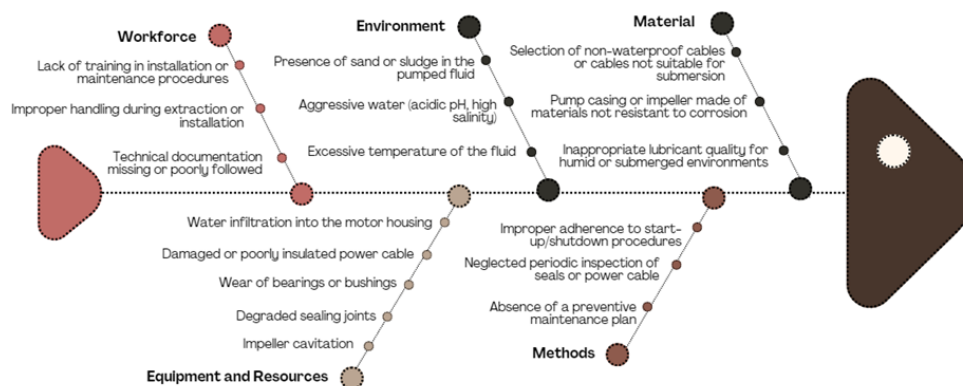


FIGURE 2.9 – Ishikawa Diagram of Submersible Pump Defects

2.4.1.2 Fault Tree Analysis (FTA)

Définition

Fault Tree Analysis (FTA) is a graphical and deductive technique widely used in reliability engineering to model the logic behind system failures. It begins with a top-level undesired event (such as system breakdown or critical malfunction) and works backward to identify its potential causes. This top-down approach enables a structured examination of how combinations of failures at the component level can lead to system-wide issues [24].

Principle of the FTA Method

FTA is based on the following core principles :

- It begins with the predefinition of an undesired event, often called the **top event**, which represents the system-level failure under investigation.
- The method then traces back all possible contributing causes, including individual component failures, human errors, or environmental factors, and expresses their logical relationships using Boolean logic gates :
 - **AND gate** : The undesired event occurs only when all input events occur simultaneously.
 - **OR gate** : The undesired event occurs if any one of the input events occurs.
- The output is a tree-like hierarchical structure, where intermediate and basic events are linked logically to the top event. The graphical representation uses standardized symbols to improve clarity and facilitate analysis [24].

Application of Fault Tree Analysis to the Submersible Pump

To illustrate the use of the FTA methodology, a fault tree has been constructed for a common undesired event in submersible pump systems : “No pressure increase”, a critical malfunction that compromises the system’s ability to deliver water.

As shown in Figure 2.10, the fault tree decomposes this top-level event into its possible causes through successive levels of intermediate and basic events :

- The **top event** “*No pressure increase*” may result from either :
 - No water suction.
 - No water diffusion.

Branch 1 : No water suction

- **Lack of water suction from the tanks** : possibly due to a supply pump failure.
- **Pump blockage** : potentially originating from a malfunction in the electric motor.

Branch 2 : No water diffusion

- **Water supply interruption** : involving a hydraulic coupler.
- **Failure to distribute water** : related to issues in the diffuser.

Each of these **basic events** represents a tangible failure point that can be investigated during preventive maintenance planning.

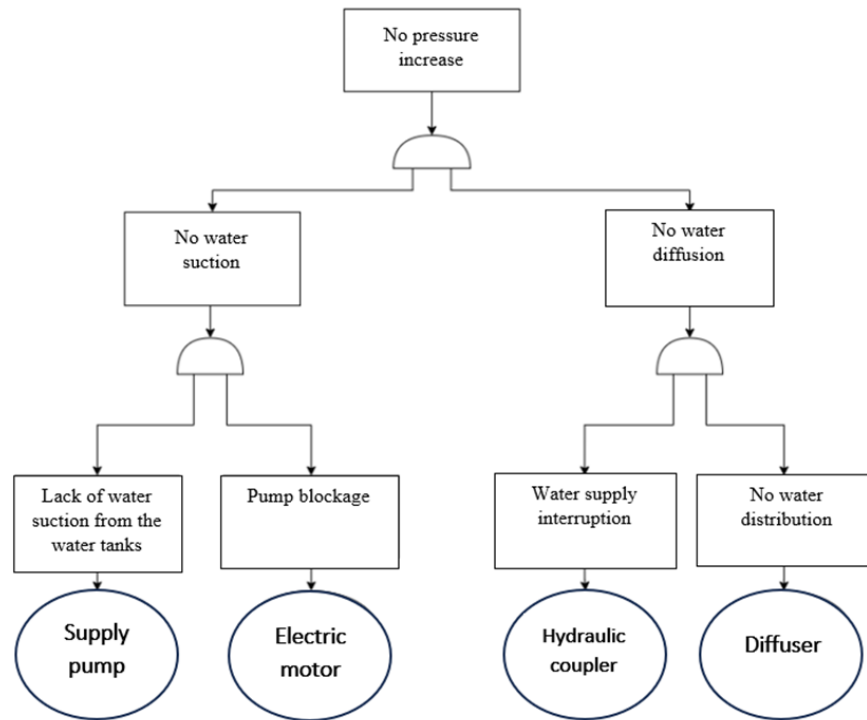


FIGURE 2.10 – The fault tree for the submersible pump

2.4.1.3 FMECA Studies

Review

FMECA is a preventive reliability analysis methodology aimed at identifying, evaluating, and mitigating potential failure modes within a system, while also assessing the associated consequences and criticality of each failure mode [25].

Objectives of FMECA

- **Identify potential failure modes** : The primary aim is to thoroughly identify possible failures in a system, product, or process.
- **Assess the consequences of failures** : The goal is to analyze the impact and consequences of each identified failure mode on the overall operation of the system.
- **Implement preventive measures** : This involves developing and implementing preventive actions to avoid failures or reduce the associated risks.
- **Improve system reliability and functional safety** : FMECA aims to enhance the reliability and functional safety of products, equipment, or processes by identifying critical points and taking corrective or preventive actions to improve them [25].

Types of FMECA

There are three main types of FMECA, each applied in a specific context :

- **Product FMECA** : This type focuses on analyzing potential failure modes of a product throughout its entire life cycle from the design phase to end-user operation.

- **Process FMECA** : Process FMECA aims to identify potential failures within a specific manufacturing or production process.
- **System FMECA** : This type is used to evaluate potential failure modes within a complete system, which may consist of multiple interconnected products, processes, or components [25].

FMECA Table

Figure below presents the FMECA table ;[26].

Date of the analysis	FMECA Machine – Failure Modes, Effects and Criticality Analysis					Operating phase	Page :			
	System : Submersible pump		Subsystem : Pump				Name :			
Component	Function	Failure Mode	Causes	Effect	Detection	Criticality:				Corrective action
						G	D	F	C	

FIGURE 2.11 – FMECA table

Criticality Assessment

The modalities of this assessment must be defined during the development of the study materials, based on the specific context and objectives of the analysis. The criticality index (C), also referred to as the Risk Priority Number (RPN) or Risk Priority Index (RPI), is calculated as the product of Severity (G), Occurrence (F), and Detection (D). This index reflects the reliability level of the system under analysis and is expressed as :

$$C = G \times F \times D$$

The index is composed of the following three criteria :

- **Severity Index (G)** : Reflects the consequences resulting from the occurrence of a failure mode in terms of :
Quality of the produced parts, Safety of personnel and equipment and Intervention time, which corresponds to the active time required for corrective maintenance (including diagnosis, repair or replacement, and system restart). Severity is most often rated on a scale from 1 to 5 (see Table I).
- **Occurrence Index (F)** : Relates to the frequency of failure occurrence. It expresses the combined probability of the failure mode arising from the occurrence of its root cause. The occurrence rating typically ranges from 1 to 4 (see Table II).
- **Detection Index (D)** : Relates to the ability to detect the failure (the failure mode–cause pair) before it produces its effect. Detection is rated from 1 for a highly detectable failure to 4 for an undetectable failure (see Table III) [27].

Severity Level : G	Index	Definition of Levels
Minor Severity	1	Minor Failure : - Production stoppage less than 2 minutes - No significant material degradation
Significant Severity	2	Significant Failure : - Production stoppage from 2 to 20 minutes - Short term restoration or minor on-site repair required
Moderate Severity	3	Moderate Failure : - Production stoppage from 20 minutes to 1 hour - Replacement of defective equipment required
Major Severity	4	Major Failure : - Production stoppage from 1 to 2 hours - Major intervention on a subsystem required - Production of non-compliant parts not detected
Catastrophic Severity	5	Catastrophic Failure : - Production stoppage exceeding 2 hours - Intervention requires expensive resources

TABLE 2.3 – Severity Rating Scale

Frequency Level : F	Index	Definition of Levels
Very Low Frequency	1	Rare failure : Less than one failure per year
Low Frequency	2	Possible failure : Less than one failure per quarter
Medium Frequency	3	Frequent failure : Less than one failure per week
High Frequency	4	Very frequent failure : Several failures per week

TABLE 2.4 – Frequency Rating Scale

Detection Level : D	Index	Definition of Levels
Obvious Detection	1	Effective detection allowing preventive action
Possible Detection	2	System presents risk of undetection in some cases
Unlikely Detection	3	Unreliable detection system
Impossible Detection	4	No detection possible

TABLE 2.5 – Undetection Probability Rating Scale

Application of the FMECA Method to Submersible Pumps

The FMECA analysis was carried out with the valuable collaboration of submersible pump users (see Appendix A 4.8).

Interpretation of Results

In analyzing the previous FMECA tables, we applied the criticality assessment grid to estimate the significance of each identified failure mode. Based on the criticality data, we used the Pareto principle to highlight the most impactful failure modes.

2.4.1.4 Pareto Diagram Analysis

ABC (Pareto) Diagram

The Pareto diagram is a simple tool used to rank phenomena in order of importance.

Pareto Analysis

In this analysis, the components are ranked in descending order according to their criticality. The cumulative value and cumulative percentage for each component are then calculated. The following table presents the components of a centrifugal pump along with their corresponding criticality scores.

Pareto Diagram

The Pareto diagram (figure2.12) is obtained by plotting the cumulative percentages in relation to the descending order of component criticality. This graph makes it possible to identify the most critical components. This table shows the Pareto diagram for the submersible pump.

#	Component	Criticality	%	% Cumulative	Class
1	Bearing (Pump)	24	12.77%	12.77%	A
2	Mechanical Seal	20	10.64%	23.40%	A
3	Impeller	20	10.64%	34.04%	A
4	Check Valve	16	8.51%	42.55%	A
5	Strainer - Check Valve	16	8.51%	51.06%	A
6	Bearing (Motor)	12	6.38%	57.45%	A
7	Wear Ring	12	6.38%	63.83%	A
8	Rotor	8	4.26%	68.09%	A
9	Stator	8	4.26%	72.34%	A
10	Terminal Box	8	4.26%	76.60%	A
11	Tube	8	4.26%	80.85%	B
12	Shaft	8	4.26%	85.11%	B
13	Elbow (Discharge)	6	3.19%	88.30%	B
14	Key	6	3.19%	91.49%	B
15	Elbow (Suction)	6	3.19%	94.68%	B
16	Diffuser	3	1.60%	96.28%	C
17	Volute	3	1.60%	97.87%	C
18	Orifice	2	1.06%	98.94%	C
19	Tank	1	0.53%	99.47%	C
20	Valve	1	0.53%	100.00%	C
Total		152	100%		

TABLE 2.6 – Criticality Analysis of Components

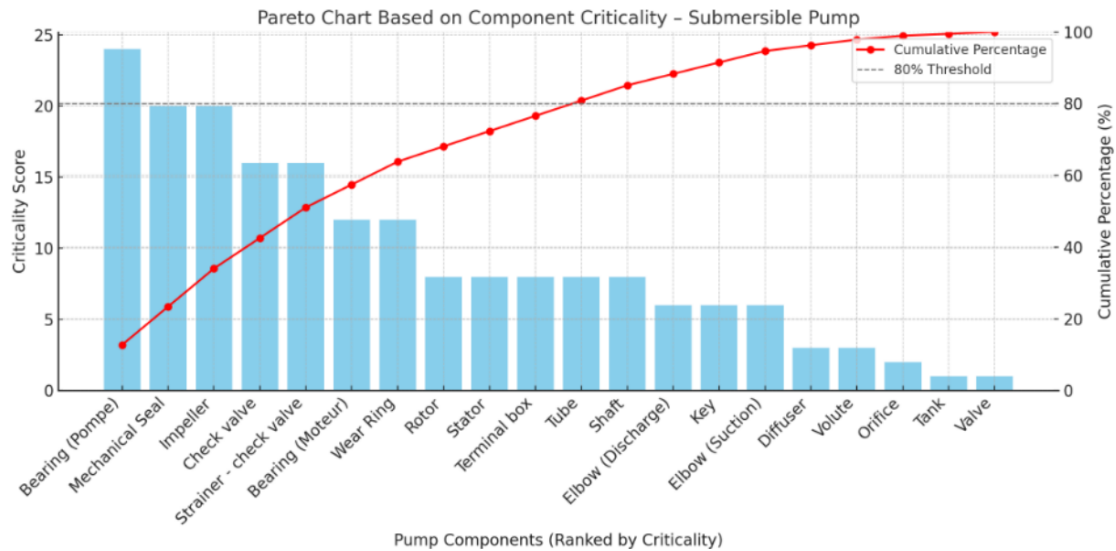


FIGURE 2.12 – Pareto Diagram

Interpretation of the Results

The Pareto diagram applied to the FMECA (Failure Modes, Effects, and Criticality Analysis) provides a systematic approach to prioritizing system components based on their cumulative criticality. This method is grounded in the 80/20 principle, which states that 20% of the causes are responsible for 80% of the effects.

- Class A : Most Critical Components (80% of Total Criticality)

The top 10 components account for more than 76% of the total system criticality (out of a cumulative score of 152). These components therefore require special attention in terms of maintenance planning and operational monitoring.

These components are responsible for the majority of critical failures within the system. They should be subject to enhanced preventive and predictive maintenance programs, including continuous monitoring of parameters such as vibration, temperature, and mechanical wear.

- Class B : Moderately Critical Components (15%)

Components classified as Class B exhibit a moderate level of criticality. While their monitoring remains important, they are less urgent compared to Class A elements. They represent approximately 15% of the cumulative criticality, spanning ranks 11 to 15 (up to 94% cumulative).

- Class C : Low-Criticality Components (6%)

Class C components have a negligible influence on the overall reliability of the system. They account for less than 6% of the total criticality and can be addressed within routine corrective maintenance schedules.

2.5 Maintenance Strategy Design

Following the functional and failure analyses conducted in the previous sections, the critical components and failure modes of submersible pumps have been clearly identified. This knowledge now serves as the basis for developing an optimized maintenance strategy that balances operational reliability with economic performance.

2.5.1 Proposal for a Preventive Maintenance Plan

To enhance system availability and reduce unplanned downtime, maintenance efforts should be prioritized around critical components and failure-prone areas. The goal is to proactively mitigate potential breakdowns and improve overall system reliability.

2.5.1.1 Definition of the Maintenance Plan

According to **NF X 60-010**, a maintenance plan is defined as :

“A document that specifies the procedures, resources, and sequence of activities necessary for the maintenance of an asset.”

This plan is typically established during the design and preparation phase of the maintenance process. It constitutes a core element of the overall maintenance strategy and is often integrated into the operational documentation of the system [28].

2.5.1.2 Objective of the Maintenance Plan

The main objectives of an effective preventive maintenance plan include [28] :

- Ensuring that the system's actual reliability level is maintained throughout its operational lifecycle.
- Restoring the expected levels of safety and reliability following any observed deterioration.
- Collecting field data to support the redesign or enhancement of components whose intrinsic reliability is deemed insufficient.
- Achieving these goals with minimal total cost, including both direct maintenance costs and indirect costs related to residual failures.

Corrective Actions

Corrective actions refer to the measures identified by the analysis team to address and reduce high-risk failure scenarios. These actions may include :

- **Technical improvements** : Modifications in the equipment design or materials.
- **Organizational measures** : Enhancements in maintenance protocols or operational procedures.

These corrective actions are directly derived from the outcomes of the FMECA and other reliability studies.

Monitoring and Follow-Up

Effective monitoring is essential to ensure the successful execution of the maintenance plan. It plays a key role in the FMECA implementation by :

- Verifying that the corrective and preventive actions are effectively deployed.
- Validating the reduction in criticality levels of the targeted components.
- Providing a quantitative measure of system confidence and reliability.

Preventive Maintenance Plan

The table below outlines the proposed preventive maintenance tasks. These actions were defined based on :

- Manufacturer guidelines.
- Operational experience.
- Feedback and adjustments to maintenance frequency.

Figure below illustrates the Preventive Maintenance Plan, The continuation of the plan can be found in **Appendix B 4.8**.

Preventive Maintenance Plan														
Date of Analysis : Mai 2025				System : Submersible pumb				Prepared by : TEDJINI Omar KHELFAOUI RABAH Abdenmour						
N°= FM	C	CI	CA	MP			RD	F					Responsible	ML
				TBM	CBM	PA		M	Q	S	A	Other		
1	24	A	Shaft alignment, lubrication, bearing replacement		X	Monthly lubrication + quarterly alignment	3h		X				I+T	3
2	20	A	Monthly cleaning, impeller check, vibration monitoring		X	Monthly vibration checks	2h	X					I+T	2
3	20	A	Mechanical seal replacement	X		Annual replacement	4h				X		I+T	3
4	16	A	Check valve replacement	X		Biannual replacement	3h			X			I+T	3

N° Colonne	Désignation	Codification
1	Failure Mode Number	Failure Mode Number: N°= FM
2	Criticality Rating	• Criticality: C
3	Criticality Classification (A/B/C)	• Class: CI
4	Corrective Action	• Corrective Action : CA
5	Types of Preventive Maintenance & Proposed Actions	• Preventive Maintenance: MP • Time-Based Maintenance: TBM • Condition-Based Maintenance: CBM • Preventive Action : PA
6	Estimated Repair Duration	• Repair Duration: RD
7	Maintenance Interval	• Frequency: F • Monthly : M • Quarterly: Q • Semi-annually : S • Annually: A
8	Assigned Personnel	• Engineer/Technician: I/T • Operator : O
9	Maintenance Complexity Level	• The Five (5) Maintenance Tiers: 1, 2, 3, 4 and 5

FIGURE 2.13 – Preventive Maintenance Plan

2.6 Conclusion

This chapter provided a comprehensive functional analysis of the submersible pump, identifying its key functions and critical components. Using tools such as the FAST diagram, SADT model, Ishikawa diagram, FMECA, and fault tree analysis (FTA), potential failure modes were examined and prioritized based on their criticality. Based on these findings, a structured preventive maintenance plan was developed to anticipate failures and improve system reliability. This analytical work serves as a foundational step for the design of the embedded monitoring and control system presented in the next chapter.

Chapter 3

Electronic Components and Arduino-Based System Prototyping

3.1 Introduction

Arduino has become a widely recognized term among university students and electronics enthusiasts. Due to its integration of electronics and programming, it has simplified the development of complex and efficient systems, requiring fewer electronic components and consequently lowering the overall cost of implementation.

Arduino is an open-source printed circuit board (PCB) featuring a microcontroller that can be programmed to analyze and generate electrical signals. This enables the execution of a wide variety of tasks, such as home automation (e.g., controlling lighting, heating, and household appliances), robotic control, and more [29].

In this chapter, we will present the various electronic components used in our project, their technical specifications, and an overview of the Arduino Integrated Development Environment (IDE).

3.2 Overview of the Arduino UNO Board

The Arduino module is a printed electronic board released under an open-source license by its inventor. However, some components on the board may not fall under this open-source license.

The Arduino UNO is primarily based on the ATmega328P microcontroller. It includes 14 digital input/output pins (six of which can be used as PWM outputs), six analog inputs, and a 16 MHz quartz crystal oscillator. The board features a USB connector for communication with a computer, which can also serve as a power source, an external power jack, and a 5V linear voltage regulator. The Arduino IDE software is used to program this board [30].

3.3 What is a Microcontroller ?

A microcontroller often mistakenly referred to as a microprocessor by uninformed individuals and even by some science journalists is essentially a small computer embedded within a single

integrated circuit package. It includes a central processing unit (similar to the microprocessor found in a personal computer), RAM (random-access memory), ROM (read-only memory), various interfaces for external communication, and the necessary electronic and logic circuitry to ensure proper functionality of the entire system [31].

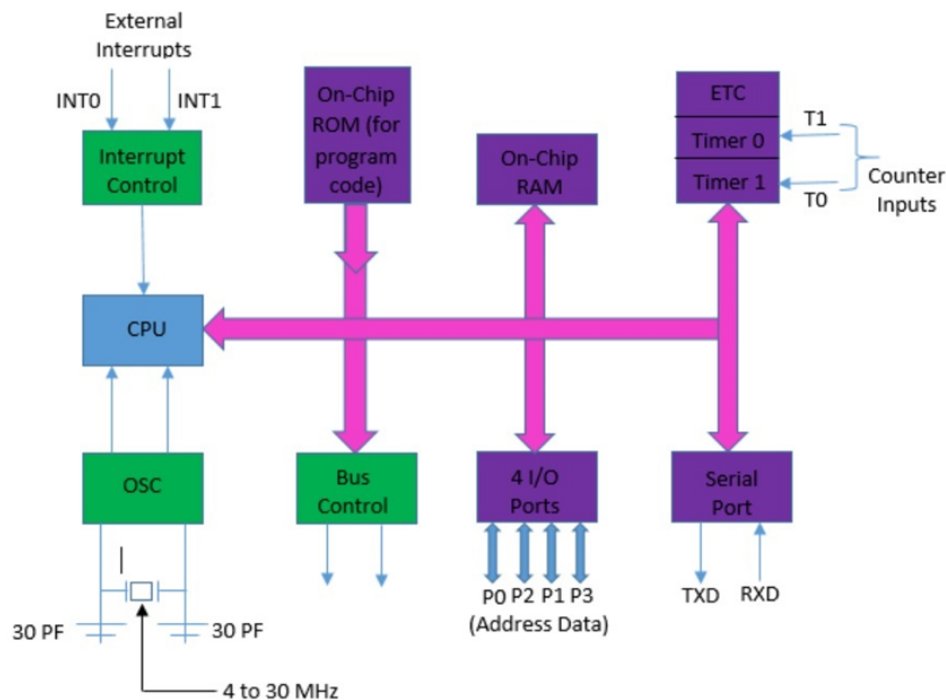


FIGURE 3.1 – Simplified Diagram of the Typical Internal Structure of a Microcontroller [31]

3.3.1 ATMEL ATmega328P Microcontroller

The microcontroller used in the Arduino electronic board is the ATmega328P. It belongs to the AVR family of microcontrollers, developed and manufactured by Atmel Corporation.

(PCINT14/RESET) PC6	1	28	PC5 (ADC5/SCL/PCINT13)
(PCINT16/RXD) PD0	2	27	PC4 (ADC4/SDA/PCINT12)
(PCINT17/TXD) PD1	3	26	PC3 (ADC3/PCINT11)
(PCINT18/INT0) PD2	4	25	PC2 (ADC2/PCINT10)
(PCINT19/OC2B/INT1) PD3	5	24	PC1 (ADC1/PCINT9)
(PCINT20/XCK/T0) PD4	6	23	PC0 (ADC0/PCINT8)
VCC	7	22	GND
GND	8	21	AREF
(PCINT6/XTAL1/TOSC1) PB6	9	20	AVCC
(PCINT7/XTAL2/TOSC2) PB7	10	19	PB5 (SCK/PCINT5)
(PCINT21/OC0B/T1) PD5	11	18	PB4 (MISO/PCINT4)
(PCINT22/OC0A/AIN0) PD6	12	17	PB3 (MOSI/OC2A/PCINT3)
(PCINT23/AIN1) PD7	13	16	PB2 (SS/OC1B/PCINT2)
(PCINT0/CLKO/ICP1) PB0	14	15	PB1 (OC1A/PCINT1)

FIGURE 3.2 – Pinout Diagram of the ATmega328P [32]

The ATmega328P is a compact chip containing a large number of electrical components such as

transistors, resistors, and capacitors integrated within a small space and protected by a black encapsulated package. It features multiple pins (or terminals), and its programming is typically carried out using the C/C++ language.

3.3.2 General Characteristics of the ATmega328P

- **Flash Memory** : 32 KB (programmable via serial interface).
- **EEPROM Data Memory** : 1 KB.
- **RAM** : 2 KB.
- **Working Registers** : 32 high-speed registers accessible by the Arithmetic Logic Unit (ALU).
- **Parallel Ports** : 3, providing 23 input/output pins.
- **Clock Frequency** : 16 MHz (maximum supported frequency : 20 MHz).
- **Clock Cycle Rate** : 16 clock cycles per microsecond.
- **Internal Peripherals** :
 - 6 analog-to-digital converters (ADC) with 10-bit resolution.
 - 1 analog comparator.
 - 1×16 -bit timer (T1), 2×8 -bit timers (T0, T2).
 - 6 PWM (Pulse Width Modulation) channels.
 - 1 watchdog timer.
 - 26 interrupt sources.
 - 5 power-saving modes.
- **Number of Pins** : 28 (as used in the laboratory version) [32].

3.4 Technical Specifications of the Arduino UNO

The Arduino UNO is a programmable microcontroller that enables control of mechanical components such as systems, lights, motors, and more. This electronic board allows users to easily program and automate tasks, even without advanced programming knowledge. It is specifically designed for inventors, artists, and hobbyists who aim to build their own automated systems through custom coding.

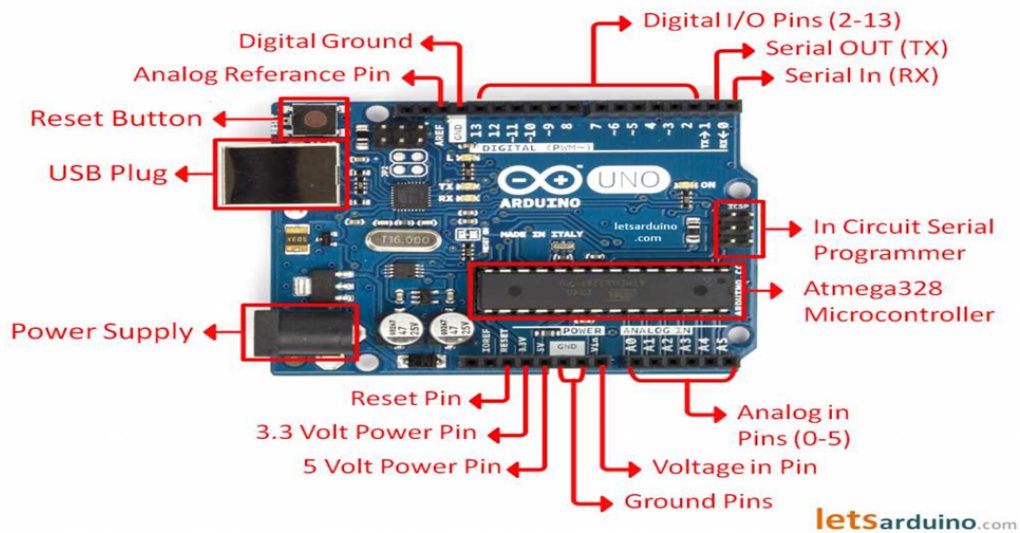


FIGURE 3.3 – Structure of the Arduino UNO Board

The following table summarizes the technical specifications of the Arduino UNO board.

TABLE 3.1 – Various Components of the Control Board

Parameter	Specification
Microcontroller	ATmega328
Clock Frequency	16 MHz
Operating Voltage	5 V
Recommended Input Voltage	7–12 V
Input Voltage Limits	6–20 V
Digital I/O Pins	14 (including 6 PWM outputs, marked by ' ')
Analog Input Pins	6 (can also be used as digital I/O pins)
Max Current per I/O Pin (5V)	40 mA (200 mA total max for all I/O)
Max Current for 3.3V Output	50 mA
Max Current for 5V Output	500 mA (via USB port)
Flash Memory	32 KB (0.5 KB used by bootloader)
Interface	USB (power supply and program upload)
External Power Supply Connector	Barrel jack
Board Dimensions	6.86 cm × 5.3 cm

3.5 Fields of Use and Applications

The Arduino system offers the possibility to combine the capabilities of programming with those of electronics, enabling the realization of a wide range of projects with applications across multiple domains. As mentioned earlier, the potential use cases of Arduino are vast. Here are some illustrative examples :

- In industrial electrical engineering, Arduino enables remote control of motors and demonstration of operational characteristics under various working conditions. (As in our current project,

which aims to control a water pump remotely using a contactor.)

- Rapid prototyping of innovative electronic projects, with Arduino facilitating experimentation during the pre-industrialization phase.
- Low-cost digital fabrication and machine-tool production, promoting a culture of technological appropriation through do-it-yourself (DIY) and improvisation.
- Scientific data acquisition and analysis (e.g., environmental monitoring, energy usage) for educational purposes, research, or civic engagement.
- Performing arts and interactive installations : thanks to Arduino's extensive interactive capabilities, it is possible to create live performances, VJing setups, or systems that respond to dancer movements to generate real-time audio-visual effects.
- Educational projects, aimed at students, professionals, or the general public, and promoted by institutions such as higher education schools, specialized training centers, or media labs [33].

3.6 Advantages of Arduino

Over the years, the world has become more open to technology, breaking the monopoly once held by a few companies producing microcontrollers such as the “PIC” series from Microchip Technology. Arduino, however, stands out in several key ways :

- **Affordability** : Considering their performance, Arduino boards are relatively inexpensive, making them highly accessible to beginners. The board used in this course, for example, costs around €25 (including tax), offering excellent value for money.
- **Openness and Freedom** : This is a defining feature of the Arduino philosophy, and it manifests in two ways :
 - The software is free and open-source, developed in Java, and extremely user-friendly even basic mouse-clicking skills are sufficient to get started.
 - The hardware design (schematics of the boards) is freely available online.

However, this openness comes with a condition : the name “Arduino” may only be used for official boards. One cannot manufacture a board based on the Arduino design and legally label it as “Arduino.” Unofficial Arduino-compatible boards are widely available for purchase online and are, in most cases, functionally identical to the official versions.

- **Compatibility** : Both the software and the hardware are compatible with the most common operating systems, including Windows, Linux, and macOS. This stands in contrast to many commercial programming tools, which are often limited to compatibility with Windows only.
- **The Arduino Community** : The Arduino community is vast and continually growing, with an ever-expanding range of resources available online. Official Arduino language references and a comprehensive collection of tutorials can be found on the Arduino website, both in English and French at arduino.cc [34].

3.7 Components of the GSM Module Control Board – SIM800L

The SIM800 or SIM800L V2 5V wireless GSM/GPRS module enables sending text messages, making voice calls, and transferring data via GPRS. It also supports additional features such as Bluetooth, FM radio, and embedded AT commands, providing time- and cost-saving functionalities.

The SIM800L module includes :

- A TTL-level serial communication interface.
- A power supply interface.
- An antenna interface for external connectivity.

With compact dimensions ($15.8 \times 17.8 \times 2.4$ mm), this module is well-suited for space-constrained embedded system designs [35].

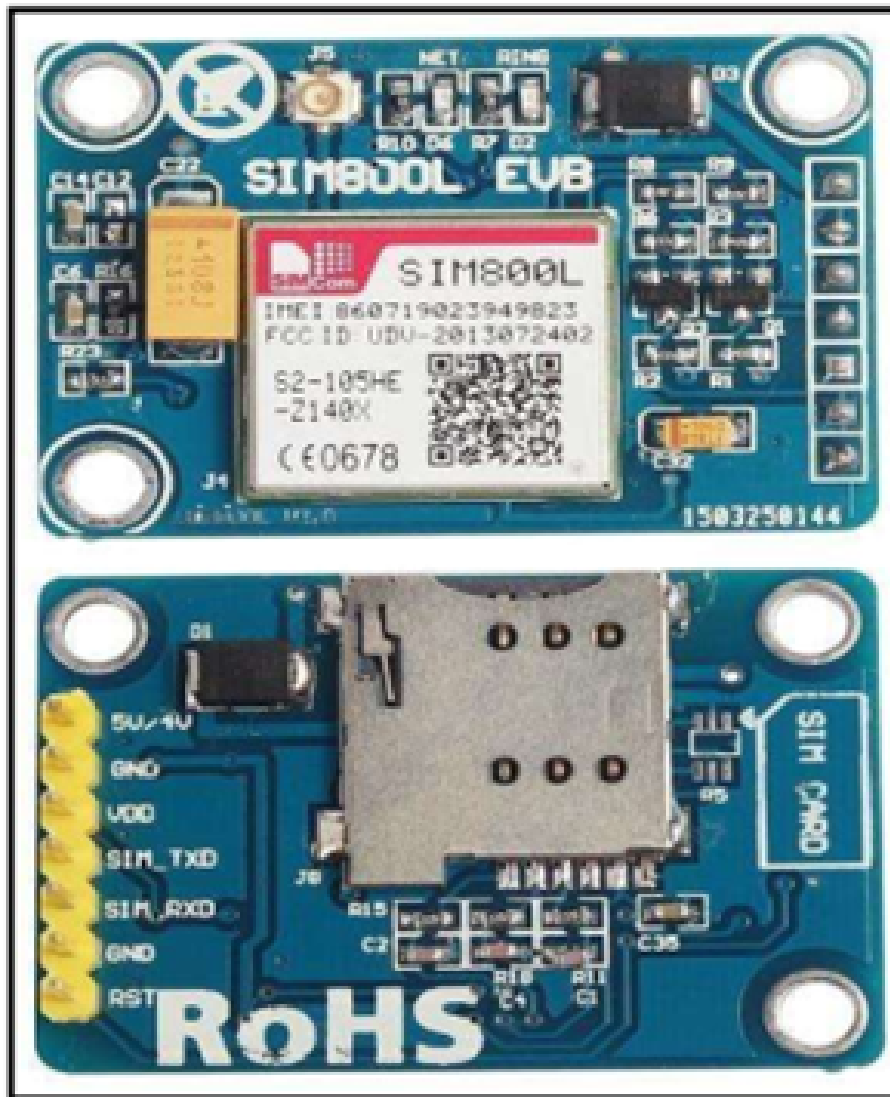


FIGURE 3.4 – Actual Image of the SIM800L V2 GSM Module [35]

This module is used in our project to send commands in the form of short messages (SMS), which are then interpreted by the module and transmitted to the Arduino board to activate

relays. It is also used to send notifications to the user's phone to inform them of the motor's status.

3.7.1 Key Features of the SIM800L GSM Module

- **Operating voltage** : 4.1–5 VDC.
- **Peak current** : 2 A.
- **SIM card type** : Micro SIM.
- **Supports quad-band frequencies** : 850/900/1800/1900 MHz, allowing voice calls, SMS, and low-power data transmission.
- Compatible with GSM Phase 2/2+.
- **Onboard status LED indicators** :
 - **Constant ON** : module powered.
 - **Slow blinking** : network signal acquired.
 - **Fast blinking** : no signal.
- **Operating temperature range** : -40°C to +85°C.

The SIM800L module has a total of 7 pins, which interface with the Arduino board :

- **VCC** : External power supply input for the SIM800L.
- **GND** : Ground (common reference).
- **VDD** : Power input from the microcontroller to the SIM800L.
- **RST** : Reset pin for restarting the module.
- **RXD** : Serial communication input (receiver pin).
- **TXD** : Serial communication output (transmitter pin).

[36]

3.7.2 AT Commands

AT commands are defined in the GSM 07.07 standard (for SMS operations, see GSM 07.05). “AT” stands for Attention, and these two characters are always used at the beginning of a text-based command line (in ASCII format). AT commands allow complete control of mobile communication modules.

Three primary entities are involved in the command structure :

- **TE (Terminal Equipment)** : Sends and displays commands.
- **TA (Terminal Adapter)** : Acts as the interface between the user and the mobile equipment.
- **ME (Mobile Equipment)** : The mobile communication device itself.

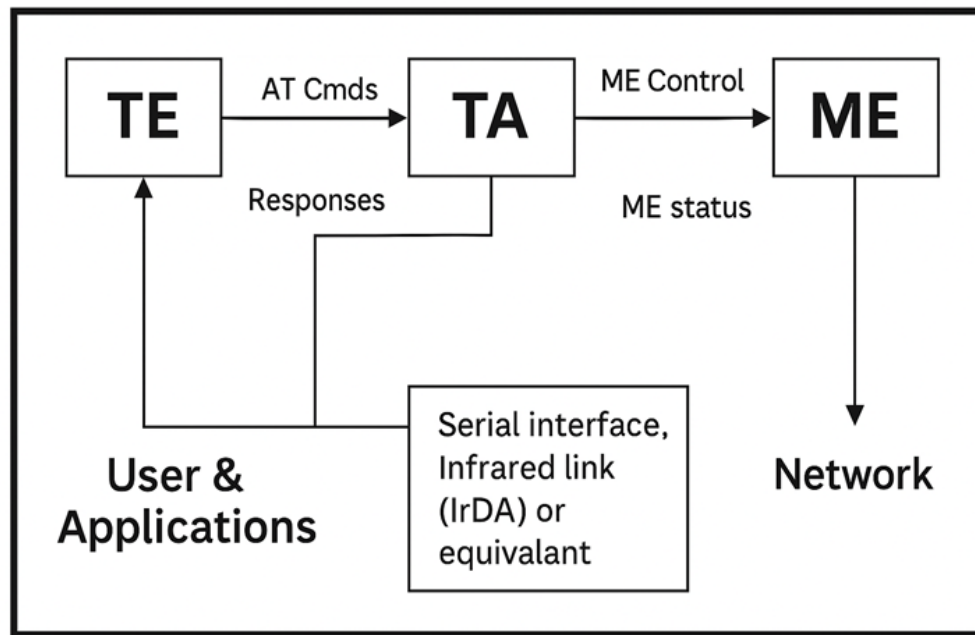


FIGURE 3.5 – Diagram of the Operation of AT Commands [35]

3.8 Relay Module

A relay is an electrical device controlled by microcontrollers like Arduino, functioning as a remotely operated mechanical switch. It separates low-power control signals (low voltage/current) from the high-power switching operations, effectively acting as a current amplifier.

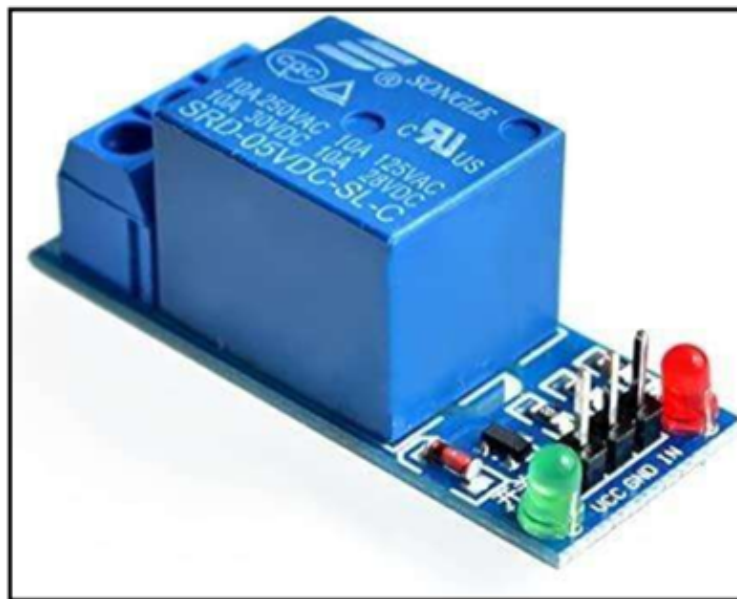


FIGURE 3.6 – 5V Relay Module

The relay module typically includes the following pin configuration :

- **VCC** : connects to 5V on the Arduino.

- **GND** : connects to Ground.
- **IN** : signal pin, connected to a digital pin on the Arduino.

3.9 Sensor Modules Used

In this project, several sensors were used to monitor the pump's electrical and thermal behavior. These sensors enable real-time data acquisition for voltage, current, and temperature, providing the necessary inputs for remote supervision and fault detection.

3.9.1 ACS712 Current Sensor

The **ACS712** is a hall-effect based linear current sensor that provides an analog voltage output proportional to the current flowing through it. It is available in different current ranges (e.g., 5A, 20A, 30A), and is used in this project to measure the current in each phase of the pump.

Connections :

- **VCC** : 5V from Arduino.
- **GND** : Ground.
- **OUT** : Analog input pin of Arduino (A1, A2, A3).

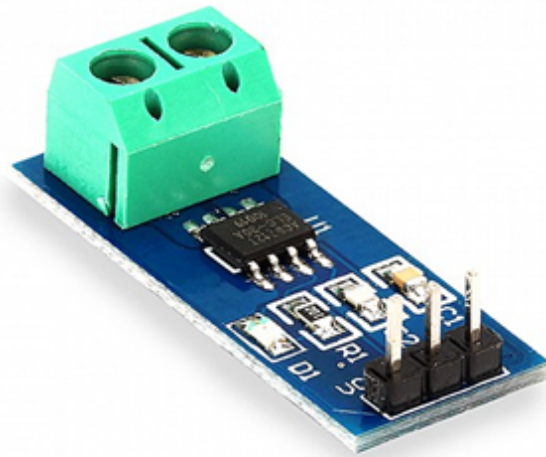


FIGURE 3.7 – ACS712 Current Sensor Module

3.9.2 ZMPT101B Voltage Sensor

The **ZMPT101B** is an AC voltage sensor module used to measure the voltage of each phase (e.g., L1, L2, L3). It provides an isolated analog output proportional to the input voltage and is suitable for single-phase measurements.

Connections

- **VCC** : 5V from Arduino.

- **GND** : Ground.
- **OUT** : Analog input pin (e.g., A4, A5, A6).

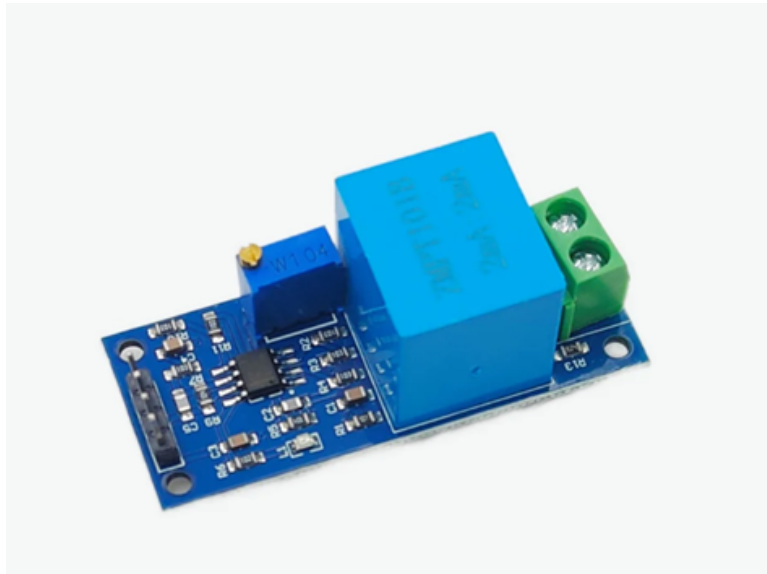


FIGURE 3.8 – ZMPT101B Voltage Sensor Module

3.9.3 DS18B20 Temperature Sensor

The **DS18B20** is a digital temperature sensor capable of measuring temperatures from -55°C to $+125^{\circ}\text{C}$ with high accuracy. It uses the *One-Wire* protocol, allowing multiple sensors to be connected on a single data line.

Connections (in parasite power mode)

- **VCC** : 5V from Arduino.
- **GND** : Ground.
- **OUT** : Digital pin (e.g., D7), with a 4.7 k Ω pull-up resistor to V_{CC} .



FIGURE 3.9 – DS18B20 Digital Temperature Sensor

These sensors collectively enable the system to perform accurate monitoring, allowing the detection of abnormal conditions such as overload, phase loss, or motor overheating.

3.10 Arduino Software

The Arduino board is a programmable electronic device that requires explicit instructions (software) to perform tasks. It uses the Arduino Integrated Development Environment (IDE), an open-source software available for free across various operating systems.

The Arduino programming language closely resembles C/C++, with some differences in program structure. A typical Arduino program consists of two main sections :

- **setup()** : Initializes settings and variables. This function is executed only once when the Arduino board is powered on.
- **loop()** : Executes instructions repeatedly after initialization in an infinite loop, until the board is turned off or reset.

Additional functions can be declared within the same program file using proper syntax. Function libraries can also be included, and must be inserted before any function declarations.

Program Structure Overview :

- Library Inclusion (optional).
- Function Declarations (if any).
- **void setup()**
 // Instructions executed once at startup
- **void loop()**
 // Instructions executed repeatedly by the microcontroller

3.10.1 The Arduino IDE

An Integrated Development Environment (IDE) is a software application used to build and manage programs, combining common development tools into a single graphical user interface (GUI). It typically includes :

- **Source Code Editor** : A text editor designed to assist in writing software code.
- **Local Build Automation** : Tools that automate repetitive tasks involved in compiling the software.
- **Debugger** : A tool used to test and debug programs, often providing a graphical interface to locate bugs within the code.[37]

In this chapter, we will focus on the IDE provided by Arduino.

The Arduino IDE features a relatively simple user interface (see Figure 3.10). It offers a clean and minimal environment for developing applications on Arduino boards. The IDE can be downloaded from the official Arduino website at : <http://arduino.cc/en/main/software> and is easy to install.

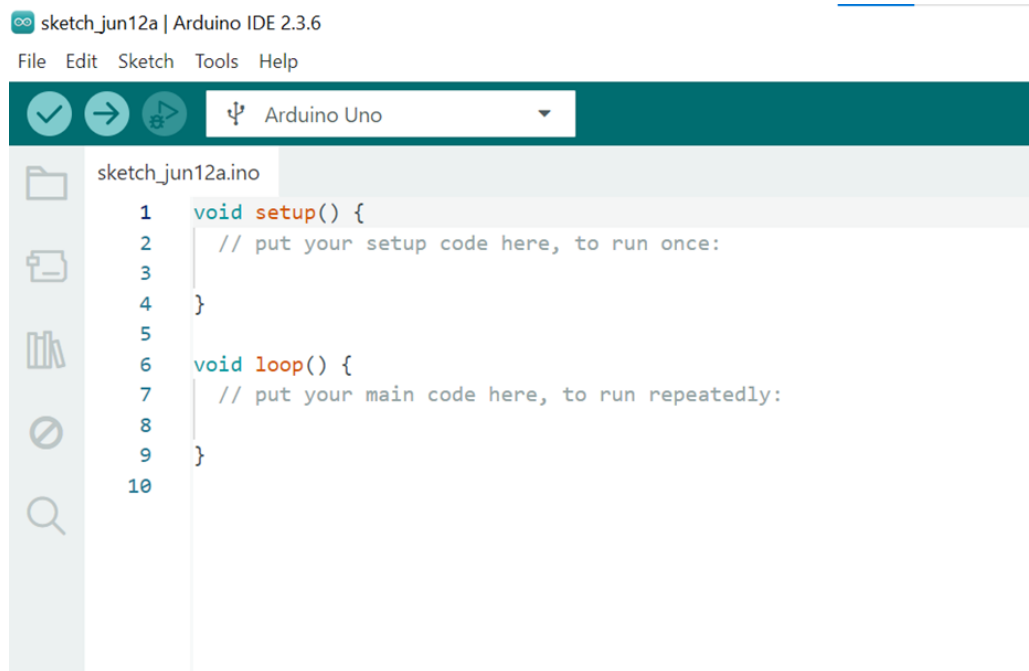


FIGURE 3.10 – Arduino IDE Interface

There are a number of functions that are specific to Arduino usage. These functions are directly accessible within the Arduino development environment without requiring the inclusion of additional libraries. [38]

Input/Output

The most frequently used functions are the input/output functions. These allow voltage to be sent to or measured from one of the board's pins.

Digital Pins

Before performing a measurement or sending a command, it is necessary to define the direction (input or output) of the pins used. This is done using the `pinMode` function, which requires the pin number and the desired direction as arguments :

```
Void setup() {
  pinMode(1,OUTPUT) ; // Broche 1 en sortie
  pinMode(2,INPUT) ; // Broche 2 en entrée
}
```

Once this configuration is set, the pins can be used accordingly. All digital pins are capable of reading and writing binary values (i.e., 0 (0V) or 1 (5V)).

digitalWrite()

To write a value to a digital pin, the `digitalWrite()` function is used. A pin configured as an output can be set to a specific value using this function :

```
digitalWrite(numéro de la broche, valeur à envoyer);
```

digitalRead()

To read a value from a digital pin, the `digitalRead()` function is used. It only takes one parameter the pin number from which the value is to be read. The function returns one of two constants : HIGH or LOW. This returned constant, although not explicitly stated, is numeric in type. It can therefore be stored in a local variable, provided that the variable is of the appropriate type :

```
byte valeur;  
  
valeur = digitalRead(le num ro de la broche);
```

Analog Pins :

Analog pins operate differently from digital pins. By their nature, they are capable of handling more than just two values. Thus, they can be used for reading a range of voltage levels rather than a simple binary state (Haut du formulaire,Bas du formulaire).

Arduino microcontrollers, such as the Arduino Uno, have analog-to-digital converters that transform analog voltages into digital values usable by programs. These converters operate at 10-bit resolution, providing values from 0 (0V) to 1023 (maximum voltage).;[39]

3.10.2 Libraries

Arduino libraries are collections of prewritten code that simplify and extend the capabilities of Arduino boards. They are typically stored in the `libraries` folder and can be easily imported into an Arduino sketch to enable specific hardware functionalities or simplify complex programming tasks.

In this project, several libraries were used to interface with sensors and communication modules :

- **#include <SoftwareSerial.h>**
Enables serial communication on digital pins other than the default TX/RX. It is used here to communicate with the SIM800L GSM module.
- **#include <OneWire.h>**
Provides support for the One-Wire communication protocol, used by devices such as the DS18B20 digital temperature sensor.
- **#include <DallasTemperature.h>**
Works in conjunction with OneWire to simplify temperature readings from DS18B20 sensors.
- **#include <ZMPT101B.h>**
A custom library used to process voltage signals from the ZMPT101B AC voltage sensor, providing readable voltage values for each phase.
- **#include <ACS712.h>**
Facilitates the acquisition and conversion of analog signals from ACS712 current sensors, allowing the system to monitor current flow in each phase.

These libraries played a key role in enabling the system to read environmental and electrical parameters, communicate via GSM, and respond to user commands effectively, while maintaining a clean and modular code structure.

3.11 Project Implementation on a Breadboard

After analyzing and understanding the role of each electronic component in the system, a functional prototype was assembled on a breadboard using jumper wires. This method allows for rapid assembly and easy modifications without soldering, making it ideal for the testing and debugging phase.

Particular attention was given to the power supply of the SIM800L GSM module, which is known to draw high current especially during network registration or SMS transmission. As the Arduino board can only provide up to 500 mA, an external 5 V power supply capable of delivering up to 2 A was used to ensure reliable operation of the module. This precaution is essential to avoid unexpected resets or failures in communication.

This stage allowed for the validation of sensor readings, relay control, and SMS-based communication, serving as a solid foundation before moving to a printed circuit board (PCB) implementation.

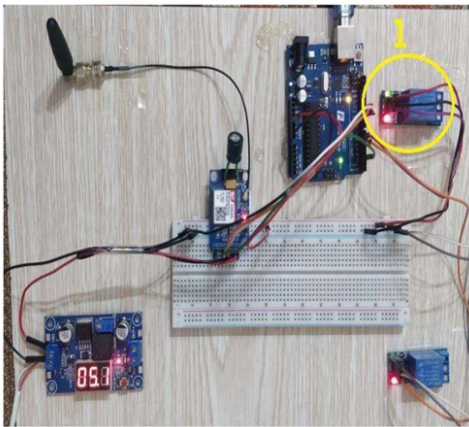


FIGURE 3.11 – ON Mode

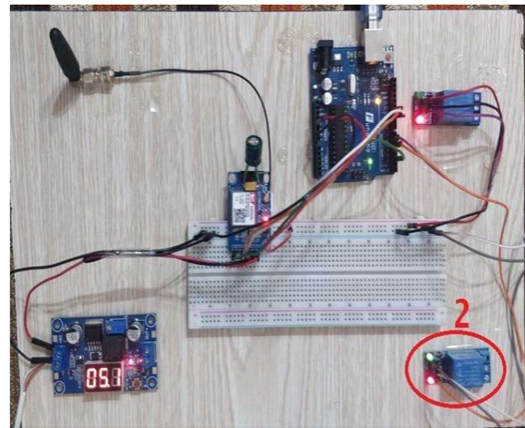


FIGURE 3.12 – OFF Mode

When the SIM800L module receives an SMS with "ON," the Arduino activates Relay 1, allowing current to flow to the pump's control cabinet. When an "OFF" message is received, Relay 2 is triggered to open the circuit and stop the pump.

3.12 Conclusion

In this chapter, we provided a comprehensive overview of the key electronic components used in our project, focusing particularly on the Arduino UNO board and its capabilities. We examined the ATmega328P microcontroller, the GSM SIM800L module for remote communication, and the various sensors implemented for monitoring electrical and thermal parameters, including voltage, current, and temperature.

Additionally, we detailed the essential software environment, including the Arduino IDE and the specific libraries used to interface with external modules and sensors. This foundational knowledge enabled us to construct a functional prototype using a breadboard, which allowed us to test the overall logic of the system particularly the control of relays and the transmission of SMS commands.

This hands-on implementation validated the theoretical design and confirmed the feasibility of integrating control, supervision, and communication features into a compact and efficient embedded system. The successful prototyping stage marks a critical step toward developing a printed circuit board (PCB), which will be covered in the next chapter.

Chapter 4

Design and Implementation of the Project

4.1 Introduction

One of the primary and most significant goals of technology is to make people's lives easier ; this is where our role as scientists comes into play.

In this final chapter, we aim to implement the proposed solution of our project by designing a compact printed circuit board (PCB) with a minimal number of electronic components, while preserving the same operational capabilities.

We will also examine whether the **ATMega328p** microcontroller can be used independently of the Arduino board and whether the software employed in the project will be affected.

4.2 Programming the ATMega328p

When developing a project idea, the Arduino board is often considered the most convenient environment for prototyping. For this reason, we initially opted for this approach. However, we also explored the use of the standalone microcontroller to leverage its advantages over the Arduino board.

These advantages include : lower cost, smaller circuit size, more available I/O pins, and the potential for higher operating speeds (up to 20MHz). However, this requires adjusting timing functions due to the Arduino IDE's default 16MHz clock setting.

4.2.1 Bootloader

Microcontrollers are typically programmed using a programmer, which allows for the installation of new firmware. However, with a *bootloader*, it is possible to load firmware without the need for an external programmer.

The bootloader is a software component whose main functions include :

- Loading an application into the microcontroller's FLASH memory via the serial interface.

The bootloader allows a program developed using the Arduino IDE to be uploaded directly to the microcontroller. It also enables the execution of the program stored in the microcontroller's memory upon power-up.

4.2.2 LOADING THE BOOTLOADER ONTO AN ATmega328

To load the bootloader onto an ATmega328P, the following circuit must be assembled :

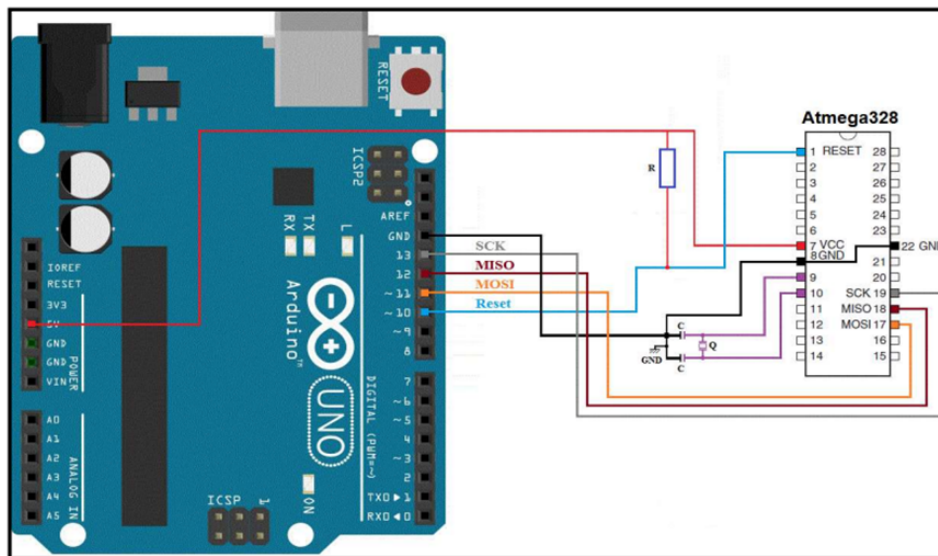


FIGURE 4.1 – Bootloader Upload Circuit

A. First, the Arduino IDE must be opened. The ATmega328 must then be selected. To do this, navigate to :

- **Tools** → **Board Type** → Select Arduino UNO

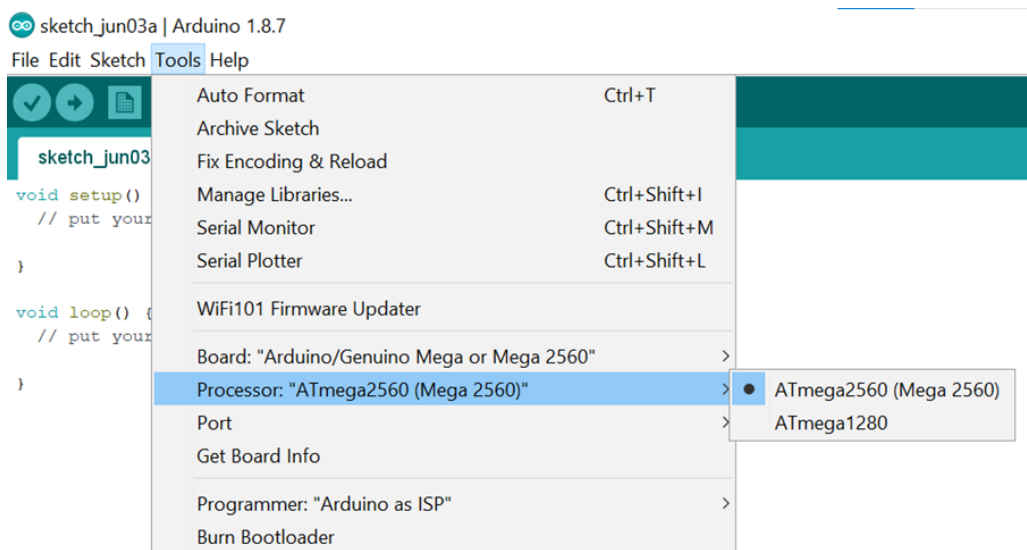


FIGURE 4.2 – ATmega328 Selection

B. the **Arduino** ISP sketch must be uploaded to the **Arduino UNO** board. Before burning the bootloader, make sure the following setting is correctly configured :

- The line above the Burn Bootloader option should indicate :

Programmer : Arduino as ISP

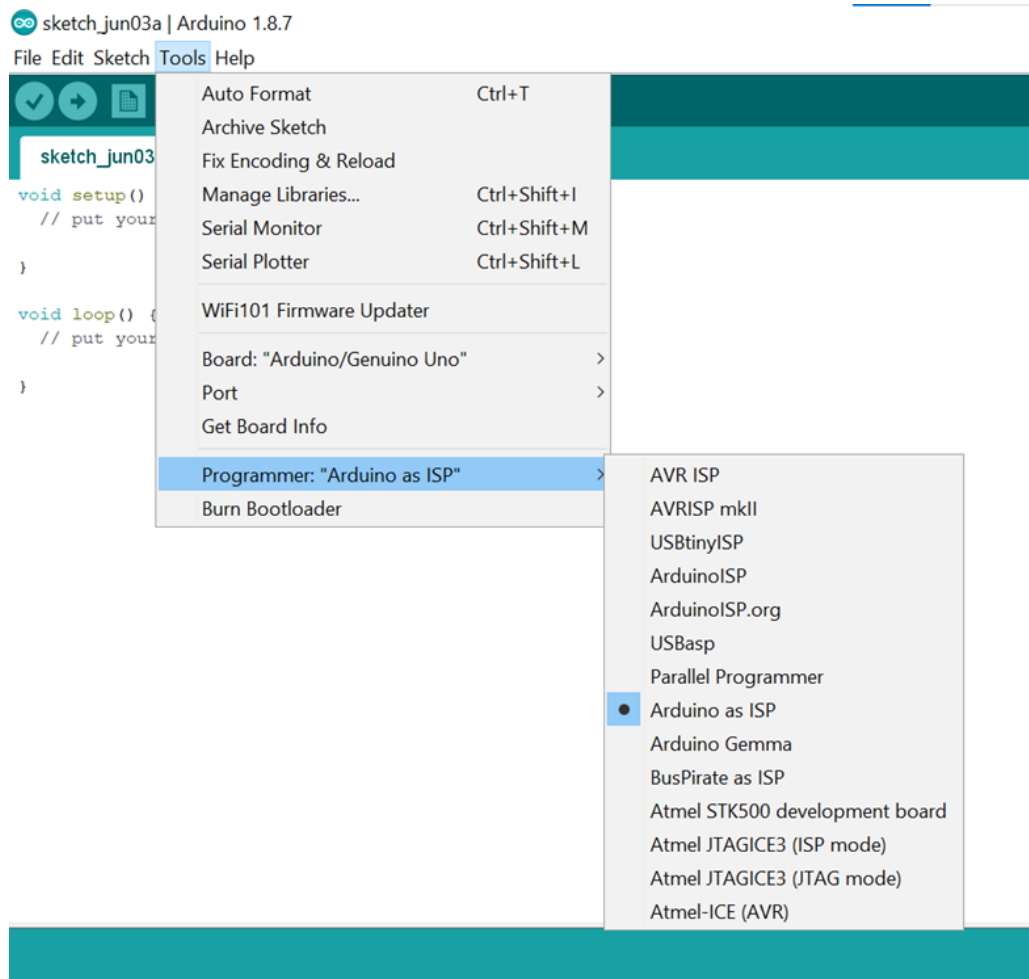


FIGURE 4.3 – Selecting Programmer : "Arduino as ISP"

C. The bootloader can now be burned onto the ATmega328.



FIGURE 4.4 – Selecting : Burn Bootloader

4.2.3 Program Upload and Uploading

Once the bootloader burning process is complete, we can disconnect the microcontroller from the bootloader programming circuit and place it onto the Arduino board, replacing the original microcontroller. At this point, we can upload our program to the ATmega328.

4.3 THE EASYEDA SOFTWARE

EasyEDA is an online-based Electronic Design Automation (EDA) tool used for creating electrical schematics and designing Printed Circuit Boards (PCBs). Unlike traditional offline software like Eagle, EasyEDA operates directly through a web browser, offering an accessible and user-friendly environment for both beginners and experienced designers.

EasyEDA is available in both free and paid versions, with the free version offering unlimited schematic sheets, multi-layer PCB designs, and cloud-based project storage. This makes it particularly appealing to students, makers, and startups.

Some key advantages of EasyEDA include :

- No installation required, as it runs directly in a web browser (Chrome, Firefox, etc.).
- Integrated component libraries, including LCSC and JLCPCB parts for real-time BOM and PCB ordering.
- Built-in simulation capabilities for circuit testing before implementation.
- Seamless transition from schematic to PCB, with auto-routing and manual routing tools.
- Online collaboration, allowing multiple users to work on the same project.
- Direct manufacturing integration, enabling users to order PCBs directly from the design platform.

Overall, EasyEDA simplifies the PCB design process by combining design, simulation, and manufacturing features in a single platform.

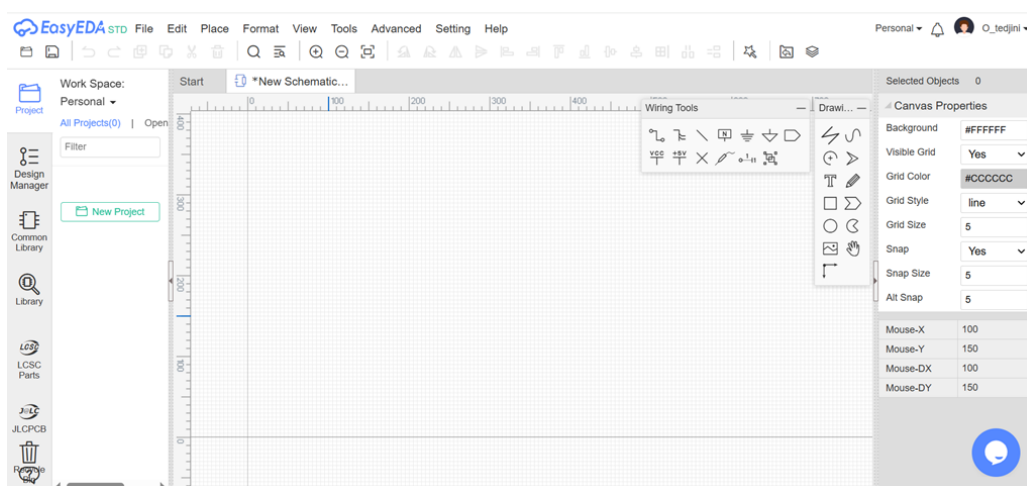


FIGURE 4.5 – EasyEDA Software Interface (Version Online)

4.3.1 The Electrical Schematic of our project using the EasyEDA software

In our project, we used EasyEDA to design the full schematic of the pump control and monitoring system. At the core of this system is the Arduino UNO, based on the ATMEGA328P microcontroller. Although the Arduino board already integrates essential components for the microcontroller to function properly, when building a custom design or PCB, these components need to be explicitly included.

These auxiliary components and supporting modules, as shown in the schematic, include :

- A stable 5 V DC power supply (provided via a LM2596 buck converter) that powers all elements of the circuit : the microcontroller, the relay, the GSM module, and sensors.
- A SIM800L GSM module, which handles SMS-based communication between the user and the pump system.
- A relay driver circuit, including a 2N2222A transistor and a diode for flyback protection, which controls the pump by energizing or de-energizing the contactor coil.
- Three ACS712 sensors, which measure the current in each of the three phases (L1, L2, and L3).
- Three ZMPT101B-based AC voltage sensors, used to measure the voltage of each phase.
- A DS18B20 temperature sensor, which monitors the surface temperature of the motor to detect any overheating.
- Push buttons connected to digital pins for manual activation or interruption if needed.

Once the microcontroller circuit is completed, it is connected to the relay and SIM800L module, and the sensor readings are managed through analog and digital inputs. An LED indicator is also included in the circuit to visually represent the system's state (e.g., ON/OFF or error).

This schematic represents the functional design of the project and provides the foundation for future PCB layout and hardware implementation.

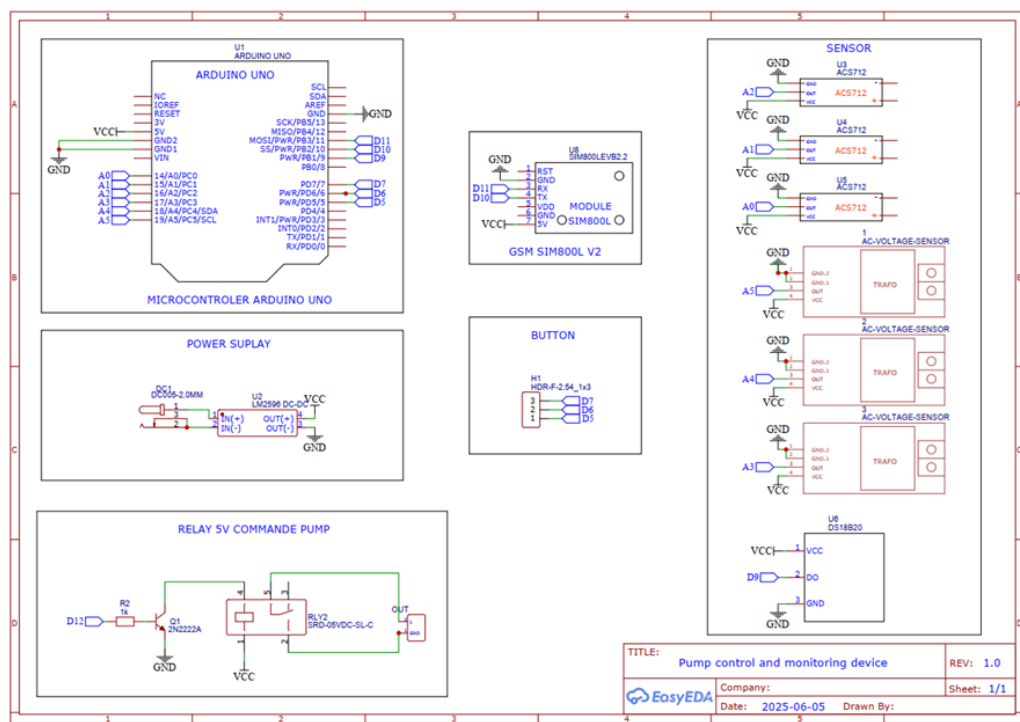


FIGURE 4.6 – The electrical Schematic of our circuit

4.3.2 Printed Circuit Design

Once the schematic design is completed and verified, the next step is to transition from the logical diagram to the physical layout by designing the Printed Circuit Board (PCB). EasyEDA offers an integrated and seamless transition between the schematic editor and the PCB design environment through the *"Convert to PCB"* or *"Switch to PCB"* function.

This phase involves organizing and placing all components on a board layout and defining the electrical tracks (routing) that connect them. The components from the schematic are automatically imported into the PCB workspace, where they can be arranged according to space constraints, thermal considerations, and accessibility.

The main steps followed during the PCB design process in EasyEDA are :

- **Component Placement** : Components are manually positioned in logical and compact arrangements to minimize trace lengths and avoid signal interference.
- **Board Outline Definition** : The physical dimensions of the PCB are defined according to project requirements.
- **Routing** : Electrical connections between components are created using copper traces. EasyEDA offers both manual routing for precise control and auto-routing for rapid prototyping.
- **Design Rule Check (DRC)** : A built-in tool verifies that the PCB follows electrical and manufacturing constraints (minimum clearance, trace width, etc.).
- **Ground Plane and Power Plane Creation** : Copper zones are added to provide stable voltage levels and reduce electromagnetic interference.
- **Export and Fabrication** : Once the layout is finalized, Gerber files are generated directly from EasyEDA and can be sent to a manufacturer, such as **JLCPCB**, for fabrication.

This stage transforms the abstract logic of the schematic into a real, manufacturable physical circuit, ready to be produced and assembled.

4.4 Exporting and Preparing the Prototype

Once the electrical schematic and PCB layout are finalized in the software, the design can be exported in various formats. The most important format is the Gerber file, which contains all the necessary data for the industrial manufacturing of printed circuit boards (PCBs). This file can be sent to specialized manufacturers who use computer-aided manufacturing (CAM) tools to produce the boards. In this project, exporting was mainly used to generate visual documentation and to prepare a functional prototype for testing and validation in the field, rather than for large-scale production.

4.5 Program Flowchart

The Arduino IDE software was used to develop the embedded control code for this project. To illustrate the logic and operational sequence of the system, a **BPMN (Business Process Model and Notation)** diagram was created instead of a traditional flowchart. BPMN provides a standardized, structured approach to model the behavior of processes, which is particularly useful for describing interactions between components and decision-based flows.

The diagram below presents the BPMN model representing the logic implemented in the Arduino sketch. It covers the main operations, such as sensor readings, SMS reception, relay control, and error handling.

The complete source code of the program is provided in **Appendix C 4.8**.

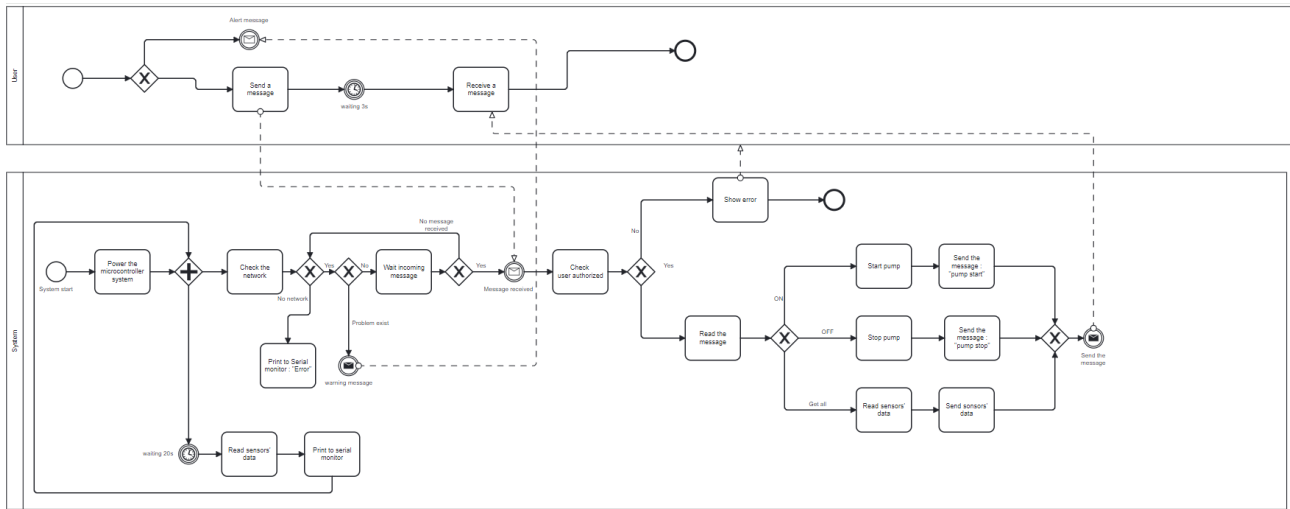


FIGURE 4.7 – The program flowchart

4.6 Results

The image below shows an electronic board designed to control a centrifugal pump. It is powered exclusively by a 5V/2A AC-DC adapter, which supplies the necessary energy for all onboard electronic components.

The circuit consists of three main components :

1) GSM SIM800L Module

- This module allows the board to receive remote control commands via SMS (such as "ON" or "OFF").
- It can also send SMS notifications to the user to report :
 - Pump activation.
 - Pump desactivation.
 - Or the detection of a fault or abnormal condition (e.g., overload, high temperature, or voltage loss).

2) ATMEGA328 Microcontroller

- This is the central processing unit of the system.
- It runs a continuous loop that reads incoming messages, analyzes their content, and determines the necessary action.
- It also monitors operating conditions and can detect faults based on inputs from connected sensors.

3) Electronic Relay

- This acts as an electronically controlled switch.
- It connects the low-voltage control circuit to the pump's high-voltage control cabinet.
- When a command is received, the relay closes the circuit to turn the pump on, or opens it to turn the pump off.

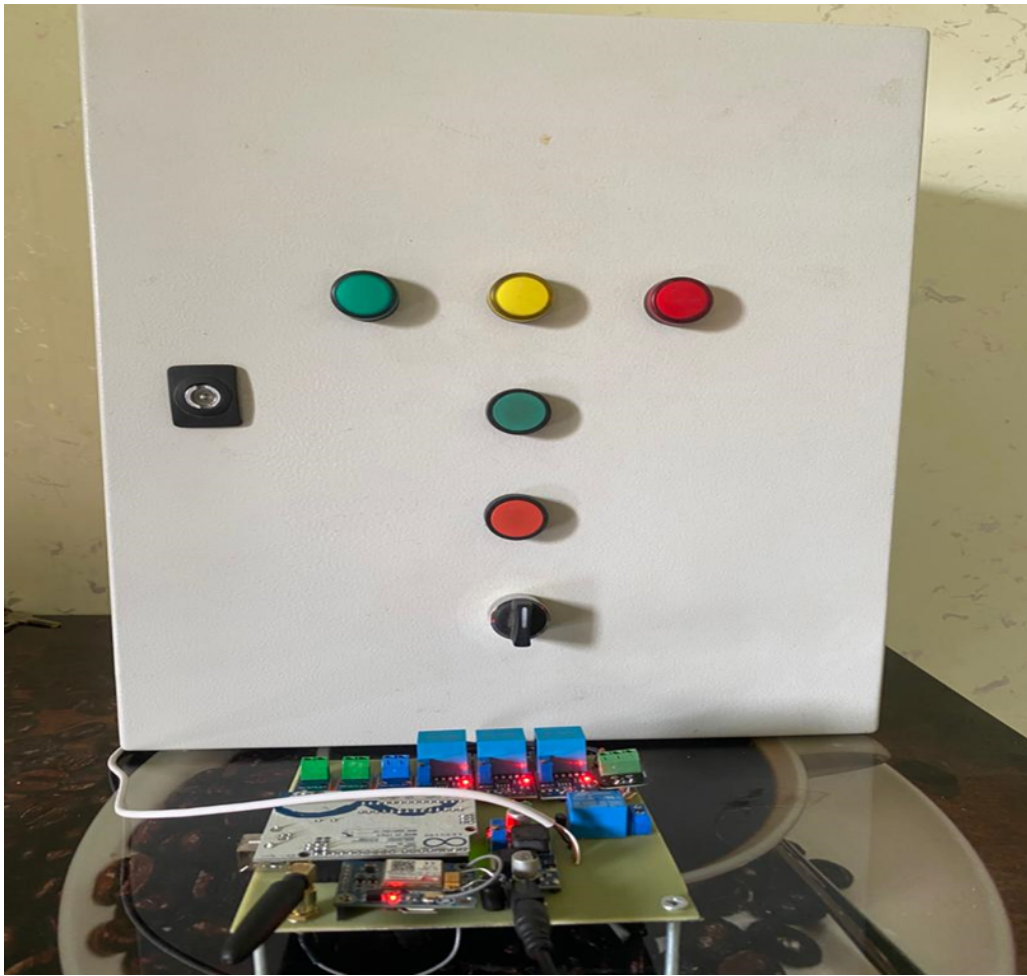


FIGURE 4.8 – Hardware implementation of the remote pump control system

4.6.1 Operating State

The pump is controlled using a single relay that is directly connected to the coil of the contactor inside the control cabinet. When the user wants to activate the pump, an SMS with the command "ON" or "0" is sent to the phone number associated with the SIM card inserted into the GSM SIM800L module.

Upon receiving the message, the microcontroller checks the sender's phone number to ensure it is authorized. If the number is verified, the microcontroller activates the relay by setting its output pin to HIGH. This action closes the relay circuit and allows current to flow to the contactor coil, thereby energizing it and starting the pump. This state is typically indicated by a green LED on the relay module As illustrated in the figure below.

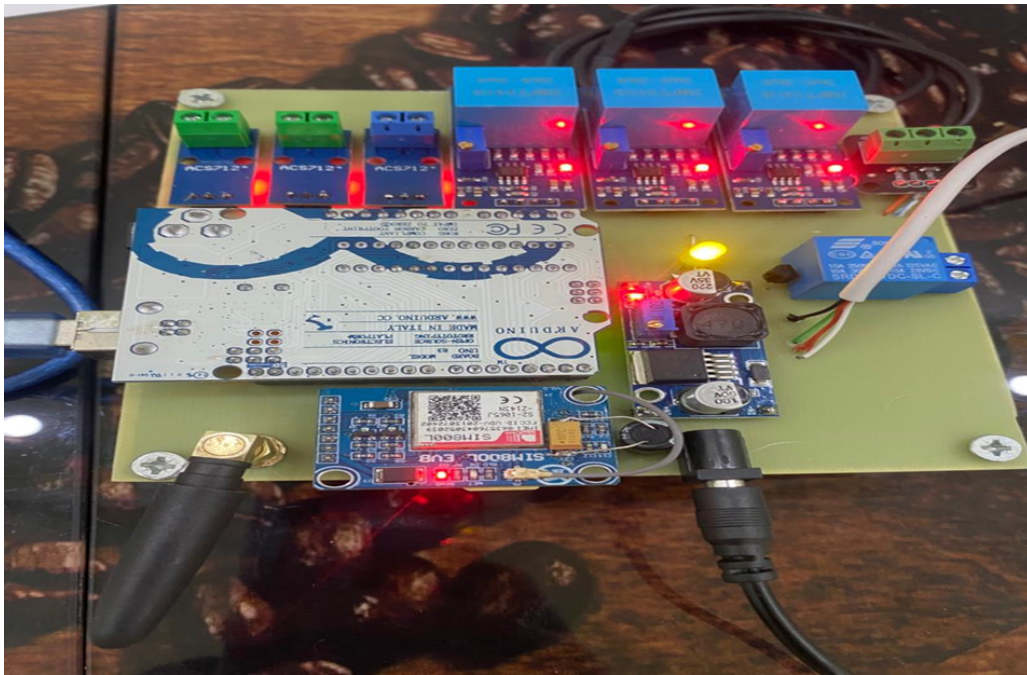


FIGURE 4.9 – The green indicator light on the single relay module signifies that the pump has been started

Once the pump is successfully activated, the system automatically sends an SMS confirmation back to the user indicating that the pump start as shown in the figure below.

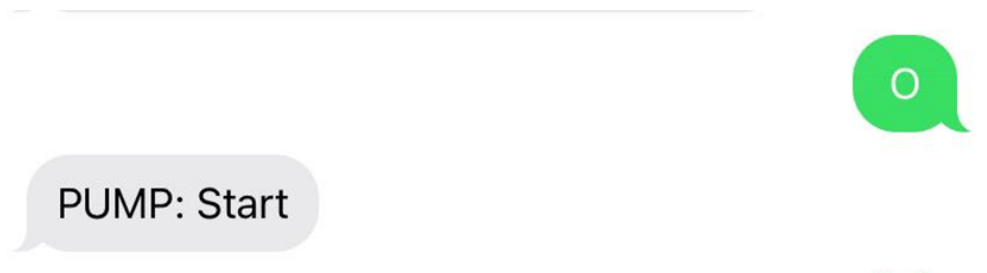


FIGURE 4.10 – Operating State SMS

4.6.2 Stopped State

To stop the pump, the user sends another SMS command with the message "OFF" or "F" to the same phone number. After validating the sender's number, the microcontroller deactivates the relay by setting its output pin to LOW. This action interrupts the current flow to the contactor coil, which causes the coil to de-energize, resulting in the pump being turned off As illustrated in the figure below.

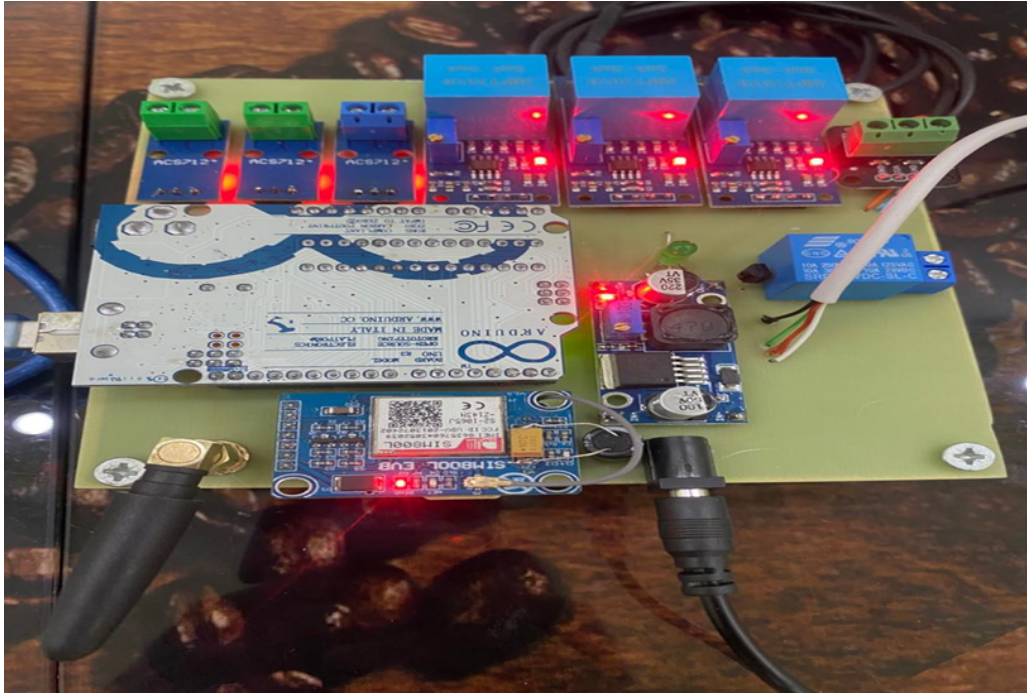


FIGURE 4.11 – The green indicator is OFF, it means that the pump has been stopped

As in the activation case, this state can also be indicated by the relay LED turning off, and the system sends an SMS back to the user confirming that the pump has been successfully stopped as shown in the figure below.



FIGURE 4.12 – Stopped State SMS

4.6.3 Supervision State : Real-Time Monitoring Request

In addition to basic ON/OFF control, the system also supports real-time supervision. When the user sends an SMS with the command "GET ALL" or "A", the system responds by measuring and reporting key electrical and environmental parameters of the pump in real time.

Once the command is received and verified, the microcontroller collects data from the following sensors :

- Voltage sensors (ZMPT101B) on each of the three phases (L1, L2, L3).
- Current sensors (ACS712) on each phase.
- Temperature sensor (DS18B20) to measure the motor's surface temperature.

Using the collected data, the microcontroller calculates :

- Line voltage per phase (V).
- Line current per phase (A).

- Electrical power per phase using the formula :

$$\text{Power (W)} = \text{Voltage} \times \text{Current}$$

- Motor temperature ($^{\circ}\text{C}$).

All of this information is compiled into a single formatted message and sent back to the user's phone. This supervision feature allows the user to monitor the pump's performance and health remotely, helping to anticipate faults and reduce downtime. The figure below shows supervision State SMS.

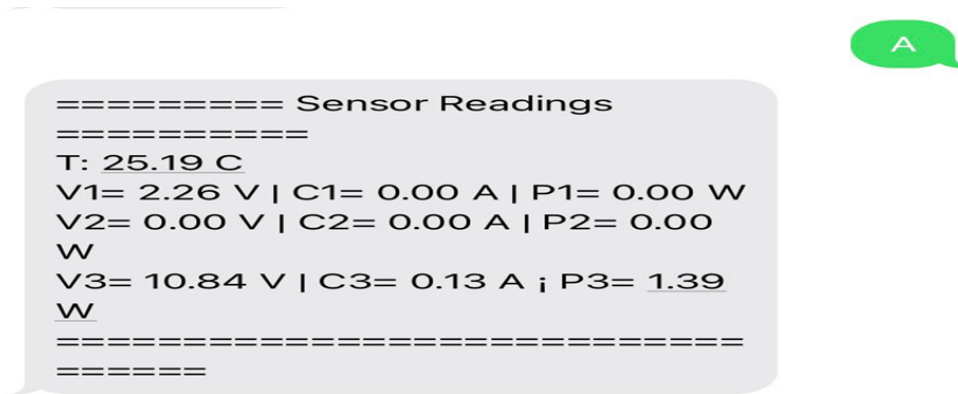


FIGURE 4.13 – Supervision State SMS

4.6.4 Warning State : Fault Detection and Alert System

To enhance safety and reliability, the system continuously monitors the pump's electrical and thermal conditions. If a fault or abnormal condition is detected, the system automatically sends a warning SMS to alert the user.

The faults detected include :

- **Overload** : current exceeds the safe threshold.
- **Short circuit** : detected by sudden current surge.
- **Phase loss** : voltage drops to zero on one phase.
- **Over-temperature** : motor temperature exceeds the set limit (e.g., 70°C).

Upon detecting any of these conditions, the system sends the following automatic SMS as shown in the figure below.

```
WARNING!
There was a problem with the pump
and it was stopped!

===== Sensor Readings
=====
T: 27.81 C
V1= 2.26 V | C1= 0.00 A | P1= 0.00 W
V2= 0.00 V | C2= 0.00 A | P2= 0.00
W
V3= 3.20 V | C3= 0.00 A | P3= 0.00
W
=====
=====
```

FIGURE 4.14 – Warning State SMS

4.7 Experimental Results of Monitoring

In order to assess the performance of the monitoring system, real-time data were acquired using current, voltage, and temperature sensors. The subsequent figures illustrate the evolution of the electrical parameters throughout a complete operating cycle of the pump.

4.7.1 Current of the three phases

This graph highlights the stability of the three-phase currents throughout the operating cycle. It shows that all three phases maintain similar current values, indicating a well-balanced load distribution. Sudden variations or imbalances would typically point to motor faults or transient overloading conditions.



FIGURE 4.15 – Variation of the three-phase current (M1, M2, M3) during operation

4.7.2 Voltage of the three phases

The voltages across the three phases remain within a stable range, which reflects the quality of the electrical power supply. Symmetry among the phases ensures proper functioning of the pump motor. Minor fluctuations can be attributed to grid variations or load demand changes.

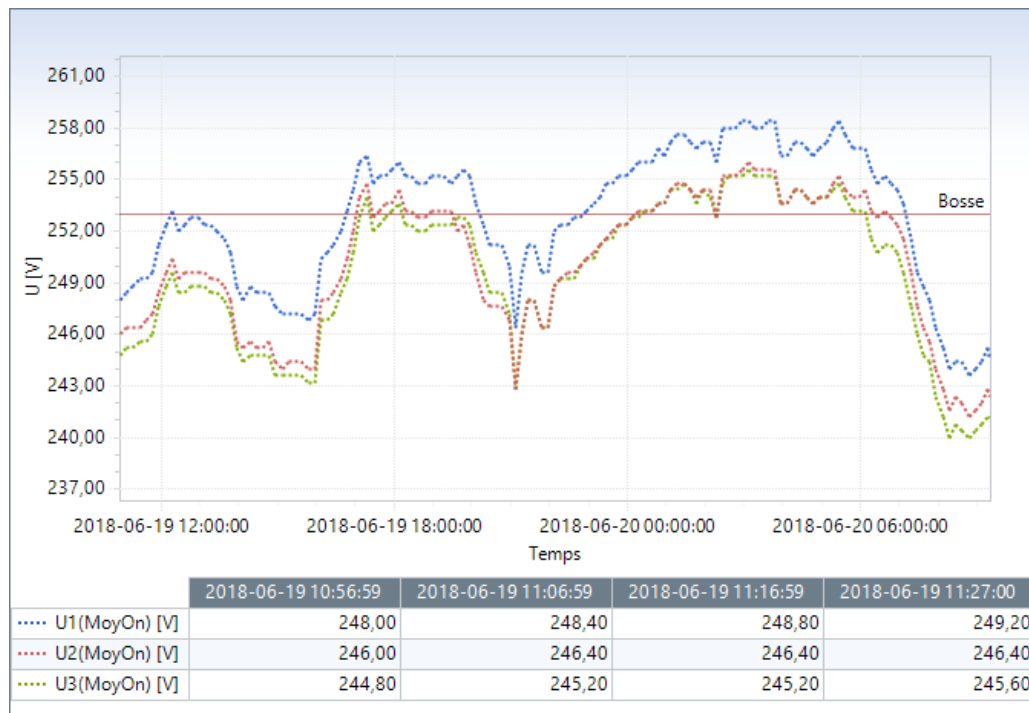


FIGURE 4.16 – Variation of the three-phase voltage (U1, U2, U3) during operation

4.7.3 Instantaneous current over 6 hours

This graph shows the variation of instantaneous current values over a 6-hour observation period. It reveals the active operating periods as well as shutdown intervals. Peaks in current typically indicate pump start-up phases or temporary overloads. These measurements are essential for real-time load monitoring.

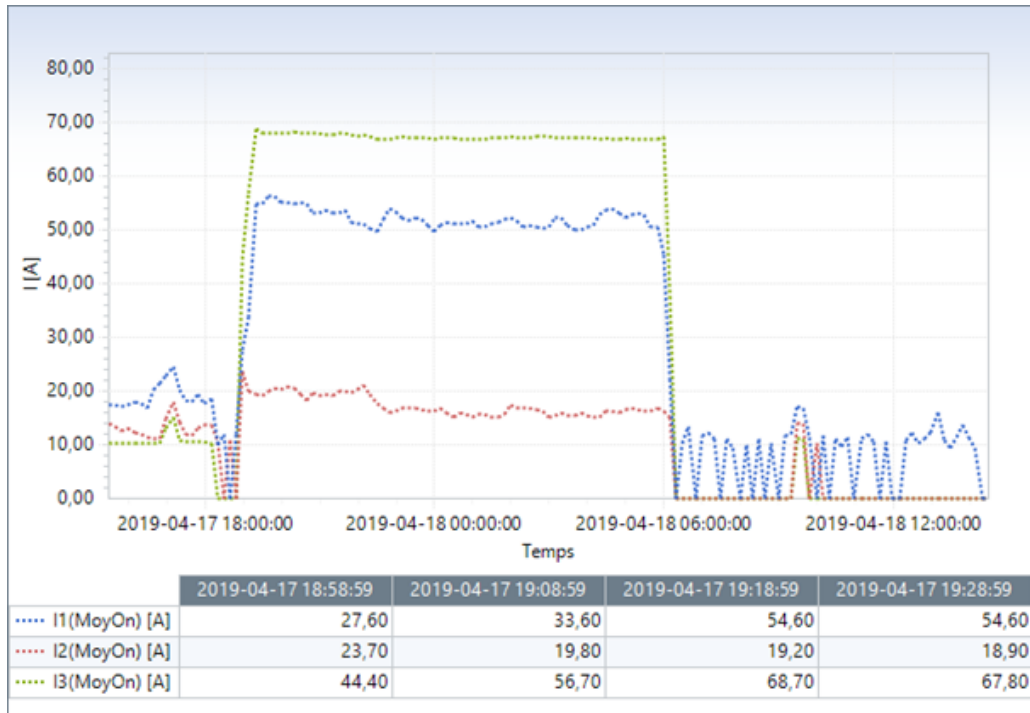


FIGURE 4.17 – Instantaneous current values for the three phases over a 6-hour period

4.7.4 Instantaneous voltage over 6 hours

The instantaneous voltage graph shows the regularity of the electrical supply over an extended period. The absence of voltage dips or spikes confirms the stability of the power network. This type of analysis is crucial for anticipating faults related to poor power quality, such as unexpected tripping or premature motor wear.

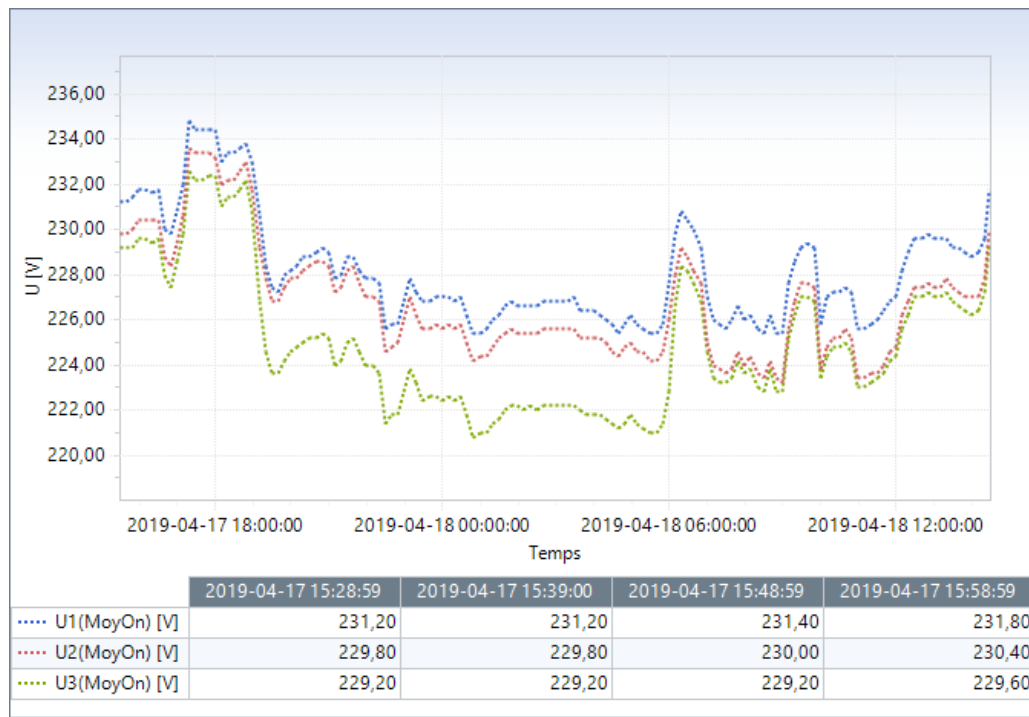


FIGURE 4.18 – Instantaneous voltage values for the three phases over a 6-hour period

the results obtained from the installed sensors demonstrate a stable electrical behavior in terms of both current and voltage, confirming the effectiveness of the implemented remote monitoring system. Real-time tracking of these parameters is essential for early fault detection and for optimizing the predictive maintenance strategy.

4.8 Conclusion

In this chapter, we successfully implemented the practical part of our proposed solution by designing and testing a functional control and supervision system for a centrifugal pump. Through the use of the EasyEDA platform, we created a complete schematic and printed circuit board (PCB) tailored to our system's requirements.

By integrating the ATmega328P microcontroller, a GSM communication module, and various electrical and thermal sensors, we developed a compact and cost-effective solution that supports remote control, real-time monitoring, and automatic fault detection. The transition from schematic design to PCB layout demonstrated our ability to move from conceptual design to hardware implementation.

Furthermore, the system's ability to notify the user via SMS about the operating status, abnormal conditions, and key parameters such as current, voltage, and temperature contributes directly to predictive maintenance practices, an essential aspect of industrial reliability.

The positive test results validate the feasibility and effectiveness of the system, reinforcing its value for field applications such as agricultural water pumping, while aligning with modern maintenance strategies focused on automation, supervision, and fault anticipation.

General Conclusion

The objective of this project was to develop a dual-purpose system that integrates an optimized maintenance strategy and a remote control solution for submersible pumps. The study covered both the theoretical and practical aspects of pump systems and maintenance methodologies, followed by the design and implementation of an electronic prototype using Arduino.

The system successfully monitors key parameters voltage, current, and temperature and transmits information to the user via SMS, enabling immediate intervention in case of malfunction. The prototype proves that combining preventive maintenance with real-time supervision can significantly enhance system reliability and reduce operational costs.

The results obtained during testing validate the system's effectiveness in detecting common electrical anomalies such as overcurrent, phase failure, and overheating. The project demonstrates how low-cost embedded systems can provide powerful tools for industrial monitoring.

Future developments may include wireless data logging, web-based dashboards, integration into IoT ecosystems, or SCADA platforms, further expanding the system's capabilities and industrial applications.

Appendix A

FMECA Table

Date of the analysis	FMECA Machine – Failure Modes, Effects and Criticality Analysis						Operating phase				Page :
	System : Submersible pump			Subsystem : Pump			Criticality:				Name :
	Component	Function	Failure Mode	Causes	Effect	Detection	G	D	F	C	Corrective action
	Impeller	Imparts velocity to the liquid	- Wear - Breakage	Excessive stress Cavitation Worn impeller vanes	- Flow reduction - Pump shutdown	- Noise - Vibration	4	1	5	20	- Monthly pump cleaning - Impeller condition check - Vibration monitoring - Replace worn impeller with a new one
	Shaft	Transmits power as torque and rotational motion	- Vibration - Wear	Poor lubrication Overload Deformation	- Pump shutdown	Vibration	4	1	2	8	- Inspect elements in contact with shaft - Replace shaft
	Mechanical Seal	Ensures pump sealing and prevents fluid leakage outward	- Face wear - Seal wear	Cavitation Poor water quality	- Insufficient flow - Pump shutdown	Water leakage	4	1	5	20	Seal replacement
	Diffuser	Guides product flow	Wear	Cavitation Dirty Water	Degraded function	- Noise - Cavitation	3	1	1	3	Corrective maintenance
	Volute	Enhances hydraulic effect of the impeller	Cracks	Cavitation Dirty water	Degraded function	- Noise - Cavitation	3	1	1	3	Corrective maintenance
	Bearing	Guide and support the pump shaft, reduce friction	Excessive wear	Poor lubrication Overload Shaft misalignment	- Excessive vibration - Shaft degradation - Pump failure	- Noise - Vibration	4	2	3	24	- Verify/adjust shaft alignment - Regular lubrication - Replace worn bearing
	Wear Ring	Protect the impeller and pump casing from wear and erosion	Excessive wear	Abrasive fluid Cavitation Excessive friction	- Reduced pump efficiency - Internal leakage	- Noise - Reduced flow rate	3	2	2	12	- Periodic inspection - Replace wear ring if necessary

Date of the analysis	FMECA Machine – Failure Modes, Effects and Criticality Analysis						Operating phase				Page :
	System : Submersible pump			Subsystem : Motor			Criticality:				Name :
	Component	Function	Failure Mode	Causes	Effect	Detection	G	D	F	C	Corrective action
	Bearing	Guide and support the rotor	- Wear - Breakage	Fatigue Vibration	- Overheating - Rotor jam	- Noise - Heat	3	2	2	12	Bearing replacement
	Stator	Generate a rotating magnetic field	- Winding burnout - Phase failure - Insulation failure	Overload Fatigue	Pump shutdown	Visual inspection	2	4	1	8	Winding rewinding
	Rotor	Ensure rotational motion	Cage failure	Overload Fatigue	Pump shutdown	Visual inspection	4	2	1	8	Cage replacement
	Terminal box	Ensure power supply to the motor	Insulation failure (short circuit)	Insulation fault	Pump shutdown	Visual inspection	4	2	1	8	Check insulation

Date of the analysis	FMECA Machine – Failure Modes, Effects and Criticality Analysis						Operating phase				Page :
	System : Submersible pump			Subsystem : Discharge Circuit			Criticality:				Name :
	Component	Function	Failure Mode	Causes	Effect	Detection	G	D	F	C	Corrective action
	Check valve	Allows water flow in one direction only	Pump runs but no water is discharged	Inverted valve installation Jammed valve	Pressure drop	Low flow	4	2	2	16	Valve replacement
	Valve	Controls or stops fluid flow	Blockage	No command signal	Water supply shutdown	Visual inspection	1	1	1	1	Valve unblocking
	Elbow	Reduces pressure losses	Pump damage	Poor elbow installation	Pump priming failure	Pressure gauge	3	2	1	6	Disassemble and reinstall the elbow

Date of the analysis	FMECA Machine – Failure Modes, Effects and Criticality Analysis					Operating phase			Page : Name :	
	System : Submersible pump		Subsystem : Coupling			Criticality:				
Component	Function	Failure Mode	Causes	Effect	Detection	G	D	F	C	Corrective action
Key	Enables the rotation of a driven element from a driving element	Coupling system failure	Loosening of assembly fittings	- Poor transmission	Visual inspection	2	1	3	6	- Realignment
			Overload	- Pump performance degradation						- Tightening of the fixing system
			Fatigue							- Coupling replacement
			Misalignment							
			Deformation							

Date of the analysis	FMECA Machine – Failure Modes, Effects and Criticality Analysis						Operating phase				Page :
	System : Submersible pump			Subsystem : Suction Circuit							Name :
	Component	Function	Failure Mode	Causes	Effect	Detection	Criticality:				Corrective action
Orifice	Direct the fluid to the impeller inlet	- Orifice overheating	Liquid evaporation	- Orifice implosion	Visual inspection	G	D	F	C	Check pressure	
		- Noise	Pressure variation	- Erosion		2	1	1	2		
Elbow	Reduce pressure losses	Pump damage	Faulty elbow installation	Loss of pump priming	Pressure gauge	3	2	1	6	Dismantle and reassemble the elbow	
Tube	Carry water suction to the suction orifice	- Noise	Vapor formation inside the pump	Cavitation	Pressure gauge	4	2	1	8	Check pressure	
		- Vibration	Air pockets in the tubes								
Strainer - check valve	Prevent solid particles from entering	- Deterioration	Presence of solid particles in the fluid	- Poor fluid filtration	Pressure gauge	4	2	2	16	Replace the strainer	
		- Clogged strainer		- Pressure drop							
Tank	Supply water to the circuit	Puncture	Presence of frost	Supply interruption	Visual inspection	1	1	1	1	Replace the tank	

Appendix B

Preventive Maintenance Plan

Nº= FM	C	CI	CA	MP			RD	F					Responsible	ML
				TBM	CBM	PA		M	Q	S	A	Other		
5	16	A	Strainer replacement	X		Quarterly replacement	2h		X				I+T	2
6	12	A	Motor bearing replacement	X		Biennial replacement	5h					2 YEARS	I+T	4
7	12	A	Periodic wear ring inspection and replacement		X	Semiannual inspection	2h			X			I+T	2
8	8	A	Rotor cage replacement	X		Annual inspection and replacement if damaged	4h				X		I+T	3

Nº= FM	C	CI	CA	MP			RD	F					Responsible	ML
				TBM	CBM	PA		M	Q	S	A	Other		
9	8	A	Stator rewinding	X		Annual inspection and rewinding if necessary	8h				X		I+T	4
10	8	A	Terminal box insulation check		X	Semiannual inspection	1h			X			I+T	2
11	8	B	Tube pressure verification		X	Monthly pressure check	1h	X					I+T	2
12	8	B	Shaft replacement if worn	X		Annual inspection	6h				X		I+T	4

N ^o = FM	C	CI	CA	MP			RD	F					Responsible	ML
				TBM	CBM	PA		M	Q	S	A	Other		
13	6	B	Discharge elbow disassembly and reassembly		X	Semiannual inspection	2h			X			I+T	2
14	6	B	Coupling realignment, fastener tightening, replacement if needed		X	Quarterly inspection	3h		X				I+T	3
15	6	B	Suction elbow disassembly and reassembly		X	Semiannual inspection	2h			X			I+T	2
16	3	C	Diffuser corrective maintenance	PM		Annual inspection and repair if required	2h				X		I+T	2

N ^o = FM	C	CI	CA	MP			RD	F					Responsible	ML
				TBM	CBM	PA		M	Q	S	A	Other		
17	3	C	Volute corrective maintenance	PM		Annual inspection	1h				X		I+T	2
18	2	C	Orifice pressure verification		X	Semiannual inspection	1h			X			I+T	1
19	1	C	Tank replacement if punctured	PM		Annual inspection	3h				X		O	1
20	1	C	Valve unblocking	PM		Semiannual inspection	1h			X			O	1

Appendix C

Arduino code

```
1  #include <SoftwareSerial.h>
2  #include <OneWire.h>
3  #include <DallasTemperature.h>
4  #include <ZMPT101B.h>
5  #include <ACS712.h>
6
7  // إعدادات SIM800L
8  #define rxPin 10
9  #define txPin 11
10 SoftwareSerial sim800(rxPin, txPin);
11
12 // إعدادات المرحل والأزرار
13 const int relayPin = 12;
14 const int buttonOnPin = 5;
15 const int buttonOffPin = 6;
16 const int warningButtonPin = 7;
17
18 #define ONE_WIRE_BUS 9
19 const String PHONE = "+213779547868";
20
21 // متغيرات الرسائل
22 String smsStatus, senderNumber, receivedDate, msg;
23
24 OneWire oneWire(ONE_WIRE_BUS);
25 DallasTemperature sensors(&oneWire);
```

```

26
27 #define SENSITIVITY 462.5f
28 ZMPT101B voltageSensor1(A5, 50.0);
29 ZMPT101B voltageSensor2(A4, 50.0);
30 ZMPT101B voltageSensor3(A3, 50.0);
31
32 ACS712 currentSensor1(ACS712_20A, A2);
33 ACS712 currentSensor2(ACS712_20A, A1);
34 ACS712 currentSensor3(ACS712_30A, A0);
35
36 bool lastWarningButtonState = HIGH;
37 unsigned long lastWarningButtonPress = 0;
38 const unsigned long debounceDelay = 300;
39
40 void setup() {
41     Serial.begin(9600);
42     sim800.begin(9600);
43
44     pinMode(relayPin, OUTPUT);
45     pinMode(buttonOnPin, INPUT_PULLUP);
46     pinMode(buttonOffPin, INPUT_PULLUP);
47     pinMode(warningButtonPin, INPUT_PULLUP);
48
49     sensors.begin();
50
51     voltageSensor1.setSensitivity(SENSITIVITY);
52     voltageSensor2.setSensitivity(SENSITIVITY);
53     voltageSensor3.setSensitivity(SENSITIVITY);
54
55     currentSensor1.calibrate();
56     currentSensor2.calibrate();
57     currentSensor3.calibrate();
58
59     delay(1000);
60
61     sim800.println("AT+CMGF=1");
62     delay(1000);
63     sim800.println("AT+CNMI=1,1,0,0,0");
64     delay(1000);
65
66     Serial.println("System Ready!");
67     digitalWrite(relayPin, LOW);
68 }
69
70 void loop() {
71     handleButtons();
72     handleWarningButton();
73     handleSMS();
74     readAndDisplaySensors();
75 }

```

```

77 void handleButtons() {
78   if (digitalRead(buttonOnPin) == LOW) {
79     digitalWrite(relayPin, HIGH);
80     Serial.println("Relay ON (Button)");
81     delay(300);
82   }
83
84   if (digitalRead(buttonOffPin) == LOW) {
85     digitalWrite(relayPin, LOW);
86     Serial.println("Relay OFF (Button)");
87     delay(300);
88   }
89 }
90
91 void handleWarningButton() {
92   int warningButtonState = digitalRead(warningButtonPin);
93
94   if (warningButtonState != lastWarningButtonState) {
95     lastWarningButtonState = warningButtonState;
96
97     if (warningButtonState == LOW) {
98       if (millis() - lastWarningButtonPress > debounceDelay) {
99         lastWarningButtonPress = millis();
100         sendWarningMessage();
101       }

```

```

102     }
103   }
104 }
105
106 void sendWarningMessage() {
107   String warningMsg = " WARNING!\n";
108   warningMsg += "There was a problem with the pump and it was stopped!\n\n";
109   warningMsg += getSensorReadings();
110
111   Reply(warningMsg);
112   Serial.println("Warning message sent!");
113 }
114
115 void handleSMS() {
116   while (sim800.available()) {
117     // parseData(sim800.readString()); // intentionally disabled
118   }
119
120   while (Serial.available()) {
121     sim800.println(Serial.readString());
122   }
123 }
124
125 void readAndDisplaySensors() {
126   static unsigned long lastSensorRead = 0;

```

```

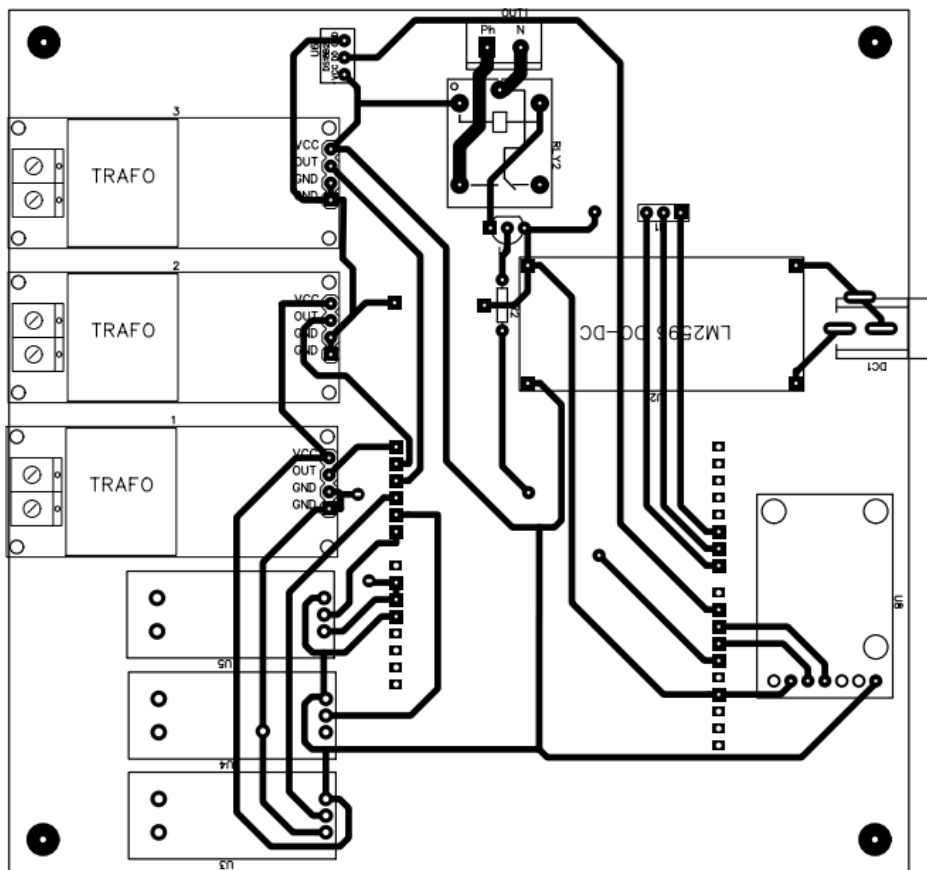
102 | }
103 | }
104 | }
105 |
106 | void sendWarningMessage() {
107 |     String warningMsg = " WARNING!\n";
108 |     warningMsg += "There was a problem with the pump and it was stopped!\n\n";
109 |     warningMsg += getSensorReadings();
110 |
111 |     Reply(warningMsg);
112 |     Serial.println("Warning message sent!");
113 | }
114 |
115 | void handleSMS() {
116 |     while (sim800.available()) {
117 |         // parseData(sim800.readString()); // intentionally disabled
118 |     }
119 |
120 |     while (Serial.available()) {
121 |         sim800.println(Serial.readString());
122 |     }
123 | }
124 |
125 | void readAndDisplaySensors() {
126 |     static unsigned long lastSensorRead = 0;

148 |     String readings = "===== Sensor Readings =====
149 | ";
150 |     readings += "T: " + String(temperature, 2) + " C
151 | ";
152 |     readings += "V1= " + String(v1, 2) + " V | C1= " + String(c1, 2) + " A | P1= " + String(p1, 2) + " W
153 | ";
154 |     readings += "V2= " + String(v2, 2) + " V | C2= " + String(c2, 2) + " A | P2= " + String(p2, 2) + " W
155 | ";
156 |     readings += "V3= " + String(v3, 2) + " V | C3= " + String(c3, 2) + " A | P3= " + String(p3, 2) + " W
157 | ";
158 |     readings += "=====
159 | ";
160 |
161 |     return readings;
162 | }

```

Appendix D

PCB layout of the fabricated board



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