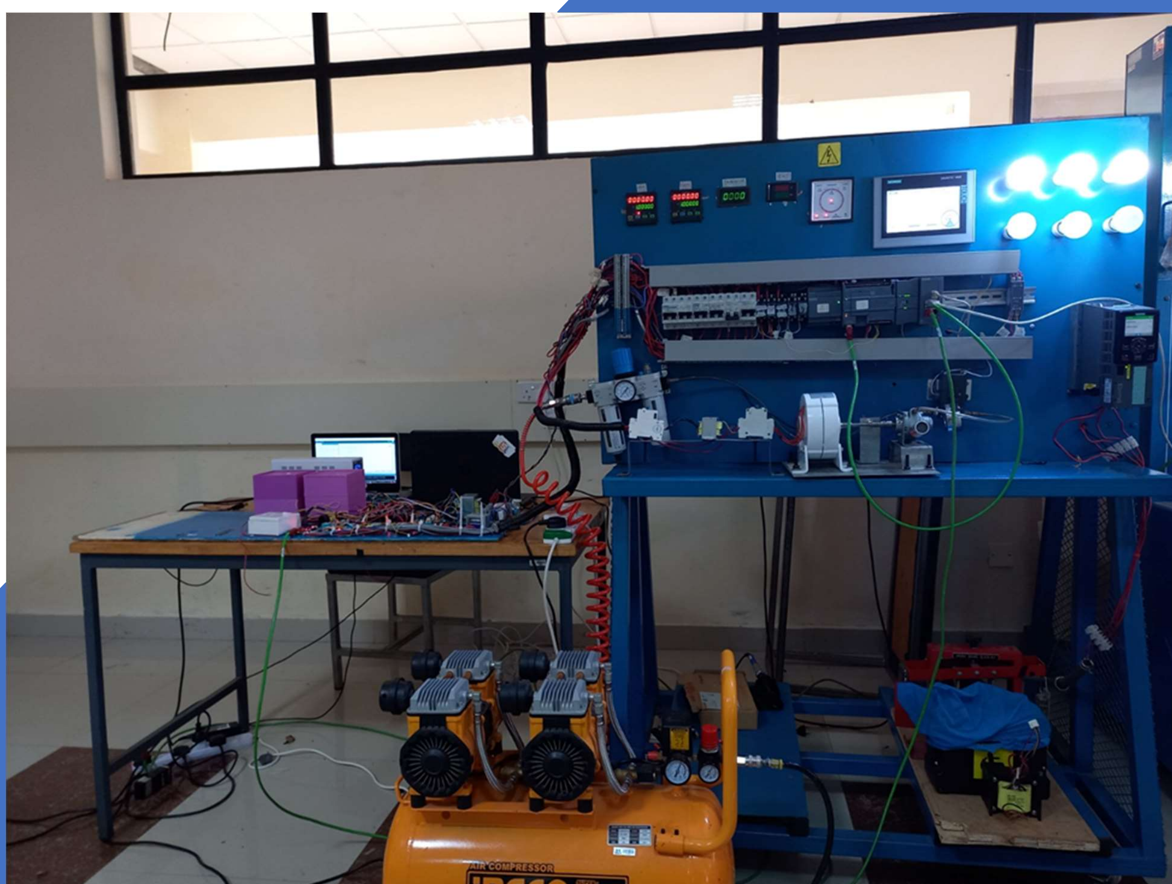
Enhanced grid synchronization of mains supply, solar power and CAES with real time monitoring using a custom SCADA system



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ENHANCED GRID SYNCHRONIZATION OF MAINS SUPPLY, SOLAR POWER AND CAES WITH REAL TIME MONITORING USING A CUSTOM SCADA SYSTEM

DECLARATION

We hereby declare that this project is our original work, to the best of our knowledge, and has not been presented for a degree or any other purpose in other institution of higher learning

CERTIFICATION

As the supervisor, this is to confirm that the students under my supervision prepared the work presented in this project report. I hereby confirm handing of the final report.

ACKNOWLEDGEMENT

We would like to appreciate the people who assisted in the success of this project, this includes: The Siemens center staff that supported us in the project, including guys like, Mr. Vincent Mworia, Mr. Aggrey and Mr. Peter Rono. We would also like to thank the mechatronics lab technicians including Mr. Nyaga, Mr. Kibe, and Madam Consolata. Special thanks to the Siemens Center director, Prof. Jean B. Bosco, the project coordinator Mr. Kamande and the Mechatronics Department chairman, Dr. Titus Mulembo for providing us with the resources required to actualize the project. We also recognize our guardians for their continued support throughout this period. We also thank the project supervisor, Dr. Morris Mwangi for his guidance throughout the project, we also extend this gratitude to our previous supervisor Mr. Alfred Mwachuga. To all the unsung heroes who made this possible we thank you.

Finally, we thank the Almighty God for His grace during the entire project period, that made the project successful.

ABSTRACT

This project presents the successful design, implementation, and integration of a Smart Grid system that harmonizes power from the mains, solar panels, and a custom Compressed Air Energy Storage (CAES) system. The primary objective of this project was to create a sustainable and efficient energy ecosystem capable of seamlessly managing various sources of electricity while ensuring reliable power supply. The integration of renewable energy sources addresses the growing need for sustainable power solutions, and the inclusion of a CAES system contributes to grid stability and energy storage efficiency.

The main elements of the Smart Grid include a mains power interface, solar panel array, and a CAES system, all interconnected through intelligent control algorithms. The CAES system effectively stores surplus energy during periods of low demand and releases it during peak demand, thus enhancing grid stability and addressing intermittency issues associated with renewable sources.

To facilitate efficient monitoring and control, a custom Supervisory Control and Data Acquisition (SCADA) system was developed. This SCADA system allows real-time monitoring of the grid's performance, providing valuable insights into power generation, consumption, and storage. Furthermore, the SCADA system is accessible remotely from any location, enhancing the system's flexibility and ease of management.

The successful integration of these components not only demonstrates the feasibility of a Smart Grid system but also showcases the potential for sustainable and resilient energy infrastructure. The outcomes of this project contribute to the ongoing efforts to create innovative solutions for future energy challenges, aligning with the global push towards clean and renewable energy sources. This project serves as a testament to the capabilities of collaborative engineering efforts in developing practical solutions for a more sustainable energy future.

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CHAPTER 1: INTRODUCTION

STATEMENT OF THE PROBLEM

With increased advocation of clean energy, renewable energy has seen their proliferation in use. However renewable energy sources cannot be utilized in their raw format therefore an exigency of a management system is necessary otherwise the threat of grid imbalance is imminent. Furthermore, due to the fluctuating nature of renewable sources there is a need to find an efficient energy storage means. These were the main factors that led to the birth of our project.

AIMS AND OBJECTIVES

This project aims to connect power from the mains supply, solar power and CAES (Compressed Air Energy Storage system) and then monitor the state of the entire grid from a custom SCADA (Supervisory Control and Data Acquisition) system; with an HMI (Human Machine Interface) on-site or remotely via a web application.

BACKGROUND INFORMATION

But to understand how we achieved this lets first take a brief look at the individual grids, the loads and how they came together.

LOADS

Our loads consist of six bulbs; three of which are high power i.e. 100W incandescent light bulbs and three 15W power saving LED light bulbs. We also have a 0.5hp three phase induction motor as one of our loads which will be driven by a motor driver that takes in a single-phase input. These loads were strategically chosen in-order to mimic or at the very least represent a small factory which the system is intended to provide uninterrupted power to.

From the nature of the loads we can see that our main task is to be able to provide single phase AC power to the loads. An in-depth look into the nature of the loads will be done later in the report.

MAINS

By the term mains I am referring to the power that we get directly from the wall outlet which is tapped from the National grid i.e. provided by Kenya Power and Lighting Company (KPLC). From various secondary sources and our own experiments, we found out that this power is at an AC voltage of around 230 Vrms and at a frequency of about 50Hz.

In line with our plan, this is our main source of power in the grid and since its format is similar to the load requirement we decided to use this format as the standard in our grid.

SOLAR

We were provided with a solar panel that could produce 18VDC when exposed to sunlight. Thus, we had to find a way of converting this to 230Vac at 50 Hz. To this we decided to create a Hybrid inverter that could convert 12VDC input to a 230 VAC output. The 12 volts is gotten from an MPPT (Maximum Power Point Charge) controller that takes the 18 volts from the solar panel and charges a 12v battery, which is the input of the inverter.

To be able to synchronize this AC output with the mains we decided to go for a SPLL method. This method will be explained in depth later in the report.

CAES

This refers to the Compressed Air Energy Storage system. This is the sub-grid that we will use to store excess power that is available in the grid. CAES systems mainly work in two modes i.e. when the energy is being stored and when energy stored is retrieved. For our project we realized a CAES system by using the combination of an air compressor, an air motor, an AC generator and a transformer. As mentioned earlier the CAES system functions in two modes, in our realization of the system, the modes were determined by the load condition. When the demand was low it meant we were in storing mode, this was realized by turning the compressor on via a relay. When the demand is high such that the demand is more than what is produced the deficit is provided by the CAES, this condition is realized by turning on a pressure valve thereby providing compressed air to the input of the air motor; this air motor is mechanically coupled to an AC generator thus producing electricity.

SYSTEM BLOCK DIAGRAM

With this brief look into the various aspects of the project we came up with the system block diagram below, as a guide on how to actualize the system:

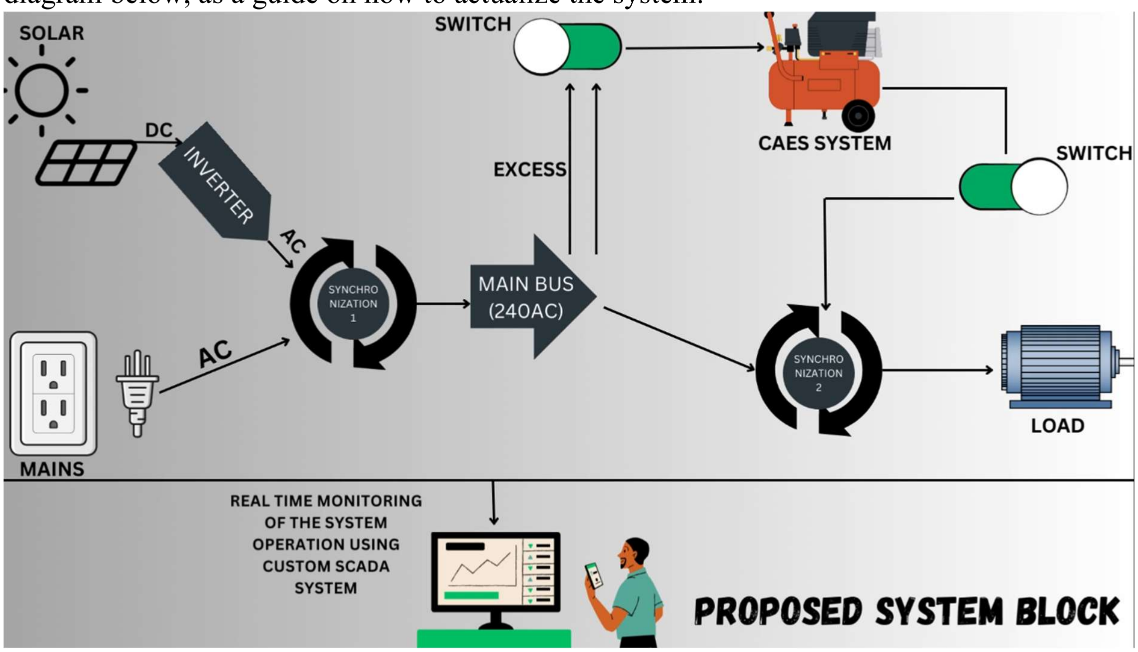

Figure 1 Proposed system block

From the diagram above and as discussed earlier we see there is a need to produce single phase 230 VAC/ 50 Hz power, since it is power in this form that is compatible/ usable by the loads; this thus dictates our first course of action is to invert DC power produced by the solar sub-grid to AC.

Now that the solar sub-grid is producing AC power there is a great probability that this power is not synchronizable to the mains due to differences in electrical parameters i.e. RMS voltage, voltage frequency and phase angle. This thus dictated our next task to be to make the solar electrical parameters equivalent to that of the mains so that the two can be synchronized to a single main bus. To do this we use the PLL (Phase-Locked Loop) technique, this will be discussed in depth later in the report.

This main bus is used to provide power to the loads and to the CAES system via a switch. The switch (input switch) is activated or deactivated depending on the current demands of the loads. If the load demand is low the input switch will be closed thus charging the CAES with the excess in the grid, in this condition the output switch is open. If the power produced is just sufficient to power the loads both the input and output switches will be open, in this condition no charging or discharging takes place, only power is stored. Lastly is the case where power demand is high, such that the main bus cannot sufficiently satisfy the loads. In this case the output switch is closed and the input switch is open i.e. we are discharging the CAES. Here we convert the power stored in form of compressed air to AC power and synchronize it to the main bus to provide the deficit.

The resultant grid will be monitored in real-time by our custom SCADA system. This will enable us to control and automate grid, check for grid stability and reliability, detect faults within the grid, perform energy management and optimization as well as perform data analysis.

SIGNIFICANCE

The main goal of this project is to be able to offer uninterrupted power to the final consumer through a consumer-oriented approach. It also greatly reduces the power that a customer consumes from the national grid system thus reducing the electric bill of the everyday mwananchi. This solution could also be ideal for use in power-critical uses such as in Hospital ICUs or in very crucial industries due to the perk of uninterrupted power. The incorporated SCADA system allows the customer to be able to monitor the grid to check for faults and even record his/her power usage.

LIMITATIONS

Even though the possibilities of this project are endless there were limitations when it came to the actual implementation of the project. The limitations that will be discussed in this section are those relating to the entire project however those relating to the subsystems within the whole will be discussed in later sections. One of the major hurdles in the project arises from the base premise on which the project was conceived, that is taking the power from the wall outlet as the main power source within the grid. This means that the grid can only function for a short duration, without power from the wall outlet, before shutting down. This is attributes to the finite nature of the batteries within the grid i.e. the lead-acid battery used in the solar sub-grid and the CAES receiver tank. This effect will be mostly at night due to the absence of the sun at this time, a possible solution would be to add a wind sub-grid to the system.

CHAPTER 2: BODY

This is the section of the report where all the details of the project will be discussed. For easier understanding the body is formatted such that the individual sub-grids are first discussed on their own then we will show how they were brought together then we will have an exposé on the SCADA system used to monitor the entire grid. Within each sub-category we will discuss the design process, that is, from the literature review, to the apparatus used, the methodologies and instrumentation employed and the final product.

We will begin our discussion by looking at the mains sub-grid, then the solar followed by the CAES, we then look at how these grids were incorporated together employing electrical, communication and mechanical principles.

MAINS POWER SUB-GRID SYSTEM

This is used to refer to the power we get from the wall outlet. In Kenya this is characterized by Alternating Current, AC power with an RMS (root mean square) voltage of around 230 volts, oscillating at a frequency of 50 Hz. As mentioned earlier this electric power source will be the primary source of power in our grid and as its format is compatible with the loads all other grids will need to conform to this format. Below is a diagram showing the sample diagram showing the sample waveform of the power we get from the mains:

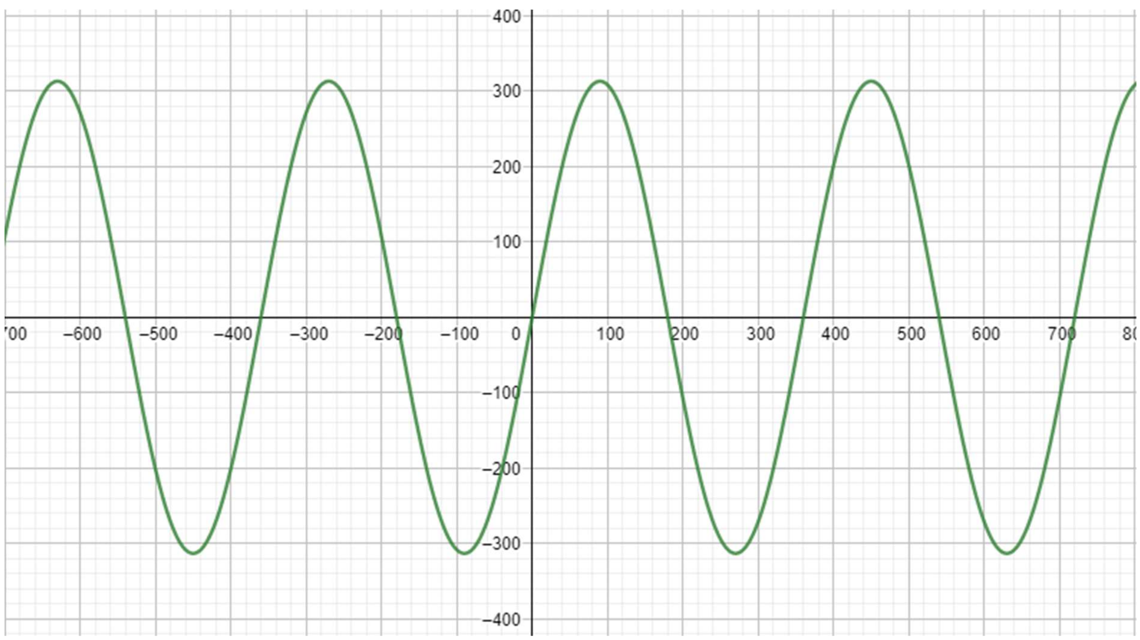

Figure 2 230Vac power

SOLAR POWER SUB-GRID SYSTEM

INTRODUCTION

Sun is a natural resource that exist across the globe. Sun can be utilized to provide energy through the use of power electronics knowledge. To utilize such enormous resource, solar panels are used to harvest the energy from the sun for commercial and domestic use. Solar panels harvest direct current (DC) at different power wattages from the sun then tapped for remote use. Direct current from the solar panels can be converted to alternating current (AC) form and stepped-up using devices such as transformers for multi-purpose use.

DISCUSSION

For this project, the solar panel used output around 18v, 40W power output. These parameters were determined from an experimental set-up that was done to determine the range of solar voltage for 24 hrs. Here is the link to download and read up on the report of the study:
https://github.com/jeremiahKiarie/finalyearGridProject/blob/main/Other%20Docs/Documentation%20of%20the%20Solar%20Panel%20data.pdf .

To make this power compatible with that of the mains two things have to be achieved, the DC power has to be inverted to AC and the produced AC power has to be synchronizable with that of the mains.

INVERTING DC to AC

Inverters, the unassuming heroes of modern electrical systems, have revolutionized the way we harness and distribute power. These electronic devices play a pivotal role in converting direct current (DC) into alternating current (AC), enabling the seamless integration of renewable energy sources, such as solar panels and wind turbines, into power grids.

The rise of inverters can be attributed to several key factors that collectively propelled their prominence in the field of electrical engineering. Firstly, the surge in renewable energy adoption has been a driving force. As solar and wind technologies gained momentum as sustainable alternatives to traditional fossil fuels, inverters became essential components in transforming the intermittent DC output from solar panels and wind turbines into the standardized AC power used in homes and industries.

Moreover, the growing demand for energy efficiency and the increasing prevalence of electronic devices necessitated a more sophisticated approach to power conversion. Inverters provide a versatile solution by not only facilitating the integration of renewables but also by improving the overall efficiency of energy systems. The ability to control and optimize the voltage, frequency, and waveform of AC output has made inverters indispensable in enhancing the reliability and performance of electrical grids.

The advent of advanced semiconductor technologies has further propelled the evolution of inverters. With the miniaturization of electronic components and the development of more efficient power conversion mechanisms, inverters have become smaller, lighter, and more cost-effective. This has led to their widespread deployment in various applications, ranging from residential solar installations to industrial-scale power plants.

There are three (3) major types of inverters.

- Sine Wave (sometimes referred to as ‘true’ or ‘pure’ sine wave).
- Modified Sine Wave (modified square wave).

- Square Wave

1. **Sine Wave Inverter**

A **sine wave** Inverter gives waveform that you get from Hydroelectric power or from a generator. The major advantage of a sine wave inverter is that all of the equipment which is sold on the market is designed for a sine wave. This guarantees that the equipment will work to its full specifications. Some appliances like bread makers, light dimmers, and some battery chargers require a sine wave to work. Pure sine wave inverters are more complex and cost more.

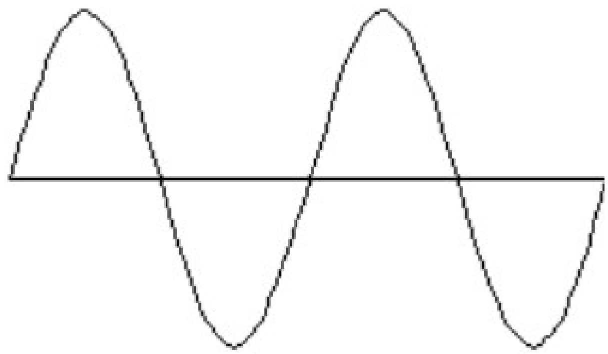

Figure 3 A pure sine wave

2. Modified Sine Wave Inverter

A **modified sine wave inverter** actually has a waveform more like a square wave, but with an extra step or so. A lot of equipment will work well on modified sine wave inverters, including motors, household appliances and other items. Some types of loads can be problematic and do require a pure sine wave converter.

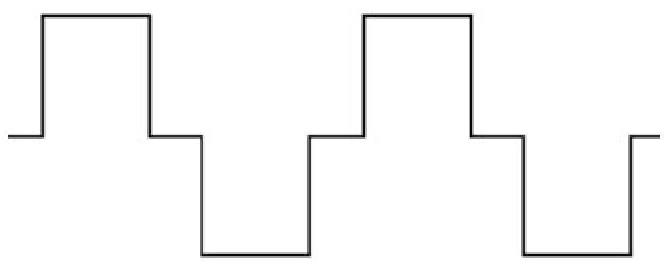

Figure 4 A modified sine wave

3. Square Wave Inverter

A **square wave inverter** is very simple, with the DC supply switched between positive and negative. They are very few, and are the cheapest inverters. A square wave inverter will run simple things like tools with universal motors without a problem, but not much else.

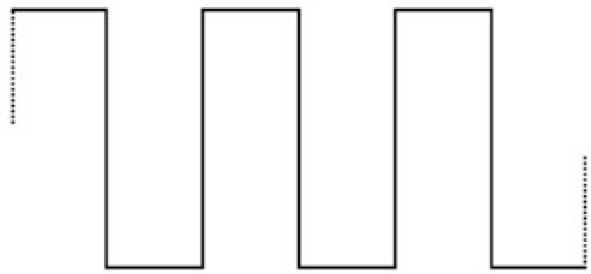

Figure 5 A square wave

For our case since we wanted the solution to be applicable in any setting we went for the Pure sine wave inverter. To be able to design a function pure sine wave inverter we used the following procedure as a guide to the design process.

Steps for DC to AC Conversion
Different components are required to convert direct current to alternating current in an inverter. The block diagram below shows the steps required to convert direct current to alternating current.

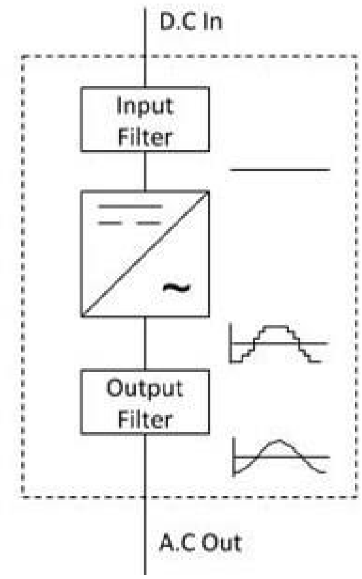

Figure 6 DC to AC conversion

a. **Input Filter** – the input filter removes any ripple or frequency disturbances on the DC supply, to provide a clean voltage to the inverter circuit.
b. **Inverter** – this is the main power circuit. It is here that the DC is converted into a multilevel PWM waveform.
c. **Output Filter** – the output filter removes the high-frequency components of the PWM wave, to produce a nearly sinusoidal output.
Inverters are complex devices, but they are able to convert DC-to-AC for general power supply use. Inverters allow us to tap into the simplicity of DC systems and utilize equipment designed to work in a conventional AC environment.

Let's go a layer deeper and have a closer look at the inverter design. We know that the main task is to convert DC to AC therefore what we require is switching of some kind, to be able to achieve this we went for a combination of the use of an SPWM signal and a H-bridge circuit. To delve into the creation of a pure sine wave inverter using SPWM (Sinusoidal Pulse Width Modulation) signals and an H-bridge circuit, it's crucial to understand the fundamental components involved.

SPWM signal

Sinusoidal Pulse Width Modulation is a technique employed in power electronics to approximate a sine wave using a series of discrete pulses. In SPWM, the width of each pulse is modulated in such a way that it mimics the amplitude variations of a sine wave. This modulation creates a series of pulses that, when filtered, result in an output waveform closely resembling a pure sine wave. SPWM is particularly advantageous in applications where a clean and distortion-free AC output is essential, as is the case in inverters designed for sensitive electronic devices. In our implementation of the inverter we generated the SPWM using a program running in a microcontroller, specifically the Atmega328p(Arduino Uno). Here is a link to the source code used for this task https://github.com/jeremiahKiarie/finalyearGridProject/blob/main/Other%20Docs/baseInverterProgram/baseInverterProgram.ino .

H-Bridge circuit

An H-bridge is a configuration of electronic switches arranged in the shape of the letter 'H.' This arrangement allows bidirectional control of the current flow through a load, such as a motor or, in the case of an inverter, the primary winding of a transformer. Each leg of the H-bridge contains a switch, typically a set of transistors, MOSFETs or insulated gate bipolar transistors (IGBTs). The upper switches (S1 and S4) and lower switches (S2 and S3) can be independently controlled to regulate the direction and magnitude of the current flow.

Creating a Pure Sine Wave Inverter

To construct a pure sine wave inverter, SPWM signals are generated to control the switching of the H-bridge circuit. The SPWM signals determine the duty cycle of each switch in the H-bridge, effectively controlling the time each switch is in the ON state during a given period. By precisely modulating the pulse width in accordance with the desired sine wave, the H-bridge circuit generates an AC output with a waveform that closely mimics a pure sine wave.

The SPWM generator ensures that the switching transitions occur at points where the instantaneous value of the PWM signal matches the instantaneous value of the sine wave, reducing harmonic distortions and producing a smoother output. The H-bridge circuit, with its bidirectional control, enables the creation of both the positive and negative halves of the sine wave, resulting in a clean and continuous AC output.

In summary, the synergy between an SPWM signal generator and an H-bridge circuit forms the backbone of a pure sine wave inverter, allowing for precise control of the switching pattern to produce an AC output that meets the stringent requirements of various electronic devices.

For our case we employed the circuit diagram below, to actualize the switches in an ideal H-bridge we employed 3 IRFZ44 MOSFETS arranged in parallel per switch.

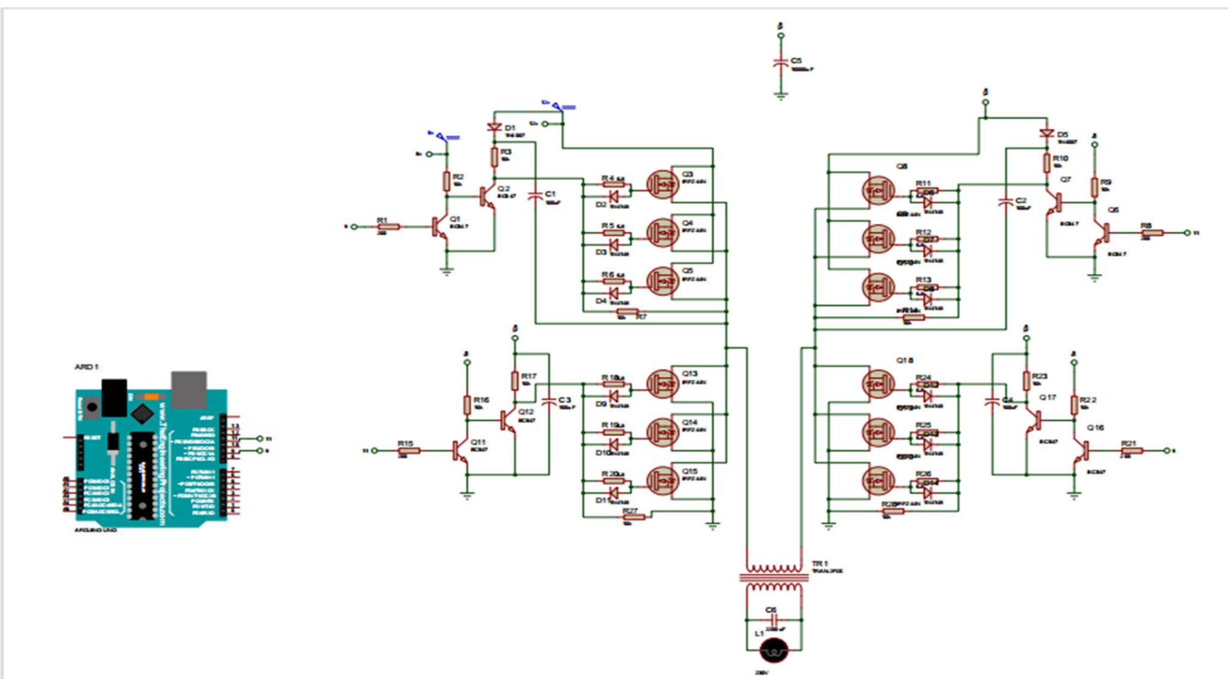

Figure 7 inverter circuit diagram

Due to the extent of the circuit diagram we created a PCB for the entire inverter design. For more information you can get the design of the inverter using the link attached, we recommend opening the design using KiCAD 6.0 or a later version; https://github.com/jeremiahKiarie/finalyearGridProject/tree/main/Other%20Docs/inverterV4 . This PCB is depicted in the diagram below:

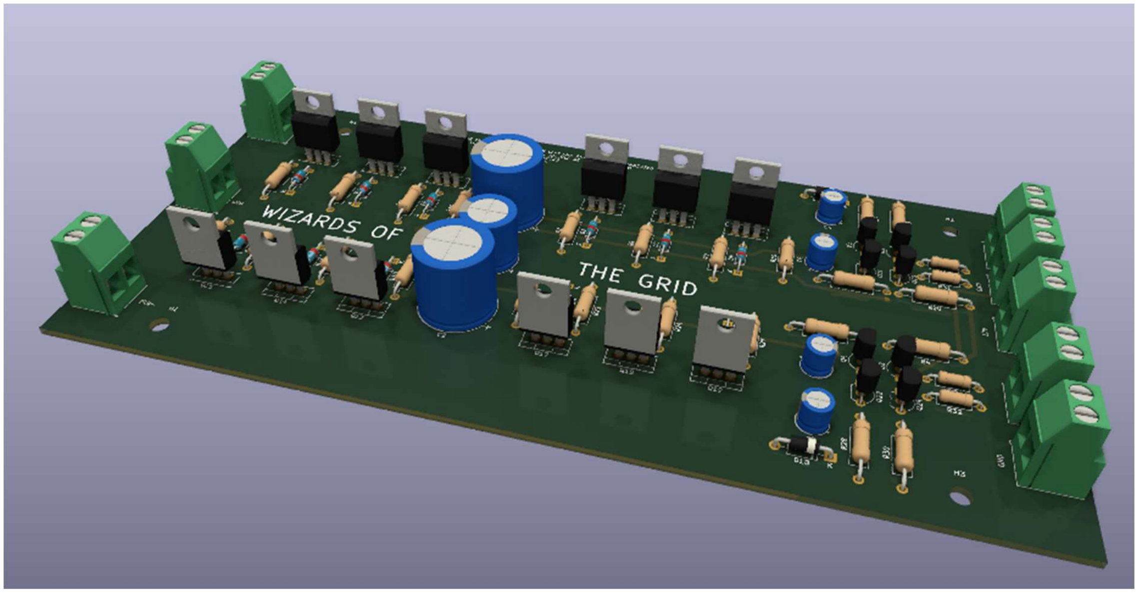

Figure 8 3D view of inverter PCB

Below is a table of the components used in the aforementioned circuit:

	Components	Number
1.	IRFZ44N MOSFET	12
2.	IN4148 diodes	4
3.	1N4007 diodes	2
4.	8 Ohms	16
	220 Ohms	4
	10K_ohms	12
5.	2200uf, 100uf, polarized capacitors	6
6.	Arduino Uno	1
7.	BC547 transistors	8
8.	Power supply	1
9.	Oscilloscope	1
10.	Digital Multimeter	1
11.	Screw Terminals	7

To be able to get feedback from the solar sub-grid and the entire grid, the solar sub-grid was created in tandem with the instrumentation of the grid. The section below shows the physical implementation of this system.

Physical implementation

The designed solar sub-grid circuit is part of instrumentation and control section which aids in collecting data of the Solar sub-grid, CAES sub-grid, and Mains grid. The data is sent to both the human machine interface (HMI) and also to the SCADA system via a deigned web server.

The Instrumentation and information system will be discussed later in the report when we get to the SCADA section. The outlined section below shows the solar sub-grid circuit.

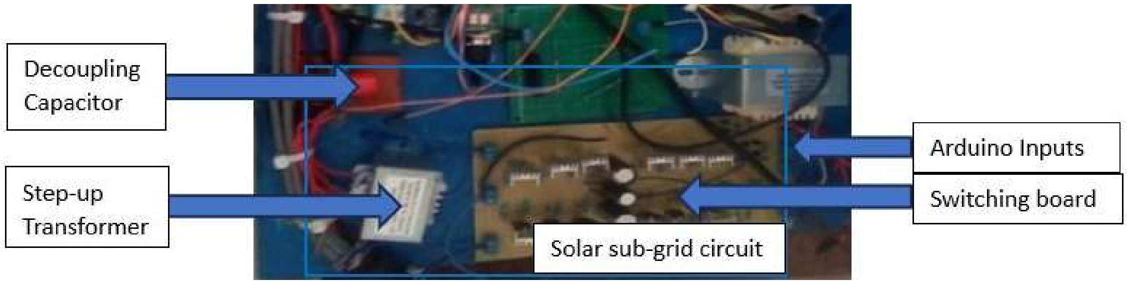

Figure 9 The solar sub-grid

The physical circuit is comprised of:

- Arduino Uno microcontroller is used to generate the SPWM signal at the specified frequency and magnitude based on the look-up table.
- A switching board to generate the sinusoidal signals at an amplitude of 16V.
- A step-down transformer (I/P 16V O/P 220V) that is reversed to operate as a step-up transformer. Input voltage on the secondary coils is 16V while output voltage on the primary coils in 220V. Stepping up of the voltage enables synchronization of either with the mains AC grid or CAES grid.
- Decoupling capacitor for smoothing the generated waveform to ensure it is sinusoidal before feeding it to the main bus.
- PZEM 004T 100A sensor is used to obtain the solar sub-grid parameters such as frequency, voltage, current, power factor, and energy consumption.
- DC Power supply is used to generate the DC voltage. It is used a representative of the direct current from the photovoltaic system.

The circuit outputs sinusoidal waveform with a Vrms of 220VAC at 16VDC from the power supply. The figure below shows the output waveform from the solar sub-grid.

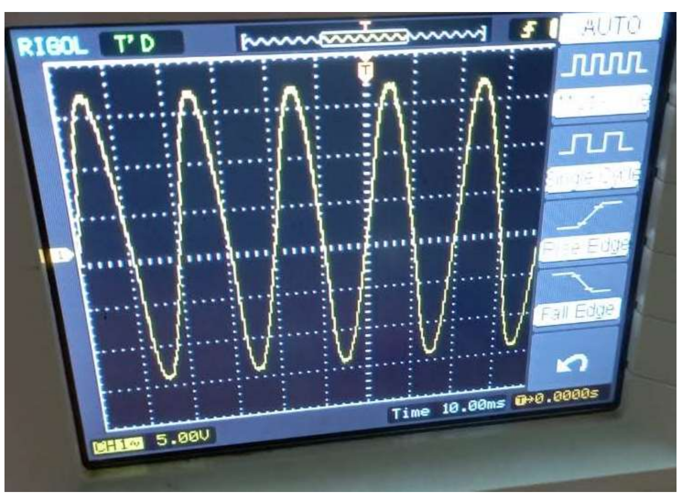

Figure 10 Solar sub-grid output waveform

SYNCHRONIZATION

Applications connected to the grid require accurate determination of the phase angle/phase sequence, accurate matching frequency, and voltage to achieve synchronization. For our case we achieved using the SPLL technique; Software Phase Locked Loop technique.

The phase angle of power devices such as photovoltaic inverters that feed power to the grid, is critical data that has to be considered to ensure accurate operation of power systems. A software phase locked loop technique is a closed loop control system that has a program acting as an internal oscillator that is controlled to keep the phase and time of an external periodical signal using a feedback loop approach. In simple terms, Phase Locked Loop is a servo system that controls the phase of an output signal from devices like PV inverters to ensure that phase error between the output signal and the reference signal is kept as minimum as possible. The quality of the lock directly affects them performance of the control loop in grid tied applications. As line notching, voltage unbalance, line dips, phase loss and frequency variations are common conditions faced by equipment interfacing with electric utility, the PLL needs to be able to reject these sources of error and maintain a clean phase lock to the grid voltage.

Functional diagram of Phase Locked Loop is shown below. It consists of phase detector (PD), low pass filter (LPF), and voltage-controlled oscillator (VCO).

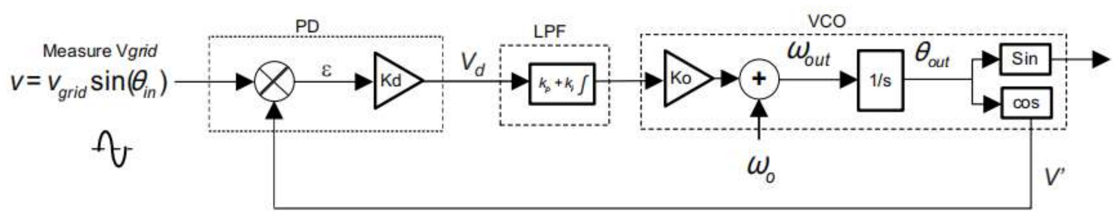

Figure 11 PLL Function diagram

Measured grid voltage written in terms of grid frequency

$$v = v_{grid}\sin(\theta_{in}) = v_{grid}\sin(w_{grid}t + \theta_{grid})$$

Now, assuming VCO is generating sine waves close to the grid sinusoid, VCO output can be written as,

$$v' = \cos(\theta_{out}) = \cos(w_{PLL}t + \theta_{PLL})$$

Physical Implementation

First, we begin by checking when the power from the Main crosses the zero, this is achieved using a custom made zero-crossing detector. Zero crossing detection is a technique that is commonly used in signal processing, particularly in waveform analysis. The zero-crossing point is where a waveform crosses the horizontal axis (x-axis), indicating a change in polarity from positive to negative or negative to positive. This concept is critical in a variety of applications, such as power systems, motor control, and energy management.

Mains AC signals in electrical power systems alternate between positive and negative voltage values as they oscillate around zero volts. The zero-crossing point is the point at which the voltage crosses the zero axis. Zero crossing detection in mains AC signals is used for synchronization and timing of when the AC signal crosses the zero axis. The circuit is comprised of the following components:

- Power plug, used to draw 240VAC from the mains which will then be stepped down.
- Step down transformer, used to step down 240VAC to 18VAC which can easily be handled by a voltage divider.
- Voltage divider, used to decrease the 18VAC from the transformer outputs to 4.83VDC which can be read by Arduino inputs to enable zero crossing detection.
- Arduino Uno is used to obtain the interrupt value each time the sinusoidal waveform crosses the horizontal axis.

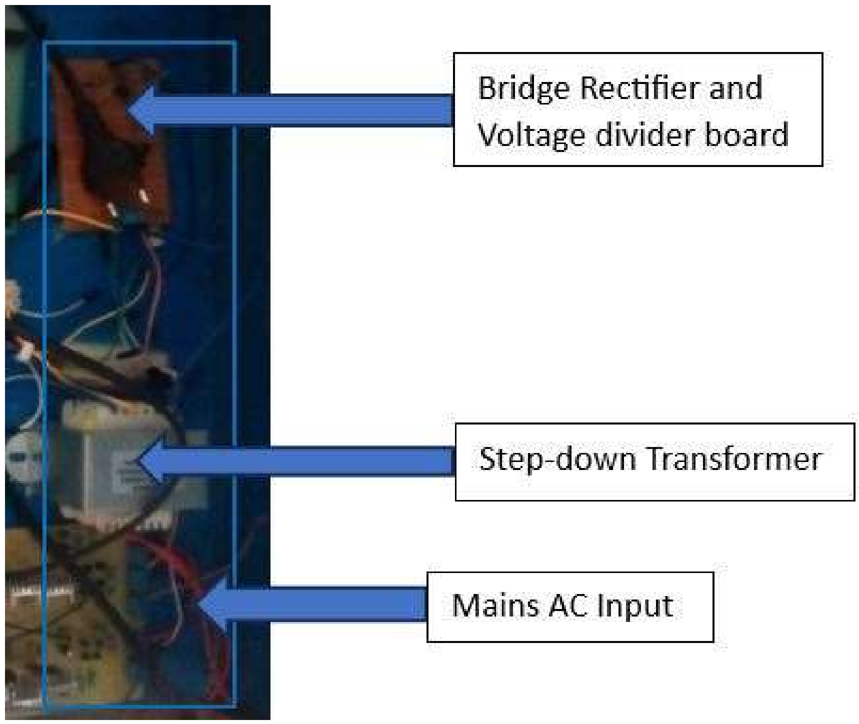

Figure 12 Mains Zero Crossing Detector

Next, we check the zero-crossing detection of the Solar line, the using the PLL technique make use of the error to lock the two lines. Below is a breakdown of the circuit used to achieve this:

- Solar AC input used to obtain 220VAC from the solar grid which will is then rectified.
- Bridge rectifier GBJ series, used to transform alternating current (AC) 240VAC to direct current (DC).
- Voltage divider, used to lower the 240VDC from the full bridge rectifier outputs to 4.85VAC which can be read by Arduino inputs to enable zero crossing detection.
- Arduino Uno is used to obtain the interrupt value each time the sinusoidal waveform crosses the horizontal axis.
- With the two different times the two waves cross the zero axis we can find the phase error. This is fed to the SPLL controller and is reduced gradually until the two waves are in sync.
- Once this sync condition is met we send a sync message to the PLC. This part will be discussed further later in the document

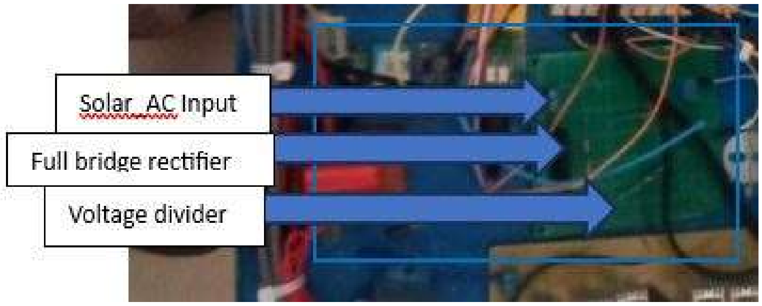

Figure 13 Solar Zero Crossing Detector

CAES POWER SUB-GRID SYSTEM

INTRODUCTION

Compressed Air Energy Storage (CAES) is a method of power generation that has a history dating back over a century. It was first developed in the late 19th century and was primarily used as a means of storing mechanical energy. In the early 20th century, CAES systems were employed to improve the efficiency of compressed air-driven machinery.

The modern development of CAES for electricity generation began in the 1970s. These systems involve compressing air and storing it in underground caverns or specially designed tanks. When electricity is needed, the compressed air is released, expanding and driving a generator to produce electricity. CAES is considered a form of grid energy storage and is particularly useful for balancing the supply and demand of electricity on the grid, as it can provide quick responses to fluctuations in power demand.

Today, CAES technology continues to evolve and gain attention as a viable energy storage solution for renewable energy integration and grid stability. It offers the potential for large-scale energy storage and can help in reducing the intermittency issues associated with renewable energy sources like wind and solar.

BODY

In the actualization of our system we used:

- A relay-controlled compressor socket
- A compressor
- An I/P transducer
- An air motor
- A shaft coupler
- A generator
- A transformer
- Other instrumentation components

In the wiring diagram below, I have highlighted the section of the CAES circuit, showing how the above components have been connected to each other.

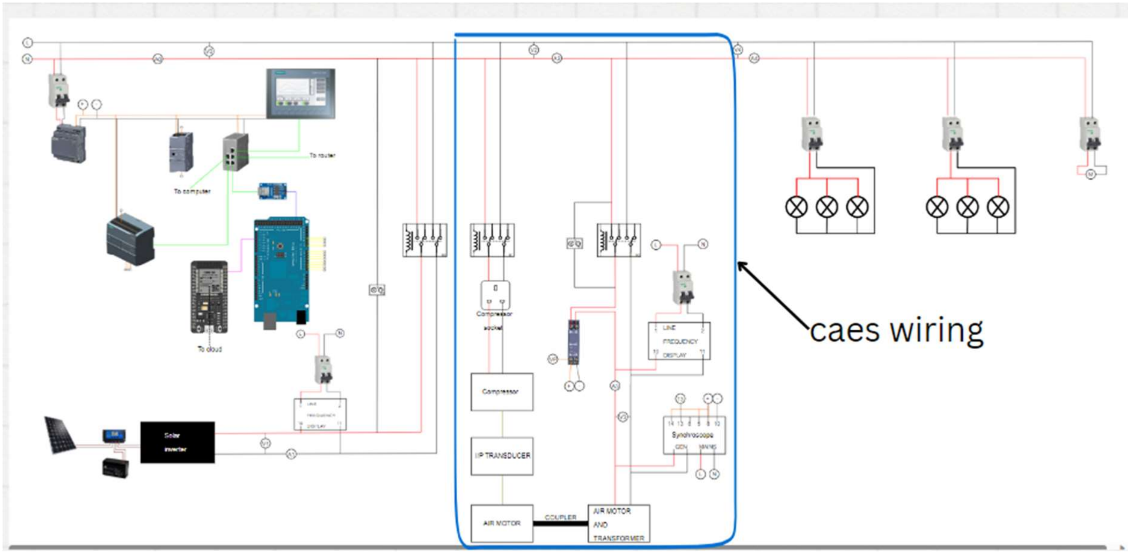

Figure 14 CAES wiring diagram

The diagram below shows a look at the physical manifestation of the CAES grid:

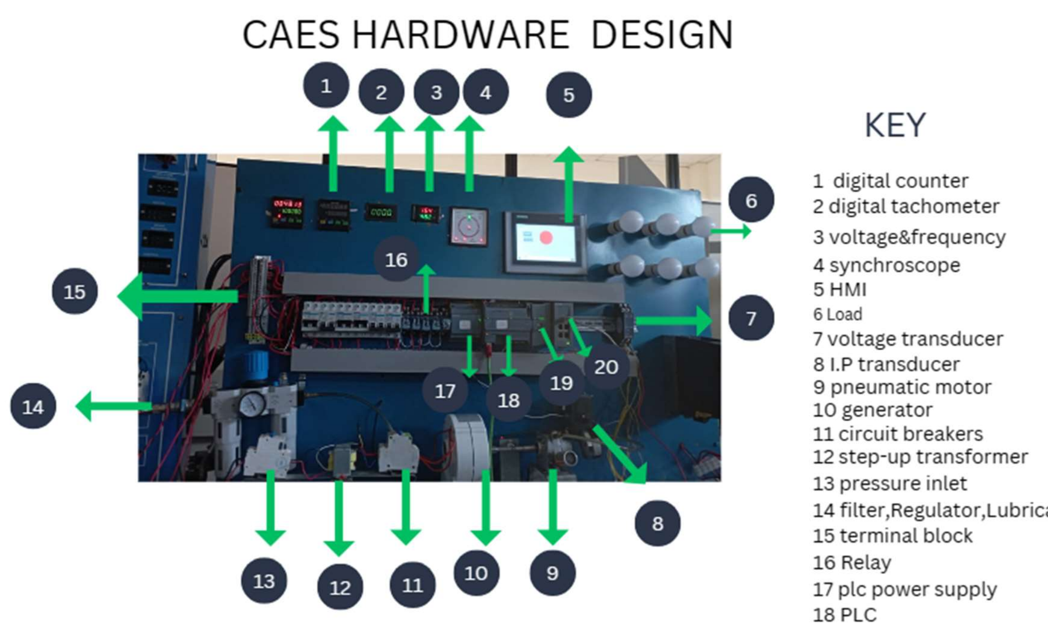

Figure 15 CAES hardware overview

CAES CHARGING AND DISCHARGING

First let's have a brief look on how our CAES system functions. A CAES system inherently works in two mode, that is, when it is charging and when it is discharging. In our system charging of the CAES happens when the compressor is turned on via the relay-controlled socket, this means that air in the receiver tank of the compressor is compressed, thus increasing the pressure of the air stored. This relay is turned on when there is excess power in the grid as dictated by the main controller. The system discharges when there is a deficit of power in the grid. The stored compressed air enters through a regulator (HC series pneumatic regulator, filter and lubricator). Here the compressed air is filtered i.e. removed impurities, the regulator adjusts the amount of compressed air flowing through. Finally, the compressed air is mixed with oil to lubricate the hoses therefore minimizing the effects of friction. The compressed air then passes to the I/P transducer which contains nozzle flapper mechanism which contains a coil powered a by a varying current signal of around 4-20mA thus regulating the amount of output pressure being fed into the pneumatic motor. The compressed air then runs the pneumatic motor which is coupled to 24V 50HZ AC generator. The output of the generator is fed to the step-up transformer where it is stepped up to 170 volts. This output voltage is fed to the digital counter for frequency measuring a well as voltage transducer for measuring frequency as well.

Below is a diagram of the pneumatic circuit used to achieve this:

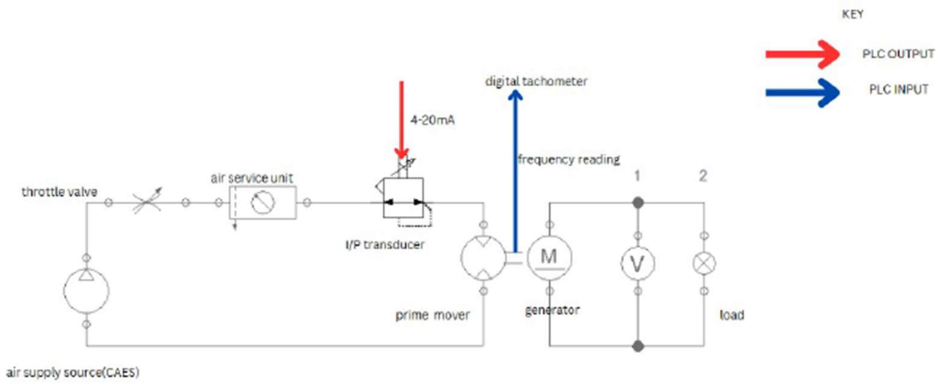

Figure 16 CAES pneumatic circuit

SYNCHRONIZATION

Grid synchronization, especially in the context of connecting a power generation source or inverter to the mains (or grid), is a critical aspect of electrical power systems to ensure the safe and efficient operation of the grid. Grid synchronization refers to the process of aligning the output of a power source, such as a generator or inverter, with the voltage and frequency of the electrical grid. This alignment is essential to ensure a smooth and stable transfer of power to or from the grid without causing disruptions or damage to the equipment.

The concept of grid synchronization

- **Voltage Synchronization**: The first aspect of grid synchronization is matching the voltage amplitude and phase of the power source with that of the grid. The voltage generated by the power source must be synchronized with the grid voltage to avoid voltage mismatches and potential disturbances. Voltage synchronization ensures that the power source's voltage waveform aligns with the grid's voltage waveform.
- **Frequency Synchronization**: In addition to voltage synchronization, frequency synchronization is equally crucial. The frequency of the power source's output, typically expressed in Hertz (Hz), must match the grid frequency. In many regions, the grid operates at a fixed frequency, such as 60 Hz in North America or 50 Hz in many parts of Europe and in Kenya. Deviations in frequency can lead to power quality issues and instability in the grid.
- **Phase Angle Synchronization**: The phase angle of the power source must also be synchronized with the grid. The phase angle represents the angular displacement

between the voltage waveforms of the power source and the grid. Proper phase angle synchronization ensures that the power source output is in phase with the grid, preventing phase mismatches and the risk of short circuits or excessive current flow.

Grid synchronization is governed by various standards and regulations set by grid operators and regulatory authorities. These standards define the permissible voltage and frequency tolerances, as well as the requirements for synchronization equipment, protection schemes, and control strategies.

Grid synchronization can be achieved through various methods, depending on the type of power source and the technology used. Some common methods include phase-locked loops (PLLs), synchro phasors, and digital controllers that continuously monitor and adjust the output of the power source to match the grid conditions.

Grid synchronization is essential for maintaining the stability and reliability of the electrical grid. Power generation sources, including renewable energy systems like solar and wind, must synchronize their output with the grid to avoid disruptions and maintain grid stability. Unsynchronized sources can lead to voltage fluctuations, frequency deviations, and grid instability, which can have serious consequences for connected loads and other power sources.

To achieve synchronization, we employed the use of a PID controller (Running in the main controller PLC) used to control the I/P transducer.

PID CONTROLLER

Our PID controller is as follows. The aim is to control the CAES (process) i.e. we are controlling the I/P transducer and our feedback sensor is an energy meter that reads the frequency of the produced voltage.

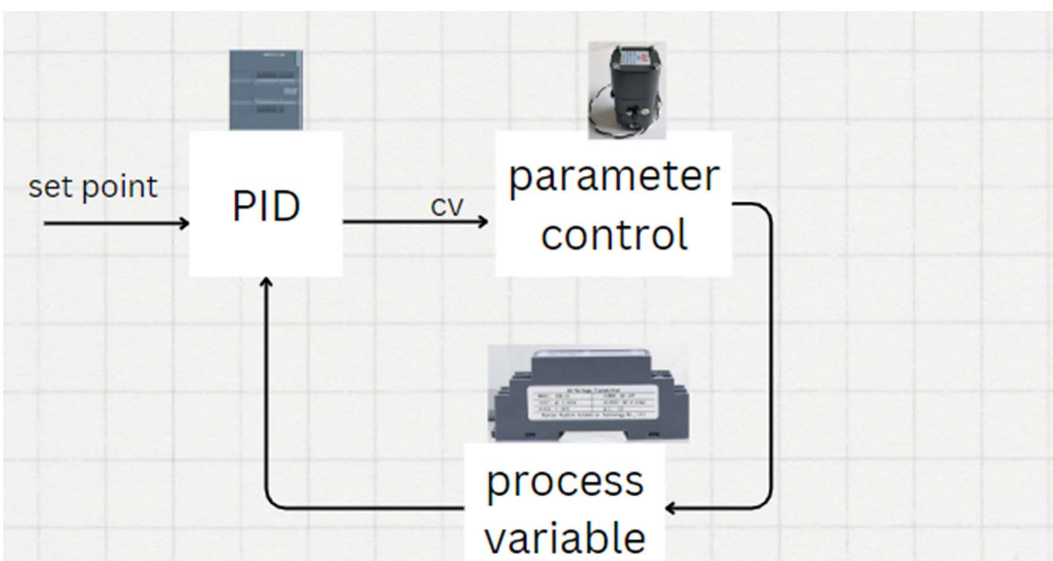

Figure 17 CAES control loop

PLC program

The program section outlined in the next few pages is not the entire PLC control code, this is just the section involving the PID controller, that is, the code section that becomes active when we are discharging the CAES; the code section that controls how we produce power from the compressor. You can find the entire plc program here: https://github.com/jeremiahKiarie/finalyearGridProject/tree/main/FinalYearProjectCode .

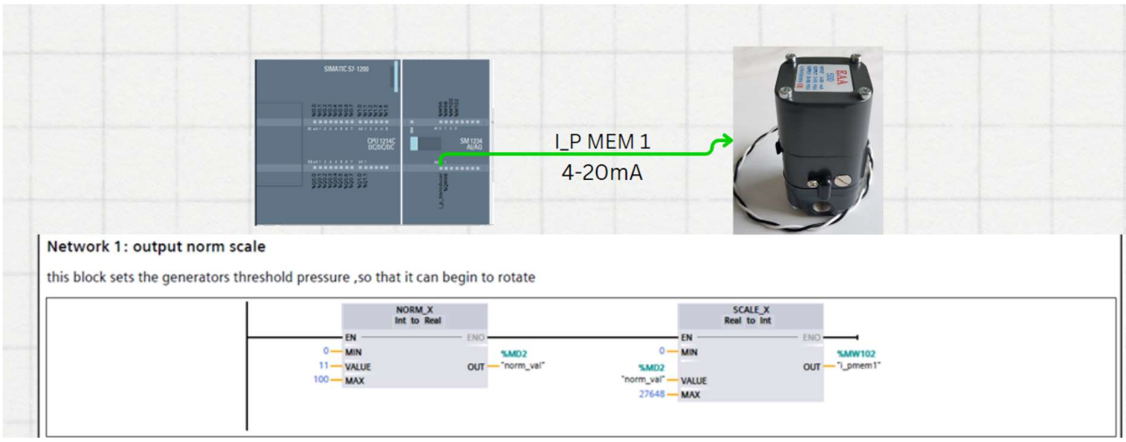

Figure 18 CAES PLC program network 1

First, we begin by opening the I/P transducer slightly such that the air motor just about rotates and the generator produces a small amount of power but not enough to be synchronizable, much less usable. This is done so that the sensor can get a reading thus our control loop has proper feedback, it also creates a lower threshold for our controller thus reducing spikes especially towards the lower end.

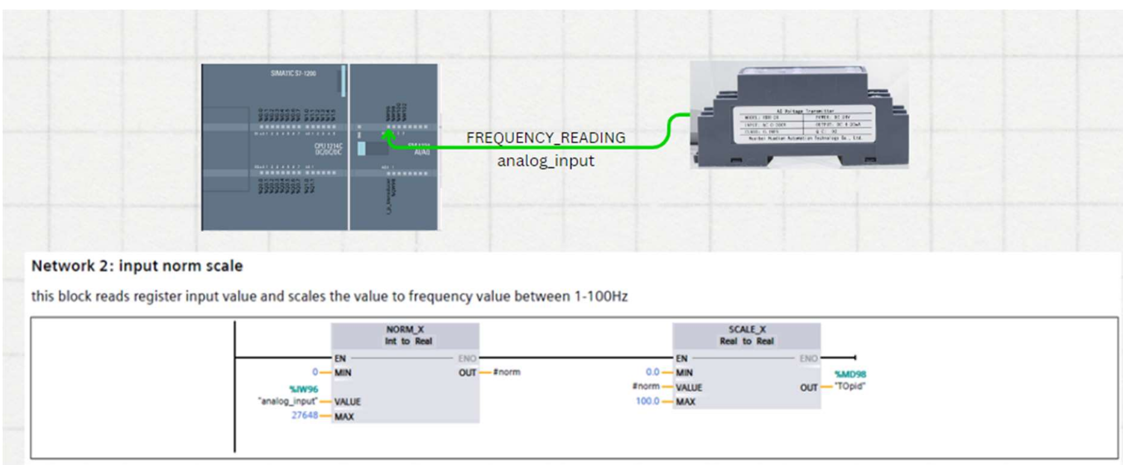

Figure 19 CAES PLC program network 2

This network reads the values of voltage transducer sensor which basically are frequency reading. The register value is normalized and the scaled to 0-100HZ. This value is stored in memory where it serves as the input to the PID.

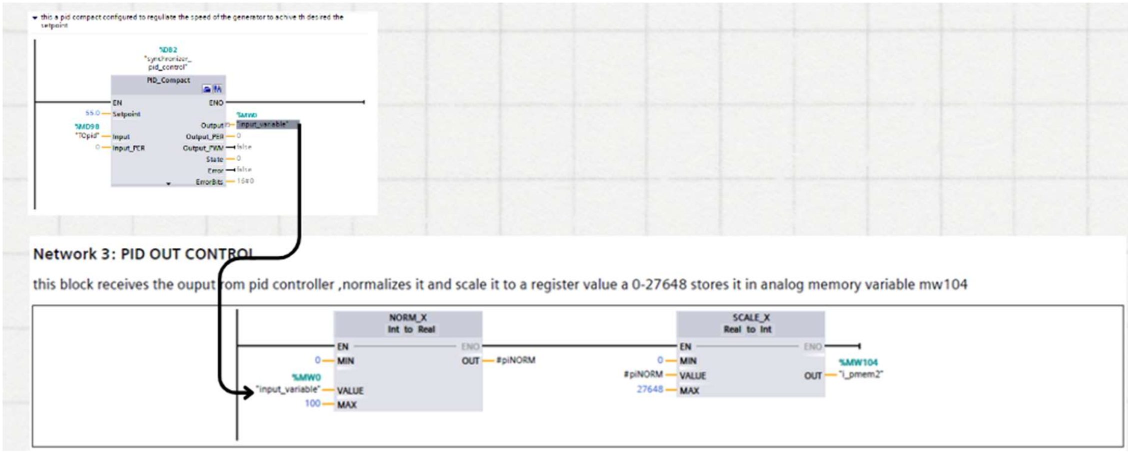

Figure 20 CAES PLC program network 3

This block receives the output or the control variable from the plc which is a pressure control variable. This value is scaled and the normalized to register values where the output of the scaled block is fed stored in memory tag for use in the program later.

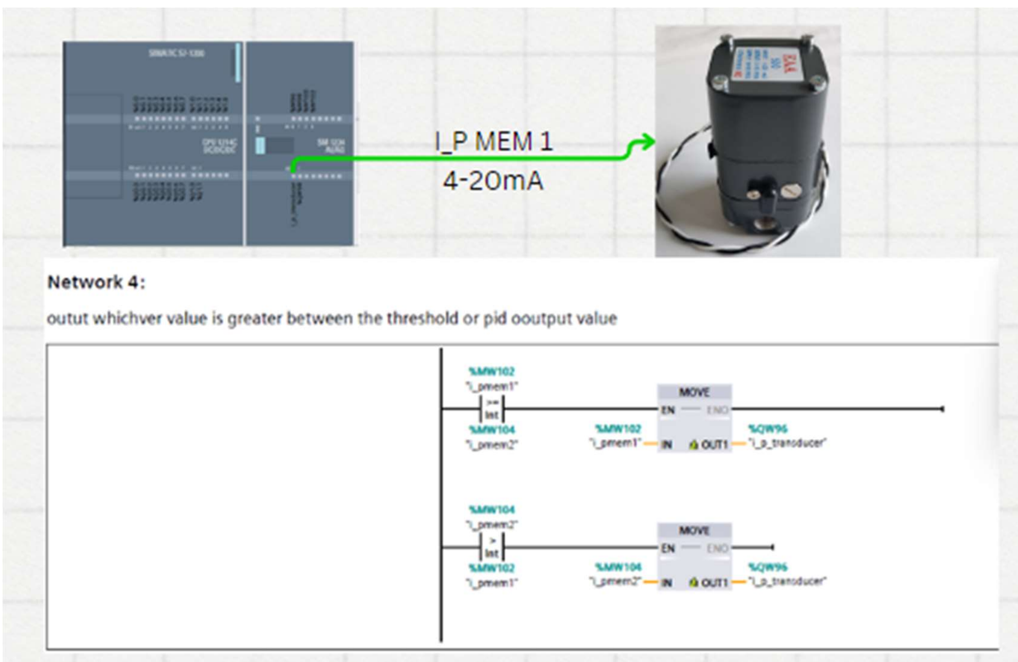

Figure 21 CAES PLC program network 4

This network compares the value of memory tags ipmem1 an ipmem2 such that whichever is greater is transferred to the analogue output channel to control the I/p transducer. This ensures that the lower threshold which was discussed earlier is met.

HMI programming

The HMI is programmed to enable the operator to visualize the PID control action as follows:

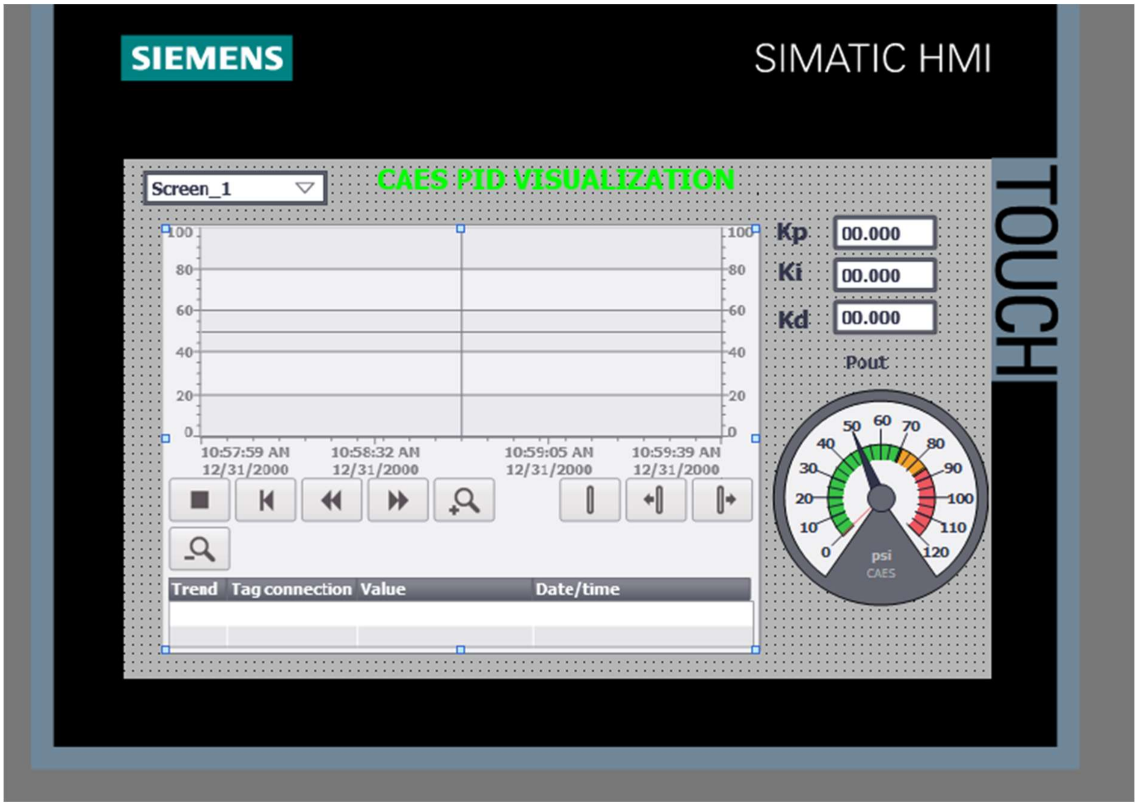

Figure 22 HMI PID operator screen

The left of the screen is a graph where the process variable, control variable and the set point are plotted. To the right is a display of the PID parameters. To the bottom right is a gauge indicating the process variable.

RESULTS

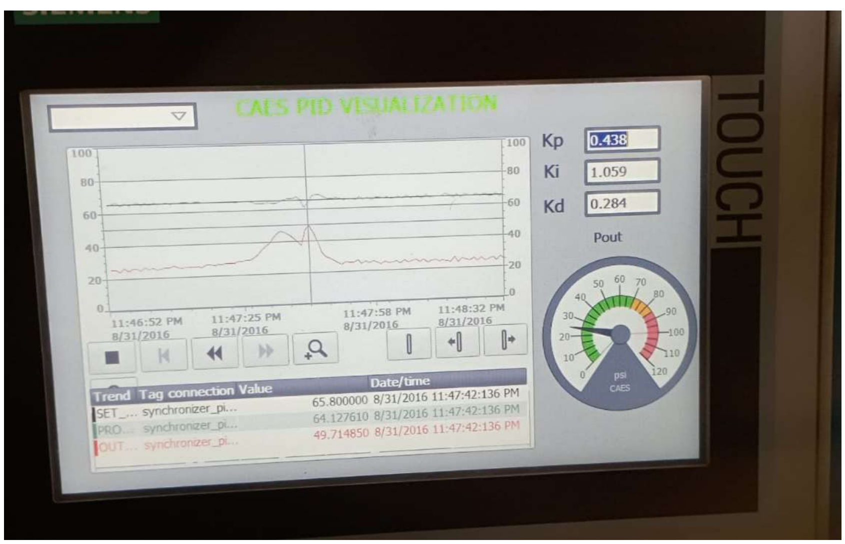

Figure 23 Active PID HMI screen

The PID can be visualized from the HMI as seen from the above HMI screen. The set point which is marked by black line. The process variable is marked by green line. The control variable is marked by the red line. The above example main's frequency at 50 Hz and we can infer that that the process variable is almost in line with the set point.

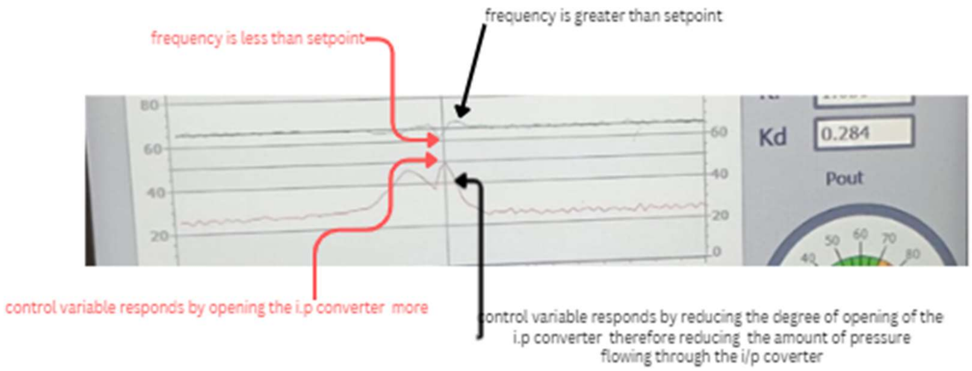

Figure 24 Analysis of the HMI screen

Due to the compressor problem addressed later in the challenges section we opted to reduce the frequency of the CAES to 40 HZ which the compressor could handle. This meant that to be able to show synchronization of this power source with another we had to ensure that the power output from the solar sub-grid was similar to this. Thus, we made the solar grid the reference with the following parameters:

- V=140v
- F=40Hz

The frequency of the solar was sent from the instrumentation panel by the Ethernet module which communicated to the plc via profinet cable as follows

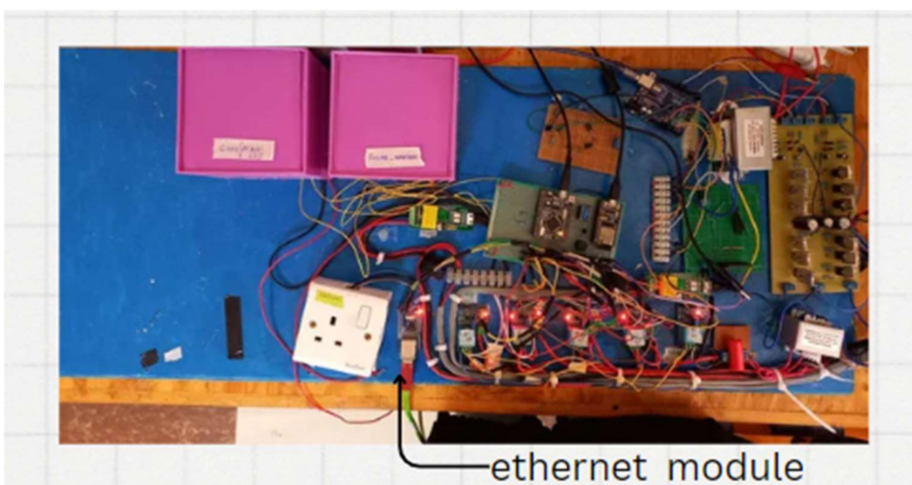

Figure 25 Solar profinet

Once the frequency is received in the plc it fed to the input of the PID block, as the set point, so that the CAES frequency can be maintained at the same frequency of the solar.

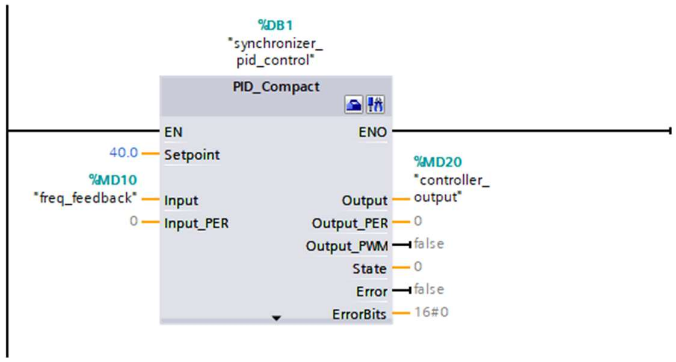

Figure 26 PLC PID block

The PID regulates the CAES process until its parameters matches that of the solar. When the parameters have matched the synchroscope LEDs are lit at around 3 LEDs on either side of the 12 o'clock LED. Since the CAES is a rotating type generator, to ensure zero phase error we had to time when the rotating LED is at 12 o'clock and close the solar-CAES synchronization relay at that instant. To aid in synchronization the solar – CAES grid were connected to a fail-safe synchronization lamp as follows:

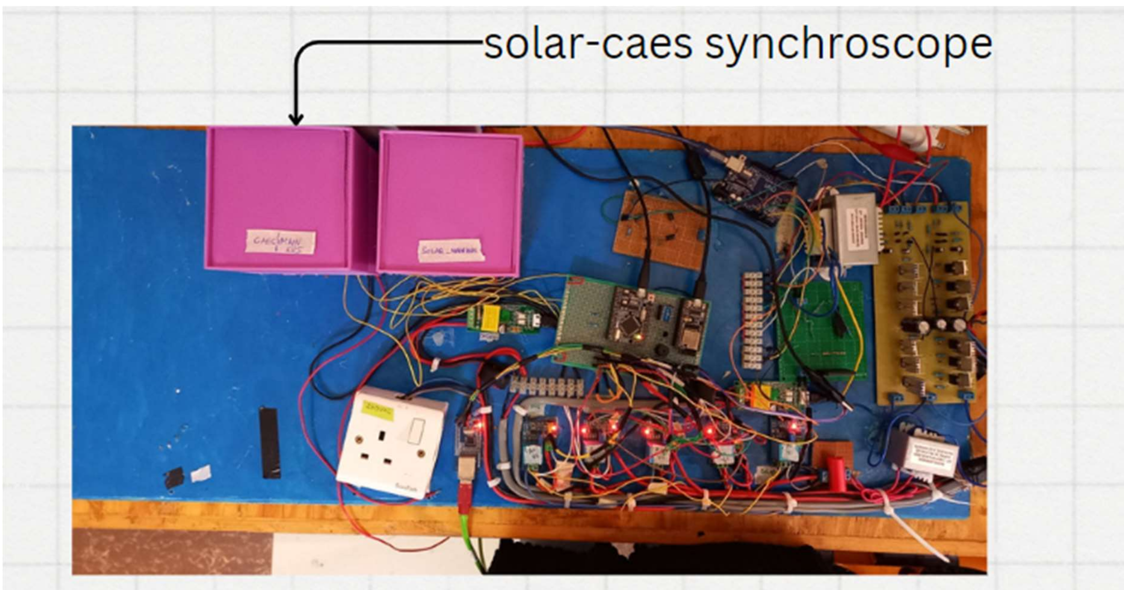

Figure 27 Solar-CAES failsafe lamp

When the two generators were in sync the bulb flickered slowly otherwise it flickered fast. By using the dark lamp method technique, we were able to monitor when the two generators were in and out of sync and therefore send the synchronization status to plc for the closing of solar-main bus relay.

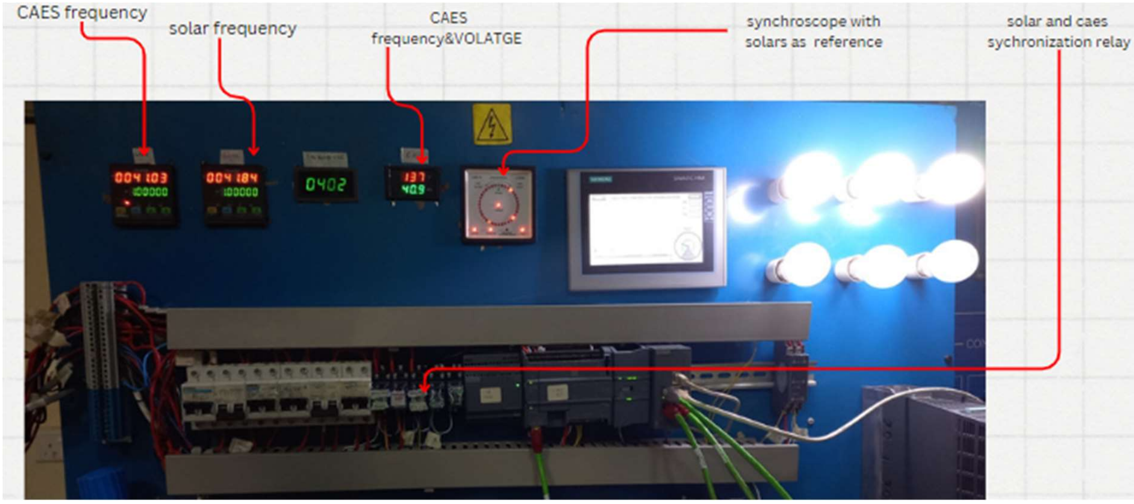

Figure 28 Active CAES panel breakdown

This process was done automatically by the PLC. However, there was a problem in communication from the Ethernet module in instrumentation board to the PLC. The challenge was that the Ethernet module could only send frequency values only once and subsequent transmission was affected greatly until a reset was performed on the microcontroller. This method was not effective as it required constant resets of the microcontroller.

However, by the help of the synchroscope we tried timing manually and the results were as follows:

- The voltage of the main bus was reduced by half of its initials value i.e. 140/2
- The frequency of the main bus reduced by half i.e. 40/2,20Hz
- The voltage and frequency of the main bus kept on reducing with time.

This problem can be attributed to error due to switching. The hand reaction to switch the relay at the instant when the rotating led is at 12 o'clock was accompanied by a delay such that by the time the relay was closed the CAES and solar were out of phase with each other.

Now that we have seen the three grids individually let's look at some of the methods we used to bring them together. In this section of the report we will emphasize on what we had to do to make this work. This will involve a look at the communication used between the grid and the mechanic involved to bring the project to life. Let's begin with a breakdown of the communication used in the project, then look at the mechanical aspect of the project.

COMMUNICATION

INTRODUCTION

Communication serves as the backbone of any system, acting as a vital conduit for coordinating the operation of various components of the system. In this project, the communication framework is of paramount importance, facilitating the seamless collaboration of various subsystems and ensuring both the safety and efficiency of the overall system through real-time monitoring in SCADA and control.

A communication protocol is a system of rules that allows two or more entities of a communications system to transmit information via any variation of a physical quantity.

Communication protocols used in this project are:

- *Ethernet*
- *Modbus*
- *SPI*
- *UART*
- *Wi-Fi*

BODY

Ethernet

At the core of the communication network lies Ethernet, a high-speed protocol that has become ubiquitous in computer networks. The adoption of Ethernet in this project is instrumental in enabling the rapid exchange of real-time data transmission and control signals. This ensures the synchronization and monitoring of power systems, a critical aspect of the project's success.

Ethernet plays a multifaceted role within the project, serving as the backbone that connects the Supervisory Control and Data Acquisition (SCADA) system to the controllers responsible for managing the mains supply, solar power, and Compressed Air Energy Storage (CAES) systems. Its deployment extends further to establish connections with strategically placed sensors throughout the system, enhancing the overall monitoring capabilities.

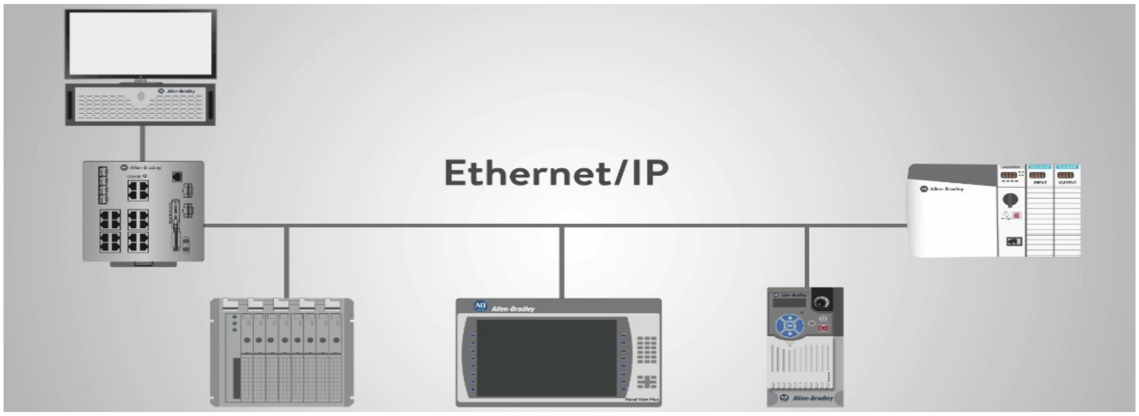

Figure 29 Ethernet protocol

The utilization of Ethernet reflects a commitment to high-speed and reliable communication, essential for the efficient operation of the project. Through Ethernet, the project can achieve both and responsive and coordinated control, laying the foundation for a robust and interconnected system.

Modbus

Another critical player in the communication framework is the Modbus protocol, renowned for its widespread use in industrial automation systems. Engineered specifically for transmitting information between electronic devices, Modbus serves as a bridge that facilitates communication between the SCADA system and individual devices such as the solar power inverter and CAES controller.

Modbus operates as a request-response protocol, following a master-slave relationship framework. Within this communication structure, interactions occur in pairs, where one device initiates a request and awaits a response. The master, typically represented by a Human Machine Interface (HMI) or Supervisory Control and Data Acquisition (SCADA) system, takes on the responsibility of instigating each interaction. On the other side, the slave device, which could be a sensor or a programmable logic controller (PLC), responds to the initiated requests. The details of these requests and responses, as well as the network layers through which these messages travel, are specifically defined by the protocol's various layers.

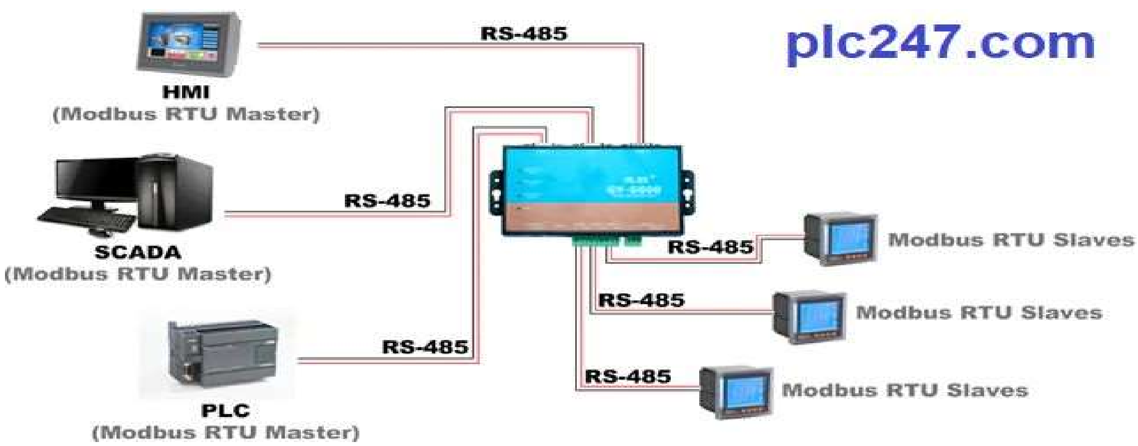

Figure 30 Modbus protocol

Modbus provides a reliable means for transmitting information, enhancing the project's ability to collect and disseminate crucial data. This level of communication proficiency is essential for ensuring that each component of the system operates in harmony, contributing to the overall success of the project.

SPI

The Serial Peripheral Interface (SPI) emerges as a pivotal component in the communication infrastructure, specifically in interfacing microcontrollers with peripherals like sensors and displays. Operating as a full-duplex protocol, SPI's capability to transmit and receive data simultaneously is a key feature that allows for efficient monitoring of essential parameters.

In the context of this project, SPI facilitates the real-time monitoring of critical parameters such as energy output, storage levels, and overall system performance. We employed this protocol to provide communication between the ethernet module and the instrumentation microcontroller. Its full-duplex nature ensures that the communication between microcontrollers and peripherals is not only fast but also synchronized, providing a comprehensive view of the system's status.

SPI's integration into the project's communication framework underscores a commitment to thorough and efficient monitoring. By providing a continuous flow of information between microcontrollers and peripherals, SPI contributes to the project's ability to adapt to changing conditions and optimize performance.

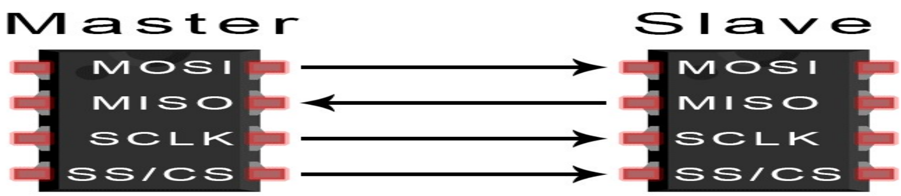

Figure 31 SPI protocol

UART

Universal Asynchronous Receiver-Transmitter (UART) is very important in communication. Its primary function is to connect microcontrollers to peripherals such as computers, establishing a direct line of communication. This feature allows for the seamless transmission of vital control signals, system status updates, and diagnostic information.

In UART communication, two UARTs communicate directly with each other. The transmitting UART converts parallel data from a controlling device like a CPU into serial form, transmits it in serial to the receiving UART, which then converts the serial data back into parallel data for the receiving device. Only two wires are needed to transmit data between two UARTs. Data flows from the Tx pin of the transmitting UART to the Rx pin of the receiving UART.

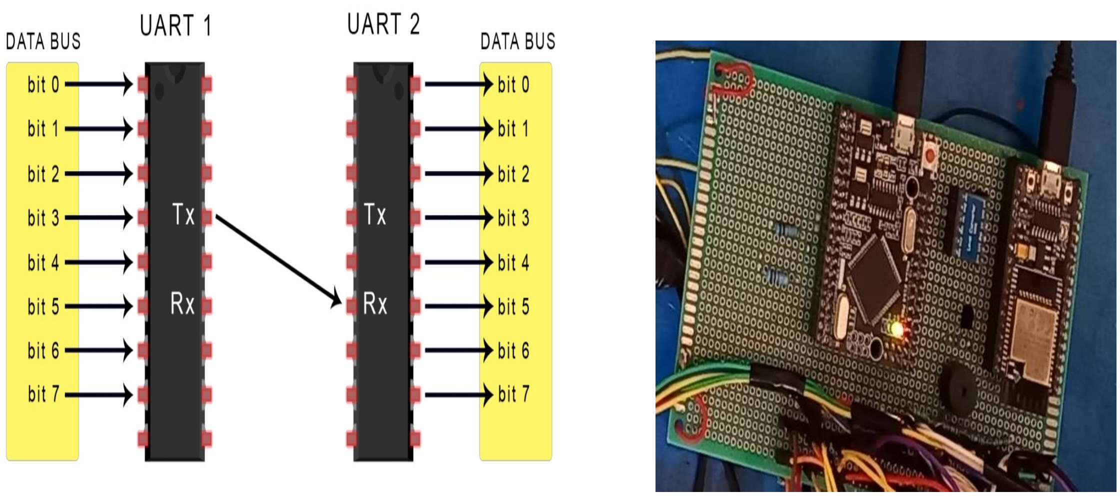

Figure 32 UART protocol

In our project, this protocol was employed for communication between the main instrumentation microcontroller (Arduino Mega) and the Wi-Fi router (ESP32). This allowed sensor data read by the main instrumentation microcontroller to be sent to the cloud via the ESP32.

Wi-Fi

Wi-Fi (Wireless Fidelity) uses Internet Protocol (IP) to communicate between endpoint devices and the LAN. A Wi-Fi connection is established using a wireless router that is connected to the network and allows devices to access the internet.

In our project this communication protocol was used to send data from the sensors to the remote SCADA system.

DISCUSSION

The combination of Ethernet, Modbus, SPI and UART in this project represents a sophisticated communication architecture designed to address the unique challenges of coordinating diverse subsystems. A comprehensive analysis of each protocol reveals that their selection is not arbitrary but driven by specific functionalities and requirements.

Ethernet's high-speed capabilities make it suitable for facilitating real-time data transmission and control signals. Its role in connecting the SCADA system to controllers and sensors establishes a robust communication backbone. Modbus, with its industrial automation focus, enhances interoperability by facilitating communication between the SCADA system and critical devices like inverters and controllers.

SPI's full-duplex communication capability is leveraged for efficient monitoring of parameters crucial to the project's success. It provides a continuous flow of information, allowing for a comprehensive understanding of energy output, storage levels, and overall system performance. Meanwhile, UART's direct communication with individual devices ensures the transmission of essential control signals and diagnostic information, contributing to the project's responsiveness.

The integration of these protocols is not just a technological choice but a strategic decision to create a communication framework that aligns with the project's objectives. Together, these protocols form a cohesive network that enables seamless collaboration and coordination, fostering an environment where different components work in unison.

While the communication framework outlined above is robust, it is essential to acknowledge potential challenges that may arise in the deployment of such a complex system. Interference, network congestion, and device compatibility issues are among the challenges that can impact the effectiveness of the communication protocols.

Interference in communication signals, particularly in industrial settings, can lead to data corruption or loss. Robust error-checking mechanisms and redundancy in communication pathways are potential solutions to mitigate the impact of interference. Additionally, the use of shielding for cables carrying critical communication signals can help safeguard against external interference.

Network congestion may occur in scenarios where there is a high volume of data traffic. Implementing Quality of Service (QoS) mechanisms within the communication network can prioritize critical data, ensuring that essential information is transmitted without delays. Bandwidth management strategies and periodic network assessments can also contribute to overcoming congestion-related challenges.

Device compatibility issues may arise when integrating components from different manufacturers or utilizing legacy systems. Standardization of communication protocols, such as the use of Modbus in this project, helps address compatibility concerns. Regular firmware and software updates, along with thorough testing during the integration phase, can further ensure seamless compatibility between devices.

As technology continues to evolve, it is crucial to design the communication framework with future enhancements and scalability in mind. The current project's architecture should be flexible enough to accommodate new communication protocols, additional components, and emerging technologies.

The Ethernet backbone, for instance, can be upgraded to higher speeds or replaced with future communication standards as they become available. Compatibility with emerging communication protocols should be considered, allowing the system to evolve without requiring a complete overhaul.

Scalability is a key consideration, especially if the project undergoes expansion or if additional functionalities are introduced. The communication framework should be designed to handle increased data traffic, additional sensors, and controllers without compromising performance. Modularity in the communication architecture facilitates the seamless integration of new components, ensuring the project remains adaptable to changing requirements.

In conclusion, communication is the cornerstone of this project, enabling the coordination, monitoring, and control of diverse subsystems. The integration of Ethernet, Modbus, SPI, and UART forms a robust communication framework that addresses the unique requirements of the system. The visual representation provided by the comprehensive wiring diagram offers stakeholders a clear understanding of the intricate communication pathways within the project.

In essence, the communication framework outlined in this project is not just a means to an end; it is a dynamic and integral component that ensures the success, reliability, and adaptability of the entire system. As technology continues to advance, effective communication will remain at the forefront of projects, serving as the linchpin for innovation and progress.

MECHANICAL DESIGN

Now that we have looked at the communication we can have a look at the mechanical section. In this part of the report we will concentrate more on what we did during the two semesters we worked on the project. First, we will look at the 3d model of the project

3D MODELING REPORT

Project Station with Compressed Air Energy System and Mains Integration in SolidWorks

INTRODUCTION

This report outlines the 3D modeling process of a project station that integrates a Compressed Air Energy System with both Solar and Mains power sources using SolidWorks. The objective is to create a comprehensive visual representation of the project station, showcasing the synergy between renewable energy and traditional power sources for enhanced sustainability and resilience.

Figure 33 Grid panel 3d model

PROCEDURE

- **Conceptualization:** The initial phase involved conceptualizing the layout and components of the project station. Considerations were made for optimal placement of the Compressed Air Energy System, solar panels, and mains power connections to maximize efficiency and usability.

- **Component Design:** Each component, including the Compressed Air Energy System components, solar panels, and mains power interfaces, was individually designed with precision in SolidWorks. The software's parametric modeling capabilities were leveraged to ensure accurate dimensions and seamless integration.
- **Assembly:** The designed components were assembled in SolidWorks to create a comprehensive 3D model of the entire project station. Careful attention was paid to the spatial relationships between the elements, allowing for a realistic representation of how the components would interact in the physical environment.
- **Integration of Power Sources:** The modeling process involved creating interfaces and connection points to illustrate the seamless flow of energy between the different power sources.

The 3D modeling of the project station in SolidWorks successfully visualizes the integration of a Compressed Air Energy System with Solar and Mains power sources. The model serves as a foundation for further analysis, simulation, and optimization before the physical implementation of the project. This 3D model not only enhances the understanding of the project's design but also aids in communication and decision-making processes, ensuring a well-informed approach towards sustainable and resilient energy solutions.

PNEUMATIC MOTOR-ALTERNATOR SHAFT

To be able to transmit mechanical rotation from the air motor to the generator, we had to design a custom shaft coupler.

Below is a short report on the design and fabrication of the shaft coupler.

INTRODUCTION

The fabrication of a pneumatic motor-alternator shaft requires careful planning and precise machining to meet the functional requirements. This report outlines the step-by- step process involved in creating the shaft from a raw workpiece. The main machining operations include saw cutting, lathe turning, boring, milling, and drilling. Each operation contributes to achieving the final dimensions and shape of the shaft as per the design specifications.

The materials we used are including but not limited to:

- Raw cylindrical stock
- Lathe machine
- Milling machine
- Pillar drill
- Hack saw
- Cutting, boring, milling, drilling tools
- Measuring instruments (calipers, micrometers)

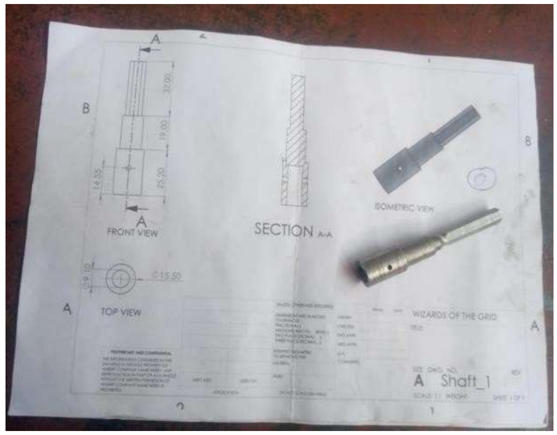

Figure 34 Shaft drawing and part

PROCEDURE

- **Saw Cutting:** The first step in the fabrication process involved saw cutting the raw workpiece into a suitable size. The workpiece was initially measured and marked, then cut to a length of76.2 mm using a saw.
- **Lathe Turning - First Step:** After cutting, the workpiece was mounted on a lathe machine. The first step was to turn the workpiece down to a diameter of 15.50 mm. This operation ensured that the shaft had a consistent diameter along its length.
- **Lathe Turning - Second Step:** Following the completion of the first step, the second step was turned down to a diameter of 12.00mm. The transition between the first and second steps was gradual and precise to meet design specifications.
- **Lathe Turning - Third Step:** The third step was turned to a diameter of 9.47 mm using the lathe machine. This step was also carefully executed to achieve the desired dimensions.
- **Boring:** A hole with a diameter of 9.10 mm was bored into the bottom face of the shaft using a boring tool. This hole was essential for accommodating specific components of the pneumatic motor-alternator system.
- **Milling:** To give the third step its required hexagonal shape, a milling machine was employed. The milling operation reduced the diameter of the third step to 8.20 mm and ensured that it had six flat surfaces with equal angles between them, forming a hexagonal shape which is to mate with the alternator fixture.
- **Drilling:** Lastly, a hole with a diameter of 2.9 mm was drilled on the surface of the first step. This hole houses the pin which ensure secure fastening between the pneumatic shaft and this shaft.

Throughout the fabrication process, measurements were taken at critical points using calipers, micrometers, and other precision instruments to ensure that the dimensions met the design specifications. Additionally, visual inspections were performed to check for surface imperfections and defects.

FAIL-SAFE DESIGN

Throughout the project report you have probably noticed two pink cubes in the grid system, and I am sure you are wondering what they are. These cubes:

Figure 35 Custom fail-safe

This section of the report will look at what they are and the design and thinking process behind them. However, if you have gone thoroughly through the report these 'cubes' have been mentioned before, especially in the CAES section of the report.

INTRODUCTION

This comprehensive report explores the intricate process of developing a custom fail-safe system, employing cutting-edge technologies such as 3D printing, precise bulb holder installation, and strategic placement of a Light-Dependent Resistor (LDR). The primary objective is to meticulously detect and respond to phase asynchrony between two lines, effectively mitigating potential operational discrepancies. The fail-safe system adopts a multifaceted approach, not only safeguarding line synchronization but also ensuring the robustness of its components within a specially designed 3D- printed housing.

FABRICATION STEPS

- **3D Printing of a Cube:** The foundational step in the fabrication process involves utilizing 3D printing technology to create a cube with dimensions of 120mm x 120mm x 120mm. This cube serves as the primary housing for the fail-safe system, providing both a shield for its intricate components and a stable platform for subsequent installations. The incorporation of 3D printing technology ensures precision in design and enhances the overall structural integrity of the system.
- **Fixing the Bulb Holder:** The installation of a bulb holder within the 3D-printed cube is a critical stage in the fabrication process. The bulb holder is securely affixed to the internal surface using a combination of suitable fasteners and advanced adhesives. The strategic positioning of the bulb holder within the cube is paramount, poised to illuminate upon the detection of phase asynchrony, as further elucidated in subsequent sections of this report.
- **Fixing the LDR:** Within the confines of the 3D-printed cube, an intricate placement of a Light-Dependent Resistor (LDR) is undertaken. This high-precision positioning near the bulb holder is essential for the LDR to effectively detect changes in light intensity, playing a pivotal role in identifying and responding to instances of phase asynchrony within the fail-safe system.

WORKING PRINCIPLE

The fail-safe system operates on a sophisticated principle aimed at ensuring the synchronization of two lines and preemptively averting operational issues arising from phase asynchrony. Functioning as an integral part of the system, it is actively connected across the lines, continuously monitoring voltage levels. When a deviation from synchronized phase occurs, a discernible voltage differential manifest, triggering the illumination of the strategically placed bulb. This change in light intensity is promptly detected by the Light-Dependent Resistor (LDR), orchestrating the subsequent cascade of events within the system.

The fail-safe mechanism's detection and response capabilities are finely tuned to the nuances of phase asynchrony. As the bulb within the 3D-printed cube illuminates, signaling a deviation from synchronized phase, the LDR adeptly senses the increased light level. This sensitive optical component is intricately linked to a monitoring system, often a microcontroller or a computer equipped with specialized software. The intricately programmed software is designed to discern and analyze subtle variations in light intensity, promptly initiating a pre-defined response mechanism. This not only rectifies the detected phase asynchrony but also diligently ensures the maintenance of synchronization between the two lines, showcasing the fail-safe system's resilience and efficiency in real-world scenarios.

SCADA

In this section of the report we will look at the SCADA(Supervisory Control and Data Acquisition) system we used to remotely monitor the entire grid. During the conception of the SCADA system we used the following objectives as guidelines to creating it:

- To meticulously monitor the CAES system, Mains Grid, and Solar Grid in real-time.
- To curate an interface that displays real-time data and system status accurately.
- To facilitate real-time graphical analysis of voltage changes and energy consumption.
- To create a visual narrative of the power flow and synchronization processes.

INTRODUCTION

The Supervisory Control and Data Acquisition System (SCADA) represents a sophisticated and robust technological framework that plays a pivotal role in the monitoring and control of complex industrial processes. The underpinning architecture of the SCADA system is intricately designed within the contours of a web-based paradigm, meticulously crafted to optimize accessibility and facilitate streamlined maintenance procedures.

BODY

ARCHITECTURE

At the forefront of this technological marvel is the user interface, serving as the crucial nexus connecting operators and administrators with the wealth of intricate system data. This interface is meticulously constructed using a deft combination of web development technologies, including HTML, CSS, and JavaScript. The amalgamation of these front-end technologies ensures not only the responsiveness of the interface but also an engaging and intuitive user experience, thereby enhancing the overall efficacy of the SCADA system.

Beneath the surface lies the backend, functioning as a crucible where data processing and server-side logic converge to orchestrate the seamless operation of the SCADA system. This pivotal backend architecture is powered by a dynamic duo of programming languages, namely PHP and C#, leveraging their respective strengths to execute the intricate tasks required for efficient system management.

DATABASE INTEGRATION

The integration with Firebase Realtime Database stands as more than just a feature within the SCADA system; it serves as the pulsating heart, orchestrating a dynamic symphony of data management that defines the system's unparalleled responsiveness. Far beyond a mere component, this integration is a crucial element that ensures each data point seamlessly mirrors the real-time state of the system, eliminating latency and providing operators with the indispensable capability to make informed decisions instantaneously.

At the core of this integration is the commitment to real-time data synchronization. Firebase Realtime Database excels in its ability to propagate changes in data instantaneously, ensuring that any modification in the system's status is promptly reflected in the database. This rapid synchronization not only minimizes delays but also guarantees that the information presented to operators is consistently up-to-date, enabling them to navigate the complex landscape of industrial processes with precision and confidence.

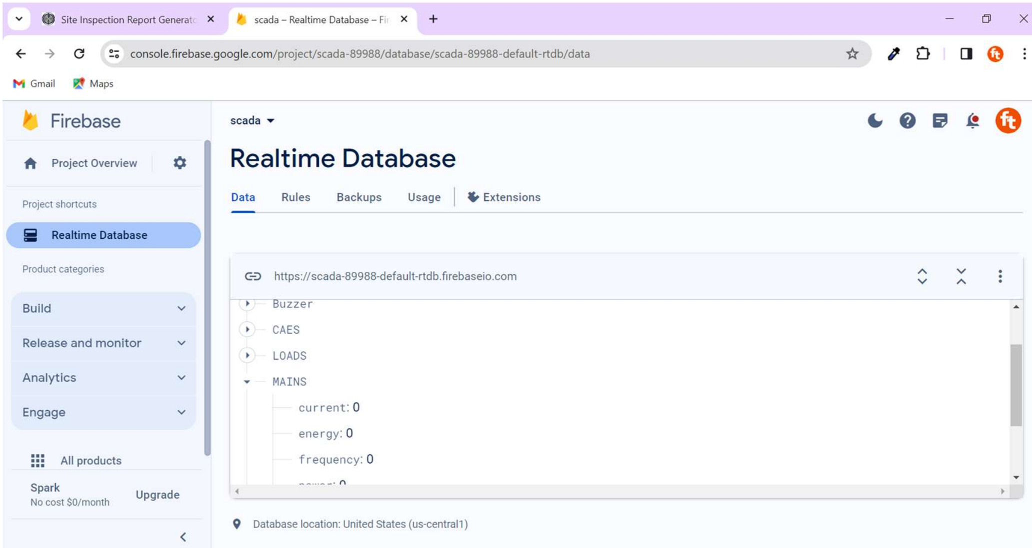

Figure 36 Firebase Realtime database page

Some of the advantages of firebase include:

- **Real-time Database:** Firebase Realtime Database enables real-time data synchronization, ensuring instant updates across all connected devices. Facilitates seamless collaboration and communication in applications requiring live data interaction.
- **Scalability:** Firebase scales effortlessly to handle growing amounts of data and increasing user loads, making it suitable for applications of various sizes. Automatic scaling capabilities accommodate fluctuations in demand, promoting a smooth user experience.
- **Serverless Architecture:** Firebase is a serverless platform, eliminating the need for infrastructure management. Developers can focus on building features without worrying about server maintenance or configuration.
- **Authentication and Security:** Offers robust authentication services with easy integration, supporting various authentication providers.

SYSTEM COMPONENTS AND MONITORING

- **Compressed Air Energy Storage (CAES):** The CAES is a pivotal component in the energy matrix. The SCADA system offers:
  - **Pressure Monitoring:** An intricate algorithm continuously calculates and displays the pressure IN and OUT of the CAES, with sensors providing real-time data feeds. Real-time data feeds from sensors are seamlessly integrated, enabling operators to have an up-to-the-moment understanding of the pressure dynamics within the CAES system.
  - **Voltage Supply:** A dedicated module within the SCADA system captures the voltage output from the CAES, providing operators with a critical understanding of its role in overall grid stability and supply.
- **Solar grid monitoring:** The SCADA system keeps track of the following:

    - **DC Output:** This monitoring feature captures the raw electrical output from the solar panels. It's an essential metric, as it reflects the immediate capturing of solar energy before any conversion or loss.
    - **Inverter Output:** The SCADA system meticulously tracks the conversion of DC to AC power, showcasing the performance of the inverter circuit through metrics such as Voltage, Frequency, and Phase Angle.
    - **Grid Status:** A specialized algorithm evaluates the solar grid's status, determining if it can meet the energy demand and supply power to the load.
- **Mains grid monitoring:** The mains grid is under constant surveillance, with voltage, frequency, and phase angle being measured. The data collected here is pivotal for maintaining system integrity and ensuring the delivery of stable and reliable power.
- **Active grid indication:** A dynamic display system indicates the current grid powering the load, alongside the status of other grids. This is essential for grid management and contingency planning.

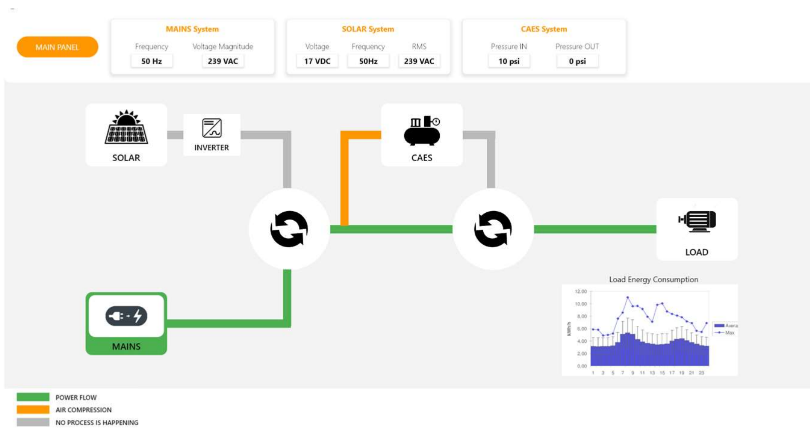

Figure 37 Active grid indication page

VISUALIZATION AND CONTROL FEATURES

- **Real-time Graphs:** Sophisticated graphing algorithms translate voltage and other electrical data into visual formats over various time scales, offering operators both micro and macro perspectives of grid performance.
- **Load Status Animation:** The system uses animated indicators such as lamps that light up or dim to reflect the power supply status, creating an intuitive and immediate visual cue for operational status.
- **Energy Consumption Graph:** These graphical representations provide insights into energy usage patterns, efficiency, and potential areas for conservation.
- **Synchronization Status:** The SCADA system employs complex visualizations to indicate the synchronization status between the MAINS and Solar, and between MAINS and CAES, which is critical for the seamless transfer of power and stability of the overall system.
- **Power Flow Visualization:** The power flow within the system is translated into an animated circuit representation, with active power lines highlighted in green and inactive sections in gray. This serves as a quick, visual reference for system status and power distribution efficiency.

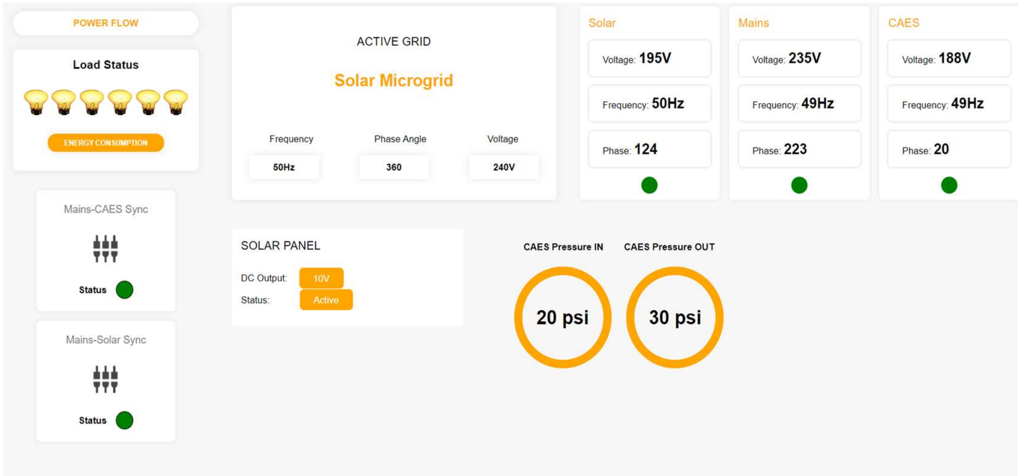

Figure 38 SCADA home page

RTU CONFIGURATION

In our system, the Remote Terminal Unit (RTU) serves as a critical nexus, combining the robust functionality of an Atmega Promini for sensor data acquisition and an ESP32 for seamless communication with the database. This advanced RTU is designed to facilitate comprehensive monitoring across multiple aspects of our energy infrastructure. Here's an overview of the key components and functionalities:

- **Atmega Promini Sensor Interface:** The Atmega Promini, known for its compact size and energy-efficient operation, is dedicated to reading data from various sensors dispersed throughout our energy infrastructure. Specifically, sensors such as the PZEM are integrated to measure essential parameters like voltage, current, power, frequency, power factor, and energy for both the mains and solar lines. The Atmega Promini's capabilities enable precise data acquisition, ensuring accurate and reliable information from these critical points in our energy network.
- **ESP32 Database Communication:** The ESP32, renowned for its versatility and robust connectivity features, takes charge of the communication aspect, bridging the RTU with our centralized database. Leveraging the ESP32's capabilities, the RTU seamlessly transfers sensor data to the database in real-time, enabling a dynamic and up-to-the-moment representation of our energy system. The ESP32's Wi-Fi capabilities ensure a reliable and high-speed connection, facilitating the swift transfer of data between the RTU and the centralized database.
- **PZEM Sensors for Mains and Solar Line:** The inclusion of PZEM sensors in our system allows for comprehensive monitoring of both mains and solar lines. These sensors provide valuable insights into voltage, current, power, frequency, power factor, and energy consumption, offering a holistic view of the performance of our energy sources.
- **Dedicated Voltage and Current Sensors:** For specific components like the Compressed Air Energy Storage (CAES) and the main bus, dedicated voltage and current sensors are employed. These specialized sensors ensure precise measurement of voltage and current in critical areas, contributing to a detailed understanding of the CAES and main bus performance.

The integration of both Atmega Promini and ESP32 enables real-time monitoring and analysis of sensor data. The RTU processes data at the edge, allowing for quick decision-making and reducing latency in the communication with the central database.

Real-time insights empower operators to promptly respond to changes in energy parameters, enhancing the overall efficiency and reliability of our energy infrastructure.

By combining the efficiency of the Atmega Promini for sensor data acquisition and the connectivity prowess of the ESP32 for seamless database communication, our RTU forms a robust foundation for comprehensive monitoring in our energy system. This configuration, along with the inclusion of specialized sensors, ensures that we have a detailed and real-time understanding of the various components contributing to our energy matrix.

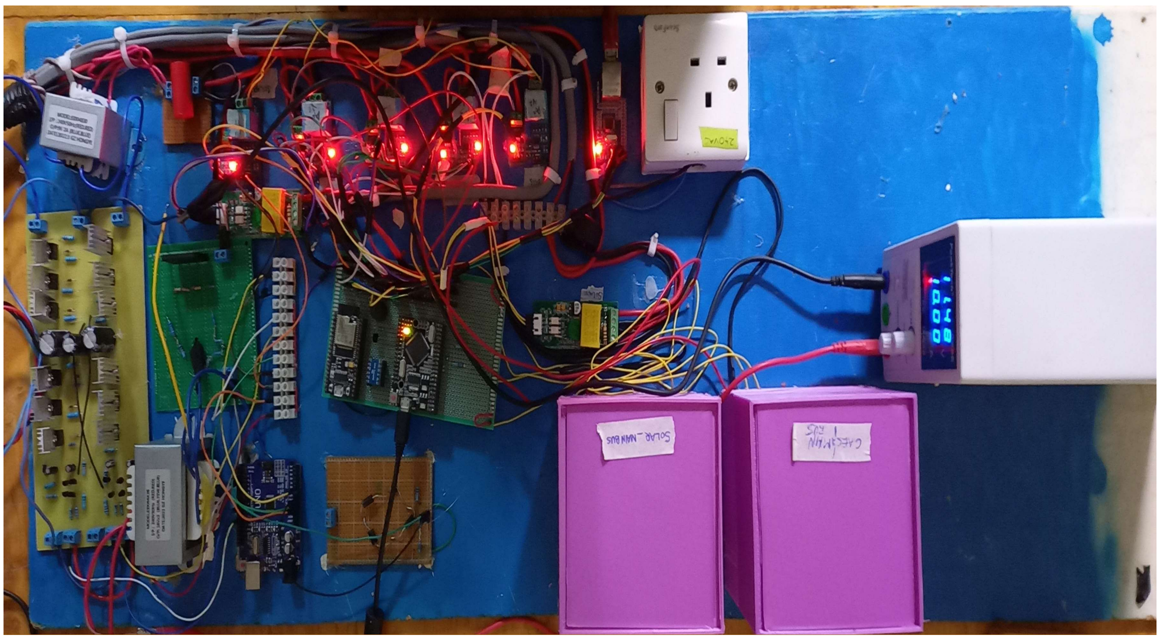

Figure 39 Instrumentation section

CONCLUSION

In conclusion, the successful execution of this project marks a significant milestone in the pursuit of sustainable and efficient energy solutions. The integration of a Smart Grid system, encompassing mains power, solar energy, and a custom Compressed Air Energy Storage (CAES) system, demonstrates the feasibility and potential of a comprehensive approach to address the challenges of contemporary power generation and distribution.

The synchronized operation of diverse energy sources within the Smart Grid attests to the adaptability and reliability of the developed system. The project not only achieved its primary objective of creating a harmonious energy ecosystem but also successfully navigated the intricacies of optimizing power generation, storage, and distribution. The inclusion of a CAES system not only provided an effective means of energy storage but also significantly contributed to grid stability, particularly in managing fluctuations associated with renewable energy sources.

The development of a custom Supervisory Control and Data Acquisition (SCADA) system further enhances the project's impact by providing real-time monitoring and remote accessibility. This feature not only simplifies the management of the Smart Grid but also positions the system as a flexible and scalable solution for diverse applications.

The success of this project underscores the importance of interdisciplinary collaboration and innovative thinking in addressing the pressing challenges of modern energy infrastructure. The outcomes contribute to the broader discourse on sustainable energy solutions, aligning with global initiatives for a cleaner and more resilient power grid.

As we move forward, the insights gained from this project offer valuable lessons and inspiration for future endeavors in the field of renewable energy and smart grid technologies. The accomplishments of this project represent a stepping stone towards a more sustainable and technologically advanced energy landscape, demonstrating the potential for positive change through dedicated engineering efforts and collective innovation.

RECOMMENDATIONS

- **Overall recommendations:**
  - An inspection of the existing wind turbine to identify and address any mechanical or electrical issues. Prioritize repairs and maintenance to restore the turbine to optimal working condition. Ensure that the turbine's control of the systems are updated to meet current grid integration standards.
- **Solar sub-grid recommendations:**
  - Re-design a solar sub-grid circuit that takes 12VDC as input from the DC supply and outputs 220 VAC as the output after stepping up using a transformer.
  - Optimizing the synchronization control algorithm to reduce the losses of voltage and instability in the circuit.
  - Procurement of quality components such as a step-up transformer, and capacitors.
- **CAES sub-grid recommendations:**
  - A big issue in the CAES sub-grid was the fact that when the power produced was at 50Hz the voltage was nowhere near 230Vrms, this was attributed, in part, to the transformer that we were using, this is because we used a step-down transformer in reverse instead of a proper step-up transformer. Thus, the proper transformer should be procured for future implementations.
  - Another hurdle was the compressor we used, which was not nearly large enough i.e. it could not sufficiently run the grid at 50Hz sufficiently. This prompted us to implement the grid at 40Hz which is not ideal. Thus, for future iterations a compressor with a larger capacity in both volume and pressure should be employed.
- **Communication recommendation:**
  - This mainly affected synchronization on the CAES side. This led to problems synchronization errors as discussed earlier. A solution to this would be to use a different communication pipeline, we employed Modbus, or remove the need for communication between the PLC and instrumentation microcontroller altogether by using PLC-compatible sensors.

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