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Creation of a start-up for the installation of automatic drip irrigation system powered by PV panels

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Abstract
this thesis explores the integration of modern technology and renewable energy into agricultural irrigation systems to enhance food security. It begins by addressing the global challenges facing food production, including climate change and outdated irrigation methods. Moving forward to present the components of a smart irrigation system, including sensors, pumps, valves, and human-machine interfaces. Next we introduce the integration of solar energy through photovoltaic panels, MPPT algorithms, and power converters (Buck, Boost, Buck-Boost). Finally, we have shown the practical implementation using Arduino, sensors, and a control system small prototype. A startup guide is included for scaling the solution to market.

Keywords: Food security – Smart irrigation – Renewable energy – Photovoltaic – MPPT – Arduino– Drip irrigation – HMI – Power electronics

Résumé
Cette thèse explore l'intégration des technologies modernes et des énergies renouvelables dans les systèmes d'irrigation agricole afin de renforcer la sécurité alimentaire. Elle commence par aborder les défis mondiaux liés à la production alimentaire, notamment le changement climatique et les méthodes d'irrigation obsolètes. Elle présente ensuite les composants d'un système d'irrigation intelligent, tels que les capteurs, les pompes, les vannes et les interfaces homme-machine. L'intégration de l'énergie solaire est ensuite introduite à travers les panneaux photovoltaïques, les algorithmes MPPT et les convertisseurs de puissance (Buck, Boost, Buck-Boost). Enfin, une mise en œuvre pratique est présentée à l'aide d'un prototype réduit basé sur Arduino, des capteurs et un système de commande. Un guide de démarrage est inclus pour permettre le passage à l'échelle et l'introduction sur le marché.

Mots-clés : Sécurité alimentaire – Irrigation intelligente – Énergie renouvelable – Photovoltaïque – MPPT – Arduino –Irrigation goutte-à-goutte – IHM – Électronique de puissance

ملخص:

تناقش هذه المذكرة إدماج التكنولوجيا العصرية و الطاقات المتجددة في مجال الري الزراعي. البداية مع تحديد التحديات التي تواجه الصناعة الغذائية منها التغير المناخي و أساليب الري القديمة. ثم ننتقل الى توضيح مكونات نظام الري الذكي، منها المستشعرات، المضخات، الحنفيات، و واجهة الإنسان و الألة. بعدها نذكرالطاقة الشمسية مع خوارزميات تتبع نقطة الطاقة القصوى. و محولات الجهد. الفصل الاخير يوضح التطبيق مع استعمال اردينو و مستشعرات للتحكم في نموذج مصغر. هنالك ايضا ملحق لإنشاء مؤسسة ناشئة.

كلمات مفتاحية: الأمن الغذائي- الري الذكي – الطاقات المتجددة – الكهروضوئية –اردينو- الري بالتقطير- واجهة الإنسان ألة- إلكترونيات الإستطاعة.

Dedication

To my beloved parents Alarbi and Wahiba, who never got tired of this reckless boy.

To the dearest siblings abd el nour, abd el basset and aya.

To my role model in life, my cousins Mohamed, kaci, ishak, mariem, amina and bassema.

To my aunt al-charifa and her late husband benyoussef.

To my aunt Zineb and her husband Kamel.

To my uncle Mouloud and his sons abd el wahab, Mohamed and Ahmed the people that gave me a wonderful childhood.

To the people who made my teenage years wholesome Oussama bolix, Fayçal

To Dhia outouat and Walid ziane

To Ishak ben hafri the most joyful soul I have ever known,

To abushamla Youssef the craziest person to ever exist.

To the robotics' so called master el-nouri and his patient friend Riyadh.

To hadjam saber and Mohamed ziainnia, the raciest people on earth.

Ibrahim Faci

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Abbreviations

Q: Flow rate.

N: rotational speed.

Hs: Suction head (from water source to pump inlet).

Hd: Delivery head (from pump outlet to water tank).

Hf: Losses due to friction (pipes, valves….).

ρ: Water density (1000 $Kg/m3$).

g: Gravity (9.81 $m2/$).

Q: Flow rate ($m3$/s).

H:Total dynamic head.

: pump efficiencey.

V: Water velocity.

A: pipe area.

$HMajor$: Losses due to friction (m).

f: Friction factor.

L: Pipe length.

V: Water velocity.

g: Gravity.

D: Diameter.

Re: Reynolds number.

V: Water velocity.

D: Pipe’s diameter.

ρ: Water density.

μ: Dynamic viscosity of water.

v: Kinematic viscosity.

E: Energy of the photon.

h: Plank's constant.

λ: Wavelength of a photon.

c: Speed of light.

I_{PV}: Current produced by the solar cell.

D: A diode that represent the p-n junction of the semi-conductors.

R_{int}: Represents internal resistances due to wiring, contacts, and the semiconductor material.

: Represents leakage currents due to defects in the solar cell.

v: Load voltage.

I: Load current.

P: power.

PWM: pulse width modulation.

MPPT: maximum power point tracking.

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General Introduction

Food security has always been a fundamental concern for humanity, and it has become increasingly urgent in the face of rapid population growth, climate change, and mounting pressure on natural resources. According to the United Nations Department of Economic and Social Affairs, the global population is projected to reach 9.7 billion by 2050, raising serious concerns about the ability to meet future nutritional demands [1]. Agriculture, as the cornerstone of food production, plays a central role in addressing these concerns. However, its sustainability and productivity are highly dependent on efficient water and energy management.

Traditional irrigation methods, such as flood irrigation, remain widespread in many regions. These techniques result in significant water losses due to evaporation, runoff, and waterlogging, with only about 60% of the water being effectively used by crops [2]. Moreover, suboptimal technologies and the lack of precision in water delivery often lead to both over- and under-irrigation, negatively impacting crop yields and resource use efficiency.

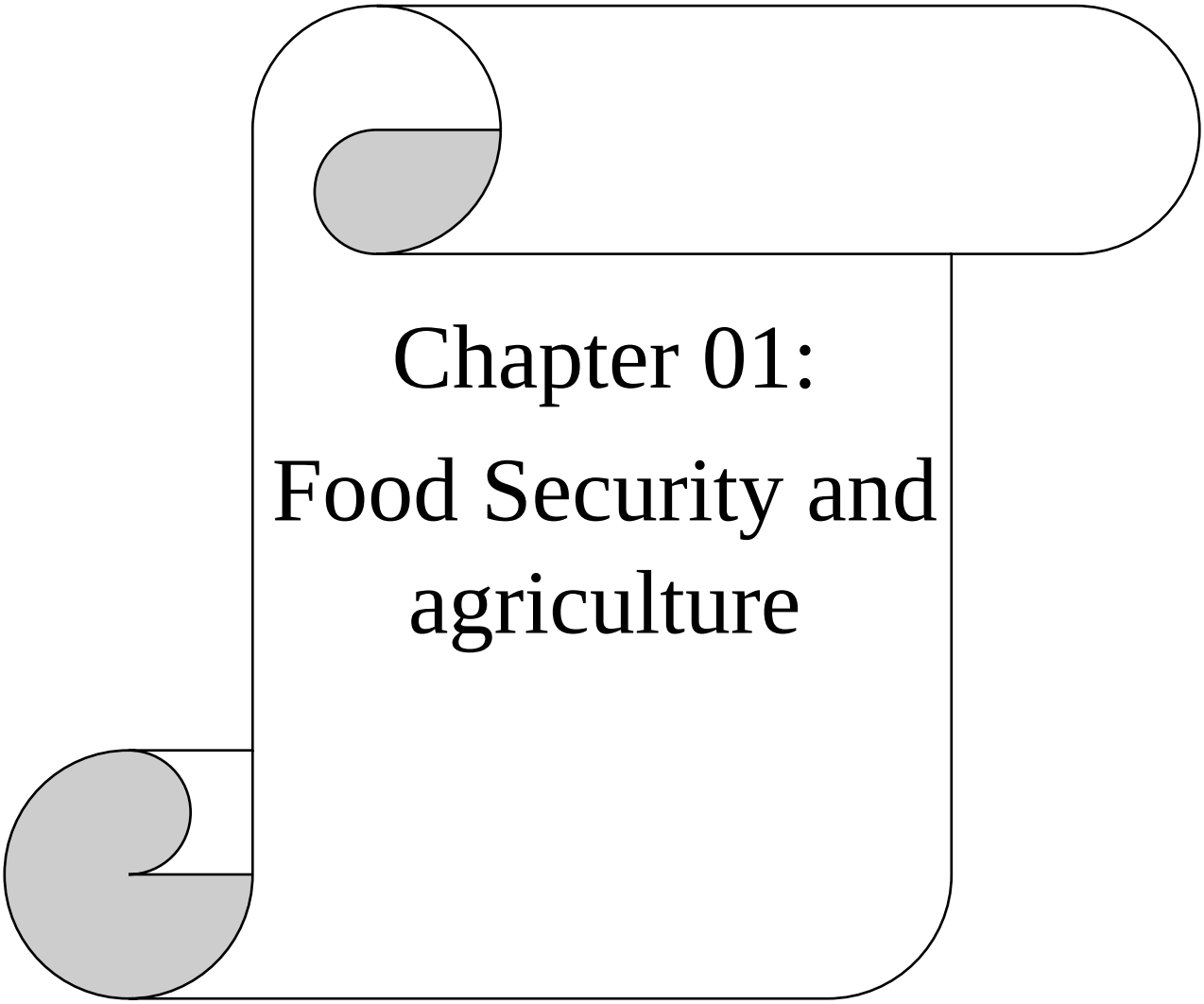
In arid and semi-arid regions—where water scarcity is a persistent challenge—there is a critical need for more sustainable and precise irrigation techniques. Drip irrigation has emerged as one of the most effective solutions, offering water savings of up to 70–80% by delivering water directly to the root zone of plants, thereby minimizing losses and improving crop health. Furthermore, this method allows for the integration of herbicides and fertilizers directly into the irrigation water, enhancing its efficiency.

To further improve the performance of drip irrigation systems, smart technologies such as sensors, microcontrollers, and automated control units can be integrated. These allow real-time monitoring of environmental conditions and enable precise irrigation scheduling based on soil moisture, weather data, and crop requirements. Such intelligent systems significantly reduce water waste and boost agricultural productivity.

Another key aspect of sustainable irrigation is the source of energy. In areas with limited or unreliable access to the electrical grid, solar photovoltaic (PV) energy presents a clean, renewable, and autonomous solution for powering irrigation systems. By incorporating Maximum Power Point Tracking (MPPT) algorithms such as the Perturb and Observe method. solar-powered systems can efficiently harness energy throughout the day, reducing environmental impact and operating costs.

This thesis explores the development of a smart drip irrigation system powered by photovoltaic energy. It focuses on the design, components, and control strategies necessary to create a fully autonomous and sustainable agricultural solution. The work is divided into three main chapters: the first discusses the global issue of food security and the role of modern irrigation; the second examines the technical elements of smart drip systems; and the third addresses the integration of solar energy and power electronics, including MPPT techniques.

By combining principles from electromechanical engineering with practical agricultural needs, this research aims to contribute to the development of innovative and sustainable farming practices that promote food security in water- and energy-constrained environments.



Chapter 01:

Food Security and agriculture

I.I. INTRODUCTION

Agriculture plays a fundamental role in ensuring food security and sustaining economic development, particularly in countries with significant rural populations like Algeria. However, this sector faces increasing challenges due to population growth, water scarcity, and climate change. These issues are further exacerbated by inefficient irrigation practices, land degradation, and the increasing variability of rainfall patterns, placing pressure on already limited water and energy resources.

In recent years, the demand for innovative, sustainable agricultural methods has grown, especially in arid and semi-arid regions. Traditional irrigation systems, while historically significant, often lead to water wastage and reduced crop productivity. In contrast, modern techniques such as drip irrigation, when powered by renewable energy sources like solar photovoltaic systems, offer an efficient and sustainable alternative that aligns with global efforts to reduce greenhouse gas emissions and combat climate change.

This chapter provides a comprehensive overview of the relationship between food security and irrigated agriculture, with a specific focus on Algeria. It explores traditional and modern irrigation methods, highlights the impact of climate change on agricultural productivity, and discusses the importance of integrating renewable energy into agricultural practices. By addressing these themes, this chapter lays the foundation for a practical and innovative solution: a solar-powered drip irrigation system, which is developed and evaluated in the subsequent sections of this thesis.

I.II. Food security

According to the 1996 World Food Summit, Food security is a condition in which all individuals, at all times, have physical and economic access to enough safe and nutritious food to meet their dietary needs and preferences for a healthy and active life [3] . Food security is defined by the following key components:

- Availability: the physical access to enough food to meet the needs of every individual. This involves sufficient food production and stable food stocks; if these two factors were not to meet, resorting to importing food is the solution.
- Accessibility: the case where all individuals have the economic capacity to cover their daily needs of nutrition.
- Adequacy: even if the food is available and accessible, it must be of sufficient quantity and healthy quality.
- Acceptability: Ensuring proper nutrition through the consumption of safe, nutritious, religiously and culturally acceptable food, along with access to clean water, sanitation, and healthcare.
- Stability: Maintaining reliable access to food over time even when facing natural disasters, economic crises, or conflicts.

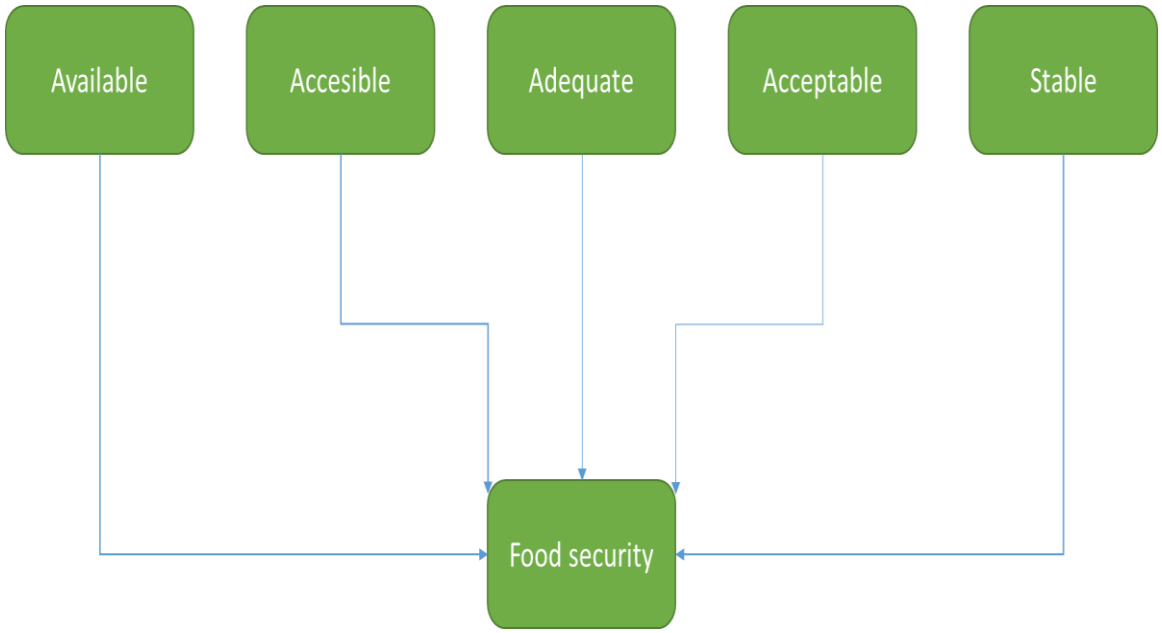


FIGURE I- 1: key components of food security

I.III. The role of agriculture in protecting food security

Agriculture plays a pivotal role in ensuring global food security by providing the vast majority of the world's food supply. According to the Food and Agriculture Organization (FAO), family farms occupy between 70% and 80% of the world's farmland and produce around 80% of the world's food in value terms [22]. Moreover, smallholder farmers, operating on less than two hectares of land, produce approximately 35% of the world's food. These small farms, despite their limited land area, are crucial in maintaining food availability, especially in developing countries [22]. In summary, agriculture is responsible for producing the majority of the world's food, with family farms contributing around 80% and smallholder farms about 35%. This underscores the sector's essential role in sustaining global food security.

I.IV. Challenges Facing Food Security

Food security today is under increasing threat from a variety of global challenges. One of the most pressing is climate change, which disrupts weather patterns, reduces agricultural productivity, and increases the frequency of extreme events such as droughts and floods. The growth of Population also causes a growing demand on food production requiring more resources and land to feed billions of people. At the same time, water management has become a critical issue in many regions, particularly in arid and semi-arid zones, affecting ability to sustain irrigated agriculture.

I.V. Impact of climate changing on water reserves

Climate change is fundamentally a water crisis, driving greater variability in the hydrological cycle and inducing more frequent and severe floods and droughts, shrinking snowpack and glaciers, and accelerating sea-level rise and saltwater intrusion all of which reduce freshwater availability for billions of people worldwide [9]. These shifts have eroded natural water storage glacial melt, diminished snowpack, and loss of wetlands have led to a widening global water storage gap even as demand climbs necessitating new investment in reservoirs and other storage solutions [9] [10]. Simultaneously, population growth, agricultural expansion, and energy needs are outpacing supply, creating a projected 40 % shortfall between water demand and availability by 2030 unless drastic adaptation measures are undertaken [10]. In Algeria a predominantly arid to semi-arid country these global trends are compounded by declining and more erratic rainfall, leading to increased surface and groundwater stress and prompting large-scale water resources development projects to bridge the growing gap between supply and demand.

I.VI. Impact of classical irrigation techniques on the water reserve

In recent years, the increasing impacts of global warming and the change in climate patterns have presented a growing array of challenges for farmers, directly influencing their established agricultural practices. Among these issues, there is drought that stands out as a critical concern. This is characterized by a discernible and concerning trend of decreasing rainfall rates observed year after year, a phenomenon unequivocally illustrated in the accompanying chart. This reduction in precipitation has profound implications for soil moisture, water availability for irrigation, and ultimately, the viability and productivity of agricultural lands.

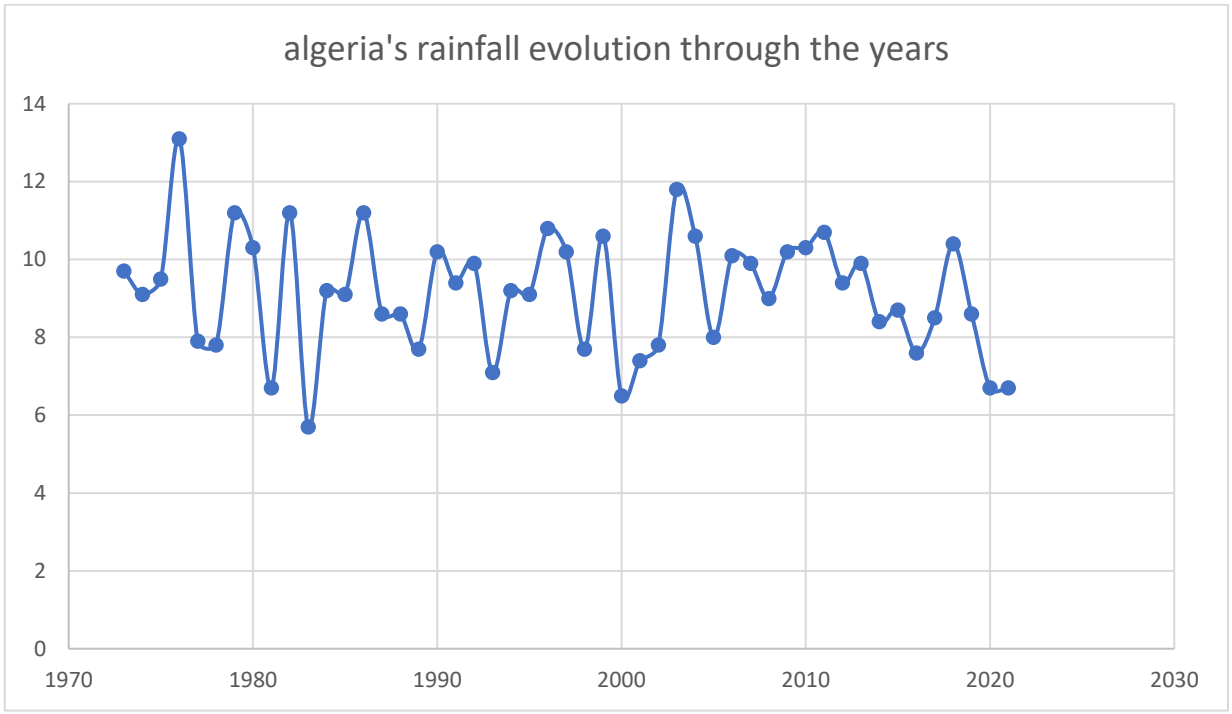


FIGURE I- 2: Algeria rainfall through the years

This decrease in rainfall puts a huge pressure on farming activities, especially considering that agriculture alone consumes about 70% of the world's available freshwater. However, studies have shown that only around 60% of this water actually reaches the roots of the crops [2]. The rest is lost through evaporation, runoff, and other inefficiencies—mainly due to poor water management strategies or the continuous use of outdated and traditional irrigation techniques. These growing losses highlight the urgent need to adopt more efficient and sustainable irrigation methods in order to protect our limited water resources and ensure long-term agricultural productivity. Following we present some old inefficient irrigation methods:

I.V.1- Surface irrigation

Water is supplied by covering the entire field by using channels which leads to significant water losses through evaporation and difficulty in controlling the amount of water that reaches each plant, meaning there will be unequal water distribution. Also, the huge amount of water supplied can

cause waterlogging, root rot, and nutrient leaching, causing reduced growth in response to the absence of oxygen.



FIGURE I- 3: surface irrigation

I.V.2- Basin irrigation

The field in this case is divided into a basin in which the water flows; this method is also inefficient due to major water evaporation, especially in the case of high temperature, and another inconvenience is that the water stagnation creates an adequate environment for mosquitos to breed, and the danger of over irrigation remains.

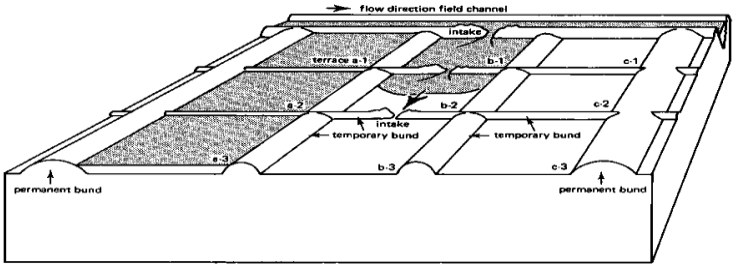


FIGURE I- 4: BASIN IRRIGATION

I.V.3- Flood irrigation

The entire field is flooded with water, which leads to considerable waste of water and a significant loss of essential nutrients from the soil. This method is not only inefficient but also contributes to leaching and poor root development. Moreover, during periods of drought when water becomes a scarce and precious resource flood irrigation is considered one of the least effective and most unsustainable irrigation techniques, as it consumes large volumes of water without guaranteeing even distribution or optimal absorption by the crops.



FIGURE I- 5: flood irrigation

I.V.4 manual Irrigation

Water is supplied directly by farmers through the use of buckets, which leads to a significant risk of both overwatering and under watering the crops. This method, while simple, is highly inefficient and can cause uneven water distribution, negatively impacting crop health. In addition to these risks, the technique is extremely time-consuming and labor-intensive, demanding a great deal of manpower to ensure the crops receive the right amount of water. This reliance on manual labor further exacerbates the difficulties faced by farmers, especially in areas where labor availability is limited or costly.



FIGURE I- 6: manual irrigation

I.VII. Impact of using old irrigation technics

Improper irrigation practices can create a cascade of hydrologic and agronomic challenges that undermine both soil health and crop productivity. When fields are flooded without adequate drainage, the water table rises and soil pores become saturated, depriving plant roots of the oxygen they need to respire and take up nutrients; at the same time, excessive percolation carries essential mobile nutrients, particularly nitrogen, potassium, and phosphorus, below the root zone, rendering them inaccessible to crops. These soil-moisture extremes also encourage soil-borne pathogens such as Phytophthora and Pythium to proliferate in stagnant, humid conditions, attacking roots and causing rot, while the combination of oxygen starvation and nutrient deficiency stunts root development and overall biomass accumulation. Moreover, traditional flood-irrigation techniques exacerbate salinization in arid regions, where evaporation leaves toxic salt residues in the root zone, promote surface runoff that erodes topsoil and transports agrochemicals into waterways, and typically waste more than half of applied water to evaporation, deep percolation, or unproductive runoff, resulting in very low water-use efficiency.

In today's world, where such losses are no longer tolerable due to the rapid development of new technologies, we have successfully developed modern, water-efficient irrigation systems. These advanced systems are designed to optimize water management, ensuring that water is used more effectively and efficiently. As a result, they not only reduce wastage but also contribute to increased crop yields, providing a more sustainable and productive solution for farmers. These innovations are crucial in addressing the challenges of water scarcity and improving agricultural productivity in an increasingly resource-constrained environment.

I.VIII.Drip irrigation

Drip irrigation is widely regarded as the most commonly used form of micro-irrigation due to its efficiency in delivering water directly to the root zone of plants. This advanced technique utilizes water applicators that are either integrated into or attached to lateral lines, which are then carefully placed on the surface of the soil. The system is designed to deliver water in a controlled, slow, and precise manner, which significantly reduces water wastage compared to traditional irrigation methods. One of the primary advantages of drip irrigation lies in its ease of implementation and management, making it an ideal solution for many agricultural settings. Additionally, the system offers precise control over the amount of water delivered to each plant, which helps to ensure optimal growth conditions. Drip irrigation is especially advantageous for crops that require delicate care, such as trellised plants like grapes, where accurate water delivery is crucial for maintaining healthy plants and enhancing overall yields. As a result, drip irrigation has become an essential tool for modern, sustainable agriculture, ensuring that resources are used more efficiently while promoting higher productivity in farming [5].This technic also offer the advantage of delivering fertilizers through the irrigation water. Among its Advantages:

- Enhanced water management: Drip irrigation is remarkably efficient for water management unlike traditional irrigation methods, drip irrigation achieves about 90% efficiency in water

usage [4]. According to MIT Tata Center, drip irrigation can reduce water consumption by 20-40% [5].

- Enhanced Yield: Studies have shown that the implement of a drip irrigation system can increase crop yields by 20-50% compared to traditional flood irrigation methods [5].

TABLE I- 1: yield increase of some plants after using drip irrigation

Crop	Typical Yield Increase Range (%)
Tomatoes	20-50%
Strawberries	30-60%
Grapes	25-45%
Citrus Fruits	15-35%
Tree Nuts	10-25%

- Improved Root Development:

Increases the root growth ensuring better drought resistance and more nutrition absorption.

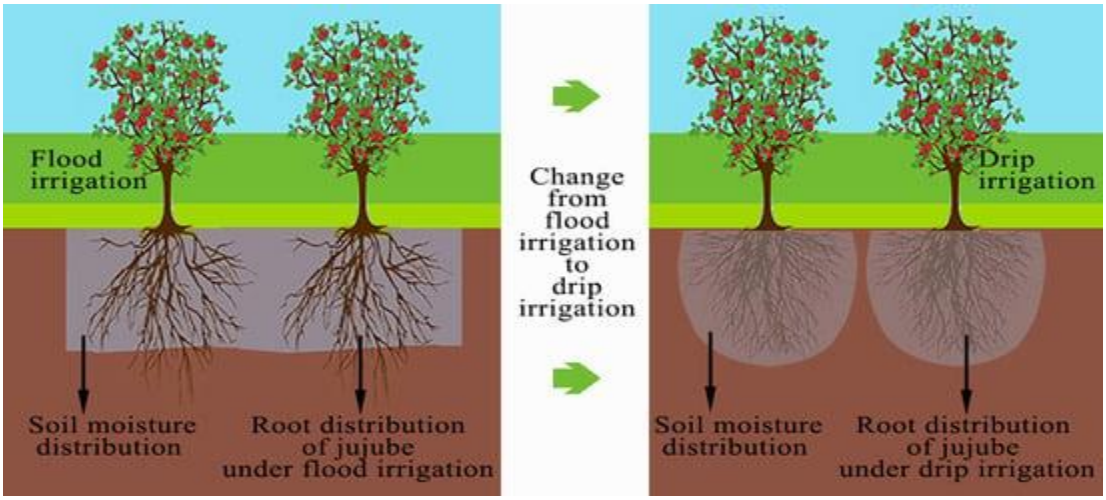


FIGURE I- 7: root development of a plant irrigated by a drip irrigation system[20]

I.IX. Conclusion

In this introductory chapter, we have established the critical importance of food security and the multifaceted challenges it faces in the context of a changing climate and dwindling water resources. We began by defining food security encompassing availability, access, utilization, stability, and sustainability, and highlighted agriculture's indispensable role in safeguarding each of these dimensions. We then examined how climate change exacerbates pressure on water reserves, reducing both quantity and reliability of supply. Classical irrigation methods surface, basin, flood, and manual techniques were shown to place heavy demands on limited water resources and often suffer from inefficiencies and high losses.

Finally, drip irrigation emerged as a promising modern alternative, offering precise, low-loss water delivery that aligns well with sustainable water management goals. By targeting the root zone directly, drip systems can significantly improve water-use efficiency, mitigate the impacts of water scarcity, and support the stability and sustainability pillars of food security. As we transition in subsequent chapters to explore photovoltaic-powered drip irrigation integrated with advanced control strategies, this foundation underscores both the urgency and the potential of marrying technological innovation with agricultural practice to ensure resilient, water-wise food production for the future.

Chapter 02:

Components of A smart drip irrigation system

II.I. Introduction

Modern agriculture increasingly relies on smart irrigation systems to ensure efficient water use, reduce waste, and enhance crop yield. These systems combine traditional hydraulic components with advanced electronic control units and sensors to adapt irrigation schedules based on real-time environmental conditions.

This chapter provides a comprehensive overview of the key components that make up a smart irrigation system. It begins with the fundamental water source and storage systems, highlighting aspects such as pressure regulation, water availability, and quality management. The chapter then explores the different mechanical components like pumps, filters, valves, pipes, and drippers, each playing a critical role in distributing water effectively.

Moreover, this chapter addresses hydraulic concepts such as friction losses and Bernoulli's equation, essential for designing efficient irrigation networks. It concludes with a detailed section on the integration of smart technologies sensors, control units, and algorithms which transform conventional irrigation into a responsive, intelligent system tailored to plant needs and environmental data.

By understanding each component, from the physical infrastructure to the digital controls, this chapter sets the foundation for designing and implementing a smart irrigation system that is both sustainable and technologically advanced.

II.II. Water sources and storage

Two forms of water sources are distinguished; firstly, there is surface water like rivers and channels, which tend to be of low quality and poor in Mineral salts and show biological hazards. If wastewater is considered as a source, its quality and clogging potential will vary based on the level of treatment. There are many sources of surface water, among them Rivers and Streams, Lakes and Reservoirs.

Secondly, there is ground water, which provides higher value and quality than the surface water; however, Iron and manganese levels should be monitored because elevated levels can cause dripper clogging, potentially requiring treatment.

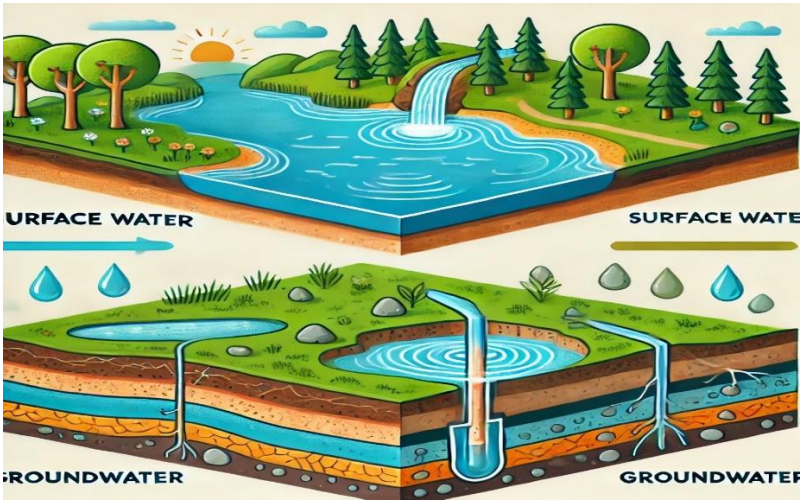


FIGURE II- 1: ground water and surface water [11].

However, the system requires a water storage to improve reliability and efficiency while lowering maintenance costs. Among the advantages provided by a water tank:

II.II.1. Pressure Regulation

A drip irrigation system operates under low-pressure water flow; natural sources cannot always provide the desired pressure for the system. Thus, using a water tank becomes necessary because it allows the integration of a pressure regulator, which helps to achieve the optimal performance.

II.II.2. Water Availability

Direct source connection may produce fluctuating flow rate. For example, surface water sources might dry up during droughts, or groundwater pumps might not meet demand during peak usage. A water tank can ensure stable flow rates.

II.II.3. Water Quality Management

Surface water might contain Sediment and Impurity such as soil particles and Industrial waste, especially in the case of wastewater. A water storage offers the ability to integrate a filter, preventing clogging of the emitters.

II.II.4. Energy efficiency

Pumping water directly from a source to a drip irrigation system may require continuous energy. With a storage system, water can be pumped into the tank during times of low energy costs or when renewable energy (e.g., solar power) is available, reducing operational costs.

II.II.5. Emergency Backup

A storage tank acts as a reservoir in case of emergencies, such as pump failures, droughts, or disruptions in the primary water source. This ensures that crops continue to receive water during critical periods.

II.II.6. Fertilizer and Chemical Mixing

A water storage tank provides a controlled environment for mixing fertilizers or other chemicals for fertigation, which is a common practice in drip irrigation systems. This helps ensure uniform delivery of nutrients to plants.

If the irrigated area is, a plan or a flatland the water flows from the water tank to the irrigation circuit by the impact of gravity by elevating the tank. However if the irrigated zone is formed of multiple hills, using a second pump for the irrigation system is required.

II.III. Pumps

A water pump is a machine that converts the mechanical energy provided by a motor into hydraulic energy to transport a fluid through a hydraulic circuit. Generally, the most commonly used type of pumps in drip irrigation systems is centrifugal pump.

II.III.1. Components of a centrifugal pump

1. Inlet

The inlet of a centrifugal pump is the opening where the fluid enters the pump; it is often referred to as the suction or eye of the pump. Fluid enters through the inlet of the pump and into the eye of the impeller.

2. Impeller

The heart of the centrifugal pump is connected to the motor shaft and rotates at the same speed as the shaft. The centrifugal force created by the rotation of the impeller causes water to be sucked into the inlet, and the water particles move radially out through the vanes.

3. Volute casing and volute chamber

In a centrifugal pump, the volute chamber or volute casing is the spiral-shaped chamber that surrounds the impeller. Its primary function is to convert the kinetic energy of the fluid leaving the impeller into pressure energy.

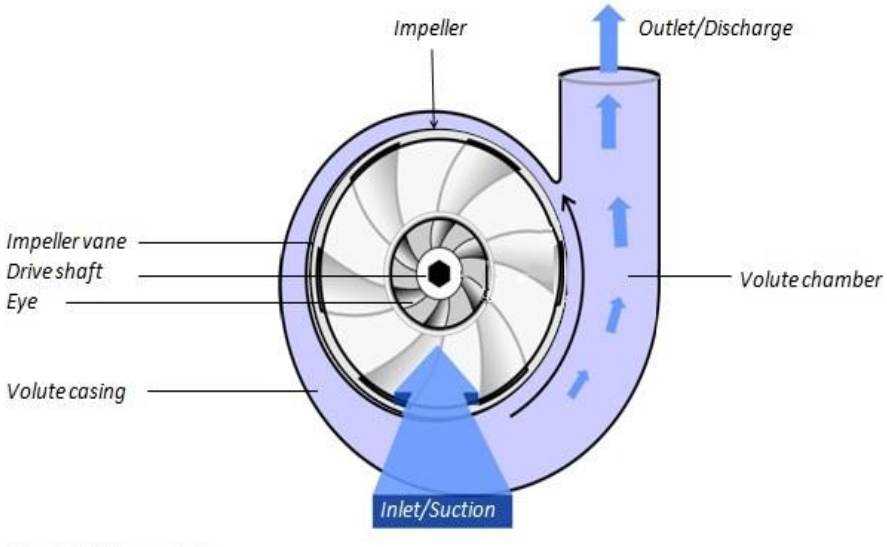


FIGURE II- 2: CENTRIFUGAL PUMP'S DIAGRAM [12].

II.III.2. Placement of a centrifugal pump

Depending on the type of mounting, we distinguish two types of centrifugal pumps. The first type is called Submersible centrifugal pumps, which are directly installed into the fluid source, such as a well or tank, eliminating the need for long suction pipes and reducing the risk of cavitation, making them suitable for deep wells. They are also quieter and more compact than surface-mounted pumps.

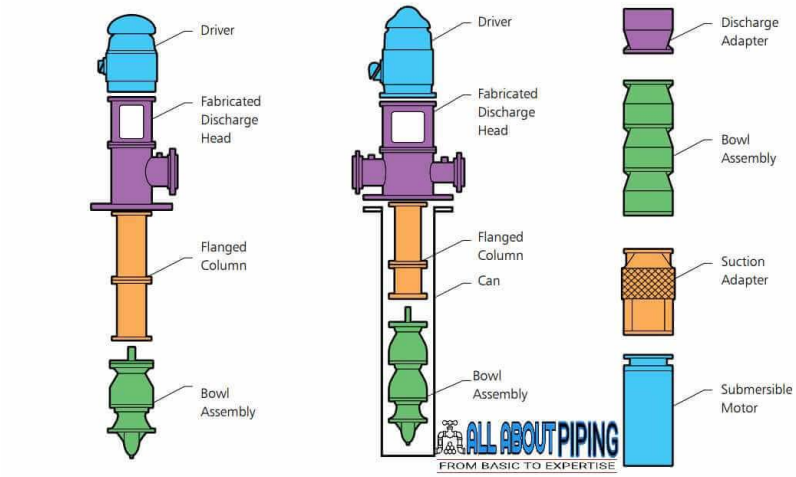


FIGURE II- 3: SUBMERSIBLE PUMP [13].

Secondly, there is Surface-mounted pumps, are installed above ground and require a suction pipe to draw fluid from the source. This makes them more susceptible to cavitation if the suction pipe is too long or if the fluid level drops significantly. However, surface-mounted pumps are generally easier to maintain and repair, as they are more accessible.



FIGURE II- 4: surface mounted pump [14].

II.III.3. The criteria for choosing a pump a centrifugal pump

Various factors are considered to select a centrifugal pump for an irrigation system such its flow rate, its power, the pressure limit, dynamic head and other factors depending on the energy and water sources.

1. Flow rate

The flow rate is the amount of water delivered in the unit of time, measured in liters per seconds, liters per minutes or cubic meter per hour. The flow rate can be calculated using the following formula:

$$Q = \frac{\pi \times D^2 \times N \times H}{4g} \qquad \text{Eq II.1}$$

- $\pi \times D^2$: represent the impeller area (m^2).
- N: The pump speed (RPM).
- H: Head (m).

The flow rate then can be regulated by adjusting the pump speed. For example using a variable frequency drive using scalar control in the case of induction/synchronous motor or a chopper in the case of DC motors.

2. Head

Head refers to the height to which the pump can lift the water. It is a very important parameter because it measures the kinetic energy transferred by the pump to the water. The total dynamic head is given by the following equation:

$$H = H_s + H_d + H_f \quad \text{Eq II.2}$$

- H: Total dynamic head.
- H_s: Suction head (from water source to pump inlet).
- H_d: Delivery head (from pump outlet to water tank).
- H_f: Losses due to friction (pipes, valves….).

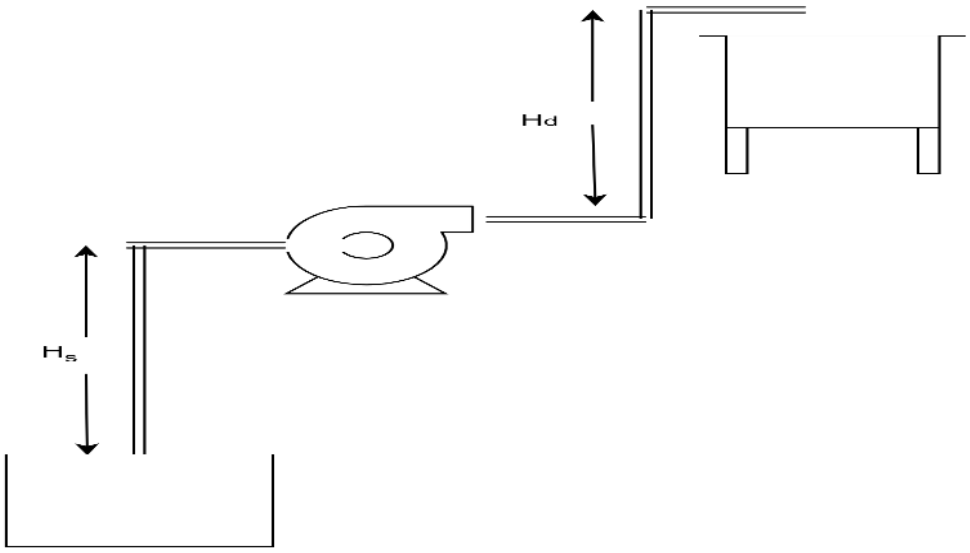


FIGURE II- 5: total dynamic head of a centrifugal pump

3. Required power

$$P = \frac{\rho g Q H}{\eta} \quad \text{Eq II.3}$$

- ρ: Water density (1000 Kg/m^3).
- g: Gravity (9.81 m^2/s).
- Q: Flow rate (m^3/s).
- H:Total dynamic head (m).
- η : pump efficiencey.
-

II.IV. Filtration

Filtration is the physical process of removing sediments and impurities from irrigation water to ensure consistent water quality. This process is essential for preventing clogging in pipes, emitters, and valves while extending the lifespan of irrigation equipment. In irrigation systems, three major types of filters are distinguished:

II.IV.1. Screen filters

A screen filter is a type of water filtration devices that uses a fine mesh to physically impurities from water. It is commonly used in irrigation systems, industrial applications, and water treatment to protect pumps, valves, and other downstream equipment from clogging.

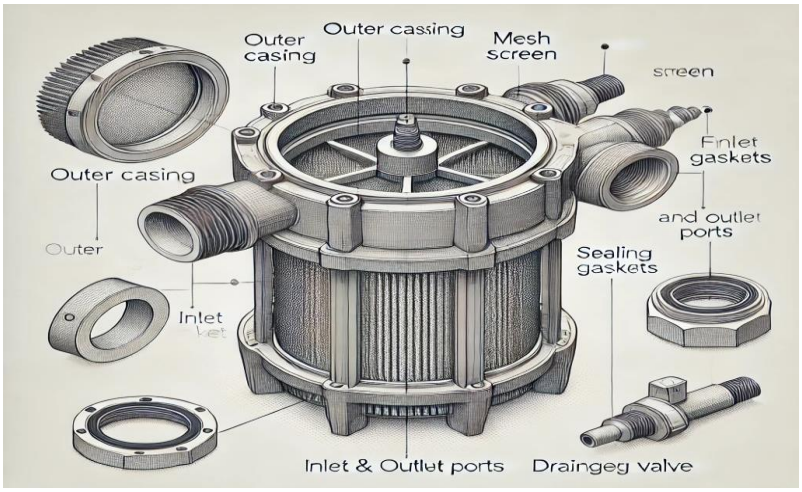


FIGURE II- 6: components of a screen filter [11].

Screen filters operate by physically trapping particles within their mesh or perforated metal structure. As water flows through, debris larger than the screen's openings is intercepted and retained. This accumulated debris gradually reduces the filter's efficiency. To maintain proper filtration, the screen must be cleaned regularly. Cleaning methods can vary, including manual removal and washing of the screen or automated processes such as backflushing or self-cleaning mechanisms.

II.IV.2. Disc Filters

A disc filter is a system that uses a stack of grooved, plastic, or ceramic discs to remove. It is widely used in agriculture, industrial applications, and wastewater treatment due to its high efficiency, compact design, and easy maintenance.

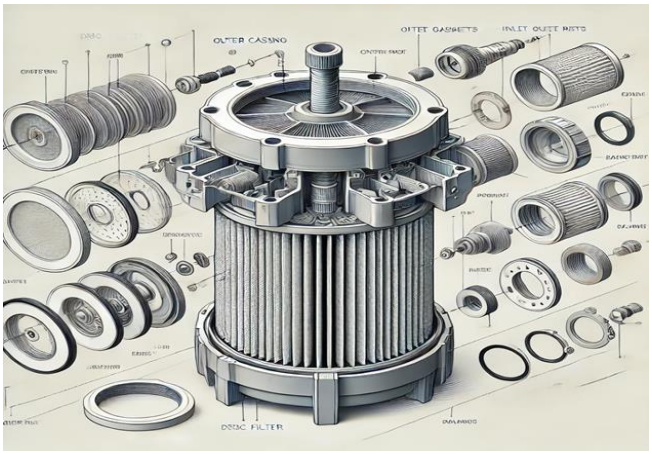


FIGURE II- 7: COMPONENTS OF A DISC FILTER [11].

Disc filters utilize a series of grooved discs that are tightly compressed together. As water flows through this assembly, particles are trapped within the grooves while clean water passes through. The accumulation of debris between the discs gradually restricts water flow. To restore filter efficiency, the discs are typically loosened, and the system is backwashed with reverse water flow to remove trapped particles. Some disc filter systems incorporate automated back flushing mechanisms for enhanced convenience and efficiency.

II.IV.3. Media Filters

A media filter is a type of water filtration systems that uses granular or porous materials, such as sand, gravel, anthracite, or activated carbon, to remove contaminants from water. These filters are widely used in agriculture, industrial processes, and wastewater treatment due to their efficiency in removing turbidity and organic matter.

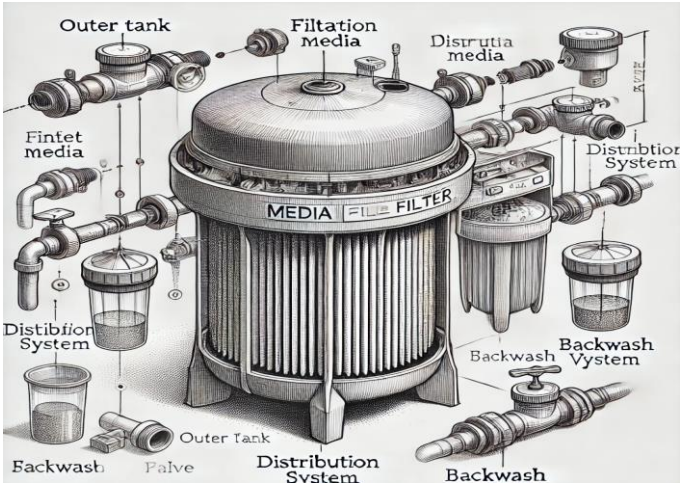


FIGURE II- 8: components of a media filter [11].

Media filters operate by passing water through a bed of specialized materials. During the filtration phase, suspended particles in the water are trapped within the filter media, allowing clean water to

flow through. However, as the filter operates, particles accumulate within the media, gradually reducing its filtration efficiency. To maintain optimal performance, a backwashing process is periodically employed. This involves reversing the flow of water through the filter, effectively flushing out the accumulated debris and restoring the filter's capacity to remove impurities from the water.

II.V. Valves

In order to operate smoothly a drip irrigation system requires a set of valves each have its own function and purpose.

II.V.1. Main Shutoff Valve

Located at the head of the system-allowing turning on or shutoff the entire system's water flows at ones. Typically, a ball valve or gate valve is used for simpler on/off control.

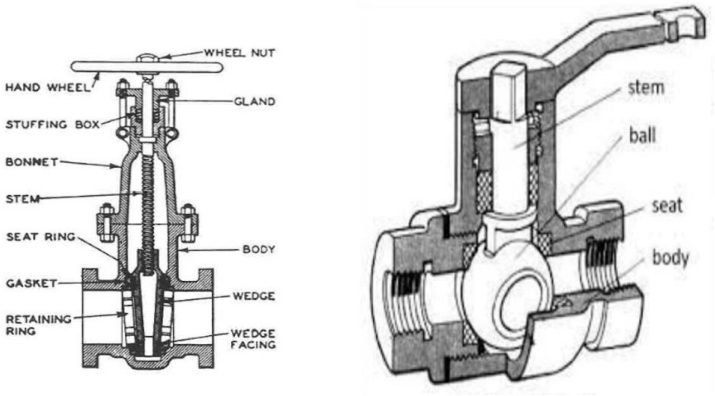


FIGURE II- 9 : Shutoff valve [15] [16].

II.V.2. Control/ Zone Valves

The purpose of this type is to divide the irrigated area into different zones to obtain optimal water management like separating zones in the case of maintenance or independent watering schedules and prevents overwatering in the case of multiple corps. Used a solenoid valve controlled by an irrigation controller (microcontroller or PLC).

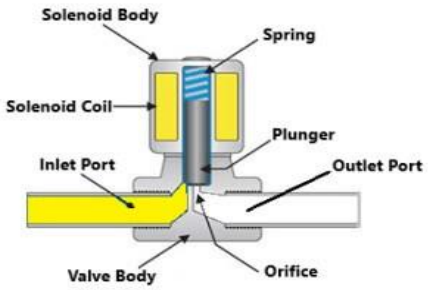


FIGURE II- 10: solenoid valve [17].

II.V.3. Pressure Reducing Valve

Reduces incoming water pressure to a level suitable for the drip emitters. High pressure can damage the emitters and reduce their lifespan.

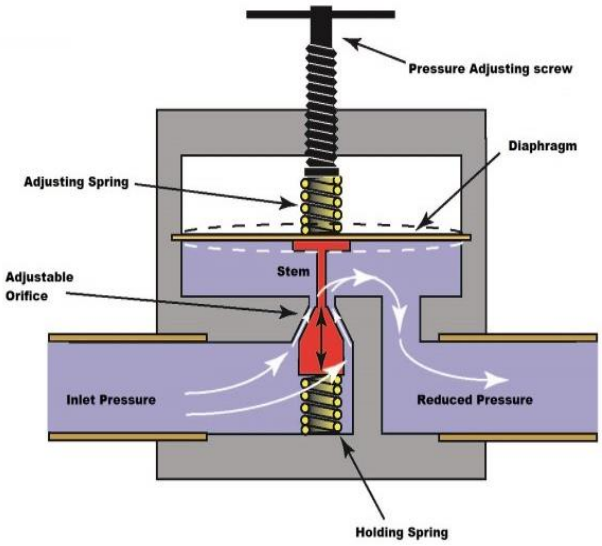


FIGURE II- 11: Pressure reducing valve[18].

II.V.4. Air Release Valve

An air release valve is a mechanical device used to release trapped air or gas from a system, typically in pipelines, tanks, or other pressurized systems. It ensures that air pockets do not accumulate, which could otherwise cause issues like reduced efficiency, damage to the system, or even a complete system failure.

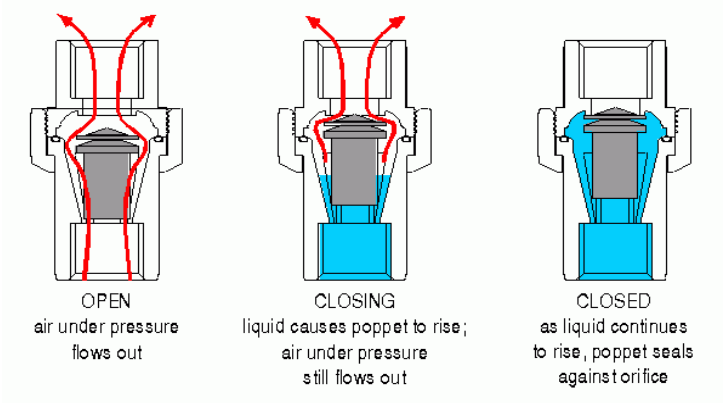


FIGURE II- 12: air release valve [19].

II.VI. Pipes

A pipe is a hollow cylindrical conduit used for transporting water through the irrigation system. Pipes are typically made from materials like metal (steel, copper), plastic (PVC, polyethylene). In drip irrigation systems water is delivered through two types of pipelines.

II.VI.1. Mainline

The pipe that delivers water from the source to the irrigated area, usually it is the thickest in the whole system.

II.VI.2. Sublines or Lateral Lines

Smaller pipes that branch off from the mainline. They run closer to the plants and are the lines to which the emitters or drippers are directly attached.



FIGURE II- 13: driplines

The following relation calculates after a pipe dimension:

$$Q = V \times A \qquad \text{Eq II.4}$$

- Q: Flow rate through the pipe (m^3/s).
- V: Water velocity (m/s).
- A: pipe area(m^2).

II.VII. Bends and branches

II.VII.1. Bends

Bends, also called elbows are fittings that create angles in pipelines used to change the direction of water flow. Elbows are characterized by their angle among them:

- 90° elbows, which are used to create a 90° angle. High friction losses.

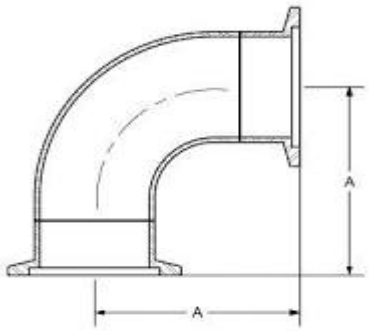


FIGURE II- 14: 90° elbow [20].

- 45° elbows that have a reduced friction losses compared to a 90° elbow.

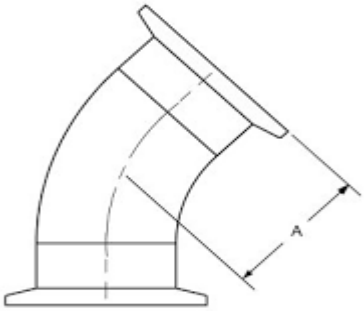


FIGURE II- 15: 45° elbow [20].

- 180° elbows also called U-bends, their purpose is to reverse the flow direction.

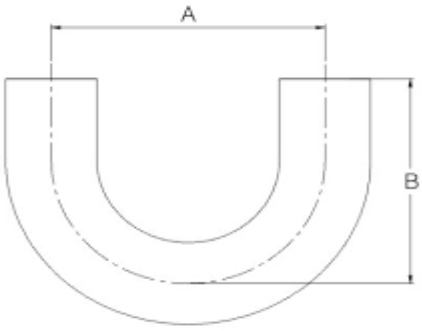


FIGURE II- 16: ISO symbol of a U-bend

II.VII.2. Branches

- T-joint Split the main line into two branches at 90°.

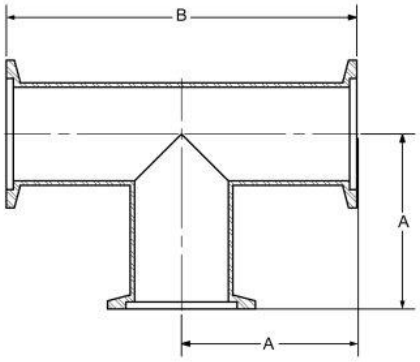


FIGURE II- 17: T-joint [20].

- Y-Joints Provide a smoother split, reducing turbulence and pressure loss compared to T-joint.

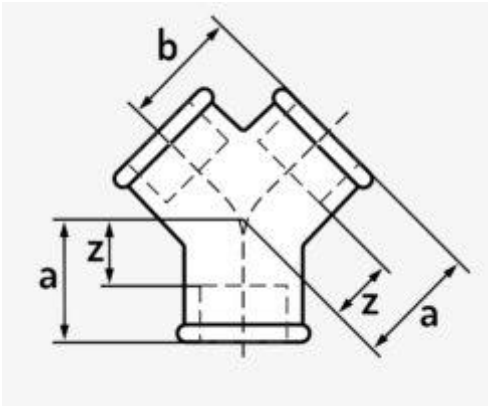


FIGURE II- 18: Y-joint

II.VIII. Drippers

Also called emitters are the small devices that regulate the flow of water and deliver it directly to the base of plants. They are essential for the efficiency of drip irrigation. The flow rate primary depends on the dimension of drippers and it is calculated according to the following formula:

$$Q = Total\ number\ of\ emitters \times Flow\ rate\ per\ emitter \qquad \text{Eq II.5}$$



FIGURE II- 19: drippers

II.IX. Friction losses

Designing a pumping station requires the calculation of losses that have an impact in reducing performance and efficiency. These losses occur due to the resistance encountered by water as it flows through the hydraulic circuit.

II.IX.1. Types of friction losses

1. Major losses

Occur due to friction inside a pipe depending on pipe length, diameter, roughness, and fluid velocity. Calculated using the of Darcy-Welsbach equation:

$$H_{Major} = \frac{f \times L \times V^2}{2gD} \quad \text{Eq II.6}$$

- H_{Major}: Losses due to friction (m).
- f: Friction factor.
- L: Pipe length (m).
- V: Water velocity (m/s).
- g: Gravity (m/s^2).
- D: Pipe's diameter (m).

The value of friction factor depends on the value of Reynolds number, which determine the flow nature laminar, transitional, or Turbulent Flow.

$$R_e = \frac{\rho VD}{\mu} = \frac{VD}{v} \quad \text{Eq II.7}$$

- R_e: Reynolds number.
- V: Water velocity (m/s).
- D: Pipe's diameter (m).
- ρ: Water density ($1000\ Kg/m^3$).
- μ: Dynamic viscosity of water ($0.001\ Pa.s$ at T=20 ℃).
- v: Kinematic viscosity (1x10^6 m^2/s).

TABLE II- 1: flow nature according to Reynolds

Reynolds number	Laminar	Transitional	Turbulent
Re < 2000	×		
2000 < Re < 4000		×	
Re > 4000			×

In a drip irrigation circuit where the velocity of water is low, the flow nature is laminar and friction factor is calculated by:

$$f = \frac{64}{Re} \quad \text{Eq II.8}$$

However in part that include transporting the fluid from the source to the tank the flow nature can be transitional due to high velocity, and in this case the friction factor value.

2. Minor losses

Appears due to the flow disturbance generated by valves, bends, fittings and sudden expansion or contraction in the pipeline. Calculated by minor losses equation.

$$H_{Minor} = \frac{K \times V^2}{2g} \quad \text{Eq II.9}$$

- H_{Minor}: Friction losses (m).
- K: Loss coefficient (depends on geometry).
- V: Water velocity (m/s).
- g: Gravity (m/s^2).

II.IX.2. Impact of friction losses in a drip irrigation station

1. Increased energy consumption

The higher the calculated losses, the higher is the required pump power to maintain the necessary flow rate and pressure. This result in more energy consumption and increasing the bill and in large-scale agriculture a low increase in power demand can produce higher operational costs. In the third chapter of this thesis, we will discuss how the integration of a renewable energy source can solve this issue.

2. Under/over irrigation

Excessive losses lead to a pressure drop causing to uneven water distribution resulting in under irrigation in some areas and over irrigation in the other areas.

II.X. Bernoulli equation

The Bernoulli Equation is a fundamental principle in fluid mechanics that describes the conservation of energy in a moving fluid. This equation is used to calculate the required pump after choosing the other components of the hydraulic circuit and evaluating the total friction losses.

$$P + \frac{\rho}{2}V^2 + \rho g H = constante \quad \text{Eq II.10}$$

- P: Pressure energy.
- $\frac{\rho}{2}V^2$: Kinetic energy.
- $\rho g H$: Potential energy.

II.XI. Smart irrigation: introducing the technology of sensors

To ensure optimal system control while reducing water losses and meeting the plant's daily needs, we must adopt a modern solution. Therefore, we need to integrate a control unit, a sensor measurement chain, and a human-machine interface to display data.

II.XI.1. Control unit

The control unit is the brain of the system. Its function is to process sensor data and implement algorithms or rules to determine when and how much to irrigate. This unit can be a microcontroller or a PLC (Programmable Logic Controller), depending on the system's complexity and requirements. The following table shows the main differences between a PLC and a MICROCONTROLLER

II.XI.2. Sensor Measurement Chain

The sensor measurement chain refers to the series of components responsible for acquiring and transmitting sensor data to the control unit. It typically includes:

1. Sensors

Devices that measure various environmental parameters such as soil moisture in our case, and convert them into electric signals. Among the used sensors, we find soil moisture sensors such as the YL69.

2. Signal Conditioning

The process of filtering the raw sensor data and amplify it, making it adaptable to the analog-digital converter.

3. Analog-to-Digital Conversion (ADC)

Convert the analog signals from the sensors into a digital format that can be read and processed by the control unit.

II.XI.3. Human machine interface HMI

The Human-Machine Interface is the user interface that allows operators to interact with the system. It displays real-time data and provides a means to monitor, control, and adjust the irrigation system. A display make the provided data visible to the users Allowing them to input commands, such as adjusting settings for irrigation times or activating manual controls. Common input methods include touchscreens, buttons, or rotary dials. For example, the TFT screen offers a clear and intuitive visual representation of key data, such as soil moisture levels, pump status, and energy consumption. With its touch functionality, users can easily adjust irrigation schedules, activate manual watering, or even monitor solar panel performance. The interface enhances user experience by providing interactive features, making system management more efficient and accessible.

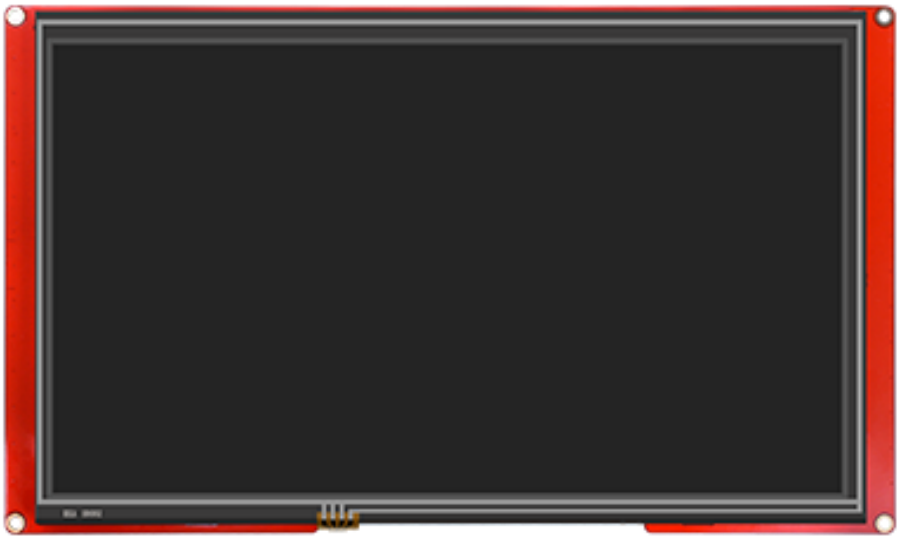


FIGURE II- 20: nextion 10-inch screen

II.XI.4. Irrigating algorithm

Like every automated system, ours has an operating algorithm to control the irrigating process and ensure efficient water distribution to the plants. The algorithm is built to control soil moisture levels, to ensure reducing the impact of environmental conditions such as temperature and sunlight, and activate the water pump accordingly. When the moisture sensor detects that the soil is drier than a predefined threshold, the system initiates the irrigation cycle. And when the soil moisture reach the desired value, it stops the irrigating process.

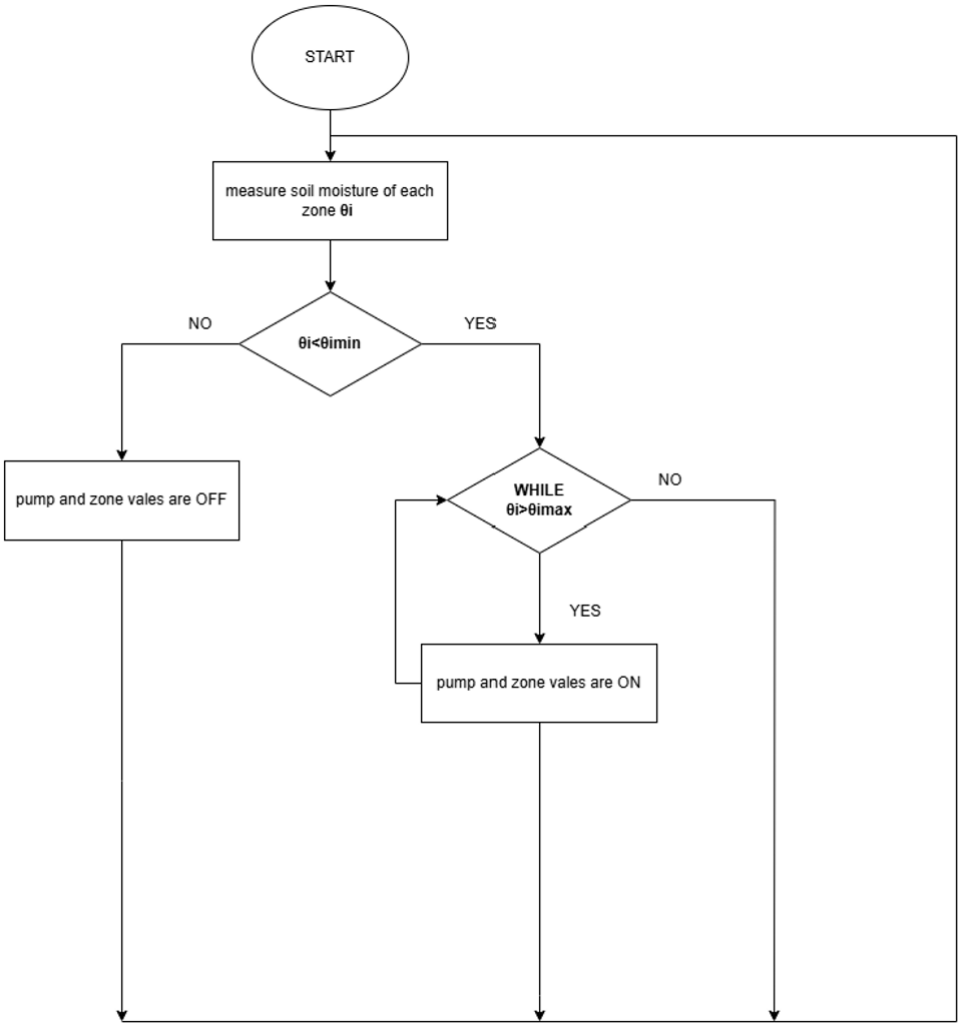


FIGURE II- 21: irrigation flowchart

II.XI.5. Conclusion

The development of a smart irrigation system requires the seamless integration of both traditional irrigation components and modern technologies. From water sources, pumps, filters, valves, and pipelines to the final emitters such as drippers, each mechanical component plays a vital role in ensuring reliable and efficient water distribution. Understanding factors like friction losses, pressure regulation, and pump characteristics is essential for system optimization and energy savings.

Equally important is the technological layer of smart irrigation—sensors, control units, signal processing, and automation algorithms. These elements enable real-time monitoring and decision-making, allowing the system to respond dynamically to changing environmental conditions and crop needs.

By combining mechanical infrastructure with intelligent control, smart irrigation systems represent a significant advancement in agricultural water management. They not only increase productivity and resource efficiency but also contribute to sustainability and food security in regions facing water scarcity and climate challenges. This chapter lays the groundwork for designing such systems by detailing each component and its role within the broader framework of smart, sustainable agriculture.

Chapter 03: integration of renewable energy, introducing photovoltaic energy

III.I. Introduction

As the global demand for sustainable and clean energy continues to grow, the integration of renewable energy sources into everyday applications has become increasingly essential. Among these sources, solar energy stands out due to its abundance, reliability, and environmental benefits. Photovoltaic (PV) technology, which directly converts sunlight into electricity, plays a central role in harnessing solar energy for various uses, from small-scale systems to large power grids.

This chapter introduces the fundamental concepts of photovoltaic energy and explores its application in electromechanical systems. Beginning with the photovoltaic effect and the construction of solar cells and panels, the chapter then delves into the equivalent circuit modeling of PV cells and the identification of the maximum power point (MPP)—a critical parameter for optimizing energy harvesting. The concept of Maximum Power Point Tracking (MPPT) is examined in detail, including the use of different DC-DC converter topologies such as BUCK, BOOST, and BUCK-BOOST converters.

Furthermore, this chapter explores MPPT algorithms like the Perturb and Observe (P&O) method and its adaptive variations to improve efficiency under varying environmental conditions. Finally, the chapter discusses energy storage methods and the role of inverters, including single-phase and three-phase types, along with pulse width modulation (PWM) techniques used to convert and regulate solar-generated power for real-world applications.

Through this comprehensive overview, readers will gain a foundational understanding of how photovoltaic systems can be effectively integrated into modern electromechanical and agricultural solutions, including the development of autonomous systems powered by renewable energy.

III.II. The photovoltaic effect

The photovoltaic effect is the ability of some materials to produce electrical energy when exposed to sun light. Discovered in 1839 by Edmond Becquerel a French physicist. This effect is now the fundamental principle of photovoltaic (PV) systems. Physically this effect occur when a photon strikes a semiconductor transforming energy to an electron causing it to jump from the valence band to the conduction band. According to Einstein, the photovoltaic effect is translated by the following equation:

$$E = h \times \frac{c}{\lambda} \qquad \text{Eq III. 1}$$

- E: Energy of the photon (J).
- h: Plank's constant $(6.626 \times 10^{-34}\ J.s)$.
- λ : Wavelength of a photon (m).
- c: Speed of light $(3 \times 10^{8}\ m/s)$.

III.III. Photovoltaic cell and photovoltaic panels

A photovoltaic cell, also called solar cell, is an electronic component that that work based on the photovoltaic effect, solar cells are made from semiconductor materials most commonly silicon. When disposed to light a solar cell produces a voltage of 0.5v. The assembly of multiple cells result in forming a solar module and the association of multiple solar modules forms a panel.

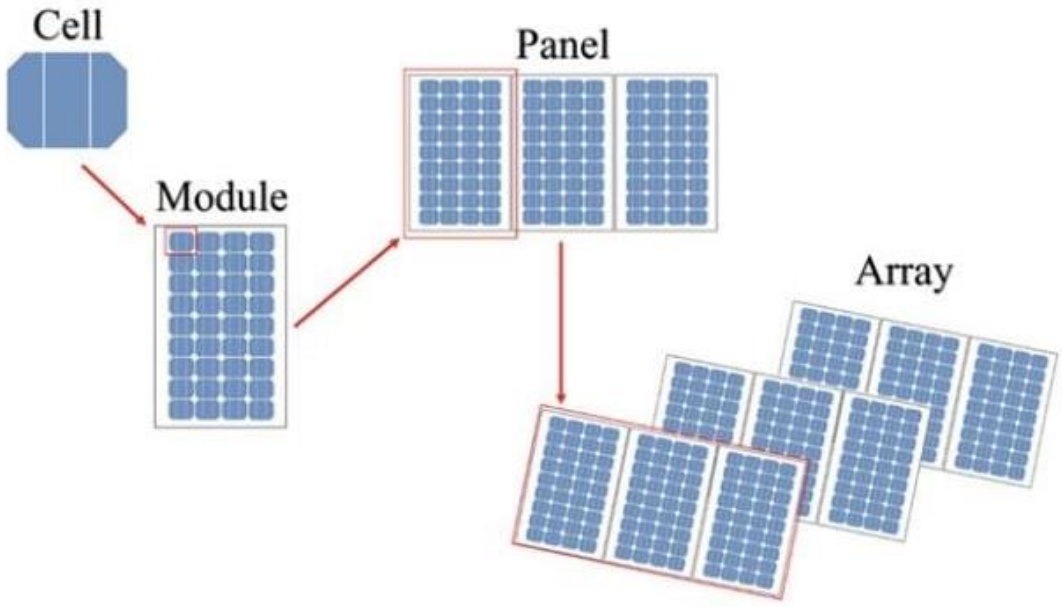


FIGURE III- 1: from a cell to a solar array.

III.IV. Equivalent circuit of a PV cell

There are two important factors to consider when choosing a PV cell short circuit current I_{sh} and open circuit voltageV_{oc}. Short-circuit current is the maximum value of current that a PV cell can produce; it is generated when the output terminals are shorted ($V_{sc} = 0$). On the other hand, open-circuit voltage is the maximum value that a PV cell can generate when the output terminals are not connected ($I_{sc} = 0$).

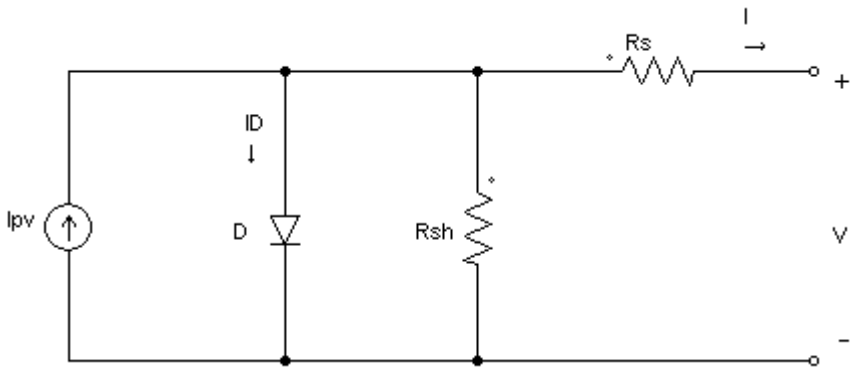


FIGURE III- 2: equivalent circuit of a solar cell.

- I_{PV}: Current produced by the solar cell (A).
- D: A diode that represent the p-n junction of the semi-conductors.
- R_{int} : Represents internal resistances due to wiring, contacts, and the semiconductor material (Ω). The higher is the value of R_{int} the greater is the power loss.
- R_{leak} : Represents leakage currents due to defects in the solar cell (Ω). The lower is the value of R_{leak} the higher is the leakage current.
- v: Load voltage (volts).
- I: Load current (A).

The load current is given by the following equation:

$$I = I_{PV} - I_{Diode} - I_{leak} \qquad \text{Eq III. 2}$$

$$I = I_{PV} - I_0\left(e^{\frac{V+R_{int}\times I}{n\frac{KT}{q}}} - 1\right) - \left(\frac{V+R_{int}\times I}{R_{leak}}\right) \qquad \text{Eq III. 3}$$

- I_0: reverse saturation current (A).
- n: Ideality factor of the diode ($n\epsilon[1,2]$).
- K: Boltzmann constant ($1.38 \times 10^{-23}\ J/°K$).
- q: Elementary charge ($1.602 \times 10^{-19}\ C$).
- T: temperature ($°K$).

The fraction $\frac{KT}{q}$ represent the thermal voltage that depend on the temperature value. The following chart shows the variation of thermal voltage in function of temperature the points where chosen between 0°C and 50°C.

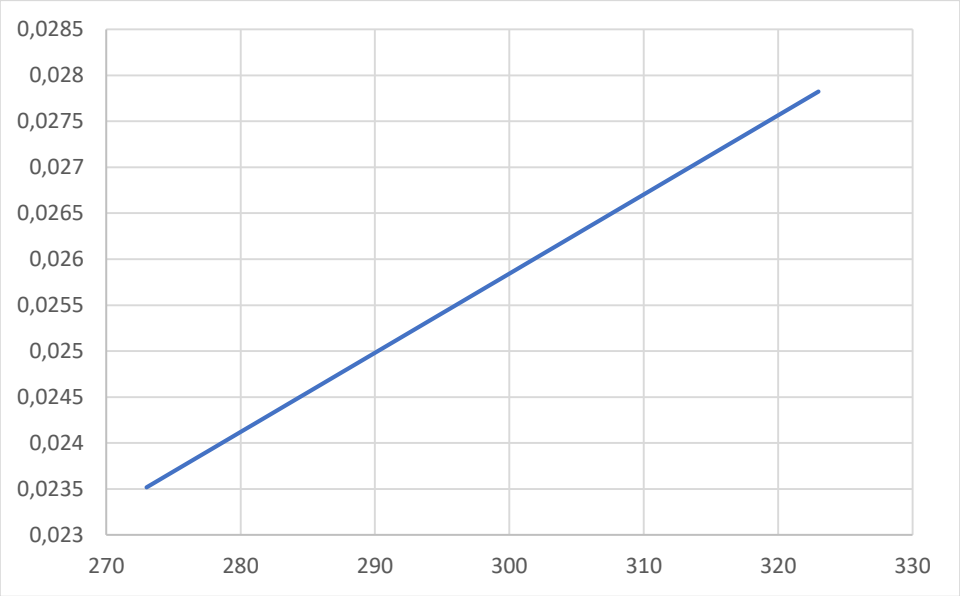


FIGURE III- 3: thermal voltage.

We observe that the average value is around 25.5 mvolts (at T=25°C). After replacing it value the precedent equation becomes:

$$I = I_{PV} - I_0(e^{\frac{V+R_{int}\times I}{n\times 0.0255}} - 1) - \left(\frac{V+R_{int}\times I}{R_{leak}}\right) \quad \text{Eq III. 4}$$

In the case of short circuit: ($V = 0$)

$$I_{short-circuit} = I_{PV} - I_0(e^{\frac{R_{int}\times I_{short-circuit}}{n\times 0.0255}} - 1) - \left(\frac{R_{int}\times I_{short-circuit}}{R_{leak}}\right) \quad \text{Eq III. 5}$$

In the case of open circuit: ($I = 0$)

$$0 = I_{PV} - I_0(e^{\frac{V_{oc}}{n\times 0.0255}} - 1) - \left(\frac{V_{oc}}{R_{leak}}\right) \quad \text{Eq III. 6}$$

III.V. Maximum power point

Maximum power point is the operating point at which a solar module produces the highest power possible. Characterized by a certain voltage $V_{mpp}$and a certain current I_{mpp} this operating point mainly depends on the irradiance and temperature.

$$P_{mpp} = V_{mpp} \times I_{mpp} \quad \text{Eq III. 7}$$

While irradiance have a positive effect on the power produced by the solar cell, high temperature can lead to significant losses.

III.VI. Maximum power point tracking

Since the power supplied by a solar source depend on environmental factors and dynamically changes through the day, a DC-DC converter must be connected to the output terminals to maintain the operation under maximum power point. A DC-DC converter is a device that convert a variable or fixed input voltage into adjustable output. Works based on the principle of switching theory, where a semiconductor switch (IGBT, MOSFET) rapidly turns ON and OFF at high frequencies.

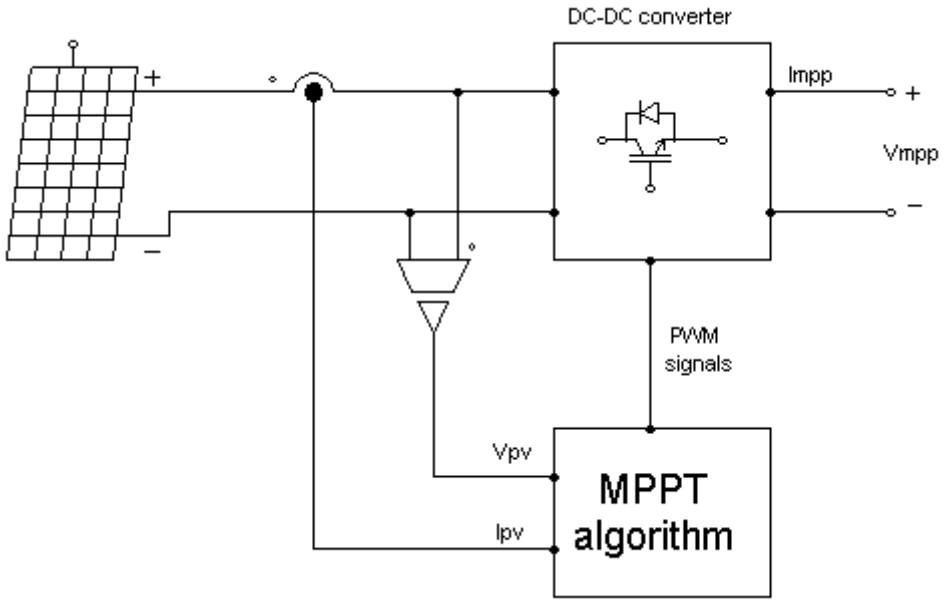


FIGURE III- 4: structure of an MPP tracker

The output voltage is a function input voltage and the duty cycle of the PWM signal. The duty cycle is the fraction between the period of time where the switch is ON and the total period:

$$D = \frac{t_{ON}}{t_{ON}+t_{OFF}} = \frac{t_{ON}}{T} \quad \text{Eq III. 8}$$

D is a number compressed between zero and one ($0 < D < 1$). The main types of DC converters are buck, boost, and buck-boost converters.

i. BUCK converter

In this case, the output voltage is less than the input voltage while the average value of the output current is higher than the input current. The switch is connected in series to the load to ensure reducing the voltage from the battery to a certain load such as microcontrollers.

1. Direct connection to the load

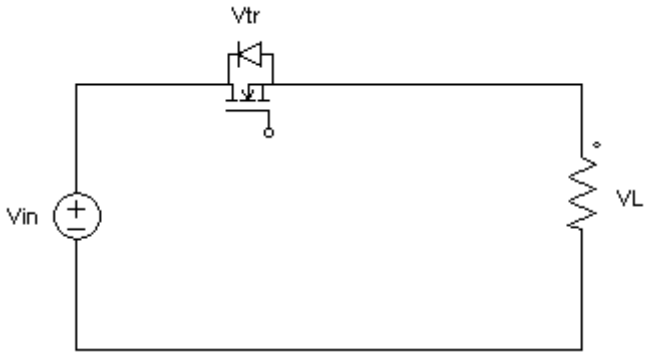


FIGURE III- 5: Buck converter.

For $0 < t < t_{ON}$ the switch is on therefore the voltage drop across it is zero ($V_{tr} = 0$). Kirchhoff's Voltage Law states that:

$$V_{in} - V_{tr} - V_L = 0 \qquad \text{Eq III. 9}$$

$$V_{in} = V_L \qquad \text{Eq III. 10}$$

Applying ohm's law, we obtain:

$$V_{in} = RI_L \qquad \text{Eq III. 11}$$

$$I_{tr} = I_L \qquad \text{Eq III. 12}$$

For $t_{ON} < t < T$ the switch is off meaning there is no current supplied to the load:

$$V_{tr} = V_{in} \quad V_L = 0 \quad I_L = 0 \qquad \text{Eq III. 13}$$

The average value of voltage is:

$$\bar{V_L} = \frac{1}{T}\int_0^T V_L \, dt = \frac{1}{T}\left(\int_0^{t_{ON}} V_{in} \, dt + 0\right) = \frac{V_{in}}{T}(t_{ON} - 0) \qquad \text{Eq III. 14}$$

Knowing that $t_{ON} = D \times T$

$$\bar{V_L} = D \times V_{in} \qquad \text{Eq III. 15}$$

$$\overline{I_L} = \frac{\overline{V_L}}{R} = \frac{D \times V_{in}}{R} \qquad \text{Eq III. 16}$$

A simulation of the circuit with the following parameters done with the help of PSIM:

$V_{in} = 100\ volts\ ,\ R = 1K\Omega, D = 0.5$

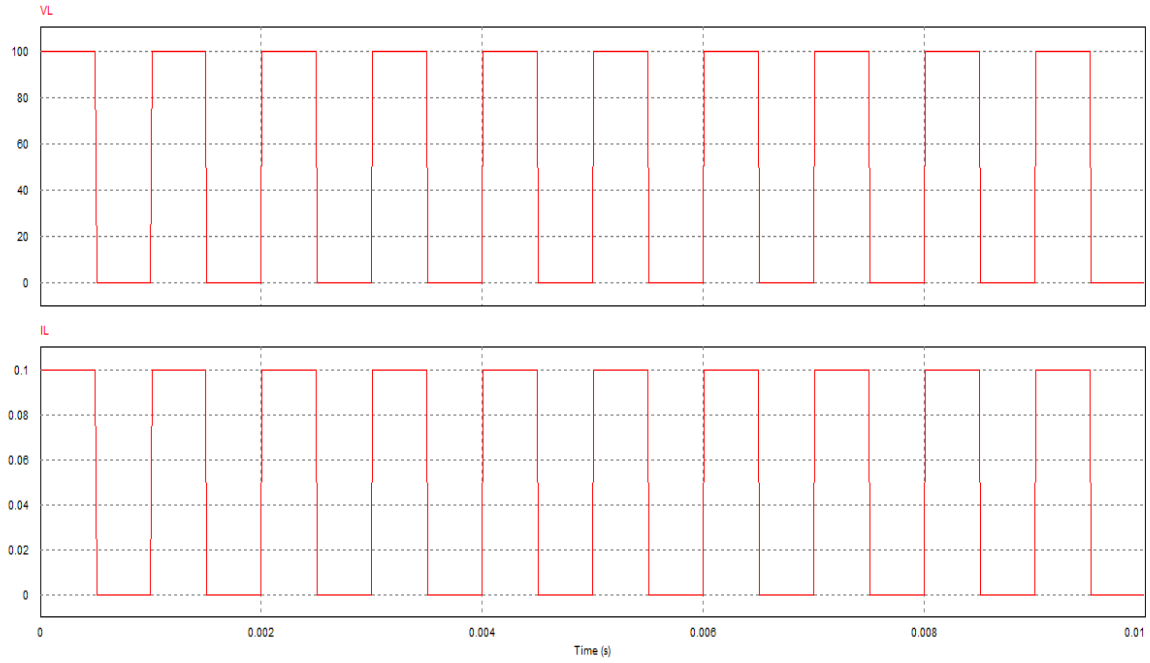


FIGURE III- 6: output voltage and current of a buck converter.

Average value of voltage and current using Eq III. 17 and Eq III. 18:

$$\overline{V_L} = D \times V_{in} = 0.5 \times 100 = 50\ volts$$

$$\overline{I_L} = \frac{D \times V_{in}}{R} = \frac{50}{1000} = 0.05\ Amp$$

However, the output voltage in this case is a periodic function that can harm some loads such as microcontrollers, sensors, and integrated circuits that require a steady state voltage to operate safely. Furthermore, the fast switching of the switch generates high-frequency noises.

2. Connection through a low pass filter

Connecting an LC filter before the load ensure a better steady state performance and lower the losses by reducing both voltage and current ripples. The inductor smooth the current waveform and prevent from sudden changes by storing magnetic energy. On the other hand, the capacitor filter out the high frequency noise and reduce the voltage ripple. The diode is used to help discharging the inductor while the switch is OFF.

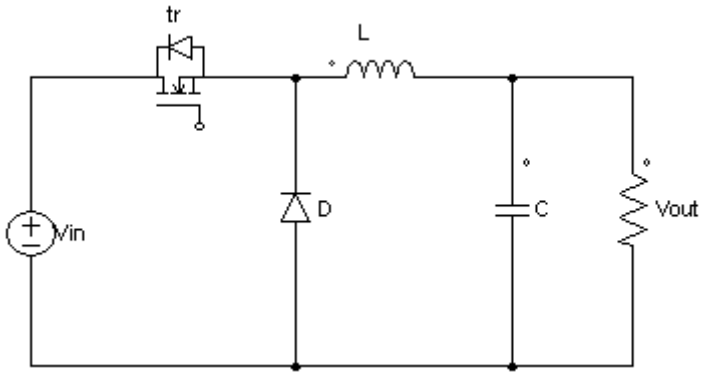


FIGURE III- 7: a buck converter connected to a low pass filter

- Function analyses:

To choose the filter components it is better to study the variation of voltage drop for the inductor while considering that the value of the capacitor is sufficient for a constant output voltage. For $0 < t < t_{ON}$ the switch is on therefore the voltage drop across it is zero ($V_{tr} = 0$) and the inductor start storing the energy.

Kirchhoff's Voltage Law states that:

$$V_{in} - V_{tr} - V_L - V_{out} = 0$$

$$V_{in} = V_L + V_{out} \Rightarrow V_L = V_{in} - V_{out}$$

The current expression is:

$$L\frac{dI}{dt} = V_{in} - V_{out}$$

By integrating both terms, we obtain:

$$\int_0^t LdI = \int_0^t (V_{in} - V_{out})dt \ , \ t\epsilon[0, DT]$$

$$L(I(t) - I(0)) = (V_{in} - V_{out})(t - 0)$$

$$I(t) = \frac{(V_{in} - V_{out})}{L} \times t + I(0)$$

Knowing that this current is a periodic function and by neglecting the transient state:

$$I(0) = I_{minimum}$$

And this implies that:

$$I(t) = \frac{(V_{in} - V_{out})}{L} \times t + I_{minimum}$$

For $t = DT$:

$$I(DT) = I_{maximum} = \frac{(V_{in} - V_{out})}{L} \times DT + I_{minimum}$$

Calculating the voltage ripple:

$$\int_0^{DT} LdI = \int_0^{DT} (V_{in} - V_{out})dt$$

$$L(I_{maximum} - I_{minimum}) = (V_{in} - V_{out})(DT)$$

$$\Delta I = \frac{(V_{in} - V_{out})}{L} \times DT$$

For $t_{ON} < t < T$ the switch is off meaning and the inductor discharge to supply the load and the capacitor:

$$V_{tr} = V_{in}$$

$$0 = V_L + V_{out}$$

$$L\frac{dI}{dt} = -V_{out}$$

By integrating both terms, we obtain:

$$\int_{DT}^{t} LdI = \int_{DT}^{t} (-V_{out})dt \ , \ t\epsilon[0, DT]$$

$$L(I(t) - I_{maximum}) = (-V_{out})(t - DT)$$

$$I(t) = \frac{(-V_{out})}{L}(t - DT) + I_{maximum}$$

For $t = T$:

$$I(T) = I_{minimum} = \frac{(-V_{out})}{L}(T - DT) + I_{maximum}$$

- Calculating the current ripple:

$$\Delta I = I_{maximum} - I_{minimum} = \frac{(V_{out})}{L}(T - DT)$$

- Average value of voltage V_{out} :

For a steady state performance, the average value of the inductor voltage is zero, thus:

$$\overline{V_L} = \frac{1}{T}\int_0^T V_L dt = \frac{1}{T}\left(\int_0^{DT}(V_{in} - V_{out})dt + \int_{DT}^{T} -V_{out}\, dt\right) = 0 \quad \text{Eq III. 19}$$

$$\frac{1}{T}\int_0^{DT}(V_{in} - V_{out})dt + \frac{1}{T}\int_{DT}^{T} -V_{out}\, dt = 0 \quad \text{Eq III. 20}$$

$$\frac{1}{T}(V_{in} - V_{out})(DT - 0) - \frac{1}{T}V_{out}(T - DT) = 0 \quad \text{Eq III. 21}$$

$$DV_{in} - DV_{out} - V_{out} + DV_{out} = 0 \quad \text{Eq III. 22}$$

$$V_{out} = DV_{in} \quad \text{Eq III. 23}$$

- Average value of I_{out}:

$$R\overline{I} = V_{out}\ \ \overline{I} = \frac{V_{out}}{R} \quad \text{Eq III. 24}$$

Another simulation is done with the following parameters:

$V_{in} = 100\ volts\ ,\ R = 1K\Omega, D = 0.5,\ V_{out} = 50\ volts, I_{out} = 0.05A,\ f = 10KHz$

$\Delta I = 0.001A, L = 2.5H, C = 1.013212 \times 10^{-10}F$

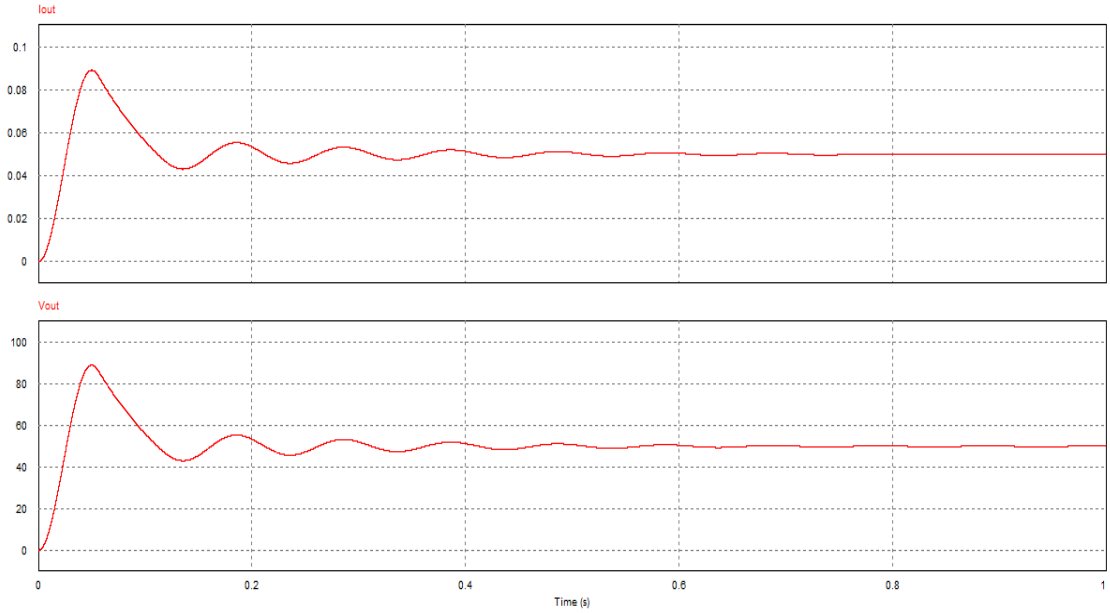


FIGURE III- 8: FILTERED OUTPUT VOLTAGE AND CURRENT OF A BUCK CONVERTER

ii. BOOST converter

In this case, the output voltage is higher than the input voltage and the output current is lower than the current supplied by the source. The switch is connected in parallel to the load. The inductor prevent the short circuit of the input voltage and reduce the current ripple. This circuit is used to charge the solar battery.

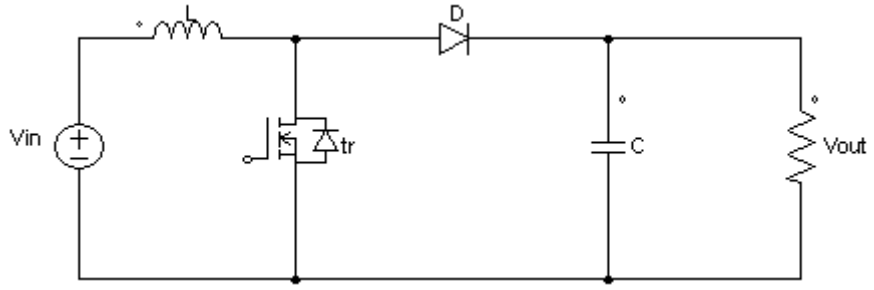


FIGURE III- 9: BOOST CONVERTER

For $0 < t < t_{ON}$ the switch is on therefore the voltage drop across it is zero ($V_{tr} = 0$) and the inductor start storing the energy also the value of the capacitor is sufficient for a constant voltage.

Kirchhoff's Voltage Law states that:

$$V_{in} - V_{tr} - V_L = 0 \quad \text{Eq III. 25}$$

$$V_{in} = V_L \quad \text{Eq III. 26}$$

$$V_{in} = L\frac{dI}{dt} \quad \text{Eq III. 27}$$

The current equation for this phase:

$$I(t) = \frac{V_{in}}{L}t + I_{minimum} \quad \text{Eq III. 28}$$

For $t = DT$:

$$I(DT) = I_{maximum} = \frac{V_{in}}{L}DT + I_{minimum} \quad \text{Eq III. 29}$$

Calculating the current ripple:

$$\Delta I = I_{maximum} - I_{minimum} = \frac{V_{in}}{L}DT \quad \text{Eq III. 30}$$

For $t_{ON} < t < T$ the switch is off meaning and the inductor discharge to supply the load and the capacitor:

$$V_{tr} = V_{in} - V_L \quad \text{Eq III. 31}$$

$$V_{in} = V_L + V_{out} \quad \text{Eq III. 32}$$

$$V_L = V_{in} - V_{out} \quad \text{Eq III. 33}$$

The current equation for this phase:

$$I(t) = \frac{V_{in}-V_{out}}{L}t + I_{maximum} \quad \text{Eq III. 34}$$

For $t = T$:

$$I(T) = I_{minimum} = \frac{V_{in}-V_{out}}{L}T + I_{maximum} \quad \text{Eq III. 35}$$

Calculating the current ripple:

$$\Delta I = I_{maximum} - I_{minimum} = -\frac{V_{in}-V_{out}}{L}T \quad \text{Eq III. 36}$$

- Average value of V_{out}:

$$\overline{V_L} = \frac{1}{T}\int_0^T V_L dt = \frac{1}{T}\left(\int_0^{DT} V_{in}dt + \int_{DT}^{T}(V_{in} - V_{out})dt\right) = 0 \quad \text{Eq III. 37}$$

$$\overline{V_L} = \frac{1}{T}\left(V_{in}(DT) + (V_{in} - V_{out})(T - DT)\right) \quad \text{Eq III. 38}$$

$$\overline{V_L} = V_{in}(D) + (V_{in} - V_{out})(1 - D) = 0 \quad \text{Eq III. 39}$$

$$V_{out} = \frac{V_{in}}{1-D} \quad \text{Eq III. 40}$$

$V_{in} = 50\ volts$, $R = 1K\Omega$, $D = 0.5$, $\Delta I = 0.01A$, $V_{out} = 100\ volts$, $I_{out} = 0.1A$

$f = 10KHz$, $L = 0.5\ H$:

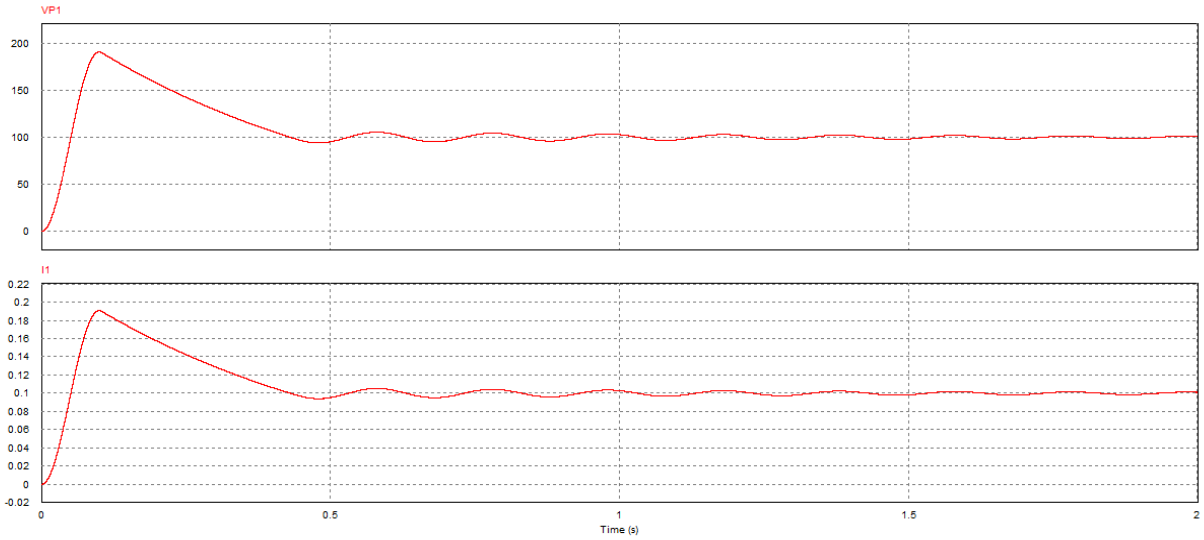


FIGURE III- 10: output voltage and current of a BOOST converter

iii. BUCK-BOOST converter

A BUCK-BOOST converter is a converter that can do both functions of elevating and reducing the input voltage, which is adequate for variable voltage application such as the case of DC pumps, where we obtain a variable flow rate, or to feed an inverter that supplies an induction pump motor. There two types of this converter, none inverting BUCK-BOOST converter that keeps the same sign of the input voltage, and inverting BUCK-BOOST converter that offer the advantage of inversing the voltage signal. The MPPT requires the use of none inverting BUCK-BOOST converter.

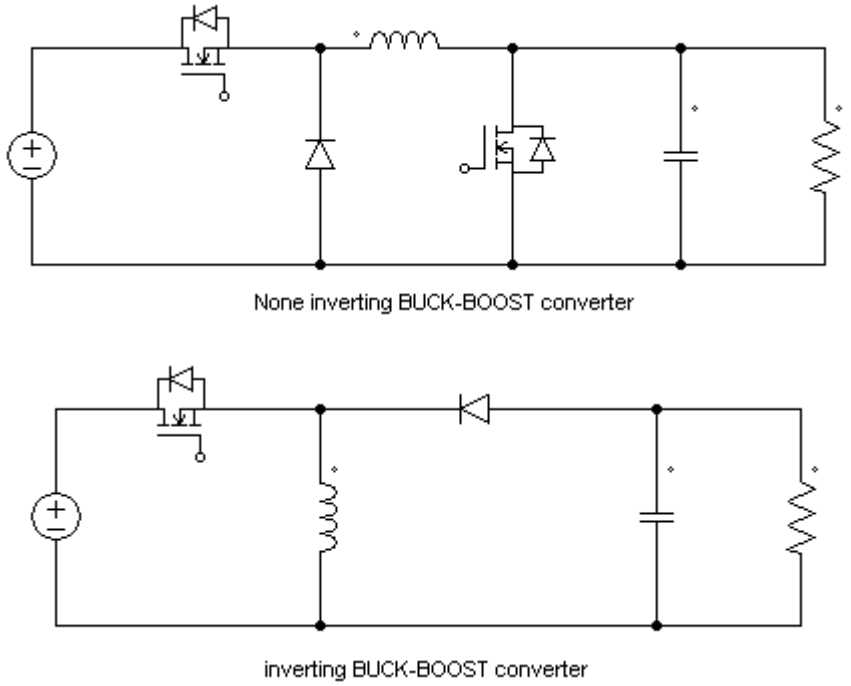


FIGURE III- 11: TYPES OF BUCK-BOOST CONVERTER

Function analyses for none inverting BUCK-BOOST converter:

For $0 < t < t_{ON}$ both switches are ON therefore the voltage drop across them is zero ($V_{tr1} = V_{tr2} = 0$) and the inductor start storing the energy also the value of the capacitor is sufficient for a constant output voltage.

$$V_L = V_{in} \qquad \text{Eq III. 41}$$

The current equation for this phase:

$$I(t) = \frac{V_{in}}{L} t + I_{minimum} \qquad \text{Eq III. 42}$$

For $t = DT$:

$$I(DT) = I_{maximum} = \frac{V_{in}}{L} DT + I_{minimum} \qquad \text{Eq III. 43}$$

Calculating the current ripple:

$$\Delta I = I_{maximum} - I_{minimum} = \frac{V_{in}}{L} DT \quad \text{Eq III. 44}$$

For $t_{ON} < t < T$ the switches are off meaning and the inductor discharge to supply the load and the capacitor:

$$V_L = -V_{out} \quad \text{Eq III. 45}$$

The current equation for this phase:

$$I(t) = \frac{-V_{out}}{L}(t - DT) + I_{maximum} \quad \text{Eq III. 46}$$

For $t = T$:

$$I(T) = I_{minimum} = \frac{-V_{out}}{L}(T - DT) + I_{maximum} \quad \text{Eq III. 47}$$

Calculating the current ripple:

$$\Delta I = I_{maximum} - I_{minimum} = \frac{V_{out}}{L}(T - DT) \quad \text{Eq III. 48}$$

- Average value of V_{out}:

$$\overline{V_L} = \frac{1}{T}\int_0^T V_L dt = \frac{1}{T}\left(\int_0^{DT}(V_{in})dt + \int_{DT}^{T} -V_{out}dt\right) = 0 \quad \text{Eq III. 49}$$

$$\overline{V_L} = \frac{1}{T}\big((V_{in})(DT) + (-V_{out})(T - DT)\big) \quad \text{Eq III. 50}$$

$$\overline{V_L} = (V_{in})(D) + (-V_{out})(1 - D) = 0 \quad \text{Eq III. 51}$$

$$V_{out} = \frac{DV_{in}}{1-D} \quad \text{Eq III. 52}$$

For $D = 0.5$: $V_{out} = V_{in}$

For $D < 0.5$: $V_{out} < V_{in}$

For $D > 0.5$: $V_{out} > V_{in}$

A two-phase simulation is done to verify the performance of a non-inverting BUCK-BOOST converter. The following parameters were considered:

$R = 1K\Omega$, $D = 0.5$, $\Delta I = 0.01A$, $V_{out} = 100\ volts$, $I_{out} = 0.1A$, $f = 10KHz$, $L = 0.5\ H$

- First phase: $V_{in} = 50\ volts$ the converter acts the same as a BOOST converter:

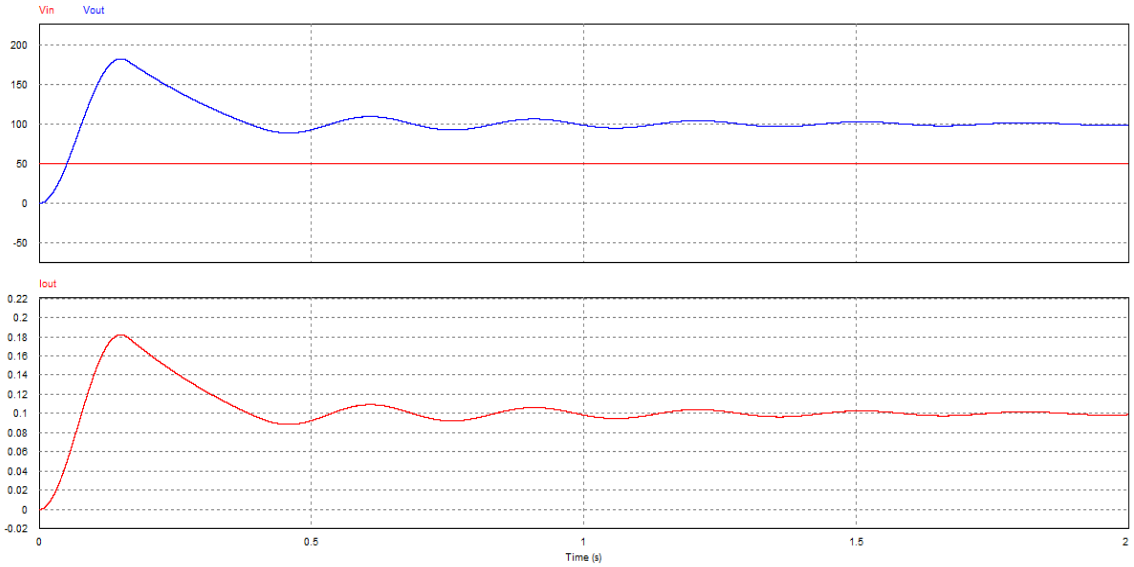


FIGURE III- 12: operating in boosting mode

- Second phase: $V_{in} = 200\ volts$ the converter acts the same as a BUCK converter:

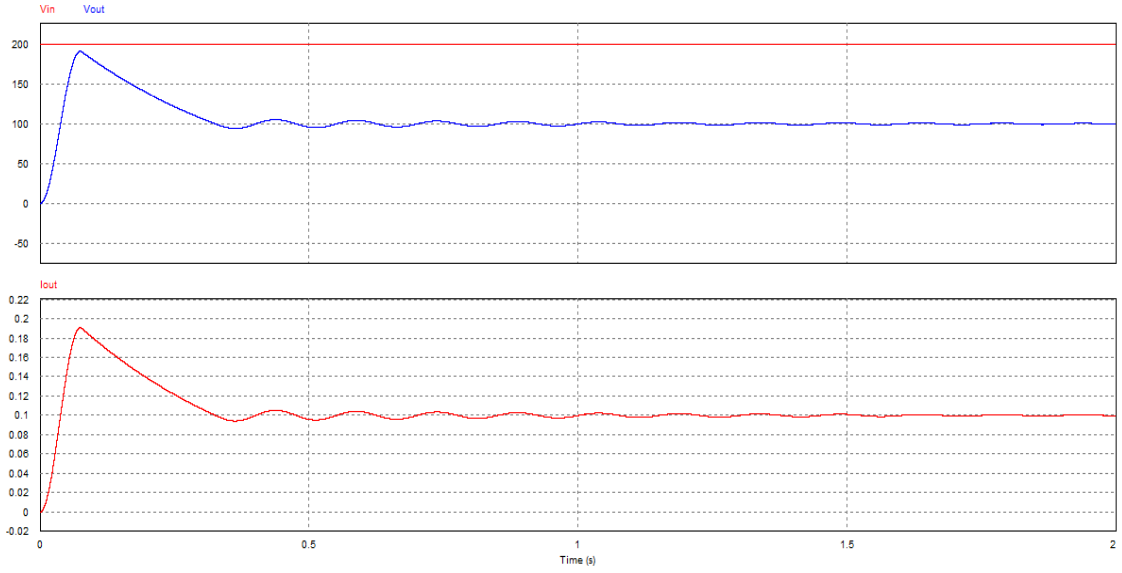


FIGURE III- 13: operating in buck mode

However, MPPT requires permanent measurement of the input voltage also the converters has a harsh transient response that need to be regulated in order to preserve the battery and the other components.

III.VII. Perturb and observe algorithm

The perturb and observe method is a widely used technic for locating the MPP, famous of its simple algorithm. The P&O algorithm consists on perturbing the PV voltage while observing the change in power. If increasing the voltage leads to a higher value of power the operating point is less than MPP, else if it cause a lower value that means we have surpassed the MPP. The following figure explains the working principle of the P&O method:

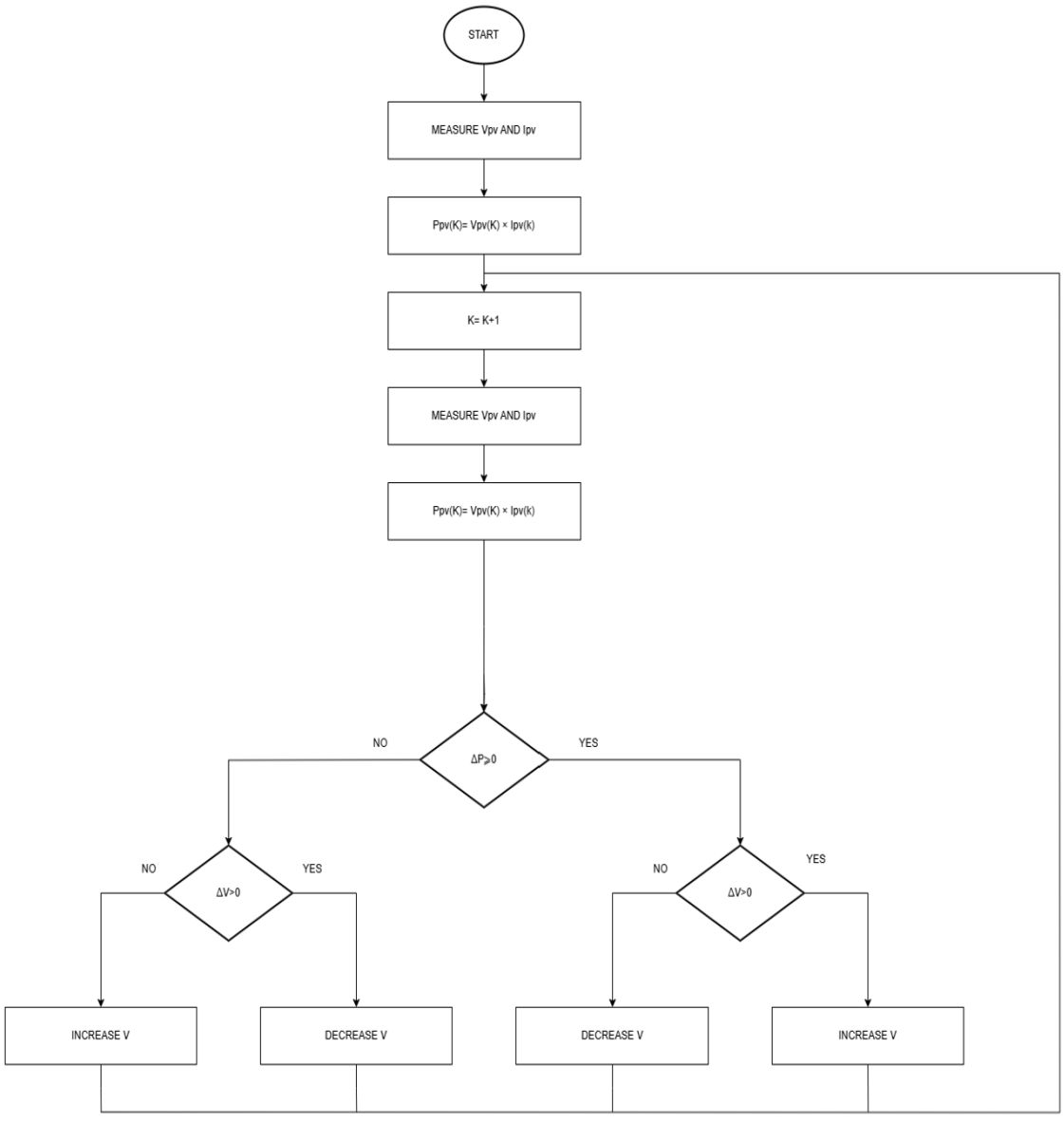


FIGURE III- 14: flow chart of a P&O algorithm

However, this technic present certain limitation when sudden variation in climate conditions or load occurs which leads the algorithm to misinterpret the direction in which to adjust the operating point to reach the MPP. For example, under a given irradiation level, the system could initially operate

at a point near MPP. However, following a voltage perturbation, the operating point may surpass the MPP. If the irradiation remains constant, this can result in a negative power derivative. Consequently, the algorithm inverts the direction of the perturbation, leading to oscillations around the MPP in steady-state conditions. The main cause of this issue is that the algorithm operates using a fix step for voltage perturbation.

III.VIII. Adaptive step P&O algorithm

This method shows enhanced performance in finding the MPP because it operates using a variable step for perturbing the voltage leading to a stable steady state performance. Unlike the conventional P&O method, it consist on adjusting the step size base on operating conditions. If the operating point is far from the MPP, the algorithm uses a high step and start to decrease it when reaching MPP. The following flowchart represent an adaptive step P&O algorithm:

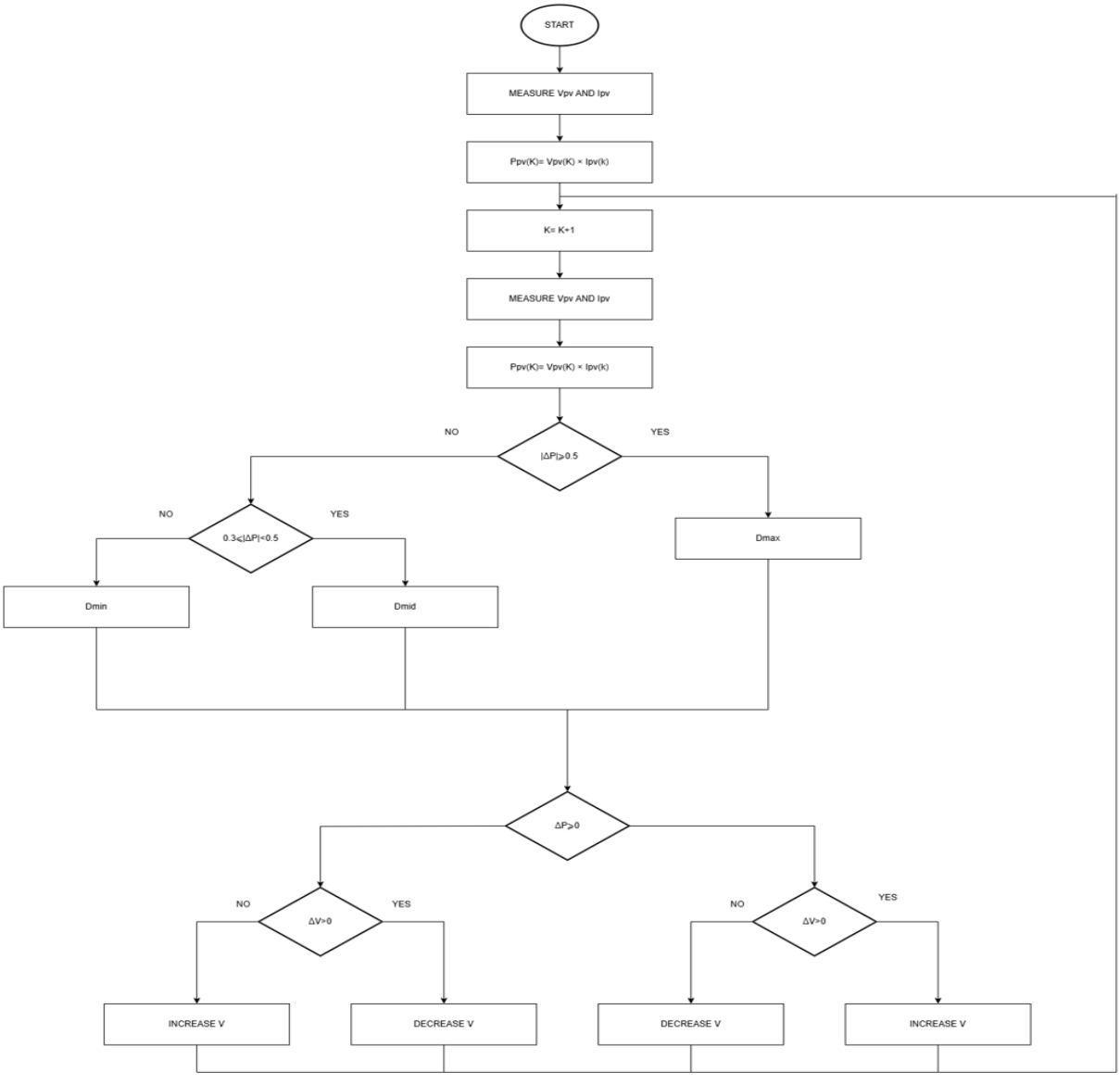


FIGURE III- 15: flow chart of adaptive step P&O algorithm

III.IX. Solar power storage

After extracting maximum power from photovoltaic panels using MPPT algorithm, a storage of the PV energy becomes essential to ensure stable consumption. Solar energy storage systems, typically implemented through rechargeable batteries, allow for the accumulation of excess energy generated during periods of high irradiance for use during times when solar input is insufficient or unavailable. This approach enhances the overall reliability and stability of solar-powered systems by providing a consistent power supply despite fluctuations in the environment. Furthermore, energy storage contributes to improved system efficiency, as it prevents energy loss by enabling surplus power to be stored rather than wasted. Integrating storage also facilitates better load management and autonomy, reducing dependence on real-time solar generation and allowing for more flexible and continuous operation of the system. The following table shows the main factors that must be considered to choose the best possible storage solution for a system:

TABLE III- 1: factors for choosing a battery.

Factor	Description	Why It Matters	Recommended Range
Battery Type	Li-ion, $LiFePO_4$, Lead-acid (AGM, Gel, Flooded)	Affects lifespan, efficiency, size, cost, and safety	$LiFePO_4$ for best performance
Voltage	Common: 12V, 24V, 48V	Must match the system design (inverter, charge controller, etc.)	12V for small systems
Capacity (Ah)	Amp-hours (e.g., 100Ah, 200Ah, etc.)	Determines how long a system can run loads without charging	Based on daily consumption
Energy (Wh or kWh)	Voltage × Ah (e.g., 12V × 200Ah = 2400Wh)	Total energy storage capacity	Sized for a calculated periode (hours or days)
Cycle Life	Number of charge/discharge cycles (e.g., 2000–5000+)	Affects long-term reliability and cost-efficiency	2000+ cycles recommended
Depth of Discharge (DoD)	% of capacity you can safely use	Higher DoD = more usable energy	80–100% for $LiFePO_4$
Round-trip Efficiency	% of energy stored vs. retrieved (e.g., 90–95%)	Higher means less energy loss during charge/discharge	90%+ is ideal
Temperature Range	Operating temperature (charging/discharging)	Important for outdoor or hot climates like Algeria	$LiFePO_4$ handles heat well
Maintenance	Water refilling (flooded), checks (AGM), BMS ($LiFePO_4$)	Impacts ease of use and lifespan	$LiFePO_4$ is maintenance-free
Cost	Upfront cost per battery or per usable kWh	Affects project budget	$LiFePO_4$ higher upfront, lower over time
Battery Management System (BMS)	Monitors health, prevents over/under charge/discharge	Crucial for safety and performance, especially in lithium batteries	Always choose with BMS
Size & Weight	Physical dimensions and mass	Matters for portability and installation space	$LiFePO_4$ is lighter & smaller

III.X. Inverters

Inverters are electronic devices that convert DC voltage to an AC voltage with adjustable frequency and RMS values, two types of this converter exists Standalone (off-grid) where the frequency of the output voltage must be identical to the grid voltage frequency. In addition, Grid-tied inverters where the frequency is adjust certain condition like the case of variable frequency drives VFD. These devices are commonly used in various application such as Backup power supplies, AC machines speed drives and induction heating. For the drip irrigation project the studied inverter is a standalone type.

i. Single phase inverters

This circuit uses four controllable switches (MOSFET, IGBT…) arranged in an H-bridge the inverter alternate the direction of current through the load, producing AC from a DC source. This circuit is used to supply lighting circuits or other single-phase loads. The switch off the same leg are controlled in a complementary way to prevent short-circuit.

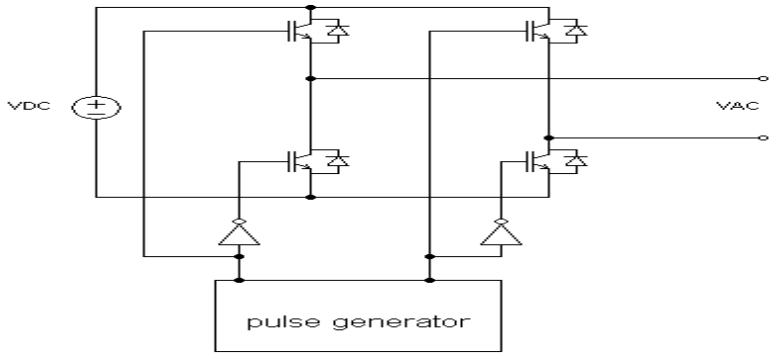


FIGURE III- 16: single-phase H-bridge inverter.

The following diagram shows the output voltage of a symmetrical control single-phase inverter where the command of the two legs is symmetrical.

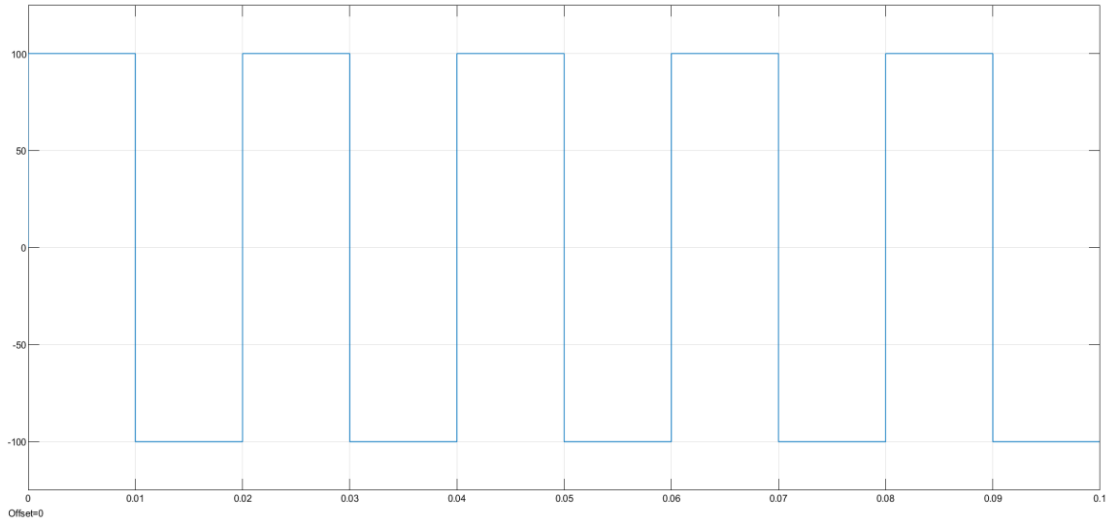


FIGURE III- 17: output voltage of a single phase inverter.

Calculating the value of voltage's RMS:

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T V(t)^2\, dt} \qquad \text{Eq III. 53}$$

$$V_{rms} = \sqrt{\frac{1}{T}\left[\int_0^{\frac{T}{2}} E^2\, dt + \int_{\frac{T}{2}}^{T} (-E)^2\, dt\right]} \qquad \text{Eq III. 54}$$

$$V_{rms} = E \qquad \text{Eq III. 55}$$

The RMS voltage of a single-phase H-bridge inverter with symmetrical control is adjustable only when the DC voltage source is variable. However, this method results in a high total harmonic distortion (THD), up to 43.5%. Another technique to reduce the THD and achieve adjustable RMS voltage is the pulse-width modulation (PWM) method, which operates by comparing a carrier wave to determine the exact moment a switch should be closed.

ii. Three Phase inverter

This circuit uses six controllable switches arranged in by mounting three half bridges next to each other this circuit can be applied to supply Three phase motors and many other three-phase loads. The command signal of each half bridge is delayed by 120 degrees to ensure power stability.

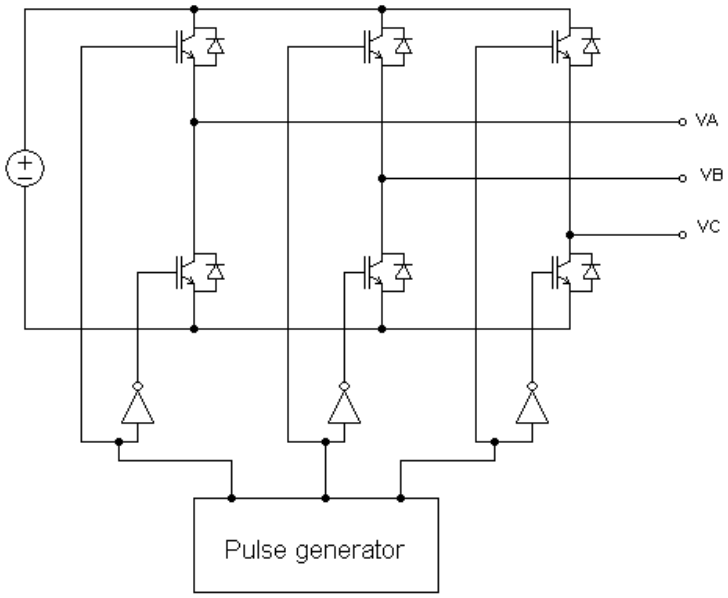


FIGURE III- 18: three phase inverter.

The following figure shows the output voltage of a three-phase inverter after applying fullwave control method:

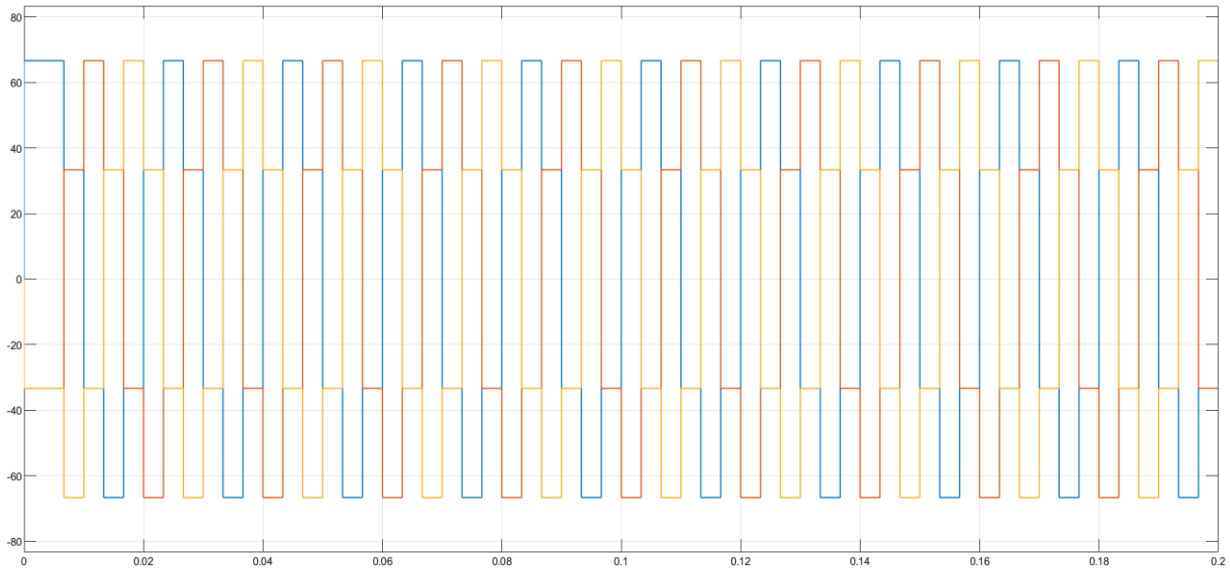


FIGURE III- 19: output voltage of a three phase inverter.

Calculating Vrms for one phase:

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T V(t)^2\, dt} \quad \text{Eq III. 56}$$

$$V_{rms} = \frac{\sqrt{2}}{3}E \quad \text{Eq III. 57}$$

The resulting RMS cannot be adjusted with the inverter and contain a THD up to 29.68%.

iii. Pulse width modulation PWM

The output voltage of the inverter in full wave mode is a rectangular waveform rich in harmonics, which can cause electromagnetic interference. This issue is addressed by using the PWM technique, which controls power flow by rapidly switching the output ON and OFF, shifting higher-order harmonics to higher frequencies where they can be easily filtered. It consists on comparing a reference wave with a higher frequency carrier wave. Among the multiple methods, Sinusoidal Pulse Width Modulation (SPWM) relies on comparing a high-frequency triangular wave with a lower-frequency sine wave. The output is high when the sine wave exceeds the triangular wave, and low otherwise, allowing for a PWM signal that closely mimics a sine waveform. To use this type if control two parameters must be evaluated frequency ratio and the modulation index. The frequency ratio m_f, defined as the ratio of the carrier frequency to the reference sine wave frequency, determines the resolution of the PWM signal. The modulation index m_a, which is the ratio of the sine wave amplitude to the triangular wave amplitude, controls the amplitude of the output voltage.

For example to control a single-phase inverter, we compare the following waveforms:

$$U_{carrier} = \begin{cases} \frac{U_c}{2}\left(\frac{4t}{T_c} - 1\right)\ if\ 0 \le t \le \frac{T_c}{2} \\ \frac{U_c}{2}\left(3 - \frac{4t}{T_c}\right)\ if\ \frac{T_c}{2} \le t \le T_c \end{cases} \quad \text{Eq III. 58}$$

$$U_{reference} = rU_c Sin(2\pi \frac{f_c}{m_f} t) \quad \text{Eq III. 59}$$

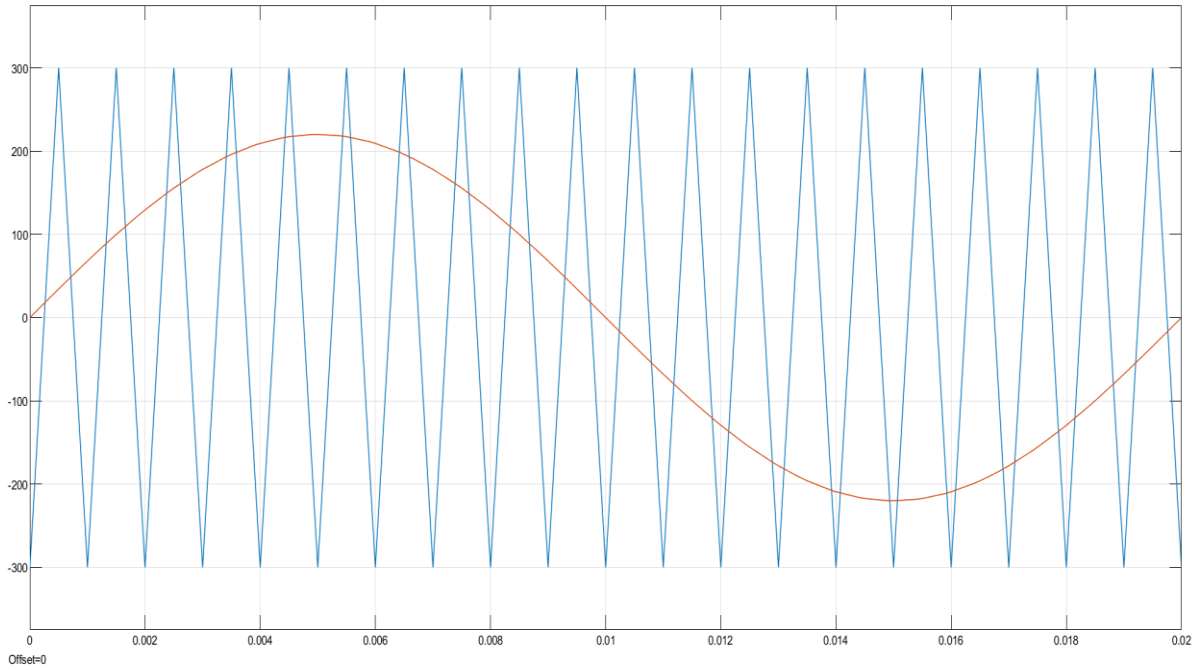


FIGURE III- 20: SINGLE-PHASE SPWM

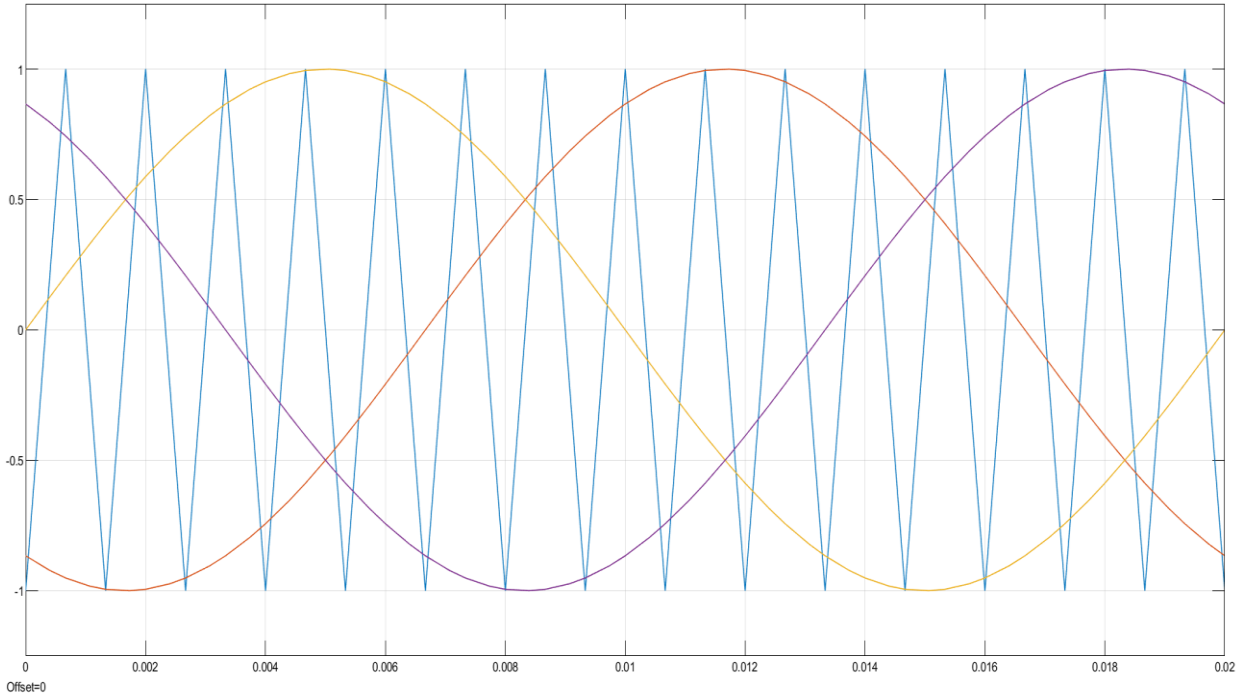


FIGURE III- 21: three-phase SPWM

III.XI. Conclusion

In this chapter, we explored the integration of renewable energy into modern systems, with a particular focus on photovoltaic (PV) energy. We began by introducing the photovoltaic effect, the fundamental principle behind solar energy conversion, and examined the structure and function of PV cells and panels. By analyzing the equivalent circuit of a PV cell, we gained insight into the electrical behavior and performance of solar modules.

A key part of efficient solar energy utilization is operating at the Maximum Power Point (MPP). To this end, Maximum Power Point Tracking (MPPT) techniques were discussed, particularly in the context of various DC-DC converters such as BUCK, BOOST, and BUCK-BOOST converters. Each converter type was analyzed with regard to its operation and its effect on the load and energy transfer, both with and without filtering stages.

We then focused on the Perturb and Observe (P&O) algorithm, a common MPPT technique, and its improved variant, the Adaptive Step P&O, which enhances tracking accuracy and system responsiveness.

Finally, the chapter addressed solar power storage, essential for ensuring energy availability during non-sunlight hours, and discussed different types of inverters—single-phase, three-phase, and those using Pulse Width Modulation (PWM)—which are critical for converting DC from PV systems into usable AC power.

This comprehensive overview lays the groundwork for understanding how photovoltaic energy can be effectively integrated into sustainable systems, especially in agricultural or isolated applications such as the solar-powered drip irrigation system proposed in this thesis.

Chapter 04:

Small prototype Of the irrigation system

IV.I. Introduction

This chapter presents the design and implementation of a small-scale prototype of a smart irrigation system aimed at optimizing water usage in agriculture. The system integrates various electronic components and sensors controlled by an Arduino microcontroller to automate the irrigation process based on real-time soil moisture and water level data. The chapter begins by introducing the Arduino platform as the core of the control unit, followed by a detailed description of the YL69 soil moisture sensor, which monitors the hydration status of the soil. A diaphragm water pump is used to deliver water from a 3D-printed reservoir, while solenoid valves manage the flow to different irrigation zones. A 2.8-inch TFT touch screen provides a visual interface for monitoring and interaction, and an ultrasonic sensor measures the remaining water in the tank. The system also incorporates a relay module for safe control of high-power components and a breadboard for prototyping and connectivity. The chapter concludes with a full presentation of the Arduino code that brings together all hardware components to function as an intelligent, automated irrigation solution.

IV.II. Arduino

Arduino is an open-source electronics platform based on easy-to-use hardware and software, designed to simplify the process of creating interactive electronic projects for both beginners and professionals. Arduino development boards are small circuit boards that contain an ATmega microcontroller, such as the ATmega328 found on the Arduino Uno. These boards can read various inputs like light or temperature through the sensors and control outputs such as motors, LEDs, or displays. There are several different types of Arduino boards, each designed for specific needs and projects. The Arduino Uno is the most popular and beginner-friendly board, ideal for basic projects. The Arduino Mega offers more memory and input/output pins, making it suitable for complex applications. For compact projects, the Arduino Nano and Arduino Pro Mini are great choices due to their small size. The Arduino Leonardo includes built-in USB support, allowing it to emulate a keyboard or mouse. There are also boards like the Arduino Due for more powerful processing and the Arduino MKR and Nano 33 IoT for Internet of Things applications. Each board has unique features tailored to different levels of complexity and connectivity. For the prototype, I will be using an Arduino Uno for MPPT code and Arduino mega to control the irrigation process and display the data.

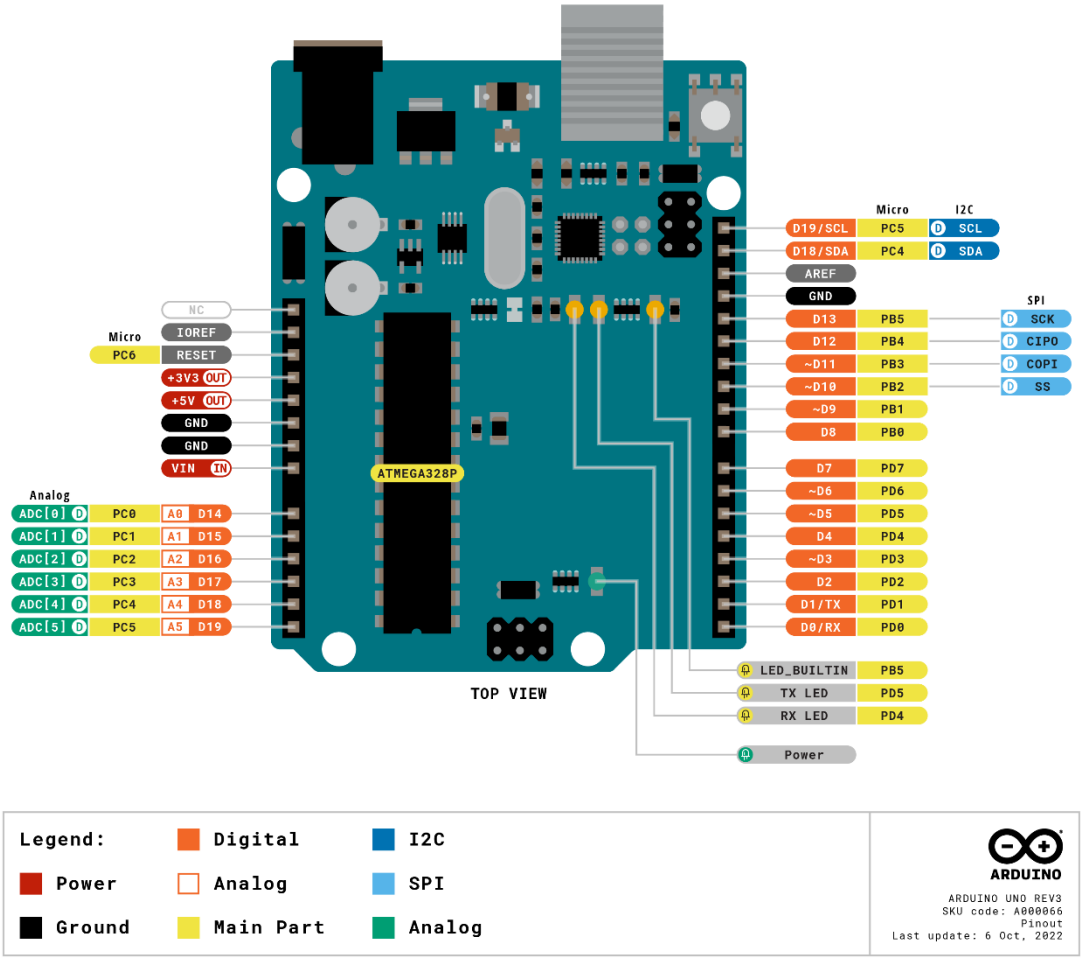


FIGURE IV- 1: Arduino UNO layout

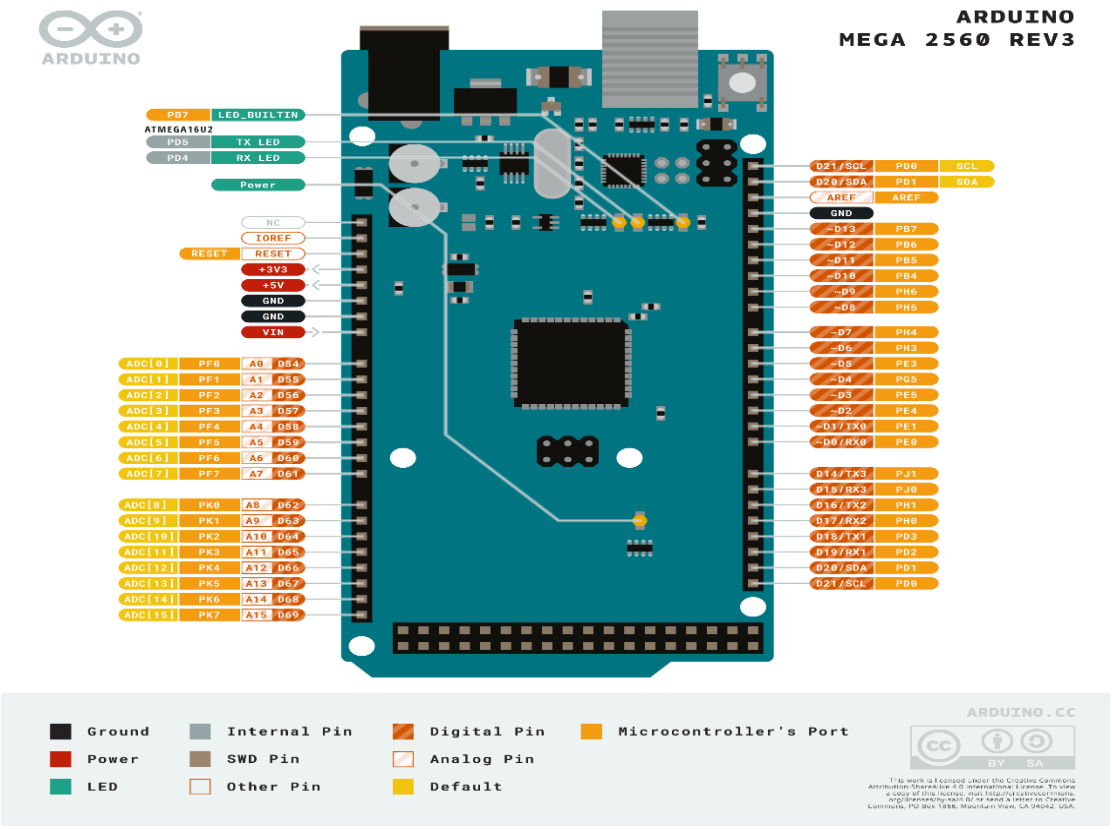


FIGURE IV- 2: ARDUINO MEGA PINOUT

The Arduino software, known as the Arduino IDE (Integrated Development Environment), allows users to write code in a language based on C/C++ and upload it to the board via USB. Arduino is widely used in applications such as home automation, robotics (including robot arms), environmental monitoring, IoT projects, and prototyping for engineering students and professionals. Its open-source nature has fostered a large global community that actively shares libraries, tutorials, and examples, making Arduino an excellent tool for learning and innovation.

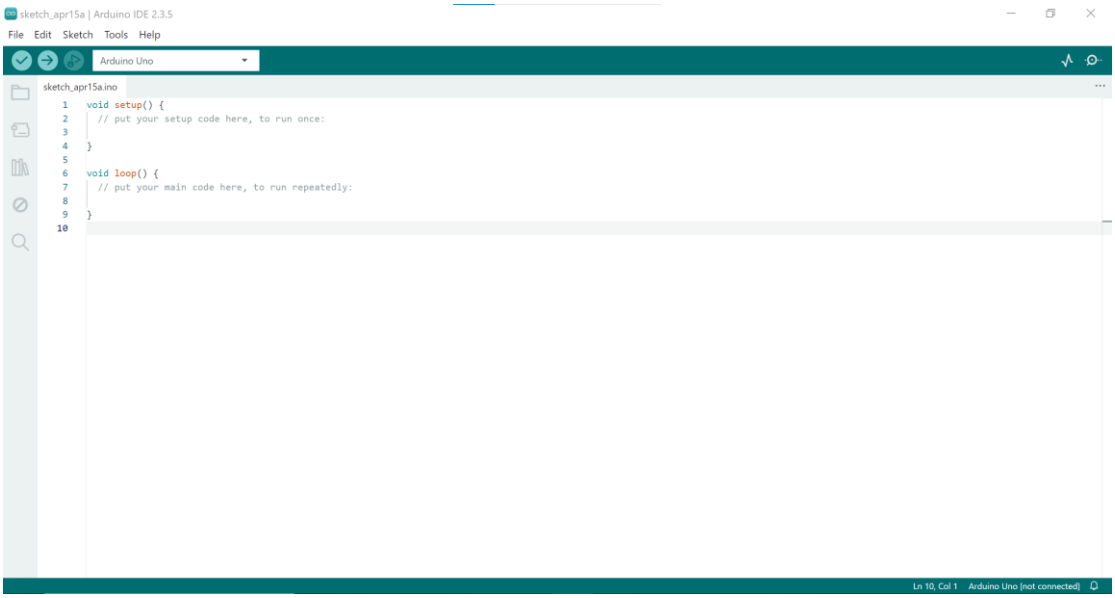


FIGURE IV- 3: Arduino IDE interface

Every single program must contain two principle function setup() and loop(). The setup() function runs once when the program starts and is typically used to initialize settings like pin modes or serial communication. The loop() function runs continuously after setup() and contains the main logic of the program that keeps executing as long as the board is powered. At the bottom right, it shows that the selected board is Arduino Uno, but it is currently not connected, which means no board is detected via USB. This environment is designed to be beginner-friendly while still powerful enough for advanced users, supporting a wide range of Arduino boards and libraries.

IV.III.YL69 soil moisture sensor

The YL-69 is a soil moisture sensor widely used in gardening, agriculture, and environmental monitoring projects. It measures the moisture level in the soil, enabling systems like automatic irrigation to function based on real-time soil conditions. The sensor consists of two main components: the YL-69 probe, a metallic sensor inserted into the soil, and a control module that processes the signal and provides both analog and digital outputs. The analog output (A0) delivers a variable voltage that reflects the soil's moisture content—higher values indicate drier soil—while the digital output (D0) provides a HIGH or LOW signal based on a threshold set by the onboard potentiometer. Operating at a voltage of 3.3V to 5V, it is fully compatible with Arduino boards. Due to its affordability, simplicity, and reliability, the YL-69 is commonly used in smart irrigation systems, plant watering reminders, greenhouse automation, and agricultural research. However, its metal probes are prone to corrosion over time, especially in wet environments, so for long-term use, it is recommended to either coat the probes or consider capacitive moisture sensors as an alternative.

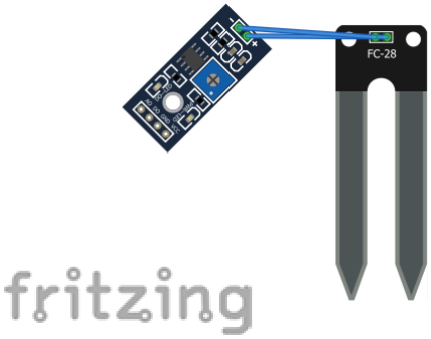


FIGURE IV- 4: YL69

IV.IV.Diaphragm water pump

A 12V diaphragm DC water pump is a compact and efficient electric pump that operates on 12 volts of direct current (DC) and uses a diaphragm mechanism to move water. It is widely favored in small-scale water transfer systems due to its reliability, low power consumption, self-priming capability, and the ability to run dry for short periods without damage. Inside the pump, a flexible diaphragm moves back and forth, creating pressure differences that draw in and push out water through one-way valves. This design eliminates the need for lubrication and allows the pump to handle clean or slightly dirty water. Typical models have a flow rate ranging from 1 to 10 liters per minute and are often equipped with features like dry run protection and self-priming functionality, allowing them to draw water from a tank positioned below. Common applications include drip irrigation systems, RV and marine water supply, solar-powered water systems, water dispensers, and misting or spraying setups. Thanks to its low-voltage operation and versatility, the 12V diaphragm pump is an excellent choice for renewable energy-powered projects, especially in off-grid or automated irrigation systems.



FIGURE IV- 5: 12V diaphragm DC water pump

IV.V. TFT 2.8 TOUCH SCREEN

The 2.8" TFT touch screen is a compact, high-resolution display commonly used in embedded systems and electronics projects. With a resolution of 240x320 pixels, it provides clear visuals and supports full-color output, making it ideal for displaying dynamic data, graphics, or interactive controls. The built-in touchscreen functionality allows for intuitive user input, making it perfect for applications where user interaction is needed, such as monitoring or controlling systems. In projects like your photovoltaic-powered drip irrigation system, this screen can serve as an interface to display real-time data, control system settings, or visualize performance metrics, all while offering a convenient, user-friendly interface.

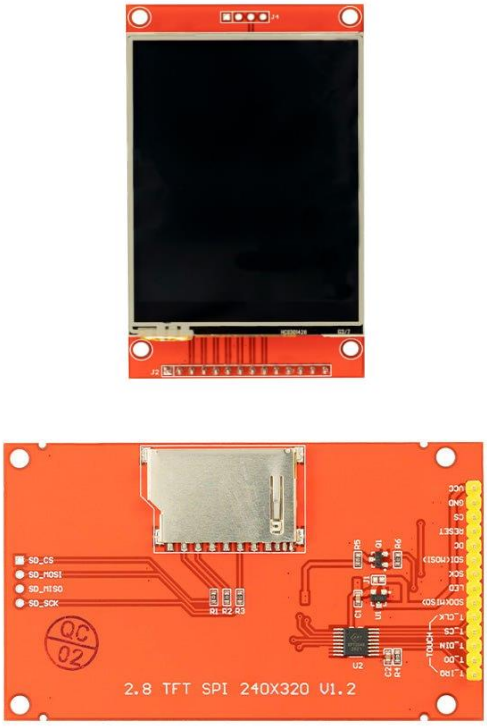


FIGURE IV- 6: TFT 2.8 screen

However sometimes it is little hard to identify the right wiring because you identify the write pins to connect on the Arduino. The following table shows the wiring for UNO and MEGA:

Table IV- 1: Pins connections for the TFT screen

TFT SCREEN	UNO	MEGA
SCK AND T_CLK	13	52
SDO AND T_DO	11	51
SDI AND T_DIN	12	50
CS	10	10
DC	9	9
RESET	8	8
T_CS	7	7

In addition, the screen operates at logic level of 3,3 volts except for the VCC and LED pins that need a 5 volts supply, to solve this issue a voltage divider is used with two resistors as following:

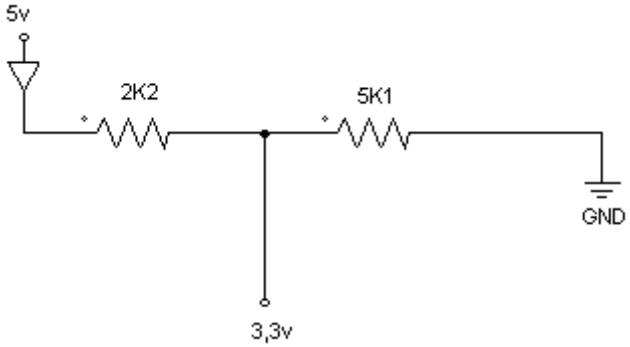


FIGURE IV- 7: voltage divider

IV.VI. Solenoid valve

In this project, a "Swing Chuck Valve Normally Closed Solenoid Valve Magnetic DC 12V Water Inlet Flow Switch 1/4" is employed to control the flow of water within the system. This component is an electromechanical solenoid valve that operates using a magnetic coil mechanism. When 12V DC is supplied, the magnetic field generated by the coil activates a plunger, opening the valve and allowing water to pass through; otherwise, the valve remains closed, classifying it as a normally closed (NC) valve. Its magnetic actuation ensures reliable operation and makes it suitable for integration into automatic control systems, such as irrigation or water purification setups. The valve features a 1/4-inch standard inlet/outlet, compatible with small-diameter tubing typically found in compact fluid control applications. The term “Swing Chuck” likely refers to the internal mechanism that aids in flow regulation, possibly involving a swinging or flapping component, although this may be a vendor-specific naming convention rather than an industry-standard term. The valve’s simple design and compatibility with Arduino-based systems make it ideal for low-voltage, microcontroller-driven automation projects, such as the photovoltaic-powered drip irrigation system presented in this thesis.



FIGURE IV- 8: solenoid valve

IV.VII. Relay module

In this project, a 4-channel 12V relay module with light coupling (optocoupler isolation) is used to enable safe and efficient control of high-power components. This module allows the Arduino microcontroller to switch devices such as water pumps, solenoid valves, and lights, which operate at higher voltages and currents than the microcontroller can handle directly. Each of the four channels on the module contains a mechanical relay, driven by an optocoupler that electrically isolates the low-voltage control circuit from the high-voltage load side, protecting the system from voltage spikes and electromagnetic interference. The relays are triggered by a low logic signal, typically 0V from the Arduino, which activates an internal transistor to energize the relay coil and close the switch. The module is powered by 12V DC and accepts 3.3V or 5V logic signals, making it fully compatible with standard microcontroller platforms. It also features status LEDs, screw terminals for connecting loads, and pin headers for control inputs. This relay module plays a vital role in the photovoltaic-powered drip irrigation system developed in this work, where it ensures reliable and isolated switching of water flow components, enhancing both system automation and electrical safety.



FIGURE IV- 9: a 4-channel 12V relay module

IV.VIII. Ultrasonic sensor

An ultrasonic sensor is an electronic device that measures the distance to an object using ultrasound waves. It works by emitting a high-frequency sound wave (typically around 40 kHz) through a transmitter. When this sound wave hits an object, it reflects back and is received by the receiver. The sensor then calculates the time it took for the echo to return and, using the speed of sound, determines the distance to the object.



FIGURE IV- 10: HC-SR04 ultrasonic sensor

IV.IX. 3D printed water tank

A custom water tank was designed and 3D printed to support the HC-SR04 ultrasonic sensor, which is used to measure the water level. The tank has a tilted shape to help with water flow and to place the sensor in a better position for accurate readings. A small slot at the bottom holds the sensor securely. The tank, shown in Figure IV-10, was printed using PLA plastic, which is easy to work with and strong enough for this project. This design makes it easy to connect the tank to the rest of the irrigation system and allows for future changes if needed.

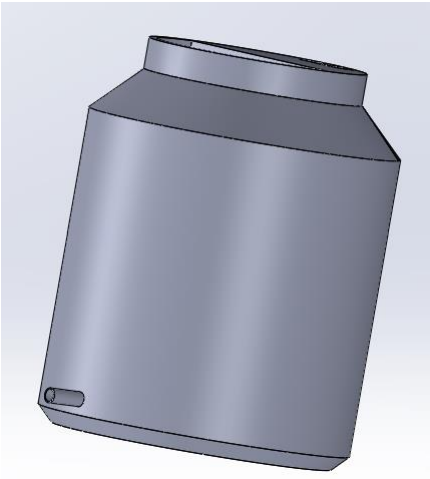


FIGURE IV- 11: 3D DESIGN OF WATER TANK IN SOLIDWORKS

IV.X. Bread board

A breadboard is composed of several key parts that make it convenient for prototyping electronic circuits. At the top and bottom of the breadboard, there are long horizontal rows called power rails, which are typically marked with red and blue or black lines to indicate positive and negative voltage. These rails are used to distribute power across the board. In the central area, the breadboard contains vertical columns of interconnected holes, usually grouped in sets of five. These columns are used for placing and connecting electronic components like resistors, capacitors, and transistors. Running down the middle of the board is a horizontal gap known as the trench, which separates the two sides of the vertical columns and is designed to fit dual in-line package (DIP) integrated circuits (ICs). Underneath the surface, metal strips connect the holes in specific patterns, allowing components to be electrically linked without soldering. The entire setup sits on a plastic base with a grid of holes, making it easy to modify circuits during testing and development.

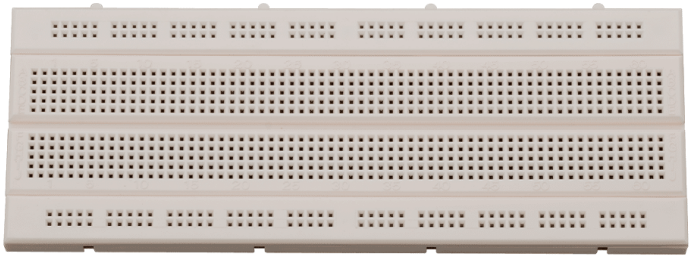


FIGURE IV- 12: BREAD BOARD

IV.XI.Power supply

A compact and efficient switching power supply designed to convert standard AC mains voltage (110/220V ±15%) into a stable 12V DC output, capable of delivering up to 15 amps of current. With a total power rating of 180 watts, this unit is ideal for powering a wide range of low-voltage electronic devices and systems such as LED lighting, CCTV setups, 3D printers, and microcontroller-based projects like Arduino and Raspberry Pi. Its metal casing with ventilation holes ensures adequate heat dissipation during operation. Made in China, the S-180-12 power supply is a reliable choice for both industrial and hobbyist applications, offering robust performance and consistent output under varying load conditions.



FIGURE IV- 13: S-180-12

IV.XII. Bluetooth module HC-05

The HC-05 is a Bluetooth module that facilitates wireless serial communication between devices. It is a popular choice for adding Bluetooth functionality to projects, particularly those involving microcontrollers like Arduino. The module can operate in both master and slave modes, allowing it to both initiate connections and respond to connection requests.



FIGURE IV- 14: HC-05

To facilitate Bluetooth communication between an Arduino board and an Android device, the Ardutooth library was integrated into the project. Developed by Giuseppe Brb, Ardutooth is a lightweight Android .aar library that simplifies serial data exchange over Bluetooth by providing a stable and easy-to-implement interface. It is particularly useful for real-time monitoring and control applications, making it well-suited for embedded systems and IoT-based irrigation projects. In parallel, the Arduino Bluetooth Terminal application—also referred to as ArduTooth—created by

Frederik Hauke, was used for direct interaction with the Arduino board from an Android device. This application allows visualization of sensor data and enables users to send commands wirelessly, streamlining the human-machine interaction in the system.

IV.XIII. Arduino code

The developed Arduino code integrates multiple components for an intelligent drip irrigation system, including soil moisture sensors, an ultrasonic water level sensor, a 2.8" TFT display, and a Bluetooth module (HC-05). The system reads real-time moisture values from two zones and compares them with predefined thresholds to automatically open or close valves and control a DC pump. A visual interface is rendered on the TFT using the Adafruit_GFX and Adafruit_ILI9341 libraries, allowing clear monitoring of sensor readings and actuator status. Additionally, an emergency stop mechanism is implemented, triggered either by a physical button or Bluetooth command ("Stop" or "Restart") sent via the Ardutooth Android application. Real-time sensor data, including moisture percentages and calculated water level in milliliters, are transmitted to a smartphone through the HC-05 module using formatted serial communication.

```
#include <SPI.h>
#include <Adafruit_GFX.h>
#include <Adafruit_ILI9341.h>

// TFT pin definitions
#define TFT_DC 9
#define TFT_CS 10
#define TFT_RST 8

// Initialize TFT display
Adafruit_ILI9341 tft = Adafruit_ILI9341(TFT_CS, TFT_DC, TFT_RST);

// Sensor and actuator pins
#define SENSOR_PIN1 A15
#define SENSOR_PIN2 A14
#define VALVE_PIN1 45
#define VALVE_PIN2 42
#define PUMP_PIN 43
#define button 2
const int trigPin = 38;
const int echoPin = 39;

// For 9.5 cm the water level reaches its lowest value: 0 mL
const float e = 1.7;
float Reelheight;
float waterlevel;

int buttonstate = LOW;
```

```
bool emergencyStop = false;  // <-- Bluetooth emergency flag

// Moisture thresholds
const uint8_t DRY_THRESH1 = 45;
const uint8_t WET_THRESH1 = 60;
const uint8_t DRY_THRESH2 = 40;
const uint8_t WET_THRESH2 = 55;

// UI layout function
void drawUILayout() {
  tft.drawRect(10, 20, 300, 40, ILI9341_WHITE);
  tft.drawRect(10, 80, 300, 40, ILI9341_WHITE);
  tft.drawRect(10, 190, 300, 40, ILI9341_WHITE);
  tft.setTextSize(2);
  tft.setTextColor(ILI9341_WHITE);
  tft.setCursor(20, 30);
  tft.print("Zone 1 Moisture:");
  tft.setCursor(20, 90);
  tft.print("Zone 2 Moisture:");
  tft.setCursor(20, 200);
  tft.print("Water Level:");
  tft.drawRect(250, 140, 60, 40, ILI9341_WHITE);
  tft.setCursor(10, 150);
  tft.print("Pump: ");
  tft.drawRect(250, 140, 60, 40, ILI9341_WHITE);
}
```

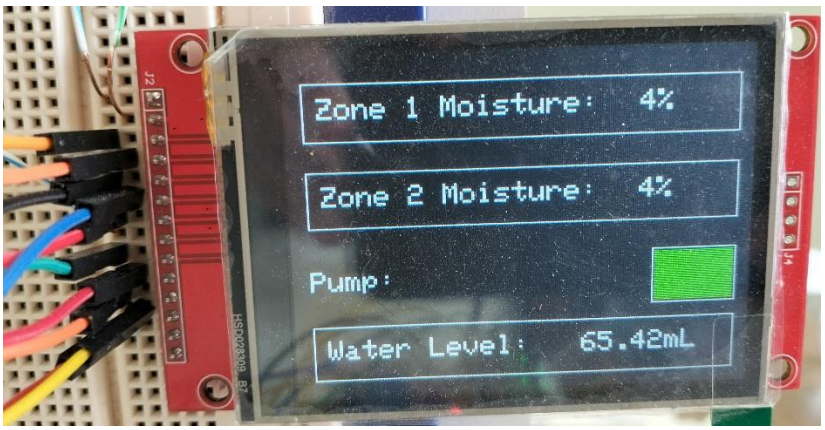


FIGURE IV- 15: HMI layout

```
// Function to send data to HC-05
void sendToArduTooth(uint8_t m1, uint8_t m2, float wl) {
  String pumpStatus = digitalRead(PUMP_PIN) == LOW ? "ON" : "OFF";
  String valve1Status = digitalRead(VALVE_PIN1) == LOW ? "ON" : "OFF";
  String valve2Status = digitalRead(VALVE_PIN2) == LOW ? "ON" : "OFF";

  Serial1.print(m1);
  Serial1.print("%");
```

```
  Serial1.print(",");
  Serial1.print(m2);
  Serial1.print("%");
  Serial1.print(",");
  Serial1.print(wl);
  Serial1.print("mL");
  Serial1.print(",");
  Serial1.print(pumpStatus);
  Serial1.print(",");
  Serial1.print(valve1Status);
  Serial1.print(",");
  Serial1.print(valve2Status);
  Serial1.print(";");
}
```

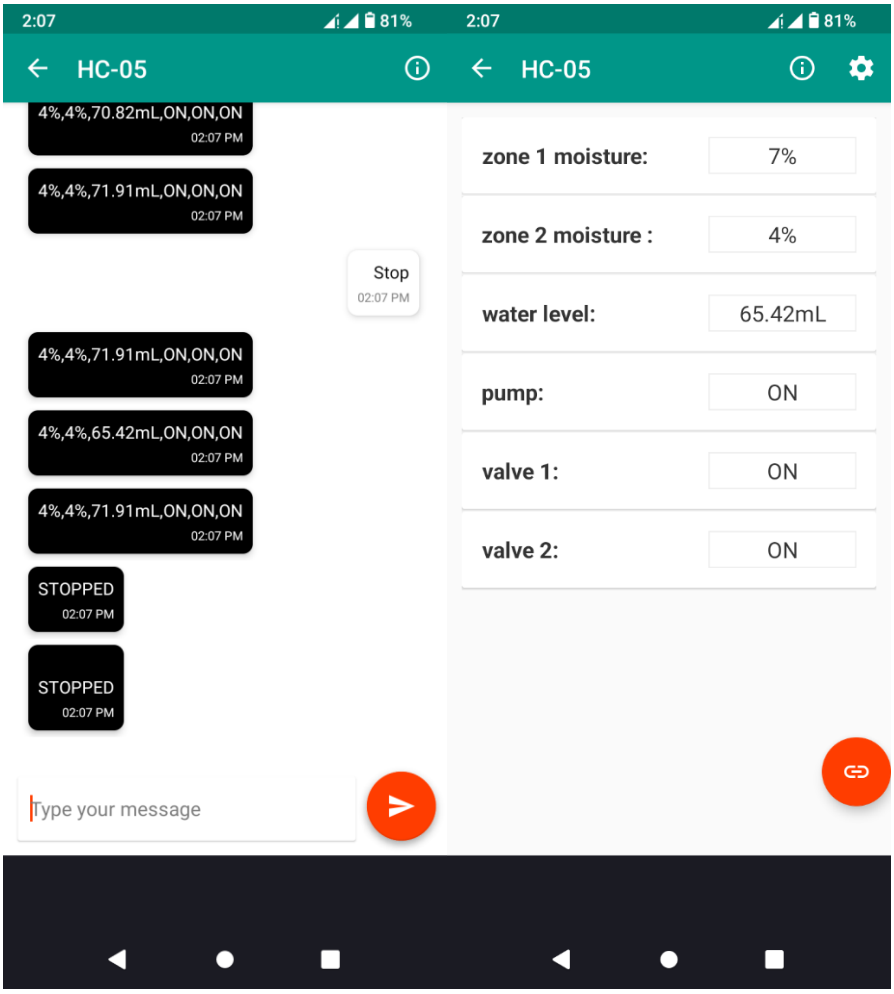


FIGURE IV- 16: ardutooth

```
void setup() {
  Serial.begin(9600);
  Serial1.begin(9600); // HC-05 default baud rate

  pinMode(PUMP_PIN, OUTPUT);
```

```
  pinMode(VALVE_PIN1, OUTPUT);
  pinMode(VALVE_PIN2, OUTPUT);
  digitalWrite(PUMP_PIN, HIGH);
  digitalWrite(VALVE_PIN1, HIGH);
  digitalWrite(VALVE_PIN2, HIGH);
  pinMode(trigPin, OUTPUT);
  pinMode(echoPin, INPUT);

  pinMode(TFT_CS, OUTPUT);
  pinMode(7, OUTPUT);
  digitalWrite(TFT_CS, HIGH);
  digitalWrite(7, HIGH);

  pinMode(button, INPUT);

  tft.begin();
  tft.setRotation(3);
  tft.fillScreen(ILI9341_BLACK);
  tft.setTextColor(ILI9341_WHITE);
  tft.setTextSize(3);
  tft.setCursor(20, 100);
  tft.print("ELECTRO-FARMING");
  delay(2000);
  tft.fillScreen(ILI9341_BLACK);

  drawUILayout();
}

void loop() {
  // ✅ Listen for Bluetooth emergency command
  if (Serial1.available()) {
    String cmd = Serial1.readStringUntil('\n');
    cmd.trim();
    if (cmd == "Stop") {
      emergencyStop = true;
    } else if (cmd == "Restart") {
      emergencyStop = false;
    }
  }

  // ✅ Read moisture sensors
  int raw1 = analogRead(SENSOR_PIN1);
  int raw2 = analogRead(SENSOR_PIN2);

  uint8_t moisture1 = map(raw1, 1023, 0, 0, 100);
  uint8_t moisture2 = map(raw2, 1023, 0, 0, 100);

  bool zone1NeedsWater = false;
```

```
bool zone2NeedsWater = false;

if (moisture1 <= DRY_THRESH1) {
  digitalWrite(VALVE_PIN1, LOW);
  zone1NeedsWater = true;
} else if (moisture1 >= WET_THRESH1) {
  digitalWrite(VALVE_PIN1, HIGH);
}

if (moisture2 <= DRY_THRESH2) {
  digitalWrite(VALVE_PIN2, LOW);
  zone2NeedsWater = true;
} else if (moisture2 >= WET_THRESH2) {
  digitalWrite(VALVE_PIN2, HIGH);
}

if (zone1NeedsWater || zone2NeedsWater) {
  digitalWrite(PUMP_PIN, LOW);
} else {
  digitalWrite(PUMP_PIN, HIGH);
}
```

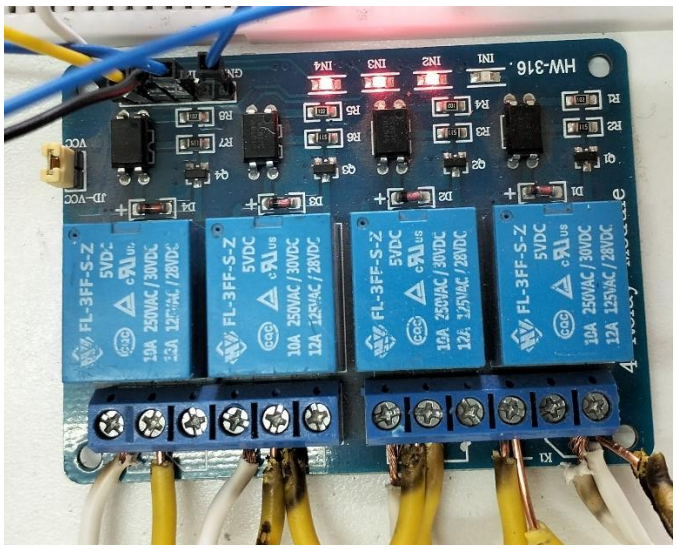


FIGURE IV- 17: relay status

```
Serial.print("Zone 1 Moisture: ");
Serial.print(moisture1);
Serial.println("%");
Serial.print("Zone 2 Moisture: ");
Serial.print(moisture2);
Serial.println("%");

tft.fillRect(240, 30, 60, 20, ILI9341_BLACK);
tft.setCursor(240, 30);
tft.setTextSize(2);
tft.setTextColor(ILI9341_WHITE);
tft.print(moisture1);
```

```
tft.print("%");

tft.fillRect(240, 90, 60, 20, ILI9341_BLACK);
tft.setCursor(240, 90);
tft.setTextSize(2);
tft.setTextColor(ILI9341_WHITE);
tft.print(moisture2);
tft.print("%");

// ✅ Water level sensor
long duration;
float distanceCm;

digitalWrite(trigPin, LOW);
delayMicroseconds(2);
digitalWrite(trigPin, HIGH);
delayMicroseconds(10);
digitalWrite(trigPin, LOW);

duration = pulseIn(echoPin, HIGH);
distanceCm = duration * 0.034 / 2;

Reelheight = distanceCm - e;
waterlevel = 604 - (Reelheight * 0.01 * 0.006361725 * 1000 * 1000);
```

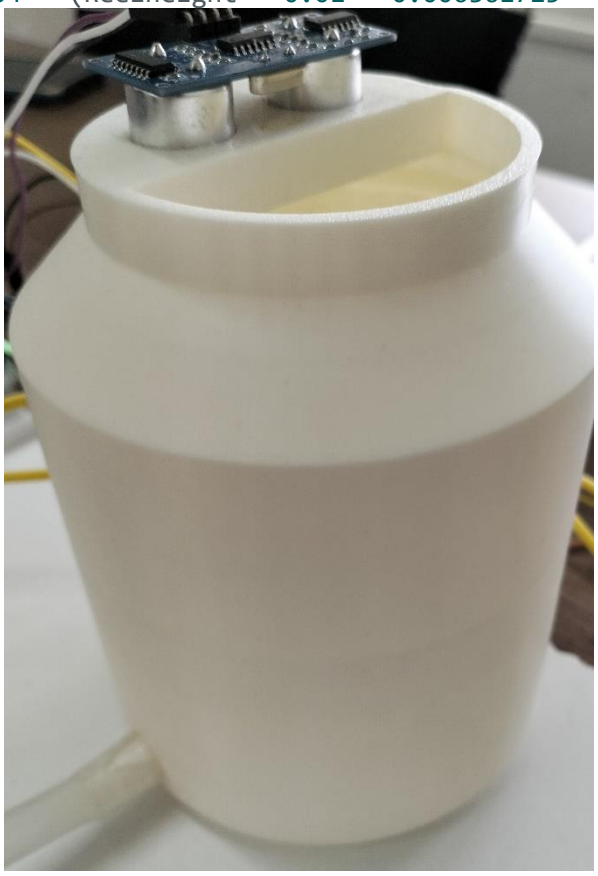


FIGURE IV- 18: measuring water level

```
Serial.println("waterlevel=");
Serial.print(waterlevel);

tft.fillRect(200, 200, 60, 20, ILI9341_BLACK);
tft.setCursor(200, 200);
tft.setTextSize(2);
tft.setTextColor(ILI9341_WHITE);
tft.print(waterlevel);
tft.print("mL");

// ✅ Send data to Bluetooth
sendToArduTooth(moisture1, moisture2, waterlevel);

// ✅ Check for emergency from button or Bluetooth
buttonstate = digitalRead(button);
if (buttonstate == HIGH || emergencyStop) {
  delay(1000);
  while (true) {
    tft.fillScreen(ILI9341_BLACK);
    tft.setCursor(20, 100);
    tft.setTextSize(3);
    tft.print("EMERGENCY STOP");

    digitalWrite(PUMP_PIN, HIGH);
    digitalWrite(VALVE_PIN1, HIGH);
    digitalWrite(VALVE_PIN2, HIGH);

    Serial1.println("STOPPED;");
    delay(2000);

    buttonstate = digitalRead(button);
    if (buttonstate == HIGH) {
      emergencyStop = false;
      delay(1000);
      tft.fillScreen(ILI9341_BLACK);
      drawUILayout();
      break;
    }

    if (Serial1.available()) {
      String cmd = Serial1.readStringUntil('\n');
      cmd.trim();
      if (cmd == "Restart") {
        emergencyStop = false;
        delay(1000);
        tft.fillScreen(ILI9341_BLACK);
        drawUILayout();
        break;
```

```
        }
      }

      delay(100);
    }
  }

  uint16_t color = (zone1NeedsWater || zone2NeedsWater) ? ILI9341_GREEN
: ILI9341_RED;
  tft.fillRect(252, 142, 56, 36, color);

  delay(500);
}
```

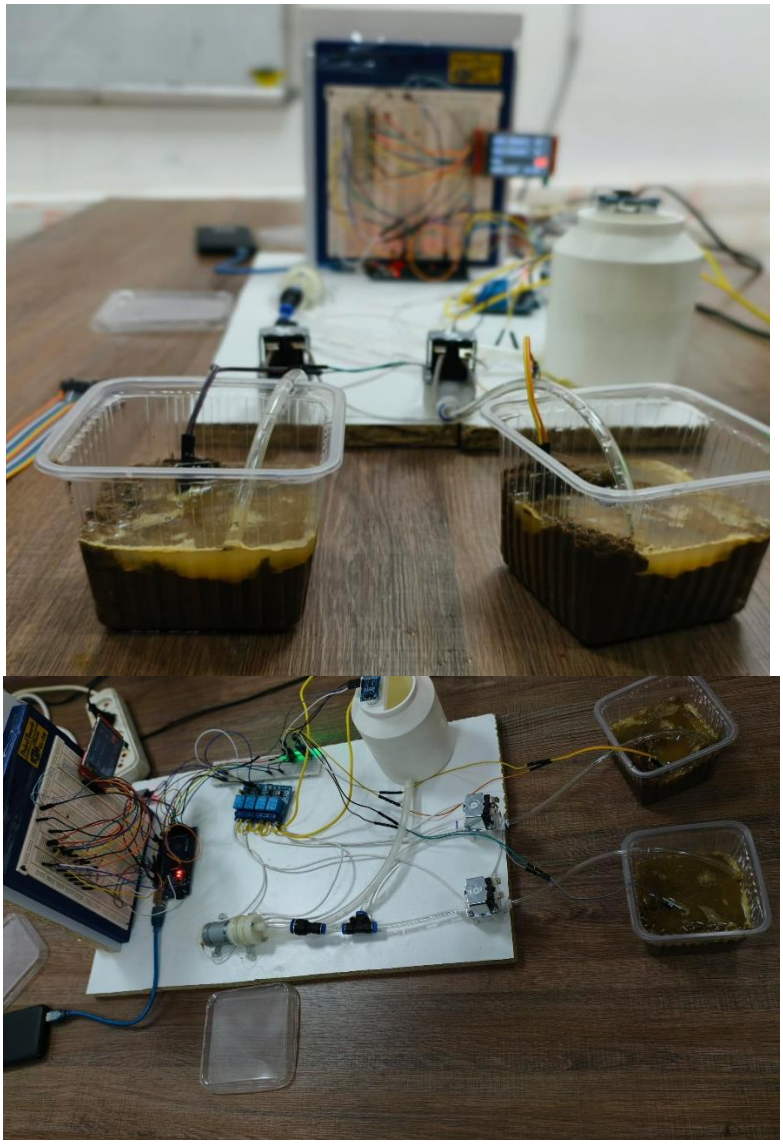
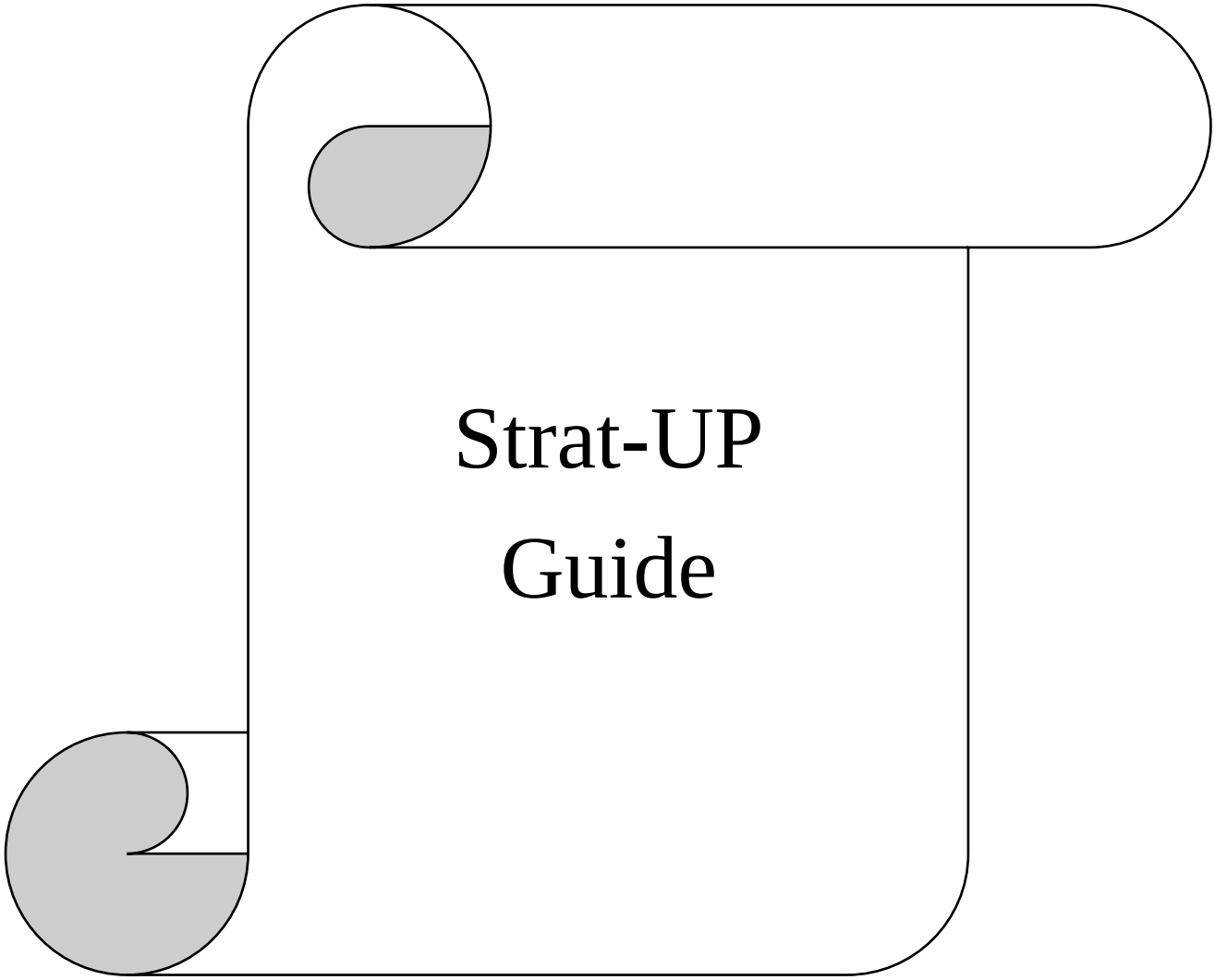


FIGURE IV- 19: FINAL PROTOTYPE

IV.XIV. Conclusion

In this chapter, a functional prototype of a smart irrigation system was successfully developed, demonstrating the feasibility of integrating low-cost electronic components for efficient water management. The combination of the Arduino microcontroller, YL69 soil moisture sensors, diaphragm pump, solenoid valves, and an ultrasonic sensor enabled real-time monitoring and automated irrigation based on soil and water level conditions. The 2.8-inch TFT touch screen served as a user-friendly interface, allowing clear visualization of system status and sensor readings. By assembling the system on a breadboard and controlling high-power devices through a relay module, a flexible and safe experimental setup was achieved. This prototype represents a scalable model that could be expanded for larger agricultural applications, and it lays the foundation for further improvements, such as wireless communication, solar energy integration, and more advanced irrigation algorithms. Overall, this chapter provides a concrete illustration of how embedded systems can support sustainable agriculture through smart, automated irrigation practices


Strat-UP
Guide

I. First axe: project presentation

i. Project Idea: The Proposed Solution

The idea of this an automated drip irrigation system occurred to my mind five years ago when I was checking the new irrigation system in my family farm. The system was really primitive, cannot operate on its own and there is no measurements at the time I started studying engineering and I told myself one day I'll make my own system, one that is modern, a system that can operate on its own, displays data, can be monitored through an app while the farmer is at home. Fast forward to autumn 2024 when I was looking for a graduation thesis and then it hit, a voice in my mind said it is now or never also, I recognized that most of research are on the integration of solar energy so I decided to add some solar panels to make the system available to every possible individual.

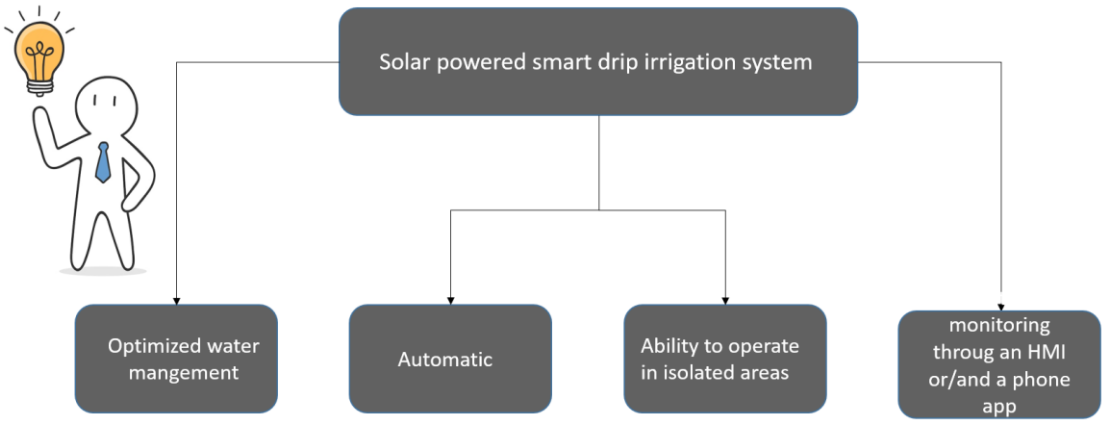


FIGURE V- 1: advantages of the system

ii. Intended value

Our Product's intended value is to modernize and increase agriculture productivity while creating a system that can adapt to every region (south/north), and simplify the process of irrigation and increase water management efficiency while remove the dependence on transmission lines all while integrating affordable modern technologies.

iii. Goals

We intend to cover the largest percentage of the market in the coming years and introduce Algeria to the world of smart agriculture, while helping farmers increase their yields and optimize resource usage through innovative, technology-driven solutions.

iv. Project Implementation Schedule

TABLE V- 1: Project Implementation Schedule

Task / Month-Week	1	2	3	4	5	6	7
Preliminary studies; selection of production unit location; preparation of required document	✓						
Solar installation training	✓	✓					
Pumping and irrigation systems training		✓	✓				
Installation of equipment training		✓	✓				
Finding our first customer			✓	✓			
Request for equipment from local suppliers and from aboard					✓	✓	✓
First installation							✓

II. Second axe: Innovative aspects

i. Nature of Innovation

Our product would fall squarely into the "Technological Innovations" quadrant. All of its core components (solar-driven pumps, precision drip delivery and touchscreen HMI control) are mature, proven technologies, yet the market has not yet validated them together as a turnkey offering. This positioning underscores both the promise and the challenge: the company can capitalize on reliable hardware and software to deliver a distinctive solution, but must also invest in education, pilot projects and strategic partnerships to build awareness, establish credibility and drive early adoption in an otherwise untapped Algerian market.

ii. Innovation aspects

Our system offers several innovation aspects among them integrating smart technologies and renewable energy to become the top company in this domain in Algeria.

III. Third axe: Strategic Market Analysis

i. Market Segment Overview

The system is directly addressed to farmers however, it might be reduced and used in home gardens application and in greenhouses. And since It contain new technologies we might end up modernizing old systems and offer a maintenance service for small scale solar systems.

ii. Measuring the intensity of competition

The competitive landscape for our fully integrated solar-powered drip-irrigation system with HMI in Algeria will be fragmented and evolving. Local distributors and regional resellers already offer individual PV pump units, drip-irrigation controllers or basic touchscreen interfaces, but few bundle all three into a seamless turnkey solution—creating pockets of direct competition around each component. International OEMs compete on price and scale, often undercutting smaller players with thin margins, while regional integrators lean heavily on established dealer networks and service agreements to lock in customers. Feature-set overlap is growing as IoT-enabled scheduling and remote monitoring become table stakes, but true end-to-end packages remain rare. High import duties on PV modules and the training costs associated with advanced HMI tools raise barriers to entry and switching, giving early movers who can demonstrate reliability and ROI a lasting advantage. To succeed, our company must differentiate through robust pilot programs, localized support, and pricing structures that reflect both the premium nature of our all-in-one system and the realities of Algerian farm budgets.

iii. Marketing strategy

Our marketing strategy will hinge on demonstrating real-world value and building trust through targeted pilots, partnerships, and tailored outreach. We will install subsidized demo systems on a range of Algerian farms—smallholders, cooperatives, and commercial operations—inviting prospects to open-farm days and virtual tours that showcase water- and energy-savings alongside peer testimonials. Strategic alliances with the Ministry of Agriculture's extension services and leading ag-equipment dealers will broaden our referral network, while certified installers in key provinces will deliver on-the-ground expertise. Messaging will emphasize our turnkey solution's "energy-free pumping," "automated scheduling," and "touchscreen ease" via Arabic- and French-language ROI calculators, case-study brochures, and HMI demo videos. To lower financial barriers, we'll offer leasing-plus-service packages and partner with local banks and microcredit schemes, highlighting renewable-energy grants where available. Digital ads on Facebook and WhatsApp will target agronomist groups and cooperatives, and we will maintain visibility at ag-tech fairs and webinars in collaboration with universities. Finally, a robust two-year maintenance plan, rapid-response hotline, and an early-adopter ambassador program will ensure ongoing support, referral momentum, and sustained market confidence in our integrated solar-powered drip-irrigation system.

IV. Fourth axe: production plan

i. Production process

Since our product relies on the assembly of multiple components each have its own function, the first thing to do is to visit the land that the final product will be implemented in then study the environment (hill or flatland, highest irradiance possible, type of soil…..). Secondly, comes the components selecting stage (selecting the right pump, solar array dimensioning…). Lastly, the transport and implementation stage where our team implement and monitor the system for a period of three days to ensure there is no disorder.

ii. 5W Framework Analysis

The 5W questions (Who, What, When, Where, Why) are a fundamental framework for information gathering and analysis. They serve as a systematic approach to identify the essential elements of any event, situation, or story, ensuring a comprehensive understanding by prompting inquiry into the key actors, the core details, the timing, the location, and the underlying reasons. They are a cornerstone of effective communication and critical thinking. For our smart drip irrigation project the questions that need to be answered are:

TABLE V- 2: 5W Framework Analysis

QUESTION	ANSWER
WHO	FARMERS
WHAT	SMART DRIP IRRIGATION SYSTEM POWERED BY PV PANELS
HOW	BY SUPPLYING CROPS WITH WATER WHEN THEY NEED IT
WHERE	BOTH SOUTH AND NORTH OF ALGERIA
WHY	TO HAVE AN EFFICIENT WATER MANAGEMENT WHILE INCREASINGμ THE YIEDS

iii. Procurement

The company relies mainly on local suppliers such as zergoun green energy to obtain solar panels, and POVAL Company located that offer both submersible and surface mounted pumps. Also, when it comes to driplines and drippers the Algerian market offer a variety of solutions. And for the sensors and the control unit and the HMI we will rely on importing.

iv. Manpower

Our project open the opportunity for about 18 jobs for the beginning (Table), we expect to double that number when the company grows to cover multiple sites at once.

TABLE V- 3: Manpower

Position	Estimated Number	Salary per Month (DA)
Agricultural Engineer	1	80,000
Irrigation System Technicians/Installers	1	50,000
Electrical or Solar Power Technician	1	50,000
Accountant or Financial Officer	1	50,000
Procurement/Supply Officer	1	50,000
Marketing or Field Sales Officer	1	50,000
Driver	1	45,000
Field Workers (Pipe/Filter Installation)	5	5×40,000

v. Main partnership

The most important partnerships in our project are with suppliers, due to their key role in the success of the project, such as Zergoun green energy that produce solar panels and Poval company that produce different types of pumps.

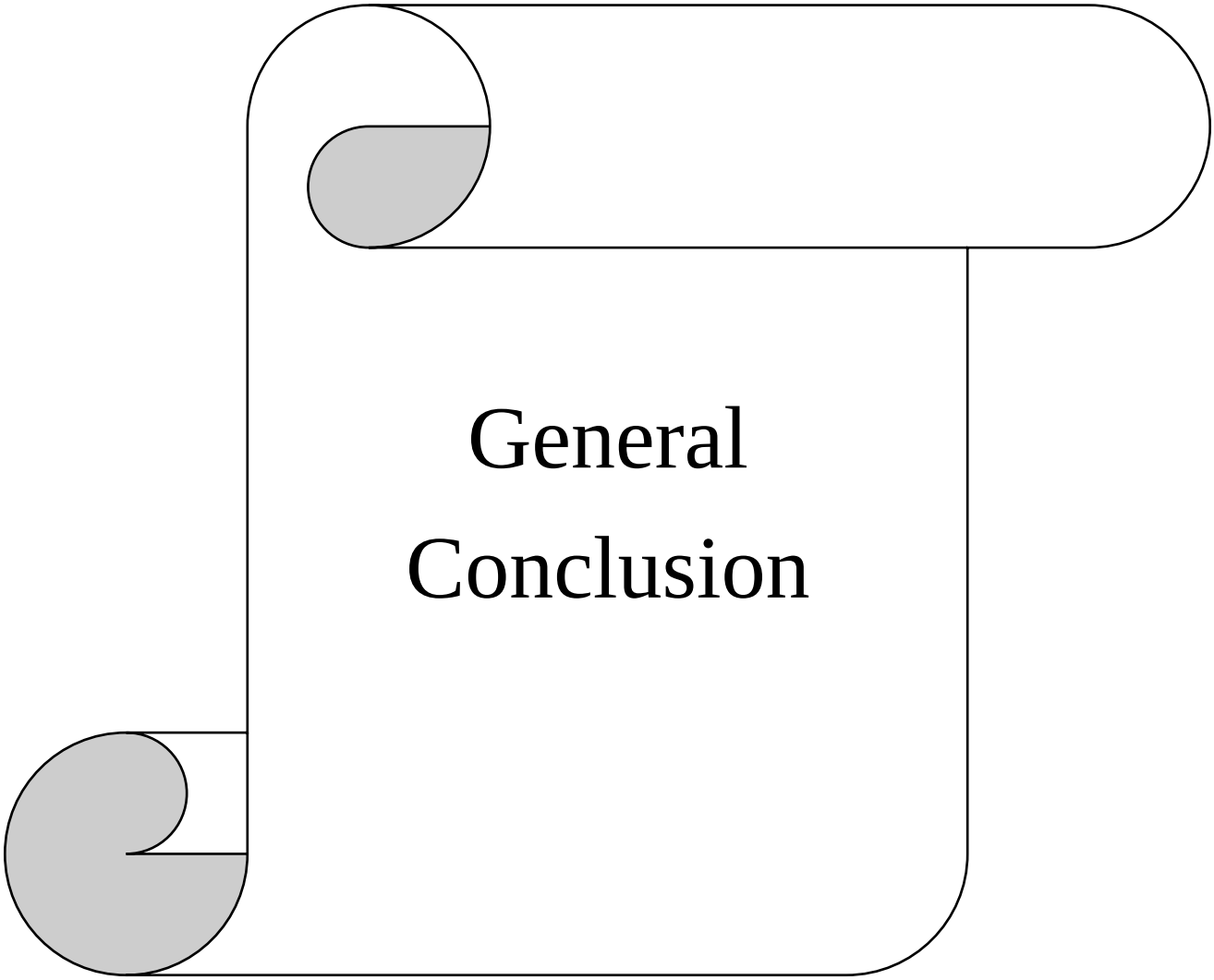
V. Fifth axe: Financial Plan

i. Costs, Revenues and incomes

The initial investment required for the project includes multiple aspects, all discussed in the following table:

TABLE V- 4: Costs, Revenues and incomes

Cost Categories	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12
Direct Materials Costs (Variable) (DA)	850,000 X 2	850,000 X 2	850,000 X 4	850,000 X 4	850,000 X 4	850,000 X 4	850,000 X 4	850,000 X 4	850,000 X 2	850,000 X 2	850,000 X 2	850,000 X 2
Labor Costs (DA)	575,000	575,000	575,000	575,000	575,000	575,000	575,000	575,000	575,000	575,000	575,000	575,000
General Expenses (Fixed Costs) (DA)	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000
Depreciation Costs (DA)	7500	7500	15,000	15,000	15,000	15,000	15,000	15,000	7500	7500	7500	7500
Revenues (DA)	170,000,0	170,000,0	340,000,0	340,000,0	340,000,0	340,000,0	340,000,0	340,000,0	170,000,0	170,000,0	170,000,0	170,000,0
Net Income Without Taxes (DA)	109,250,0	109,250,0	278,500,0	278,500,0	278,500,0	278,500,0	278,500,0	278,500,0	109,250,0	109,250,0	109,250,0	109,250,0


General
Conclusion

General conclusion

This thesis has explored the complex and critical intersection between food security, water resource management, and sustainable agricultural practices, with a particular emphasis on the use of modern irrigation systems powered by renewable energy sources.

In the first chapter, we addressed the global and local challenges to food security, emphasizing the role of agriculture and water availability, particularly in regions affected by climate change. Traditional irrigation methods were shown to be wasteful and unsustainable in the face of water scarcity, leading to the introduction of drip irrigation as an efficient and targeted solution.

The second chapter provided a detailed technical breakdown of the components of a drip irrigation system, including pumps, valves, filtration units, and drippers, as well as key concepts like friction losses and Bernoulli's equation. The integration of sensor-based smart irrigation systems highlights how precision and automation can enhance water efficiency and crop yield.

In the third chapter, the focus shifted to renewable energy, particularly photovoltaic (PV) technology, as a sustainable power source for irrigation systems. We explored PV cell behavior, power optimization through maximum power point tracking (MPPT) techniques—such as perturb and observe (P&O) and its adaptive version—and the use of DC-DC converters like buck, boost, and buck-boost topologies. Energy storage and inverters were also examined to ensure system reliability and off-grid functionality.

The final chapter outlined the practical implementation using Arduino-based control, integrating various sensors (e.g., moisture, ultrasonic) and actuators (e.g., solenoid valves, pumps), while showcasing a real prototype featuring a TFT touchscreen interface. Furthermore, a comprehensive entrepreneurial and strategic plan was presented, considering innovation, market analysis, production strategy, and financial planning—highlighting the project's potential scalability and socio-economic value.

In conclusion, this work demonstrates a viable, innovative solution for sustainable irrigation that addresses both environmental constraints and food production needs. By combining modern engineering, renewable energy, and smart control technologies, the proposed system offers a promising path toward self-sufficient agriculture, particularly in regions facing water stress and energy shortages.

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Appendix

BMC

Key Partners:

- Irrigation equipment suppliers (pipes, filters,emitters)
- Local pump and tank distributors
- PV panels suppliers
- electronic Equipements suppliers
- Agricultural cooperatives and extension services
- Government programs promoting efficient irrigation

Key activities:

- Designing customized drip systems for farms
- designing solar installations
- Installing irrigation hardware on-site
- Providing maintenance and support pending the garantie period
- Educating farmers on usage and upkeep
- Managing inventory and logistics

key resources:

- Skilled installation and engineering staff
- Inventory of irrigation components
- Company vehicles and field tools
- Local demonstration sites
- Office and coordination team

value propositions:

- Significant water savings (30–70%)
- Increased crop yield and quality
- Lower labor and fertilizer costs
- Reliable and easy-to-use systems
- Full-service: design, installation, maintenance
- Tailored solutions for Algerian climate and crops
- reliable solar installation

customer relationships:

- Direct, personalized consultancy on each project
- Maintenance contracts for continuous service
- Training for farmers and staff
- Support hotline for emergencies

Channels:

- Direct sales via field agents and engineers
- Farmer cooperatives and association
- Agricultural fairs and local expos
- Government extension and subsidy programs
- Word-of-mouth and demo plot referrals
- Local agro-input dealers as referral points

customer segments:

- Smallholder farmers seeking efficient, affordable systems
- Commercial farms requiring high-performance irrigation
- Farmers in arid regions facing water scarcity
- Greenhouses and orchard managers
- Government-backed agricultural initiatives

cost structure:

- Equipment and material costs (drippers, pipes, valves, electronics, PV panels)
- Labor (installation, maintenance, engineers)
- Transport and fuel
- Training and demo setup costs
- Office overhead and admin costs
- Marketing and outreach expenses

revenue Streams:

- One-time project fees for design + installation
- Maintenance service contracts (annual or seasonal)
- Paid training and consulting services
- Financing margins (if using installment plans)
- Optional system upgrades or automation tools