SCHEDULING STRATEGY OF A CLOUD-BASED VIRTUAL ENERGY STORAGE SYSTEM (VESS) FOR ACHIEVING ENERGY SAVING

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Electrical and Electronic Engineering with Honours

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May 2024

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"SCHEDULING STRATEGY OF A CLOUD-BASED VIRTUAL ENERGY STORAGE SYSTEM (VESS) FOR ACHIEVING ENERGY SAVING"** was prepared by **Lau Sim Yee** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Electrical and Electronic Engineering with Honours at Universiti Tunku Abdul Rahman.

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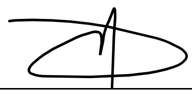
Signature : 

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ABSTRACT

This project emphasizes on seting up an Internet of Things (IoT) monitoring system and scheduling a strategy for the cloud-based virtual energy storage system (VESS) to achieve energy saving. As the cost of energy storage system (ESS) remained high, the application of VESS emerges as a financially viable alternative to manage the energy consumption of flexible loads like air conditioner to reduce the energy usage. This is due to the fact that when the air conditioner toggles one degree higher or lower, it behaves like the charging and discharging of an ESS since the energy consumed will be increased or decreased. The research explores a review of the literature on limitation of ESS, concepts of VESS, role of cloud computing and IoT in VESS as well as the control strategy algorithm. Furthermore, different case studies are conducted to investigate the load profile of the cooling system during both raining and summer seasons. Besides, the case studies also underscore the performance analysis of the PID and Fuzzy PID control algorithms. The results show that the cooling system consume higher energy in the summer season due to the greater ambient temperature. However, the energy consumption of the cooling system can be saved within the range of 17.13 % to 44.9 % and 11.91 % to 44.12 % by utilizing the PID and Fuzzy PID controllers respectively. In addition, the analysis suggests that Fuzzy PID controller contributes to a smaller rise time and higher stability in maintaining the appropriate indoor temperature when compared to PID controller. Overall, the findings highlight that the application of VESS plays a crucial role in managing energy consumption in an economical and effective manner.

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LIST OF SYMBOLS / ABBREVIATIONS

AC	air conditioner
AI	artificial intelligence
BESS	battery energy storage system
ESS	energy storage systems
FESS	flywheel energy storage system
GHG	greenhouse gases
HTES	high temperature energy storage
HVAC	heating, ventilation and air conditioning
IoT	internet of things
IR	Infrared Radiation
LA	lead-acid
LTES	low temperature energy storage
LV	low voltage
MPC	model predictive control
MQTT	message queuing telemetry transport
NaS	sodium-sulphur
O&M	operation and maintenance
PCM	phase change material
PID	proportional-integral-derivative
PV	photovoltaic
RES	renewable energy sources
SBC	single board computer
SoC	state of charge
TCL	thermostatically controlled load
T&D	generation, transmission, and distribution
TES	thermal energy storage
TOU	time of use
VESS	virtual energy storage system

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

In today's modern world, energy is a vital resource that used for a variety of daily services, including transportation, communication and production. However, the rate of energy consumption especially the electricity usage has been increasing significantly since the 1950s (Internet Geography, n.d.). This condition is contributed by factors such as population growth, technological advancement, and economic growth. As a result, energy crisis occurs as the demand for energy often exceeds the available energy supply. To address this challenge, the integration of renewable energy sources (RES) such as wind and photovoltaic power has been promoted to increase the energy supply with minimal environmental impacts. However, the stability and sustainability of electricity supply are not assured due to the intermittent nature of the majority of RES (Cheng et al., 2017). This is where energy storage systems (ESS) is introduced to store and release electricity in response to the system demands (Cheng et al., 2017).

In order to cope with the cost associated with physical installation of ESS, a novel idea known as the virtual energy storage system (VESS) has arisen. According to Barala et al. (2021), VESS is a cutting-edge energy storage system that utilizes an intelligent load management approach to control both thermostatically controlled loads (TCLs) and dynamic loads. Examples of dynamic loads include motor load and household appliances like washing machines which will vary over time depends on the usage. Apart from that, TCLs refers to the loads such as air conditioners (ACs), water heaters and refrigerators, which contribute significantly to the overall energy consumption. By coordinating the TCLs to reduce the energy usage, VESS effectively lowers the overall electricity costs. Furthermore, the potential capabilities of VESS such as providing ancillary services, fast response and having a high adaptability of control strategies, are essential in enhancing the overall effectiveness of the power system.

To effectively manage and supply energy through VESS, key parameters such as power, voltage, current, and power factor within the system are crucial to be monitored for further analysis. However, Sheeba et al. (2021) highlight that the conventional approach of having human inspectors to oversee the meter reading is proved to be time-consuming, inefficient, and error prone. Therefore, the utilization of smart energy meters has become essential to obtain the important reading easily. The data collected will then be visualized through the cloud computing and IoT technology for further analysis. By evaluating the critical readings of the system, the control strategies of VESS can be carried out more precisely. Figure 1.1 demonstrates the overview of a cloud based VESS.

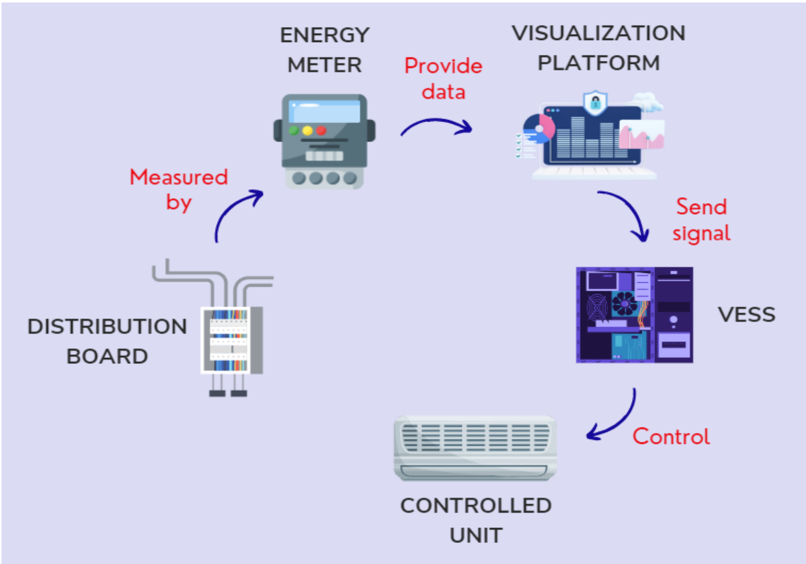

Figure 1.1: Overview of Cloud-based VESS

1.2 Importance of the Study

Over the years, energy crisis has become a major and trending topic of all sectors of society. As efficient energy supply is inevitable, virtual energy storage system (VESS) is one of the solutions to smartly manage and reduce the overall energy consumption, hence mitigating the energy crisis issue. The concept of VESS is encouraged to be introduced into the power grid due to the cost-effectiveness and high flexibility. VESS optimizes the usage of energy by coordinating the existing units in the system according to requirements rather than solely relying on the physical energy storage system (ESS) which has a high implementation cost. This significantly decreases the requirement of large-scale and expensive energy storage installation which needs a periodically maintenance. The removal of physical components also helps to lower the environmental impact as VESS will not contribute to additional gas emission. Moreover, the energy consumption of the system can be reduced by utilising VESS. A smart energy monitoring system enables VESS to monitor and analyse the energy usage over time. By applying strategies such as load forcasting and demand response , the energy usage can be managed by VESS through a controller or artificial intelligence (AI). The VESS in this study will be implemented into a cooling system to reduce the energy consumption and overall electricity cost while ensuring the thermal comfort at the same time.

1.3 Problem Statement

As the energy demand is increasing over time, more fossil fuels are burned to fulfil the requirement of energy need. Consequently, the integration of renewable energy sources (RES) becomes a solution to resolve the issue of fossil fuel depletion. In addition, the benefit of reducing the greenhouse gases (GHG) emission further leads to the growth of RES. However, the intermittent characteristic of RES does not assure the stability and reliability of electricity supply. Therefore, energy storage system (ESS) is proposed to overcome the power quality issues arise from integration of RES. ESS will store the excess energy generated by the RES and release the energy when RES generation is low. Besides, ESS can also store the energy supplied from power grid during the off-peak period and supply energy to the load during the peak load period.

In fact, on top high capital investment, ESS requires additional cost for operation and maintenance, which in turn reduce the overall benefit. At the same time, the raw materials of ESS such as batteries will increase the negative impact on environmental issues if not disposed properly. Additionally, ESS has low flexibility as each type of storage system requires specific component and only applicable to certain applications. For instance, battery energy storage system necessitates batteries and well-suited for high-power applications while other energy storage systems require different raw materials and might not be suitable for high-power application. As a result, a single ESS may not be optimal for a wide range of applications. Hence, a virtual energy storage system (VESS) that eliminates the usage of physical components shows potentials in overcoming the limitations of ESS. Since the concept of VESS is coordinating the existing components, it has a higher flexibility to achieve the objectives such as energy and cost reduction due to the high adaptability of various control strategies.

Nevertheless, smart energy monitoring is crucial in the VESS to ensure the accuracy of data collected for analytic as well as being cost-effective. In order to perform the most precise system coordination, the control strategy and controller used in the VESS should be thoughtfully planned to maximize the effectiveness of the system. The control strategy should be selected by considering the factors such as scalability, complexity as well as the system characteristics. Furthermore, the performance of the developed control strategy should be evaluated to guarantee the efficiency of the system under different scenarios. Ultimately, a proper controller should be constructed to execute the final decision made by the VESS.

1.4 Aim and Objectives

The aim of this project is to develop a scheduling strategy to manage and utilize virtual energy storage system (VESS) for achieving energy saving of a building. The objectives of this study are:

1. To set up an IoT monitoring system for the cooling system.
2. To develop a scheduling strategy with demand response for the VESS to achieve energy saving.
3. To evaluate the effectiveness of the scheduling strategy.

1.5 Scope and Limitation of the Study

The study focuses on the effectiveness of the scheduled strategy for virtual energy storage system (VESS) to cut down the energy consumption and overall expenses. The IoT monitoring system will be developed to monitor and analyse the key metrics required for the decision-making process of VESS. In order to schedule the most appropriate strategy for the VESS employed by the cooling system of Smart Grid Lab, various feasible strategies are considered and evaluated in terms of efficiency, suitability and limitation. Besides, the controller used to adjust the temperature of the cooling system will be constructed by selecting the most suitable components. Once the scheduled strategy is planned and established, the effectiveness of the strategy in energy and cost reductions will be examined.

Apart from that, the limitations of this study include the small-scale of the developed VESS, low number of sensors used and the reliance of VESS on the control algorithm. As the layout of the targeted cooling system in this study is simple and small, the complexity to develop a VESS is low due to the few coordinating unit. As a result, challenges may be arisen when the designed system is implemented in a large-scale and massive power system. Apart from that, the accuracy of the data collected is not assured due to the low number of sensors. As different areas in the experimental environment may contribute to different measured value, the location of the sensor placed will affect the data collected. Hence, the accuracy and performance of the result generated based on the sensor data might be influenced. On the other hand, the accuracy of the control algorithm is not guaranteed especially for a large and complicated power system. The decision generated may be not precise enough, eventually leading to cost increment. This may affect the efficiency and reliability of VESS in optimizing the energy consumption.

1.6 Contribution of the Study

The research of scheduling strategy of a cloud-based virtual energy stotage system (VESS) for achieving energy saving demonstrates a possible cost-effective solution to reduce the energy usage without implementing a energy storage system (ESS). By implementing a small-scale VESS alongside with the IoT monitoring system in the smart grid laboratory, the advantages of utilizing cloud computing and IoT technologies in the VESS are highlighted. Secondly, the evaluation of control strategy algorithms used in the VESS shows the potential of different algorithms in achieving energy efficiency. The performance analysis for different case studies underscore the energy consumption used by the cooling system with and without VESS, providing essential practical insights of the potential of VESS. In summary, the study suggests a low-cost VESS control strategy to improve the energy management of a small-scale system, laying a strong groundwork for the future integration of VESS into a large-scale system.

1.7 Outline of the Report

The report is organized and divided into 5 main chapters, analyzing different aspects of the research. The first chapter provides a general introduction and problem statement of the background of project. Besides, the importance, scope, limitation and the contribution of study are also highlighted in chapter 1 to strengthen the reader's understanding of the study. Next, chapter 2 focuses on the literature review related to the research. This chapter explores the study in conventional energy storage system (ESS), concept of virtual energy storage system (VESS), role of cloud computing and IoT technologies, as well as the control strategies of controller. Then, the system design and hardware implementation will be discussed in chapter 3. This chapter consists of the chosen hardwares, circuit connection of prototypes and the algorithm flowcharts for the subsystems of VESS designed. Furthermore, the performance of the system designed will be analyzed in chapter 4. The analysis will be emphasized on the IoT monitoring system and the energy consumption of system with and without VESS. Last but not least, a comprehensive summary will be highlighted in chapter 5, while the recommendation for future work will also be provided to enhance the effectiveness of VESS.

CHAPTER 2

LITERATURE REVIEW

2.1 Energy Storage System (ESS)

An energy storage system (ESS) can be designed based on various innovative technologies to maintain the balance between energy demand and energy generation. The most popular ESS applications including peak shaving, optimizing building energy systems and utilizing renewable energy sources (Das et al., 2018). However, the characteristics such as storage capacity, response time, efficiency, and cost of these different technologies are essential to be thoroughly investigated and evaluated to determine the most suitable energy storage system for the targeted power system according to the specific requirements. The basic concept of energy storage system is shown in Figure 2.1. Interface refers to a device or program that enables the electrical energy to be stored in certain form where the control system will make decision on charging or discharging the energy.

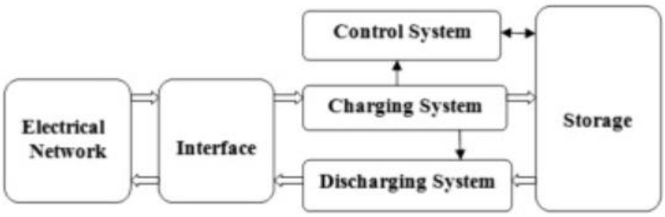

Figure 2.1: Basic concept of energy storage system (Akinyele and Rayudu, 2014a)

2.1.1 Battery Energy Storage System (BESS)

Battery energy storage system (BESS) is an advanced technology that transforms and stores the electrical energy supplied from the power grid or renewable sources such as solar and wind into chemical energy (Enelx, n.d.). Multiple electrochemical cells that consist of an anode, cathode, and electrolyte are comprised in this system. As shown in Figure 2.2, the battery of BESS accumulates energy during the charging phase and releases it during the discharging phase. Furthermore, battery types in a BESS can be classified into primary batteries and secondary batteries. Primary batteries are designed for single use as they are non-rechargeable whereas secondary batteries provide many kinds of electrode and electrolyte materials while being rechargeable (Mitali et al., 2022). The secondary batteries like lead-acid (LA) batteries, sodium-sulphur (NaS) batteries, and lithium-ion batteries are the most often used batteries in building up a BESS.

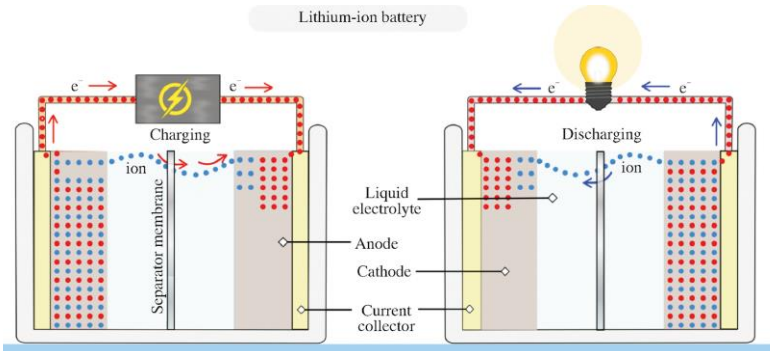

Figure 2.2: Charging and discharging process of battery (Mitali et al., 2022)

Battery energy storage system (BESS) is highly adaptable since it may be used in a variety of applications in power systems. Frequency control is known as one of the most important applications where grid-connected BESS will inject or extract frequency-dependent power to restore grid frequency during disruptions for the sake of maintaining the stability of power system (Zhao et al., 2023). On the other hand, Zhao et al. (2023) mentions that BESS can also be used to support peak shaving, energy arbitrage, bill reduction and backup solutions. These assist in reduction of peak electricity consumption and overall optimization of power system performance. Figure 2.3 shows that the charged BESS will be discharged during the peak load period to achieve peak shaving for cost reduction.

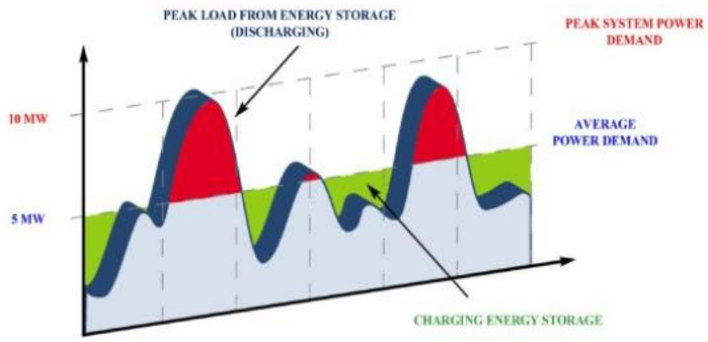

Figure 2.3: Load profile with integration of BESS (Tagayi and Kim, 2022)

2.1.2 Thermal Energy Storage (TES)

Thermal energy storage (TES) system is specifically designed to store thermal energy through various methods such as chilling, condensing, heating, or melting substances (Mitali et al., 2022). These substances will be kept in well-insulated storage facilities at either low or high temperatures while the energy recovered can be used for numerous applications. The example of thermal energy storage process is illustrated in Figure 2.4. Based on the operating temperature range, TES systems are frequently utilized for a variety of tasks. The examples of task including industrial cooling below -18°C and heating buildings between 25°C and 50°C. Moreover, TES systems can be divided into high temperature energy storage (HTES) and low temperature energy storage (LTES) systems, based on the operating temperature of the stored substance (Akinyele and Rayudu, 2014b).

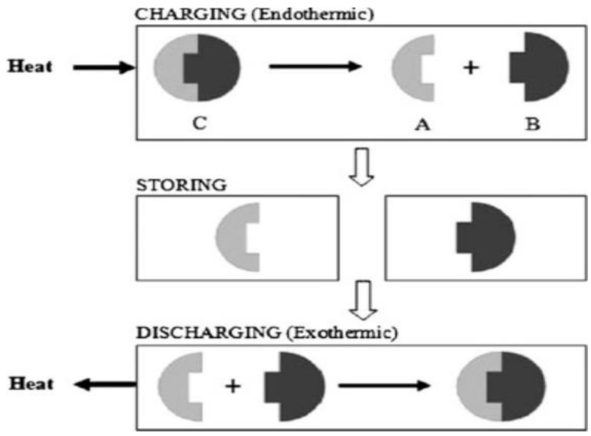

Figure 2.4: Process of thermal energy storage (Aneke and Wang, 2016)

Thermal energy storage (TES) system is frequently employed in applications such as heating, ventilation and air conditioning (HVAC) system, equipment cooling and waste heat recovery (Tawalbeh et al., 2023). The most widely used thermal energy storage technology is the sensible heat storage that utilizing a collector to collect the waste heat produced and transmit it to the appropriate stored materials. Additionally, Tawalbeh et al. (2023) further claims that TES play a crucial role in enhancing indoor comfort and peak load shifting of a building by utilizing the phase change material (PCM) that has a high thermal inertia in thermal food production, transportation and cooling system.

2.1.3 Limitation and Drawback of ESS

As conventional energy storage system (ESS) greatly contributes to the energy demand reduction, the limitations and drawbacks associated with ESS should be evaluated to determine the efficiency of a storage system. The critical challenges such as suitability of ESS for different power system, evaluation of technical and economic benefits as well as the cost required for ESS installation that will significantly reduce the effectiveness of ESS have become a big concern (Luo et al., 2015).

For instance, the primary drawback of BESS is the relatively short service life that requires periodically maintenance to ensure optimal performance and reliability. A substantial problem of high space requirement is also brought up as the installation of BESS requires a high area especially the large-capacity BESS. As reported by PILLER Power Systems (n.d.), the concern on efficiency of BESS is raised as up to 60% of power outages can be attributed to defective batteries.

Additionally, certain barriers such as stability and properties of materials utilized, complexity of system design and cost considerations need to be emphasized to determine the performance of TES systems (Celsius, 2020). The cost of storage materials, operating expenses, service charges, and the technical equipment needed for charging and discharging process are all taken into account in the anticipated cost of TES systems. Hence, the investment in TES system can be easily affected according to the wide range of performance.

These shortcomings highlight the importance of ongoing research and development initiatives to tackle the challenges and enhance the overall functionality and efficacy of the conventional ESS.

2.2 Virtual Energy Storage System (VESS)

2.2.1 Concept and Potential of VESS

Virtual energy storage system (VESS) functions similarly to an energy storage system (ESS), but with intelligent management of energy use across numerous units within the system. As described by Oh and Son (2022), VESS behaves like a collective collection of multiple energy storage resources that provides energy to smaller units when needed. The energy storage resources may refers to the thermostatically controlled loads (TCLs) like the cooling system or dynamic loads. This method enables VESS to effectively satisfy the system's energy requirements by offering greater energy capacity as compared to the individual ESS. In fact, VESS can operate individually or operate jointly with other ESS according to the requirements. As stated by Niromandfam, Movahedi Pour and Zarezadeh (2020), the joint operation of VESS and various type of ESS enables the optimization of efficiency and profit due to several benefits of VESS, such as low capital cost and fast response.

VESS has arisen as a prospective replacement for conventional ESS or as an additional aiding system for ESS due to its enormous potentials. By utilizing VESS, the power system can achieve significant cost-effectiveness and demand reduction, at the same time improving the power system's overall efficiency. One of the biggest benefits of VESS is its adaptability of control techniques, which enables intelligent energy consumption management. The control strategies like tracking electricity prices, monitoring user behaviour and forecasting future energy consumption patterns allow VESS to significantly reduce electricity expenditures and cut back on energy demand.

Furthermore, VESS has attracted an increasing amount of attention in the energy sector due to its special ability to function without employing any physical components. It is a cost-effective option because this feature eliminates the need of materials purchase and the related maintenance expenses while provide the same function as compared to the ESS. The lack of physical components also enables VESS to be environmentally friendly as it does not produce any additional gas emissions. Apart from that, VESS has a fast response time which is helpful in providing ancillary service such as voltage support and frequency regulation during the emergency conditions (Cheng et al., 2017). The discussed potentials of VESS are summarized in Figure 2.5.

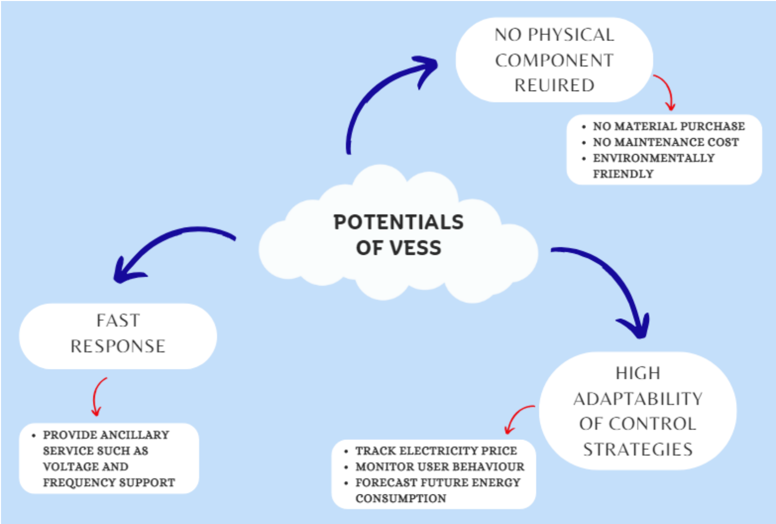

Figure 2.5: Summary of Potentials of VESS

2.2.2 Challenge of VESS

As the potentials of virtual energy storage system (VESS) significantly contribute to the energy sector, the limitations and obstacles of VESS should be considered to enhance the overall system efficiency. Barala, Mathuria and Bhakar (2021) state that the considerable technological and socioeconomic issues are the obstacles to the implementation of VESS. To increase the efficiency of VESS, challenges like data management and cybersecurity should be tackled. As VESS is mostly depending on the real-time data for decision making, the time delay or technical issue occur during the process of data collection will highly affect the effectiveness of VESS. Besides, the existing approved policies and regulations encounter problems such as insufficient to achieve economic incentives and getting enough funding (Barala et al., 2021). Hence, the development of the policies and regulations plays an essential role for the further development of VESS. In brief, it is crucial to overcome the restrictions and challenges of VESS in order to take full advantage of this innovative technology.

2.2.3 Application of VESS

According to Xie, Hui and Ding (2019), virtual energy storage system (VESS) utilizes various control strategies to assist the power charging and discharging process in main grid and microgrid. Main grid refers to the country's integrated power delivery system which supply electric power to the consumers. VESS plays an important role to regulate the frequency and voltage of the main grid to ensure the stability and reliability of power distribution. This approach avoids the lifespan of generators and compensation devices to be shorten due to frequent adjustments. Besides, microgrid is a conventional generation and distribution system that can be operated independently or attached to the main grid (Sun et al., 2019). It normally comprises components such as distributed generator, energy storage devices, controllable loads and uncontrollable loads. The main contributions of VESS in microgrid including smoothen the power fluctuation and lower the overall operating expenses. The examples of the applications of VESS are shown in Table 2.1.

Table 2.1: Examples of Applications of VESS

Application	Strategy	Details	Reference
Frequency Regulation	Coordination control strategy based on frequency set-points and state of charge (SoC) priority list	• FESS is used in VESS • Control the units in VESS to store and release energy	(Cheng et al., 2017)
Voltage Regulation	Hierarchical dispatch strategy	• Low level: Control TCLs • High level: Exchange information of required power adjustment	(Wang et al., 2018)
Cost reduction	Coordination control strategy based on switching model and time of use (TOU) price	• Control TCLs	(Barala et al., 2019)

Peak shaving and power balancing	Coordination control strategy based on state of charge (SoC) priority list	• BESS is used in VESS • Control BESS and TCLs	(Burgio et al., 2023)

2.2.3.1 Frequency Regulation

The main grid frequency can be regulated within the steady-state limits by assigning a maximum and minimum frequency set-points for each unit in the VESS (Cheng, Sami and Wu, 2017). In this case, flywheel energy storage system (FESS) is used in VESS to store and release the energy according to requirements. When the input frequency is noticed to be above or below the preset values, the respective unit within the VESS will take action by either discharging or charging the power. In order to increase the lifetime of the units within VESS, the charging and discharging process will be carried out based on the state of charge (SoC) priority list. This significantly reduces the charging and discharging cycles as multiple units will not discharge at the same time.

2.2.3.2 Voltage Regulation

A hierarchical dispatch strategy developed to control voltage regulation in low voltage (LV) grids by efficiently utilizing the virtual energy storage systems (VESSs) is introduced by Wang et al. (2018). In this case, the thermal buffering capacity of air-conditioned houses act as the VESSs used in the residential houses. To successfully regulate the voltage, this technique combines distributed control at the top level and localized control at the lower level. A detailed VESS model is created at the lower level to precisely represent the dynamic behaviour of an air-conditioned household (Wang et al., 2018). In addition, the higher level control uses a distributed control strategy to exchange the information of required active power adjustment among the aggregators to guarantee fair voltage regulation across the feeders (Wang et al., 2018). When the feeder voltage exceeds certain predefined limits, the proposed strategy will take action by controlling the thermostatically controlled loads (TCLs) to maintain the system stability. Figure 2.6 shows the voltage profile of a case study using the proposed technique to utilize VESS in voltage regulation.

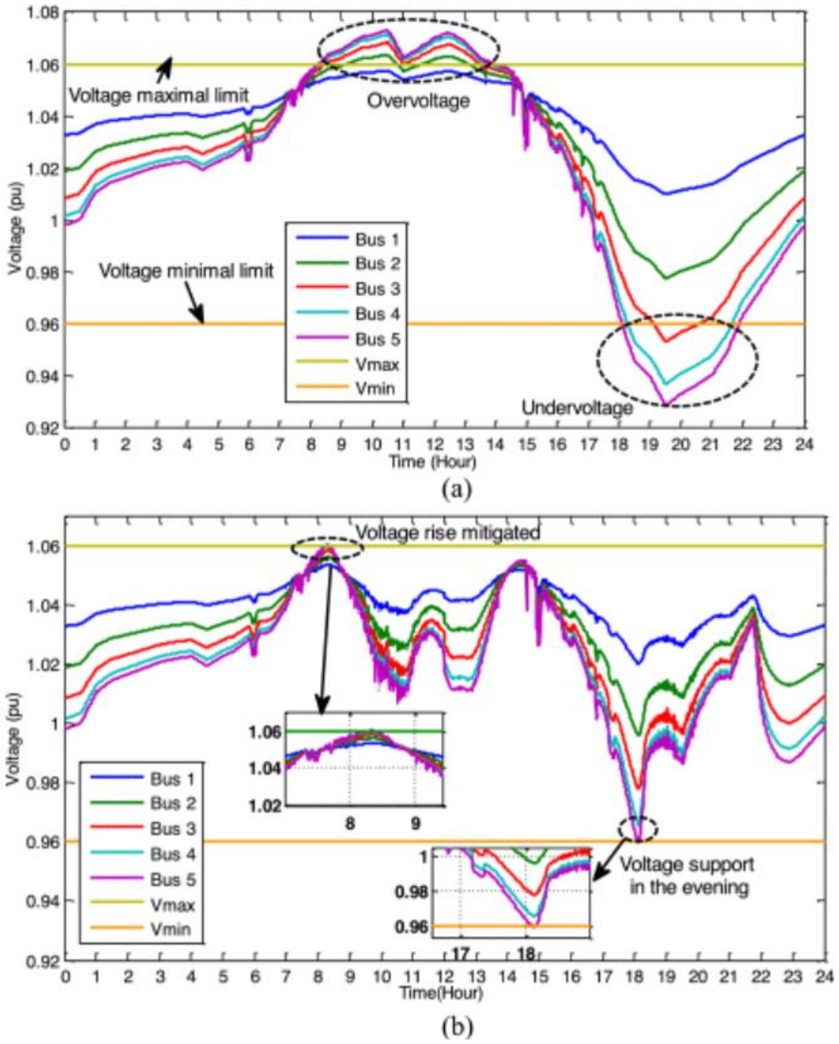

Figure 2.6: Voltage Profile of One Day (a) Voltage Profile without Control (b) Voltage Profile with Proposed Technique (Wang et al., 2018)

2.2.3.3 Cost Reduction

In 2017, a residential building in Jaipur, Rajasthan utilized virtual energy storage system (VESS) aggregator to reduce the electricity cost (Barala et al., 2019). Linear and nonlinear switching models were used to forecast the power consumption of the thermostatically controlled loads (TCLs) for the purpose of optimal analysis. In order to manage the energy consumption, VESS will control the actions of charging and discharging power from TCL. As a result, the system will consume energy when the price of electricity is low and utilize energy released from VESS when the price is high (Barala et al., 2019). Figure 2.7 demonstrates that VESS will regulate the interior temperature from 20.5°C to 24.5°C depending on the situation while the desired interior temperature in this case study was set as 22.5°C. Based on the report of Barala et al. (2019), VESS shift the load from peak hours to off-peak hours by altering the interior air temperature according to the time of use (TOU) price as shown in Figure 2.8. The electricity cost of the residential building illustrated in Figure 2.9 serves as evidence that implementation of VESS successfully reduce the daily expenses of $41.04 for the consumers.

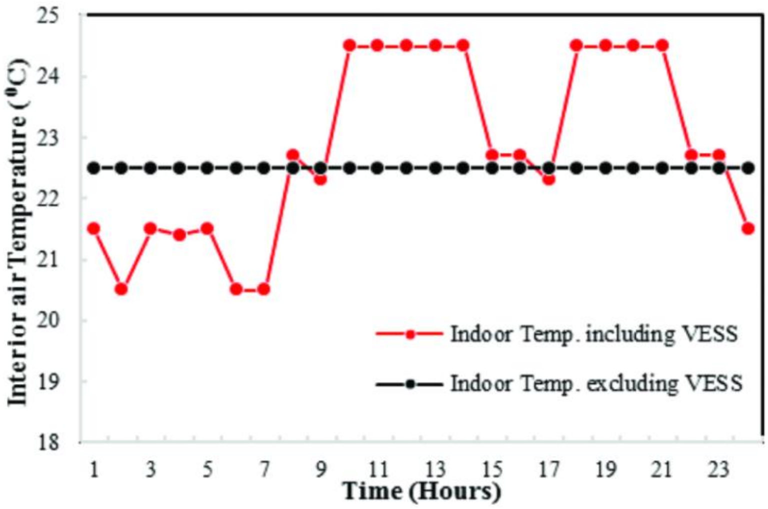

Figure 2.7: Interior air temperature with and without VESS (Barala et al., 2019)

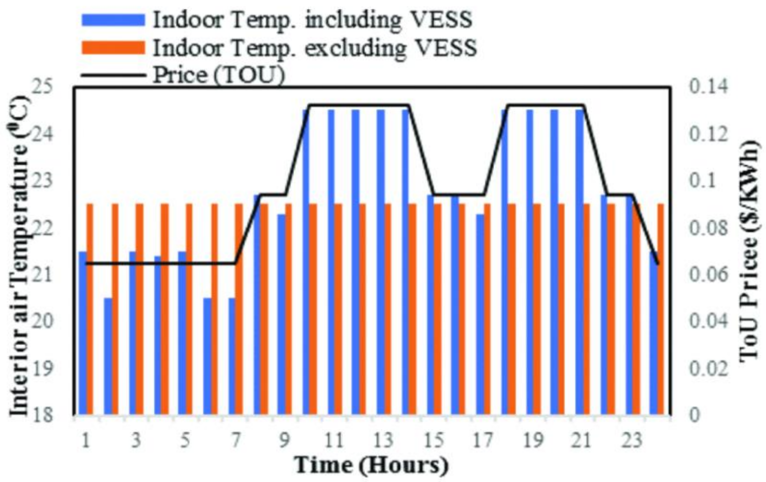

Figure 2.8: Interior air temperature and TOU price with and without VESS (Barala et al., 2019)

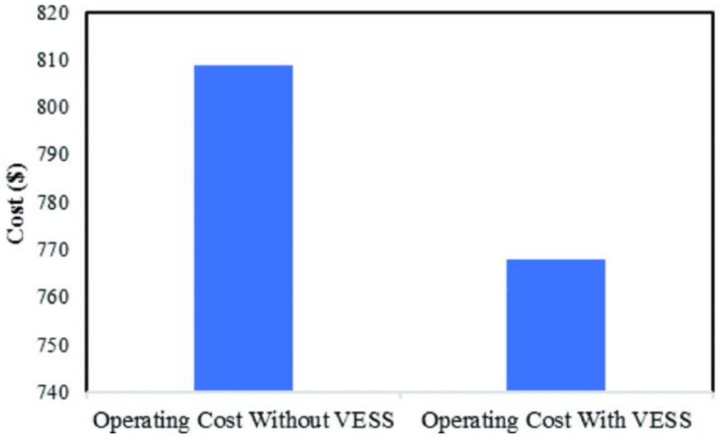

Figure 2.9: Electricity cost with and without VESS (Barala et al., 2019)

2.2.3.4 Peak Shaving and Power Balancing

According to the research, (Burgio et al. (2023) proposed a coordinated control of a large virtual energy storage system (VESS) which made up by 21 residential buildings with 168 apartments. All the apartments are installed with a battery energy storage system (BESS) and a 1.5 kW air conditioner. The proposed control strategy aims to provide the peak shaving and power balancing services to the grid operator, which is a MW photovoltaic plant. In this case study, peak shaving is attained by controlling the recharging of the residential BESS and the thermostat of the air conditioner (Burgio et al., 2023). In fact, these control actions successfully reduces the power fluctuation of the photovoltaic (PV) plant as well. The load demand of VESS before and after both services is shown in Figure 2.10.

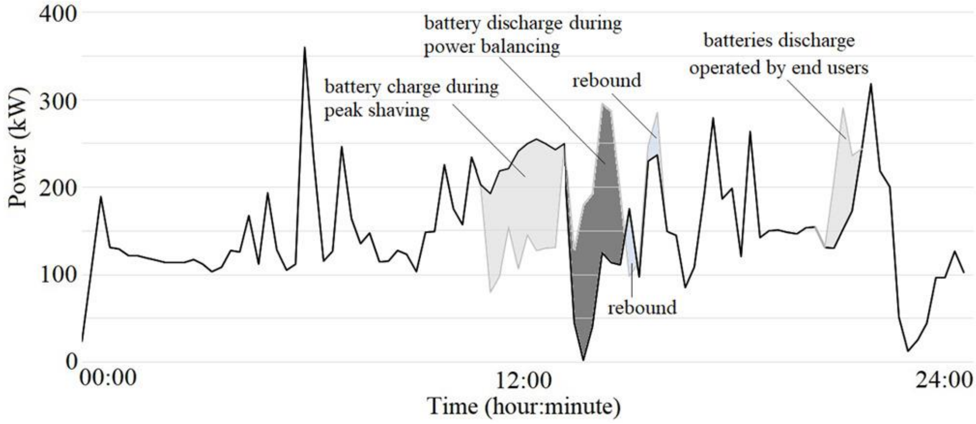

Figure 2.10: Load Demand of VESS Before and After Both Peak Shaving and Power Balancing Services (Burgio et al., 2023)

2.2.4 Cloud Based VESS

2.2.4.1 Cloud Computing and IoT

Cloud computing is a data processing approach that simplifies the usage and access of services, applications, storage and computing over the internet (Motlagh et al., 2020). The handling of data transmitted from internet of things (IoT) devices depends significantly on cloud computing technology. According to Biswas and Giaffreda (2014), IoT devices cover a wide variety of interconnected components such as sensors, cell phones, actuators, computers, buildings and automobiles. In fact, cloud computing combines both hardware systems located in data centers and accessible application services over the internet, enabling efficient large-scale data processing and offering high capabilities for complicated computations. Significant cost reduction, reliable data management and high-security standards can be accomplished by the system when utilizing cloud computing with high computational power, high storage capacity and eliminate the hardware investments (Motlagh et al., 2020). These characteristics of cloud computing empower effective analysis, management, and organization of the enormous volumes of data produced by the IoT applications. Figure 2.11 demonstrates the access of application to the data collected from IoT devices through cloud computing.

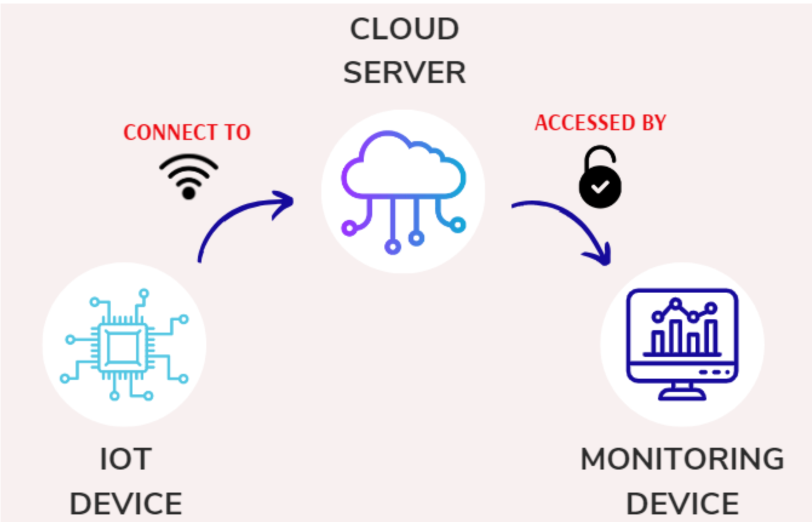

Figure 2.11: Integration of Cloud Computing and IoT Device

2.2.4.2 Role of Cloud Computing and IoT in VESS

The utilization of internet of things (IoT) assists in monitoring and managing various components in the power system by enabling the seamless integration of sensors, actuators and controller. For instance, the sensors integrated within IoT devices utilizing cloud server for computing purpose has proven to be a potential tool in the field of smart energy management systems to achieve energy-saving (Naqbi et al., 2021). These sensors enable real-time analysis to carry out energy optimization and provide new possibilities for efficient energy load management. In brief, Naqbi et al. (2021) highlight that the energy management has been significantly improved in aspects such as analytics, decision-making as well as the optimization processes by the use of sensor devices in IoT systems. This proves that by utilizing cloud computing and IoT devices in VESS, effective and sustainable energy practices can be developed to achieve a greener and better energy future.

Furthermore, IoT-enabled operation and maintenance (O&M) can greatly enhance the reliability and effectiveness of generation, transmission, and distribution (T&D) assets (Ramamurthy and Jain, 2017). On the operational side, IoT implementations result in an overall reduction of fuel consumption and gas emissions, at the same time increase the flexibility in generation. A typical example is using the smart meter network to decrease the non-technical losses. On the maintenance side, IoT plays an essential role in predictive maintenance, condition monitoring, and maintenance of assets (Ramamurthy and Jain, 2017). This innovative approach allows costs reduction and asset reliability improvement when utilized in VESS as it avoids assets failure due to high usage rate. Motlagh et al. (2020) also claim that IoT and cloud computing prevent the power system from having fault maintenance to minimize the maintenance time and safety issue. This will boots the troubleshooting speed of the defects discovered in VESS to guarantee the stability of the system.

The benefits of cloud computing and IoT in VESS are summarized in Figure 2.12.

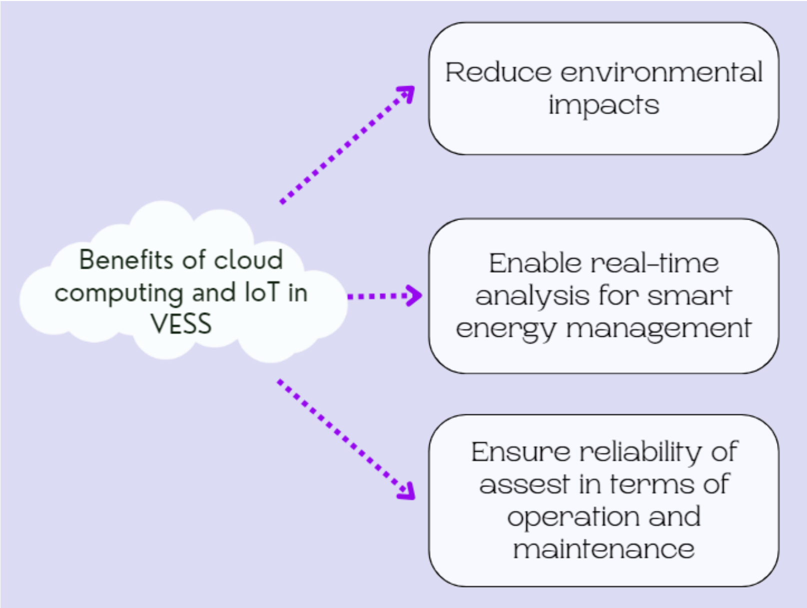

Figure 2.12: Benefits of cloud computing and IoT in VESS

2.3 Control Strategies of Controller

2.3.1 ON/OFF Control System

The ON/OFF control system is one of the inexpensive and most commonly used methods in controlling the temperature of air-conditioning system (EATON, n.d.). The working principle of the ON/OFF control system is to turn on and off the power according to the requirements. When the temperature or pressure is detected to be lower than the desired setpoint, the power will be turned on to ensure that energy is supplied to the HVAC system (EATON, n.d.). In contrast, when the temperature or pressure exceeds the preset value, the power will be turned off until the value drops back to the hysteresis setpoint. The illustration of the ON/OFF control system is shown in Figure 2.13. Even this simple and inexpensive method successfully reduces the energy consumption of the HVAC system, the frequent adjustment of component may lead to a reduction in lifetime.

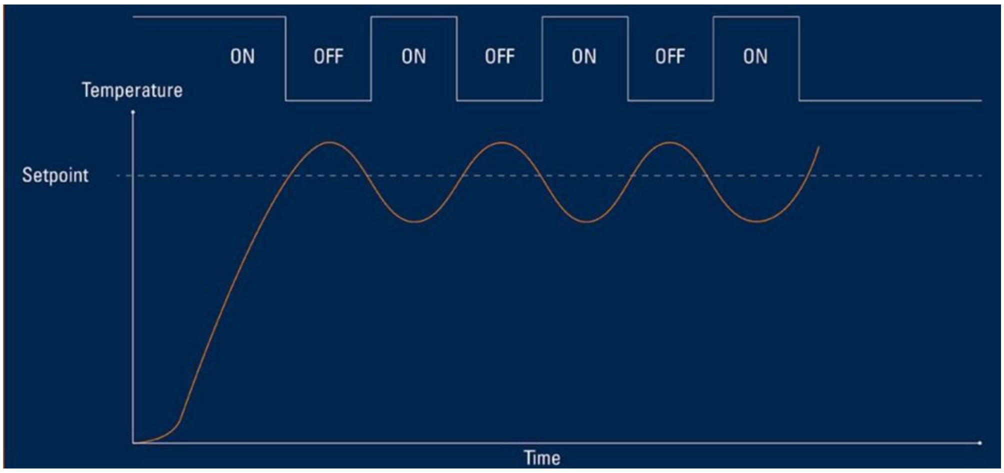

Figure 2.13: ON/OFF Control System of HVAC (EATON, n.d.)

2.3.2 Model Predictive Control (MPC) Algorithms

According to the study by Taheri, Hosseini and Razban (2022), model predictive control (MPC) algorithms are critical in enhancing the efficiency of building by anticipating the thermal behaviour. The primary goals of this algorithm include reducing energy consumption and maximizing utility time. In fact, the combination of both numerical optimization concepts and feed forward control allows MPC to precisely predict the control trajectory of a particular process (Taheri et al., 2022). The feed forward control of MPC permits the correction of quantifiable disruptions like rate of occupancy and weather forecasts to prevent the control algorithms from being affected by the disturbances.

A typical MPC consists of both predictive model and optimization model to generate the optimal control. In order to predict the future state precisely, the prediction and control horizons as indicated in Figure 2.14 should be selected meticulously to ensure the accuracy of the predictive model (Taheri et al., 2022). After that, an optimizer model is developed to obtain the optimal control sequence by tackling the optimization problems according to the input and performance requirements. The generated control action will be applied to the system and the current state of the system will be updated as well. These processes will repeat and only terminate when the predefined termination condition is met.

By utilizing MPC algorithms, the future responses such as air temperature and thermal comfort level can be forecasted to facilitate the energy and cost reduction. Taheri, Hosseini and Razban (2022) also highlight that the usage of MPC has been shown to successfully cut down the energy usage by a range of 25% to 65% as compared to the conventional on and off control technique. However, developing a MPC algorithm can be time consuming and complex as it requires a high computational resource.

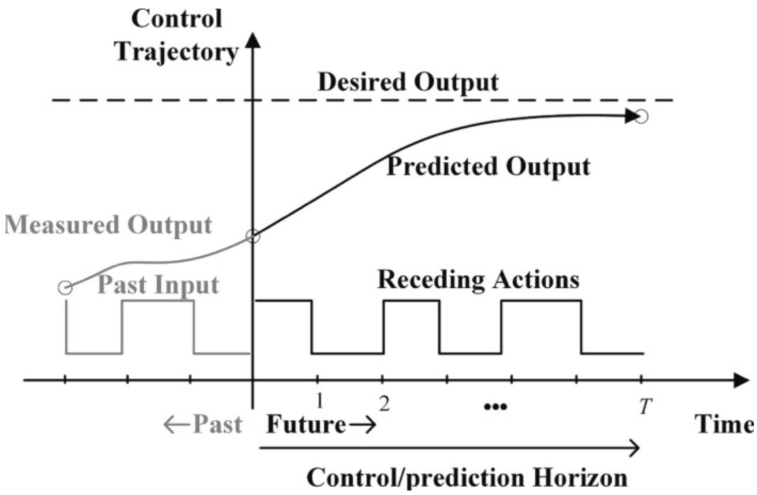

Figure 2.14: Control Scheme of MPC (Taheri et al., 2022)

2.3.3 Fuzzy PID (Proportional-Integral-Derivative) Control

As conventional approach like ON/OFF control system is not highly effective and the advanced technique like model predictive control (MPC) algorithm is time-consuming to be developed, the intermediate approach such as proportional-integral-derivative (PID) control is often used to reduce the energy consumption of the cooling system. However, Xie et al. (2022) state that the arisen limitations such as large overshoot and slow response of the conventional PID control algorithm can be further improved with the integration of fuzzy logic principles. According to Hellmann (n.d.), fuzzy logic acts as a human-like thinking to evaluate the intermediate value in between true/false or high/low. Hence, the constant parameters of the traditional PID algorithm can be changed dynamically and thus contribute to the self-adaptation by utilizing a fuzzy PID control algorithm.

Figure 2.15 illustrates the overall structure of the fuzzy PID controller where K_e and K_{ec} are the error and change in error that act as the inputs, K_1, K_2 and K_3 are the initial proportional factors of the PID controller while ΔK_p, ΔK_i and ΔK_d are the modification of PID's parameters (Xie et al., 2022). The condition of the system will be represented by linguistic variables which relates the relationship between the desired and actual values. Each linguistic variable will be assigned with a membership function to determine the strength of the present value relates to the linguistic variable. Then, the fuzzy rules in the fuzzy PID controller will make decision on the adjustment of control action according to the linguistic variables. As the gain parameters of the PID are modified, the final control action will be calculated and applied to the targeted system. While being effective in reducing the energy usage of the system, this control strategy is relatively flexible as the real-time control will have a faster response due to the less computational complexity.

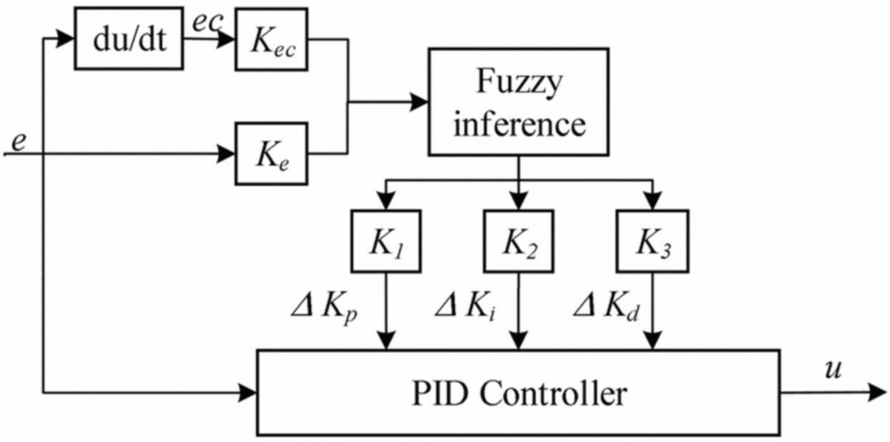

Figure 2.15: Structure of Fuzzy PID Controller (Xie et al., 2022)

CHAPTER 3

SYSTEM DESIGN AND HARDWARE IMPLEMENTATION

3.1 Introduction

The project aims to schedule a strategy for cloud based virtual energy storage system (VESS) to achieve energy saving in the Smart Grid Laboratory. The whole project involves three subsystems: data acquisition subsystem, temperature measurement subsystem and load controller subsystem.

3.2 Overview of cloud based VESS

Figure 3.1 illustrates the overview block diagram of the VESS. The data acquisition subsystem will collect the reading from the distribution board using the AWD300 wireless IoT meter and visualize the data collected using Node-RED. Moreover, the outdoor temperature measurement subsystem aims to measure the outdoor temperature and humidity with DHT22 temperature sensor and ESP32 microcontrollers. At the same time, the indoor temperature and humidity will be measured by the DHT22 temperature sensor in the indoor load controller subsystem. Before constructing the indoor load controller, an IR receiver module and ESP32 microcontroller will be utilized to obtain the required information for the controller configuration. Furthermore, the developed hybrid Fuzzy-PID control algorithm will be installed in the single board computer (SBC), which is the Raspberry Pi 4 Model B to perform decision-making with the aids of data from other subsystems. Then, the control signal will be sent to the indoor load controller which consists of the ESP32 microcontroller and IR transmitter module to control the air-conditioner.

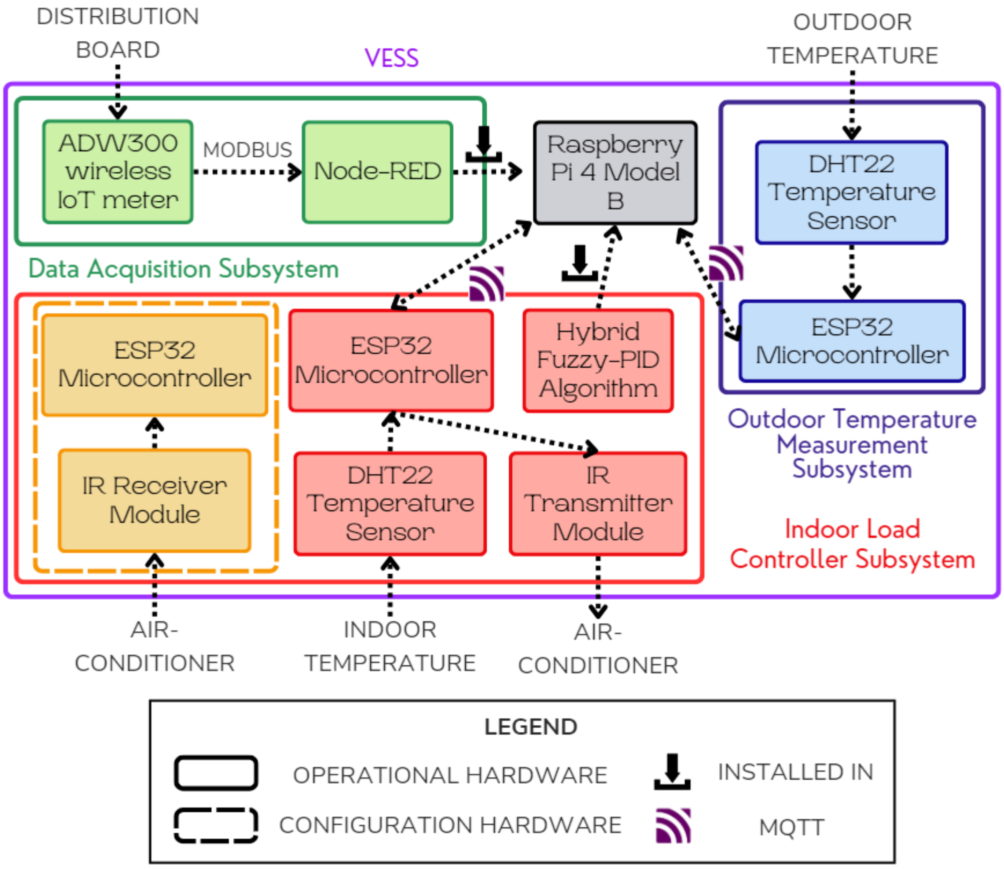

Figure 3.1: Overview of Cloud Based VESS

3.3 Data Acquisition Subsystem

3.3.1 Installation of Smart Energy Meter

Figure 3.2 shows the ADW300 wireless IoT meter used to measure the key parameters such as voltage, current and power of the desired air-conditioning system. The installation of the ADW300 meter is easy and fast as it is connected to the targeted 3-phase cables in the distribution board via 20/5A slpit core current transformer for each phase and a few wires as shown in Figure 3.3. The inputs 1 and 2 of ADW300 wireless IoT meter are used to obtain the power supply for the meter. Additionally, the meter measures the current value of the three phases utilizing inputs 4 to 9 whereas the voltage of each phase is measured through input 11 to 14. The 5 A of the connected live wires indicates the maximum allowable current of the input of ADW300 wireless IoT meter.

Figure 3.2: ADW300 Wireless IoT Meter

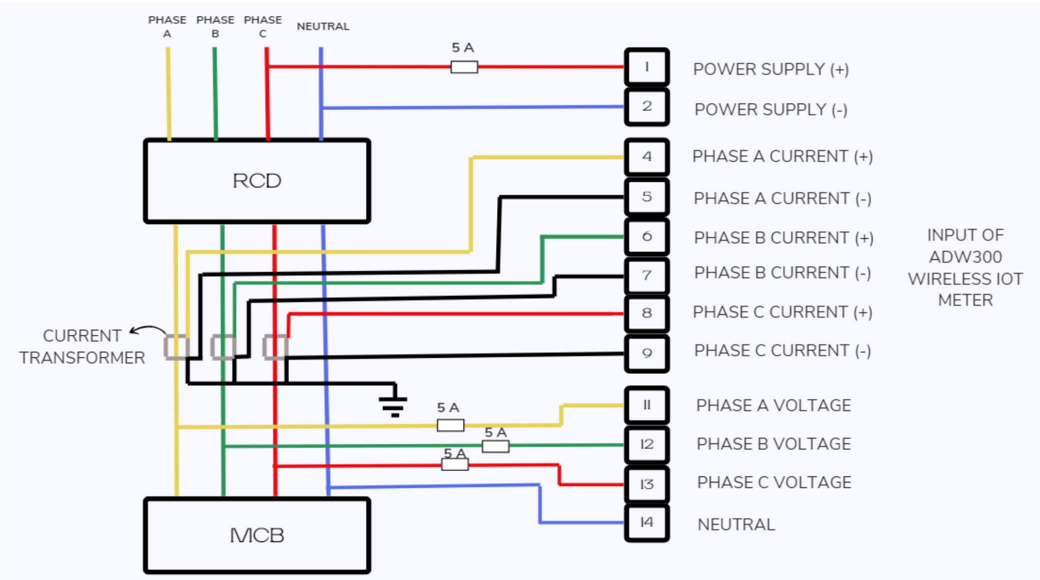

Figure 3.3: Wire Connection of 3-Phase Circuit and ADW300 Wireless IoT Meter

3.3.2 Data Acquisition and Data Visualization

ADW300 meter supports various wireless communications methods such as WIFI, LORA, NB and 4G communications. This increases the flexibility of access methods for the user to access the value measured by the meter. In this project, the ADW300 meter's adaptability in Modbus protocol enables the communication between ADW300 and a programming tool named Node-RED as shown in Figure 3.4 through RTU and TCP/IP modes.

Figure 3.4: Logo of Node-RED

Node-RED is a flow-based programming tool which enables the wiring of hardware devices, online services, and APIs in fascinating ways (Node-RED, n.d.). It can be installed and run locally on a computer, device as well as the cloud. Node-RED supports the browser-based flow editing which is convenient as it can be accessed through any browser and provides an ideal run-time environment for the event-driven application. In this project, Node-RED Dashboard which is a free downloadable plug-in of Node-RED will be used to visualize the data collected from the ADW300 wireless IoT meter to enable real-time monitoring. The example of data visualization utilizing Node-RED dashboard is displayed in Figure 3.5.

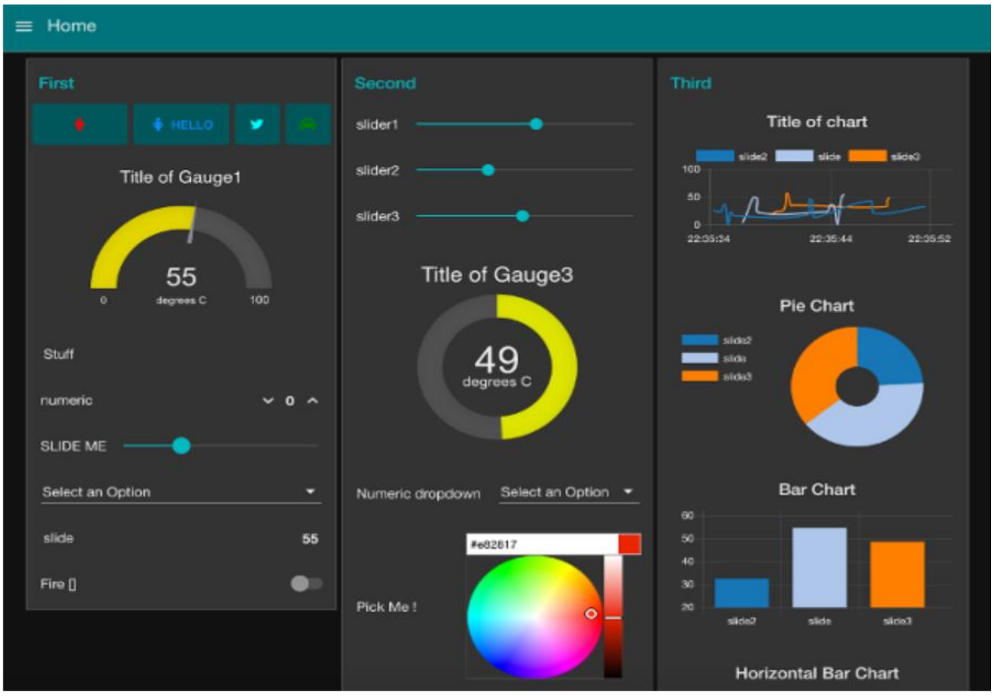

Figure 3.5: Example of Data Visualization Using Node-RED Dashboard (Node-RED, n.d.)

3.4 Outdoor Temperature Measurement Subsystem

3.4.1 Chosen Components of Outdoor Temperature Measurement Subsystem

Figure 3.6 illustrates the low power temperature sensor used to measure the temperature and humidity in this project. DHT22 temperature sensor has a measure range of -40°C to 80°C for temperature and 5% to 99% RH for humidity. Moreover, the accuracy of the temperature achieves ±2% to ±5% RH for humidity and ±0.5 Celsius for temperature. According to Sparkfun (n.d.), DHT22 temperature sensor will receive a new reading for every 2 seconds. This sensor will be used to collect the data of temperature and humidity for both indoor and outdoor environments to deepen the analysis of load profile.

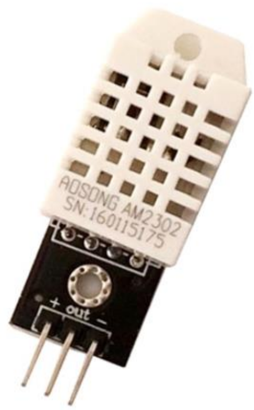

Figure 3.6: DHT22 Temperature Sensor

In order to collected data from temperature sensor, a ESP32 microcontroller as shown in Figure 3.7 is used to receive data from the sensor and send to the single board computer (SBC) for further processing. Due to its low power consumption ability, it is useful in a variety of applications. ESP32 microcontroller supports the communication with other systems through WIFI and Bluetooth connections, which makes it capable to operate alone or work as a slave device. The specifications of ESP32 microcontroller include 512 KB RAM, dual-core CPU and clock frequency of 240 MHz.

Figure 3.7: ESP32 microcontroller

3.4.2 Hardware Design of Outdoor Temperature Measurement Subsystem

The wire connection of the ESP32 microcontroller and DHT22 temperature sensor will be carried out based on Figure 3.8. The circuit will be placed at the outdoor environment for the sake of collecting more useful data that will impact the energy consumption of the air-conditioner. The positive (+) and negative (-) pins of the DHT22 temperature sensor are connected to the microcontroller for consuming electrical power. Additionally, OUT pin is used to transfer the reading obtained to the microcontroller.

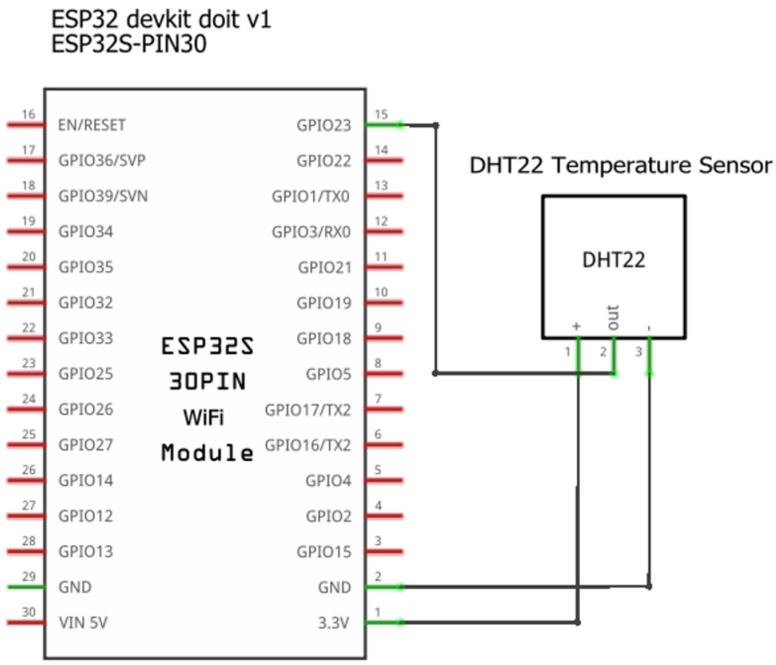

Figure 3.8: Circuit Connection of Outdoor Temperature Measurement Subsystem

The outdoor temperature subsystem prototype is configured as shown in Figure 3.9 while Figure 3.10 illustrates the overall set up of the subsystem. The plastic bag and container are utilized to protect the prototype during raining period.

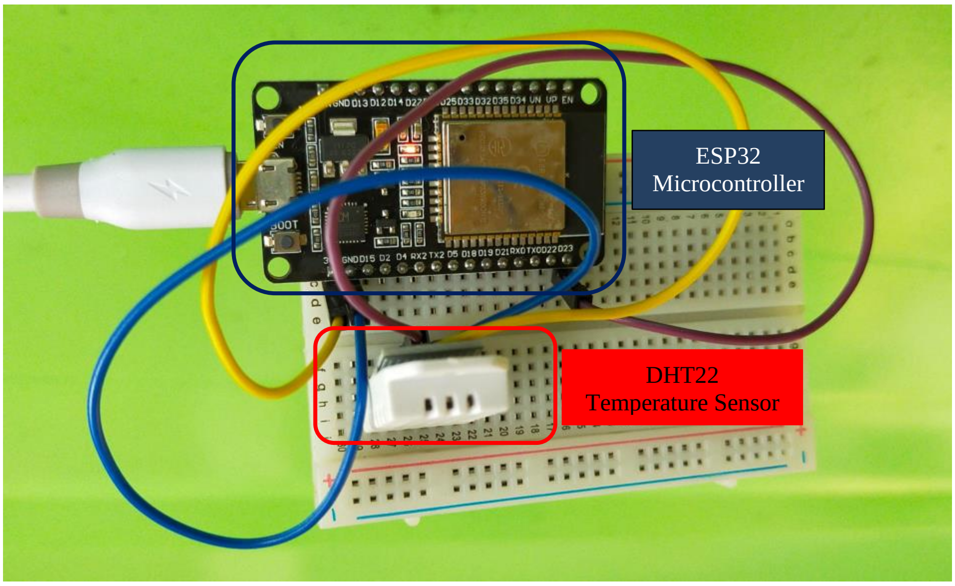

Figure 3.9: Hardware Prototype of Outdoor Temperature Subsystem

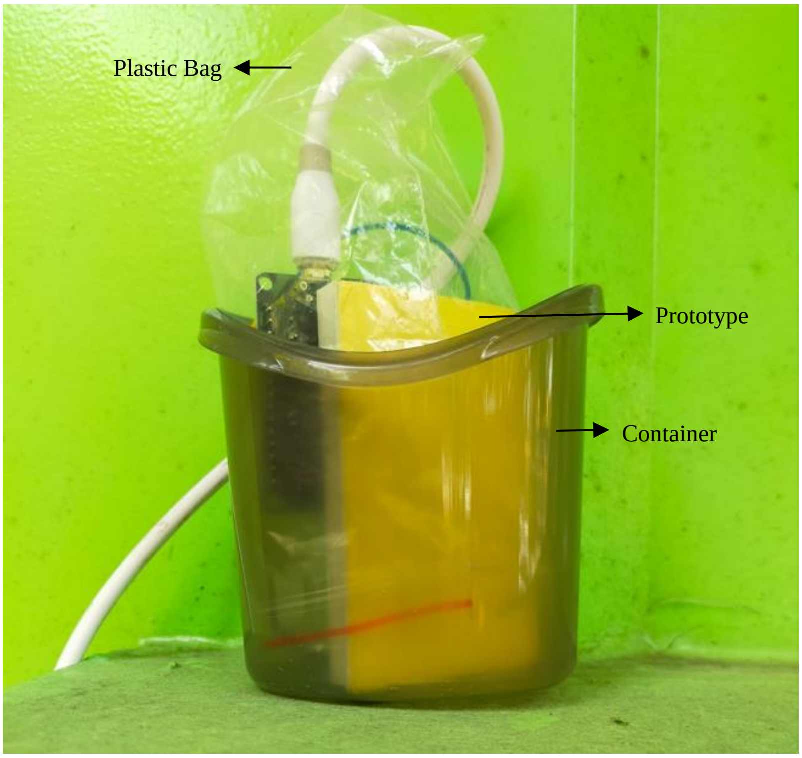

Figure 3.10: Overall Set Up of Outdoor Temperature Subsystem

3.4.3 Algorithm of Outdoor Temperature Measurement Subsystem

The flow of algorithm for outdoor temperature measurement subsystem is illustrated by the flowchart in Figure 3.11. The main loop of the algorithm will be repeated whenever the MQTT server is connected to publish the values of outdoor temperature and humidity. In fact, the sample output from Figure 3.12 indicates that the algorithm successfully read the values from DHT22 temperature sensor.

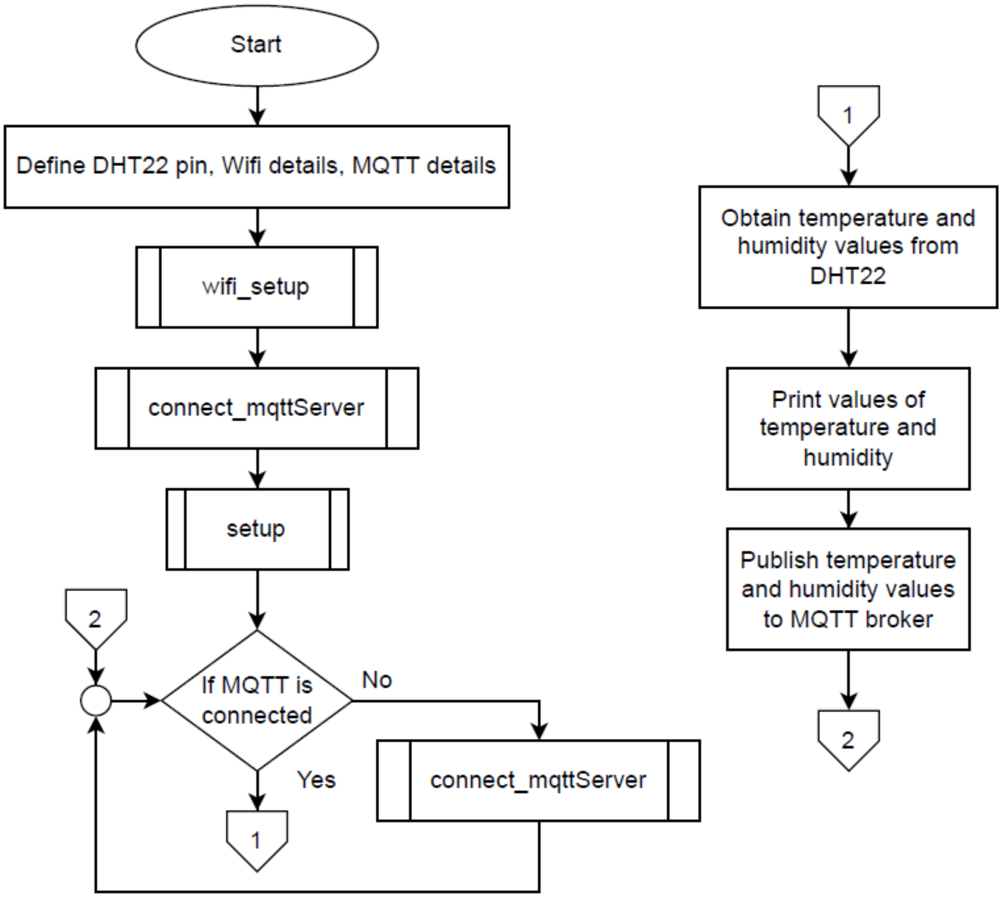

Figure 3.11: Algorithm Flowchart of Outdoor Temperature Subsystem

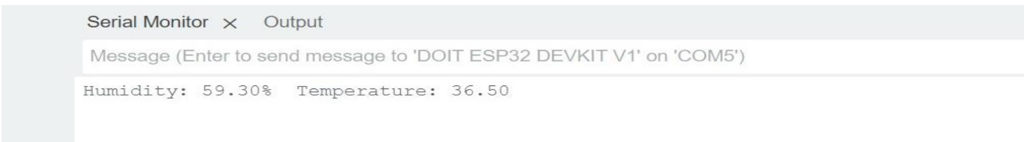

Figure 3.12: Sample Output of Outdoor Temperature Subsystem Algorithm

3.5 Indoor Load Controller Subsystem

The indoor load controller subsystem consists of two parts, which is the IR receiver module used for controller configuration, and the load controller utilized to perform the control action. The IR receiver module will only be used once to obtain the required raw codes for various air conditioner control signals. On the other hand, the load controller will be placed in the indoor to measure the indoor temperature and humidity as well as sending the control signal to the air conditioner when necessary.

3.5.1 IR Receiver Module Configuration for Initial Signal Acquisition

3.5.1.1 Chosen Components of IR Receiver Module Configuration

IR (Infrared Radiation) receiver module in Figure 3.13 is chosen in this project due to its affordable price, low power usage and relatively simple design (AUTODESK Instructables, n.d.). An ESP32 microcontroller of Figure 3.7 which mentioned in the outdoor temperature measurement subsystem will be connected to the IR receiver module for the usage of obtaining the raw codes of air conditioner temperature control signals from 18 °C to 28 °C. When the temperature of air conditioner is adjusted using the original remote control, the IR receiver module will receive and decode the control signal to form a compatible output that can be used by the load controller. All the control signals obtained are recorded and then utilized by the IR transmitter module to perform the required control action.

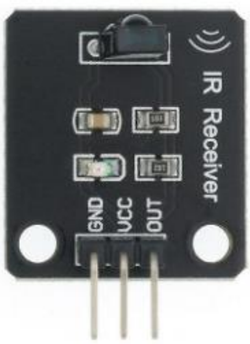

Figure 3.13: IR Receiver Module

3.5.1.2 Hardware Design of IR Receiver Module Configuration

Figure 3.14 illustrates the wire connection between ESP32 microcontroller and IR receiver module in this project. The Vin and GND pins of the IR receiver module will be connected to the 3.3 V Vin and GND pins of the ESP32 microcontroller to obtain the power supply. The S pin (OUT Pin) of the IR receiver module is used to send the signal captured from the air-conditioner to GPIO4 pin of microcontroller.

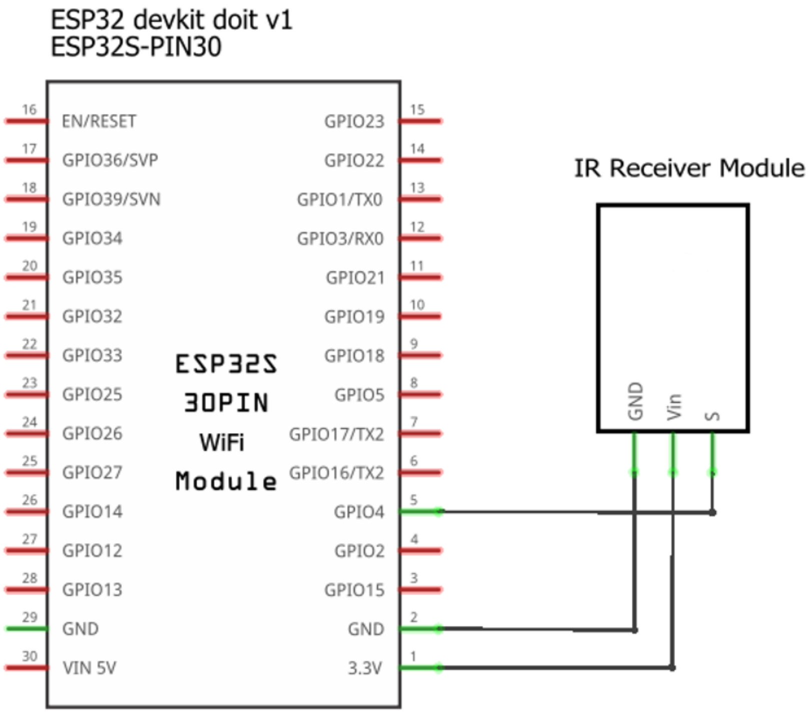

Figure 3.14: Circuit Connection of IR Receiver Module Configuration

Figure 3.15 shows the overview IR receiver module hardware prototype constructed. This prototype is only used once to collect all the required raw codes for air conditioner control signal.

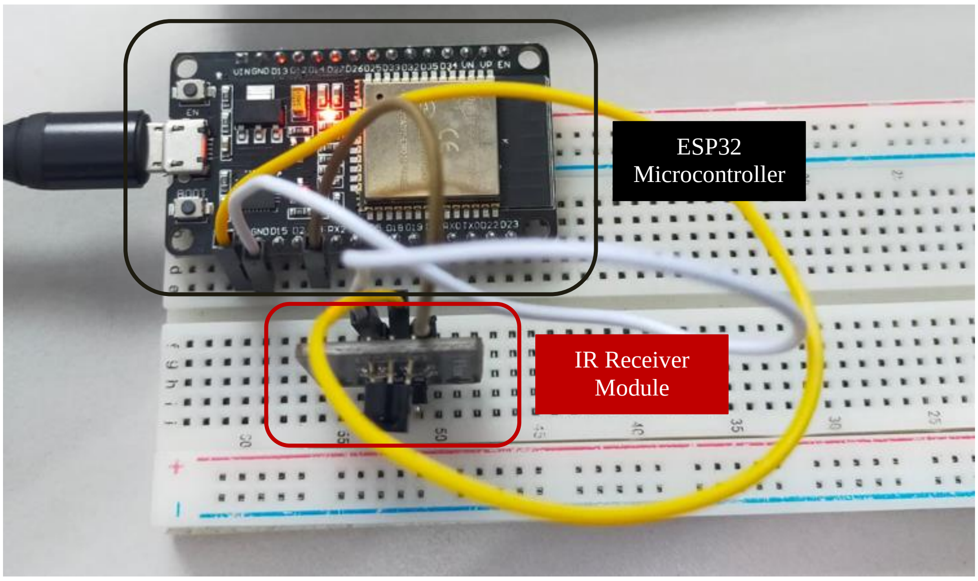

Figure 3.15: Hardware Prototype of IR Receiver Module Configuration

3.5.1.3 Algorithm of IR Receiver Module Configuration

The flowchart in Figure 3.16 displays the algorithm flow of IR receiver module. When IR code is detected by the IR receiver module, the information will be printed out as shown in Figure 3.17.

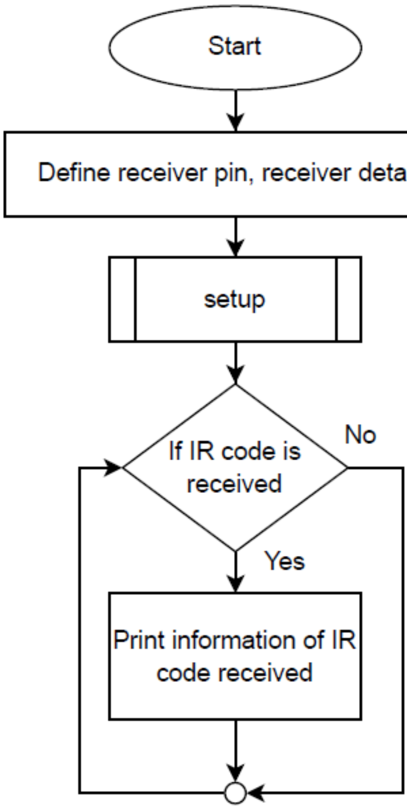

Figure 3.16: Algorithm Flowchart of IR Receiver Module Configuration

Figure 3.17: Sample Output of IR Receiver Module Configuration Algorithm

3.5.2 Load Controller Set Up for Continuous Operation

The indoor load controller consists of one ESP32 microcontroller, one DHT22 temperature sensor as well as an IR transmitter module. The DHT22 temperature sensor will measure the indoor temperature and humidity whereas the IR transmitter module will in charge of sending control signal to the air conditioner based on the message received.

3.5.2.1 Chosen Components of Load Controller

Figure 3.18 demonstrates a low price and power efficient IR (Infrared Radiation) transmitter module used to conduct wireless communication in this project. The IR transmitter module will be used as a controller to send the required decoded signals obtained by the IR receiver module to the air conditioner for temperature adjustment according to the decision made. Hence, the ESP32 microcontroller of Figure 3.7 which mentioned in the temperature measurement subsystem will be used to send the required control signal to the IR transmitter module. At the same time, a DHT22 temperature sensor mentioned in Figure 3.6 will also be connected to the ESP32 microcontroller in this subsystem to measure the indoor temperature and humidity values.

Figure 3.18: IR Transmitter Module

3.5.2.2 Hardware Design of Load Controller

Figure 3.19 illustrates the wire connection between ESP32 microcontroller, DHT22 temperature sensor and IR transmitter module in this project. IR transmitter module uses its Vin and GND pins to connect the 3.3 V Vin and GND pins of the ESP32 microcontroller respectively to obtain the power supply. Moreover, IR transmitter module will receive the signal generated by the microcontroller uses its S pin (DAT Pin). At the same time, the OUT pin of DHT22 that used to transfer the values read will be connected to the GPIO23 pin of the ESP32 microcontroller for data transfer.

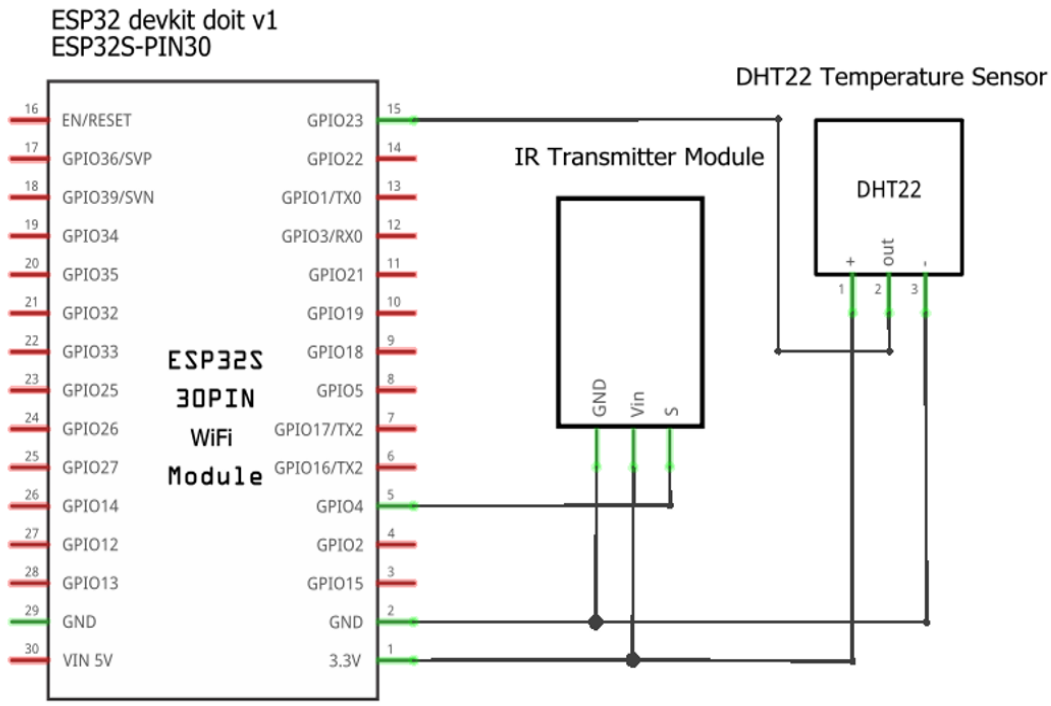

Figure 3.19: Circuit Connection of Load Controller

The constructed indoor load controller is illustrated in Figure 3.20. The IR transmitter module will send the signal of targeted raw codes obtained by the IR receiver module for temperature adjustment.

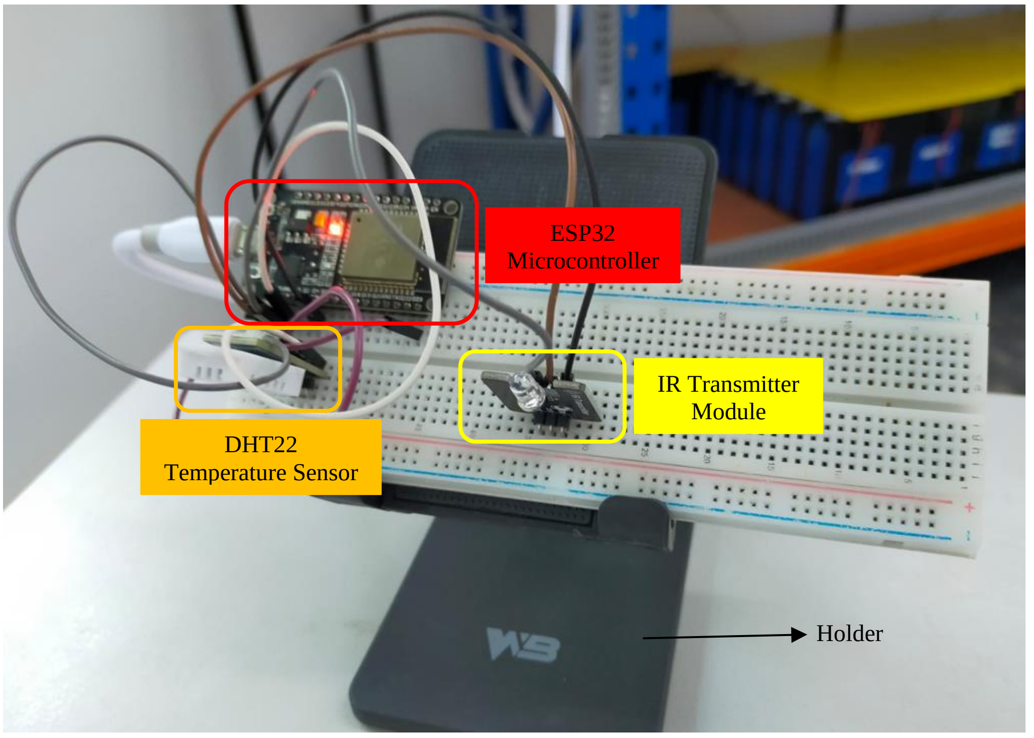

Figure 3.20: Hardware Prototype of Load Controller

3.5.2.3 Algorithm of Load Controller

Figure 3.21 demonstrates the flowchart for algorithm of load controller. The callback function indicates that the IR transmitter module will only operate to adjust the temperature of air conditioner when the adjustment message is received. On the other hand, the main loop of the algorithm which is reading the values of indoor temperature and humidity will not be affected by the callback function. The sample output as shown in Figure 3.22 proves that the indoor temperature and humidity values are successfully read while the controller is also capable to receive the adjustment message.

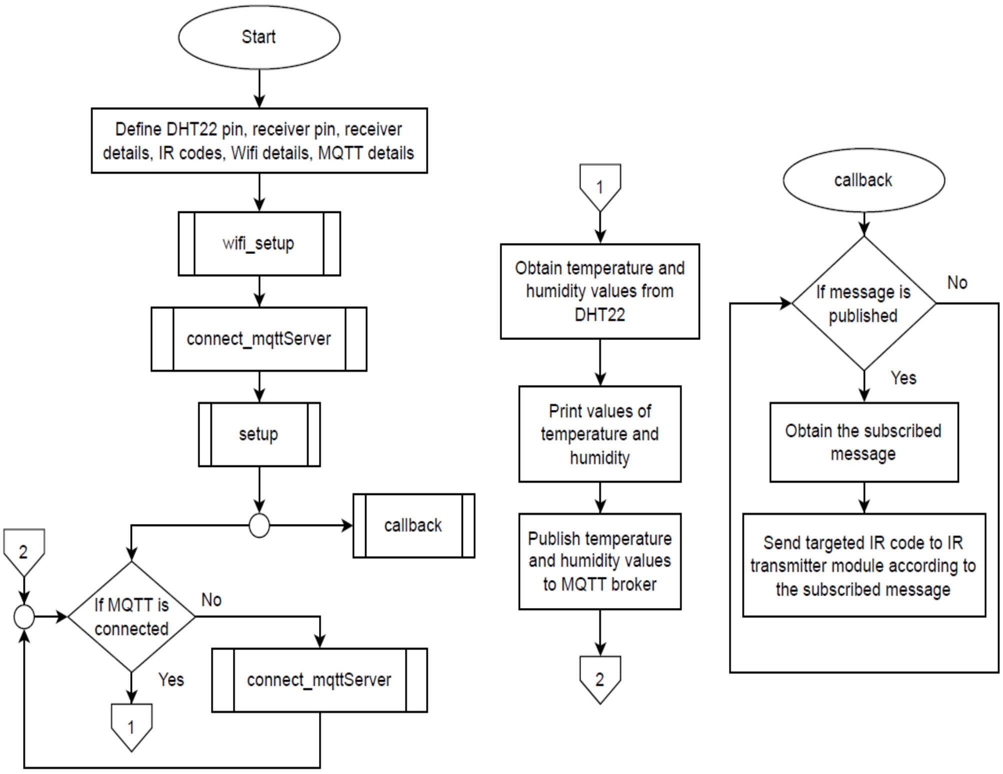

Figure 3.21: Algorithm Flowchart of Load Controller

Figure 3.22: Sample Output of Load Controller Algorithm

3.5.3 Control Strategy

3.5.3.1 PID Controller Design

Figure 3.23 demonstrates the flowchart of the PID Controller Design. The error between the measured indoor temperature and the desired temperature set point will be calculated to further compute the values of K_p, K_i and K_d. Then, the values of the three gains will be utilized to compute the output, determining the control action of the controller.

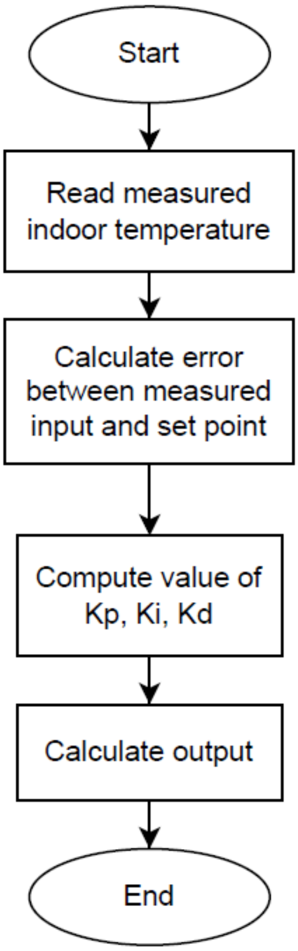

Figure 3.23: Flowchart of PID Controller Design

In addition, the values of K_p, K_i and K_d of the PID controller are tuned according to the table in Figure 3.24. As the effect of different gains will greatly influence the performance of the PID controller, the tuning process should be carried out carefully to identify the most appropriate parameters.

Parameter	Rise time	Overshoot	Setting time	Steady state error	Stability
Increase kp	Decrease	Small Increase	Increase	Decrease	Deteriorate
Increase ki	Small Decrease	Increase	Increase	Large Decrease	Deteriorate
Increase kd	Small Decrease	Decrease	Decrease	Small Change	Improve

Figure 3.24: Effect of Kp, Ki and Kd Tuning (Omarov et al., 2020)

3.5.3.2 Fuzzy PID Controller Design

The process of designing a Fuzzy PID Controller is illustrated in Figure 3.25. The input of the controller will be the error and rate of change in error of the temperature. Both equations can be represented by:

$$e = T_{desired} - T_{current} \quad (1)$$

where

e = error

$T_{desired}$ = desired temperature in °C

$T_{current}$ = current temperature in °C

$$\Delta e = \frac{e(t_1) - e(t_2)}{t_1 - t_2} \quad (2)$$

where

Δe = rate of change in error

$e(t_1) - e(t_2)$ = change in error

$t_1 - t_2$ = time interval

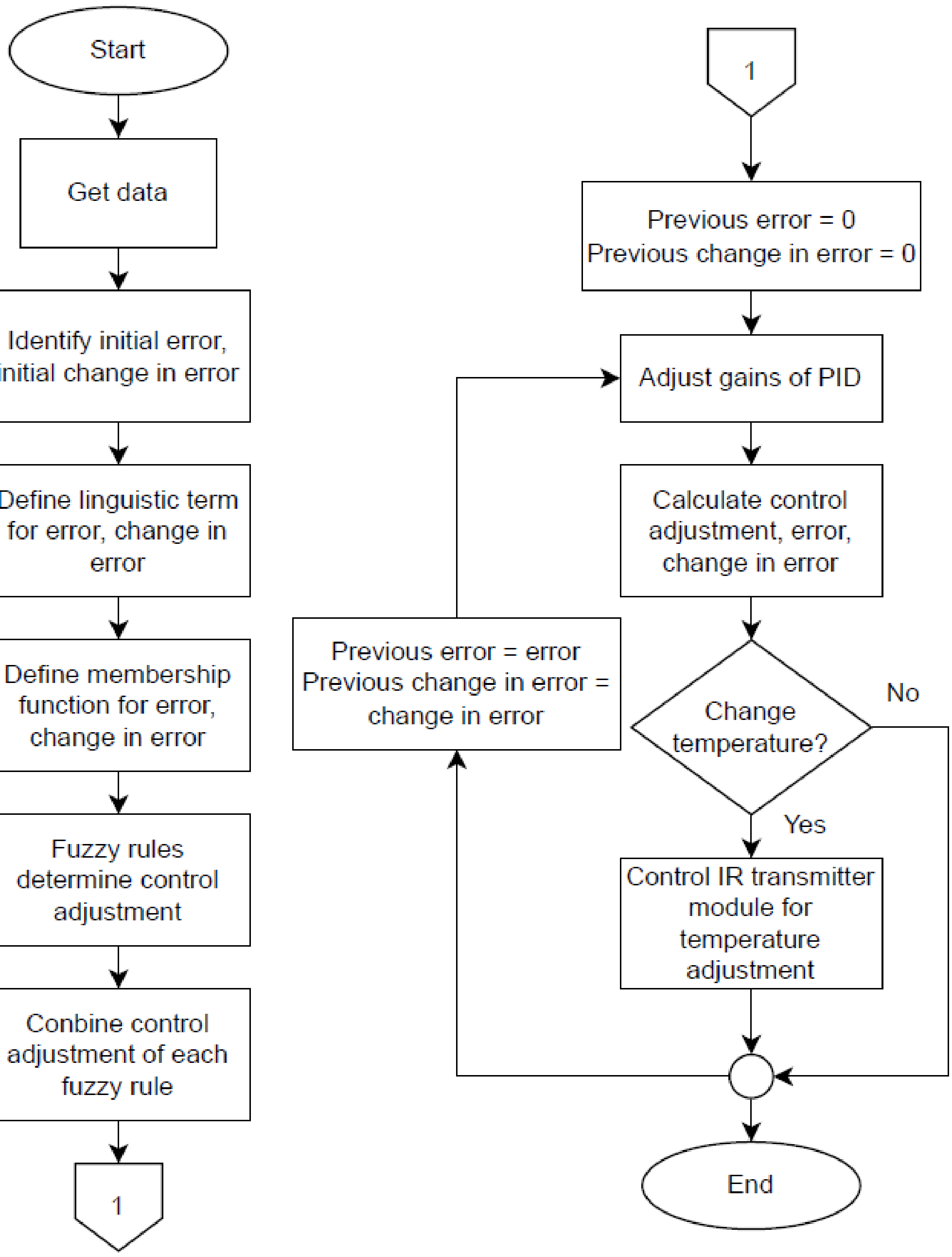

Figure 3.25: Flowchart of Fuzzy PID Controller Design

In order to convert the crisp data into fuzzy data sets, fuzzification process using membership function is needed. The linguistic terms of the error and rate of change in error are represented utilizing the triangular membership functions. In fact, the skfuzzy library module of python provide function such as "fuzz.trimf()" to generate the membership fuction. The linguistic identifier of the membership functions includes Large Positive Deviation (LPD), Average Positive Deviation (APD), Small Positive Deviation (SPD), Zero Deviation (Z), Small Negative Deviation (SND), Average Negative Deviation (AND) and

Large Negative Deviation (LND). By combining the membership functions of error and rate of change in error, the fuzzy control rules can be determined as shown in Table 3.1. Then, defuzzification process is required to convert the fuzzy output into crisp data for further control action. In this case, no specific defuzzification technique is required as the values of K_p, K_i and K_d generated from the fuzzy rules are crisp data.

Table 3.1: Fuzzy Control Rules of Controller

$\Delta e \backslash e$	**LND**	**AND**	**SND**	**Z**	**SPD**	**APD**	**LPD**
LND	C3	C3	C2	C1	NO	NO	H1
AND	C3	C2	C2	C1	NO	NO	H1
SND	C3	C2	C1	C1	NO	NO	H1
Z	C2	C1	C1	NO	NO	H1	H1
SPD	C1	C1	NO	NO	H1	H1	H2
APD	C1	C1	NO	NO	H1	H2	H2
LPD	C1	C1	NO	NO	H2	H2	H2

where

C3 = Strong Cooling

C2 = Average Cooling

C1 = Slight Cooling

NO = Without Changes

H1 = Heating 1

H2 = Heating 2

3.5.3.3 Flowchart of Control Strategy Algorithm

The flowchart of the control strategy algorithm is shown in Figure 3.26 and Figure 3.27. The developed control strategy algorithm will be installed into the single board computer (SBC) for decision-making. The critical data required for the calculation will be collected from the three subsystems. Then, the generated control command will be sent to the IR transmitter module for temperature adjustment if necessary.

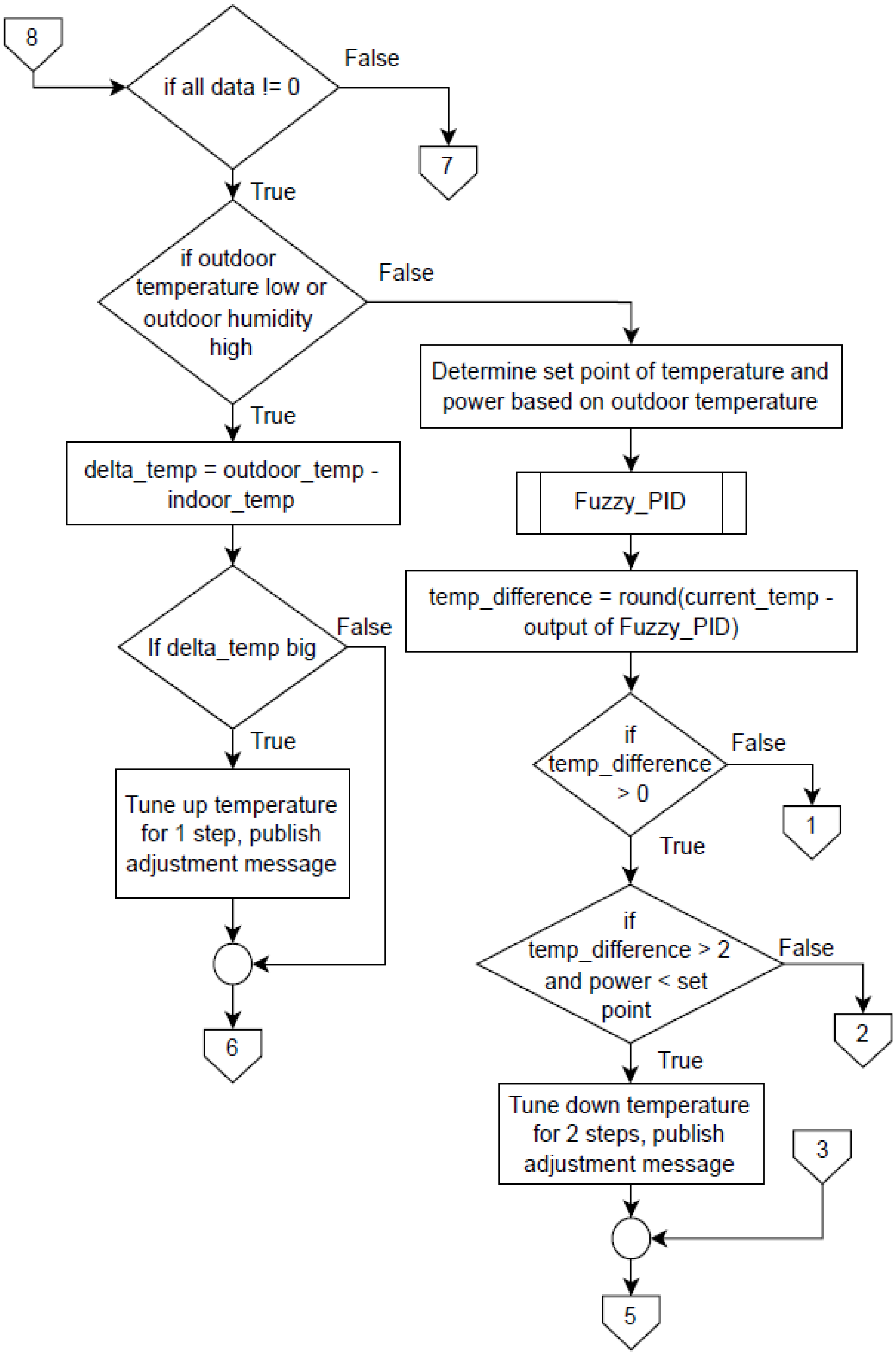

Figure 3.26: Flowchart of Control Strategy Algorithm Part 1

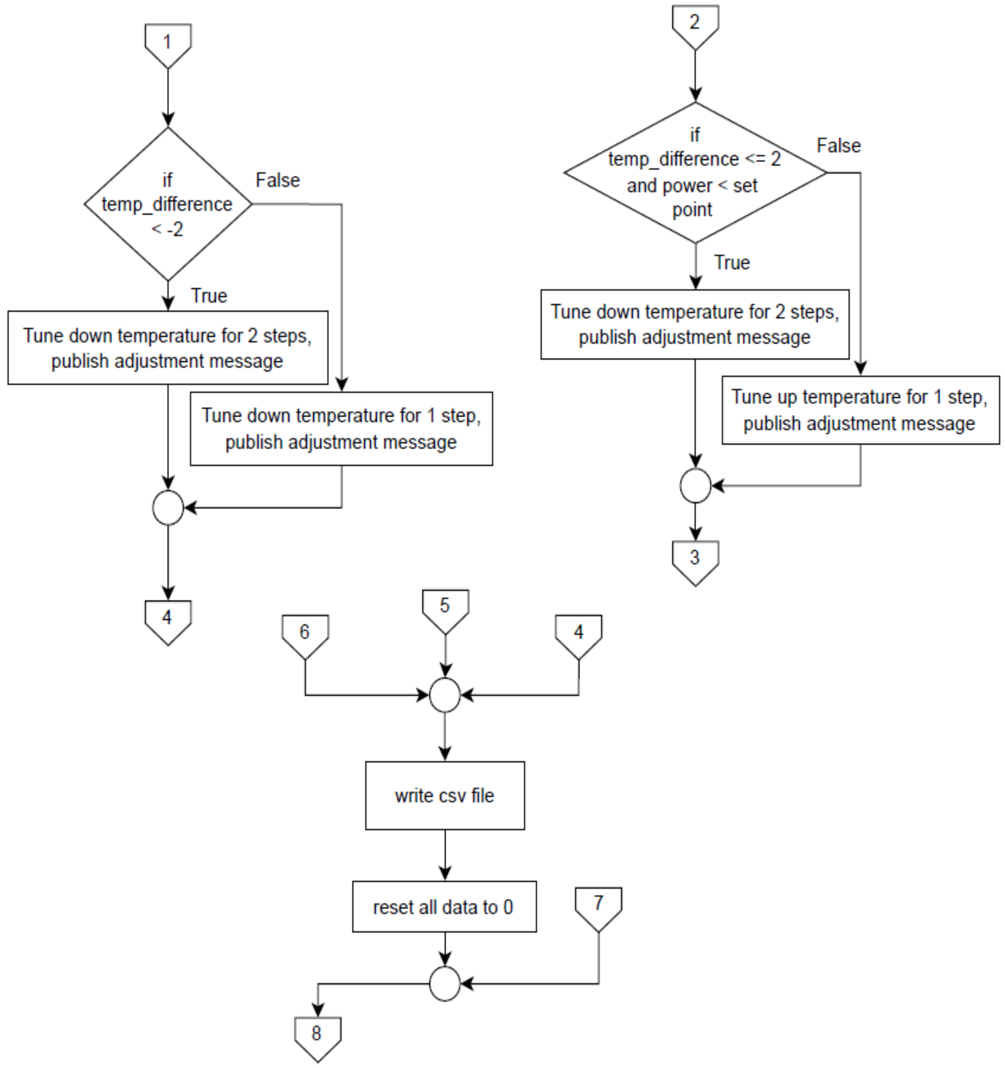

Figure 3.27: Flowchart of Control Strategy Algorithm Part 2

3.6 Single Board Computer (SBC) Set Up

3.6.1 Chosen SBC

Single board computer (SBC) is often used as an embedded computer controller to operate a wide range of complex devices. In this project, Raspberry Pi 4 Model B as shown in Figure 3.28 is chosen due to the affordability, large amount of tutorials available online and easy to be powered up. The SBC serves as the brain of the system as it will receive the relevant data from other electronic devices and compute the output according to the control strategy algorithm implemented. The generated output will then be sent to the IR transmitter module to execute the desired action.

Figure 3.28: Raspberry Pi 4 Model B

3.6.2 Communication Set Up with Subsystems

As single board computer (SBC) acts as the brain of virtual energy storage system, the communication between various subsystems and SBC should be set up properly to receive and send signals precisely. In fact, SBC can obtain the data from the data acquisition subsystem by installing Node-RED into it. Node-RED will be running in the SBC and store the data obtained into a csv file. Apart from that, the developed hybrid Fuzzy-PID algorithm will as well be installed into the SBC to perform decision-making. The ESP32 microcontrollers of outdoor temperature measurement subsystem and indoor load controller subsystem communicate with the SBC through message queuing telemetry transport (MQTT). MQTT is a lightweight and highly efficient protocol that allows the devices to exchange information such as states and changes as it provides the service of bi-directional communications (MQTT, n.d.). With this, SBC can collect the data from different subsystems and send signal to the indoor load controller subsystem for temperature adjustment. The summary of communication between subsystems and SBC is displayed in Figure 3.29.

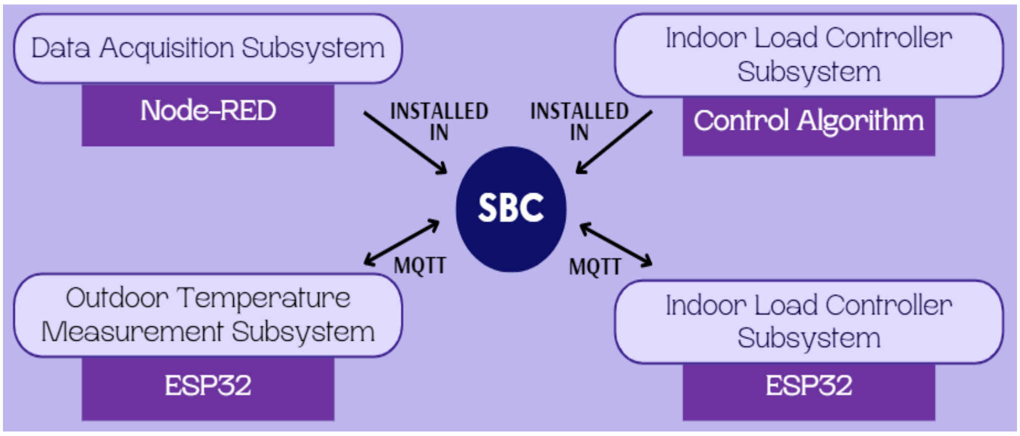

Figure 3.29: Communication of Subsystems and SBC

3.6.3 Time Schedule of Control Strategy Algorithm

To avoid any unpredicted issues or bugs during the operation of the system, the crontab file in the Raspberry Pi 4 Model B is modified to run and stop the script of control strategy algorithm at certain time. The crontab command is wisely used to create a regular schedule for the targeted jobs. As shown in Figure 3.30, the control strategy algorithm script will be run at 12:00 a.m. and stop at 11:58 p.m. everyday. This regular schedule eliminates the bugs that can be solved by rerunning the script, minimizing the risk of system failure.

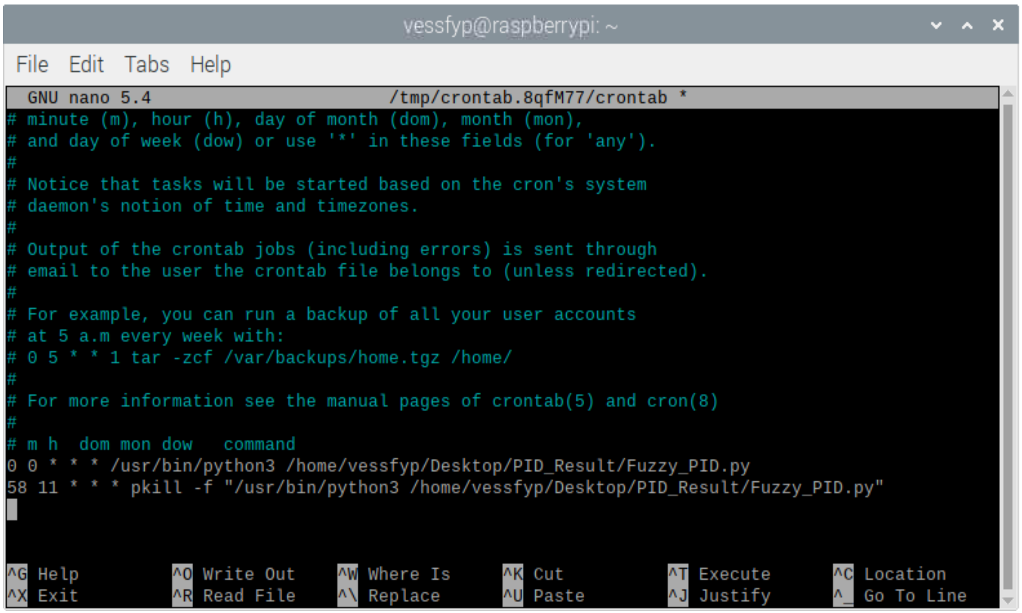

Figure 3.30: Modified Crontab File for Regular Schedule of Control Strategy Algorithm Script

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Data Acquisition Subsystem

Figure 4.1 depicted the overview of the Node-RED flow in the data acquisition subsystem. The five main sections of the flow are responsible for different purposes such as creating file, reading data, sending data, storing data and visualizing data.

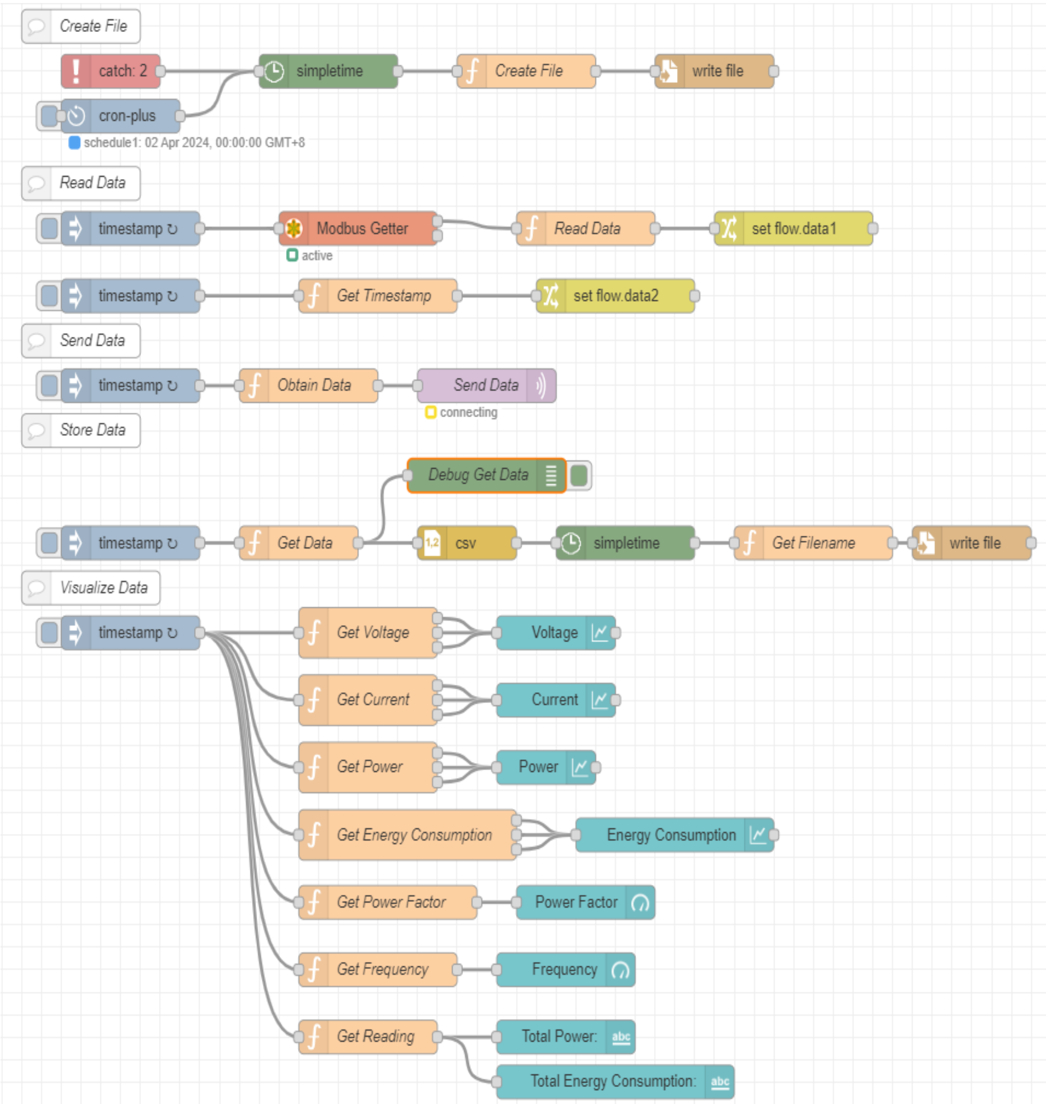

Figure 4.1: Overview of Node-RED Flow

4.1.1 Data Reading

The energy meter readings are acquired using the Modbus Getter node provided by the Node-RED platform. This node allows the user to access the desired readings from the energy meter by selecting the appropriate starting address and specifying the quantity of the holding registers. Subsequently, the Read Data node is employed to standardize the format of the readings which will then be stored into an array. Besides, a separate flow is constructed to obtain the real-time timestamp corresponding to the readings obtained.

4.1.2 Data Sending

By using the MQTT protocol, the required real-time data such as active power will be sent to the control algorithm in the Raspberry Pi 4 Module B. This allows the SBC to generate a more accurate decision according to the real-time situation.

4.1.3 Data Storing

In order to organize and manage the data acquired, a new file will be generated each day to store the readings collected during that particular day. This approach ensures that the interested data can be easily accessed by referring to the targeted filename. During the data storing process, the data acquired will be saved into the daily created file in csv format. Figure 4.2 illustrates the data storing process using Node-RED.

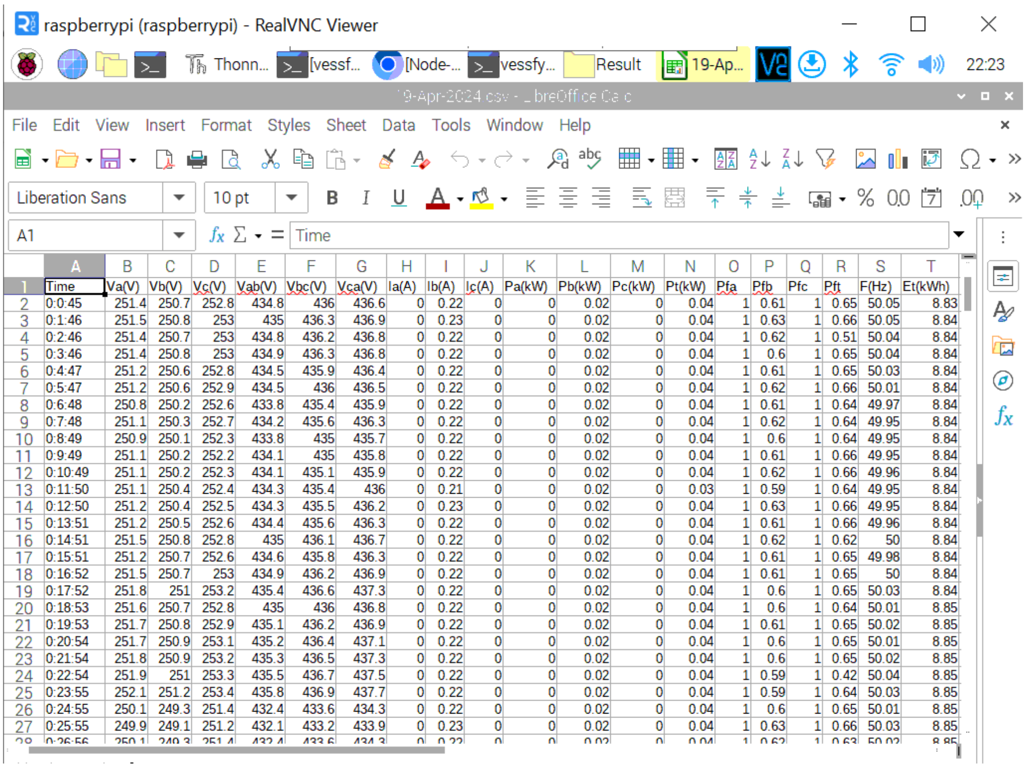

Figure 4.2: Data Storing Process using Node-RED

4.1.4 Data Visualization

The Node-RED Dashboard utilized for data visualization is shown in Figure 4.3. It presents an array of essential energy metrics for monitoring purpose. The readings of voltage, current, active power and energy consumption for all three phases are displayed in the form of line graph. This enables the user to effortlessly observe and monitor the daily trend of the crucial parameters. Besides, the total power factor and frequency of the cooling system are shown in the form of gauge for data comprehension enhancement. This visual format offers a clear and concise visualization for the user. The real-time readings of the total active power and total energy consumption are also provided in the dashboard to keep track of the real-time energy usage of the cooling system.

Figure 4.3: Data Visualization using Node-RED Dashboard

4.2 Result Analysis

All case studies include data of vital parameters like indoor temperature, outdoor temperature, power usage, energy consumption and air conditioner settings that are recorded between 10 a.m. and 5 p.m. for the purpose of analysing the load profile and accessing the performance of the cooling system. The analysis aims to pinpoint the peak demand periods and the corresponding energy consumption of the cooling system without VESS in both raining season and summer season. On the other hand, the effectiveness of VESS will be evaluated whereas the performance of PID and Fuzzy PID controllers will also be examined.

4.2.1 Case Study 1: System without VESS (Raining Season)

Table 4.1 records the daily energy consumption of the system without VESS for 7 days during the rainy season at various temperature settings (22 °C to 26 °C). The data is also visualized in the form of minimum, maximum and average values as shown in Figure 4.4. As a result, it can be noticed that daily energy consumption trends downward as the temperature setting of the air conditioner is increasing. However, the temperature setting of 24 °C appears to consume the energy within a relatively wide range. This is because the rainy season of Malaysia does not feature daily, consistent rain. Hence, varying outdoor temperatures due to different rainy spells during the day may result in a wide difference of energy consumption. Table 4.2 records the outdoor temperatures of day 3 and day 5 of the 24 °C air conditioner setting whereas their respectively hourly energy consumption during the operation hours is displayed in Figure 4.5. It is noticed that the day with higher outdoor temperature consumes higher energy when compared to the day with lower outdoor temperature.

Table 4.1: Daily Energy Consumption of System without VESS for Different Air Conditioner Setting (Raining)

Day	**Energy Consumption (kWh)**				
	22 °C	**23 °C**	**24 °C**	**25 °C**	**26 °C**
1	7.45	4.94	6.18	5.34	2.94
2	5.39	8.26	7.19	5.26	4.20
3	5.79	8.03	8.03	4.61	3.36
4	6.70	8.18	4.77	5.95	3.45
5	8.68	7.76	4.59	5.81	3.36
6	8.92	5.91	4.75	4.62	2.37
7	9.10	6.03	4.99	3.36	3.59
Average Energy Consumption (kWh)	7.43	7.02	5.79	4.99	3.33

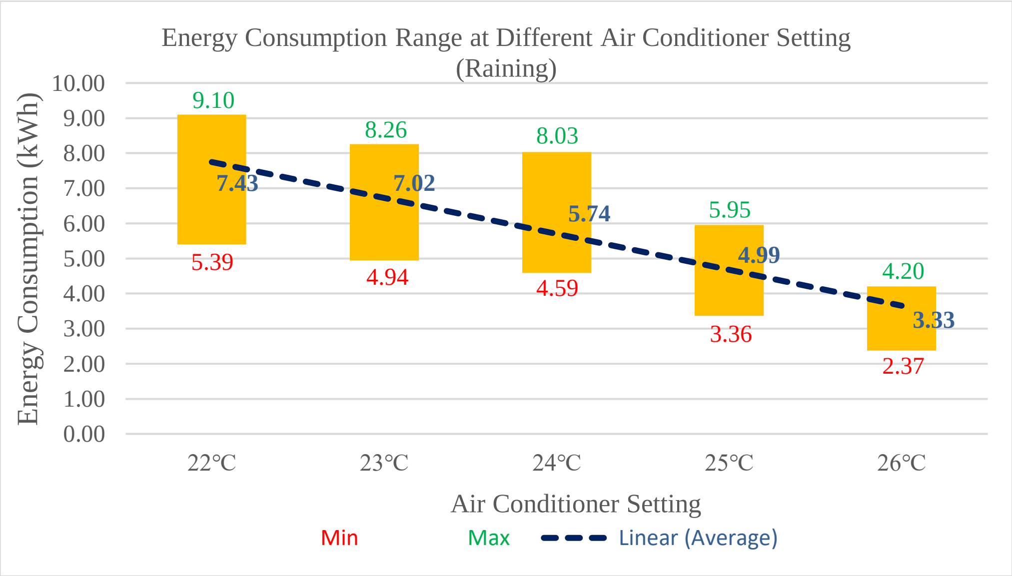

Figure 4.4: Energy Consumption Range of System without VESS at Different Air Conditioner Setting (Raining)

Table 4.2: Outdoor Temperature for Two Days in Raining Season (24 °C Setting)

Time \ Date	29/9/2023 (Day 3 of 24 °C Setting)	15/11/2023 (Day 5 of 24 °C Setting)
10:00 a.m.	31 °C	30 °C
11:00 a.m.	33 °C	31 °C
12:00 p.m.	34 °C	32 °C
1:00 p.m.	34 °C	33 °C
2:00 p.m.	34 °C	32 °C
3:00 p.m.	34 °C	32 °C
4:00 p.m.	34 °C	30 °C
5:00 p.m.	33 °C	30 °C

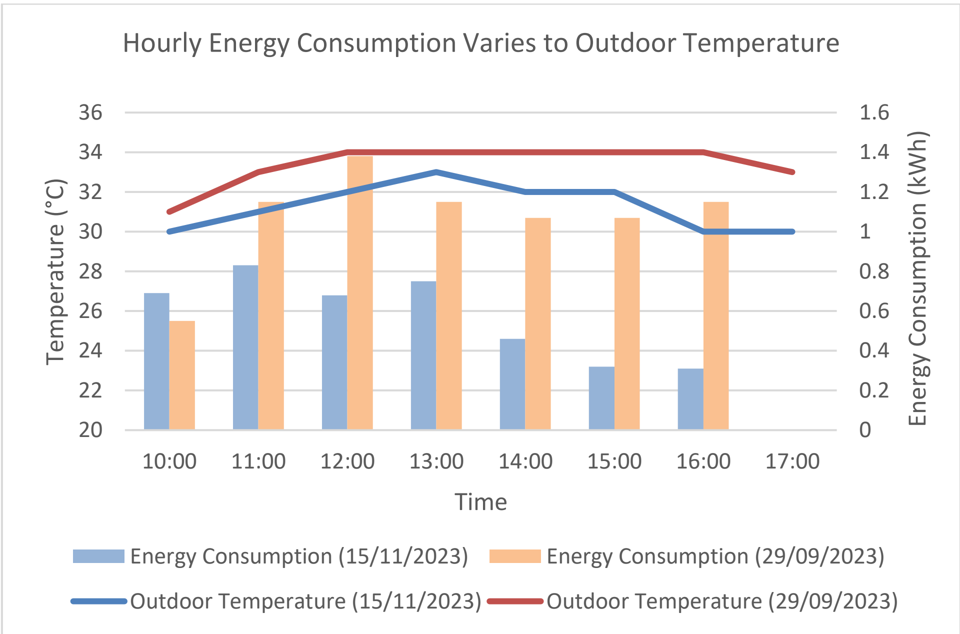

Figure 4.5: Hourly Energy Consumption of 24 °C Setting Varies to Outdoor Temperature

4.2.2 Case Study 2: System without VESS (Summer Season)

By fixing the air conditioner setting at 24 °C, the daily energy consumption of the cooling system without VESS in the summer season for 4 different days is documented in Table 4.3. The average daily energy consumption is calculated to be 8.86 kWh.

Table 4.3: Daily Energy Consumption of Cooling System without VESS (Summer)

Day	**Energy Consumption (kWh)**
1	8.23
2	8.43
3	8.59
4	10.20
Average Energy Consumption (kWh)	8.86

According to Figure 4.6, it is noticed that the power consumption of the cooling system becomes higher when the outdoor temperature is increasing. This indicates that more energy will be required to keep the indoor temperature constant when the outdoor temperature is high.

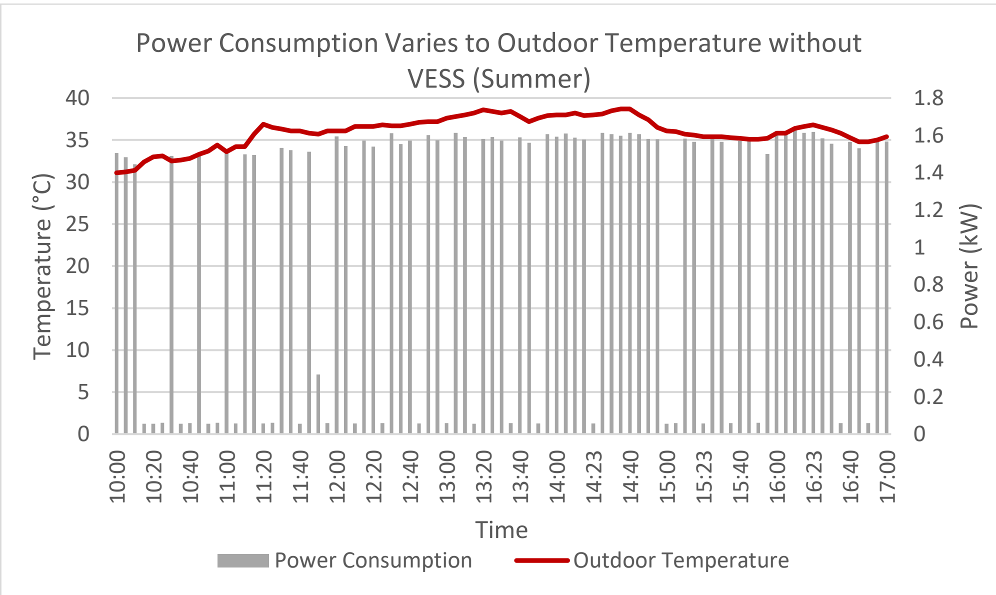

Figure 4.6: Power Consumption Varies to Outdoor Temperature of System without VESS (Summer)

4.2.3 Case Study 3: System with VESS (PID, Summer Season)

Table 4.4 demonstrates the daily energy consumption of the cooling system with VESS using PID controller in the summer season for 4 different days. With the usage of PID controller, the average daily energy consumption achieves 6.36 kWh.

Table 4.4: Daily Energy Consumption of Cooling System with VESS (PID, Summer)

Day	**Energy Consumption (kWh)**
1	6.82
2	6.54
3	5.62
4	6.46
Average Energy Consumption (kWh)	6.36

From Figure 4.7, it is observed that the air conditioner is often tuned to 26 °C and 23 °C rather than staying at the setting of 24 °C. However, the indoor temperature of the system is managed to maintain within the range of 23 °C to 25 °C as shown in Figure 4.8. As the graph shows a sine-shaped pattern for the measured indoor temperature, the power consumption of the cooling system illustrates a consistent pattern according to the trend of indoor temperature. When the measured indoor temperature rises towards 25 °C, the power consumed by the cooling system will be relatively low. On the other hand, when the PID controller is adjusting the cooling system to a lower temperature setting, there is a significant increase in power usage.

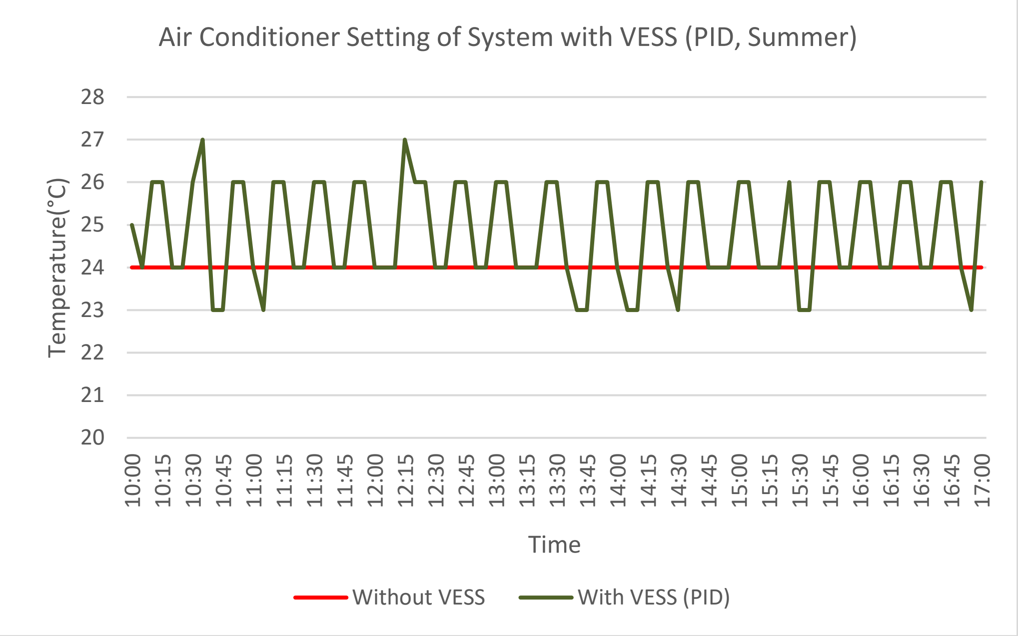

Figure 4.7: Air Conditioner Setting of System with VESS (PID, Summer)

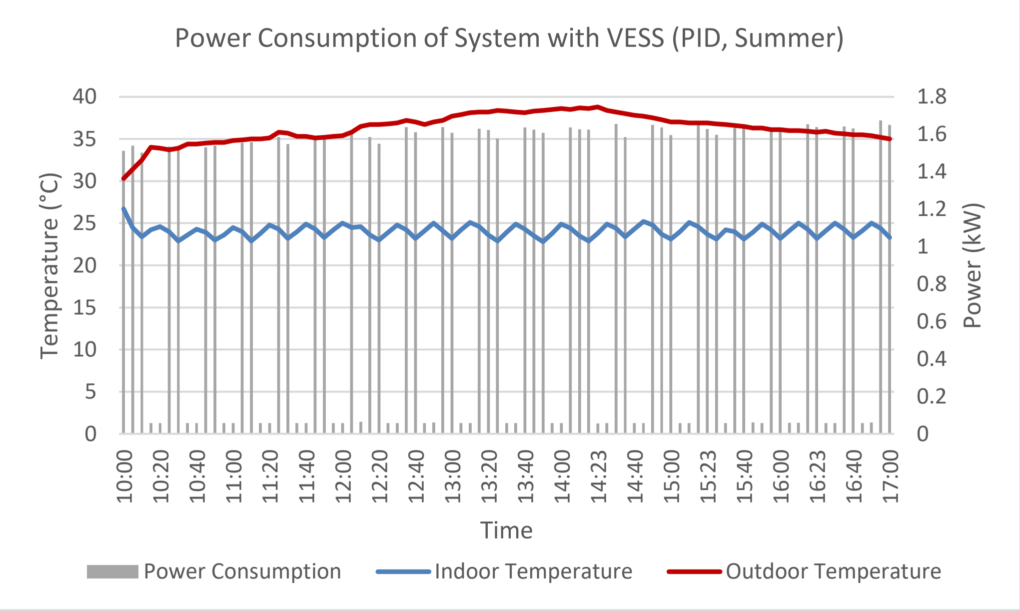

Figure 4.8: Power Consumption of System with VESS (PID, Summer)

4.2.4 Case Study 4: System with VESS (Fuzzy PID, Summer Season)

The daily energy consumption of the cooling system with VESS using Fuzzy PID controller in the summer season for 4 days is recorded in Table 4.5. It is observed that the average daily energy consumption achieves 6.54 kWh with the usage of Fuzzy PID controller.

Table 4.5: Daily Energy Consumption of Cooling System with VESS (Fuzzy PID, Summer)

Day	**Energy Consumption (kWh)**
1	6.39
2	7.25
3	5.70
4	6.82
Average Energy Consumption (kWh)	6.54

As seen in Figure 4.9, the air conditioner setting of system with VESS using Fuzzy PID controller is adjusted more frequently as compared to the PID controller. In fact, the factors influencing the decision-making process of the Fuzzy PID controller are more as compared to the PID controller because the Fuzzy PID controller will also consider the rate of error change. However, Figure 4.10 proves that the indoor temperature can be maintained within the range of 23 °C to 25 °C when Fuzzy PID controller is utilized in the system. It is also noticed that the power consumption of the cooling system shows a consistent pattern, similarly to the system using PID controller.

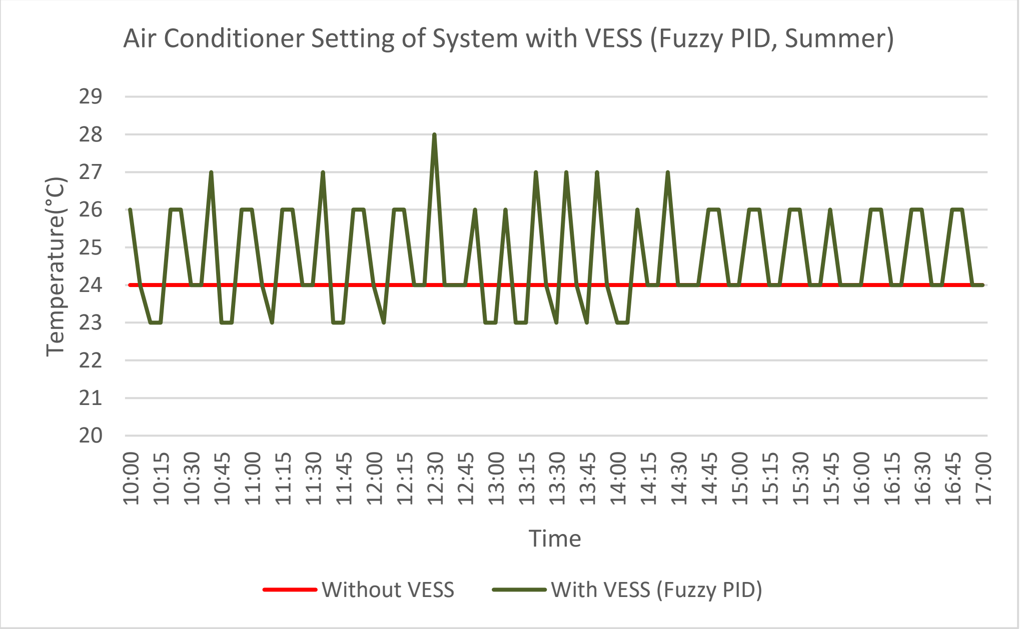

Figure 4.9: Air Conditioner Setting of System with VESS (Fuzzy PID, Summer)

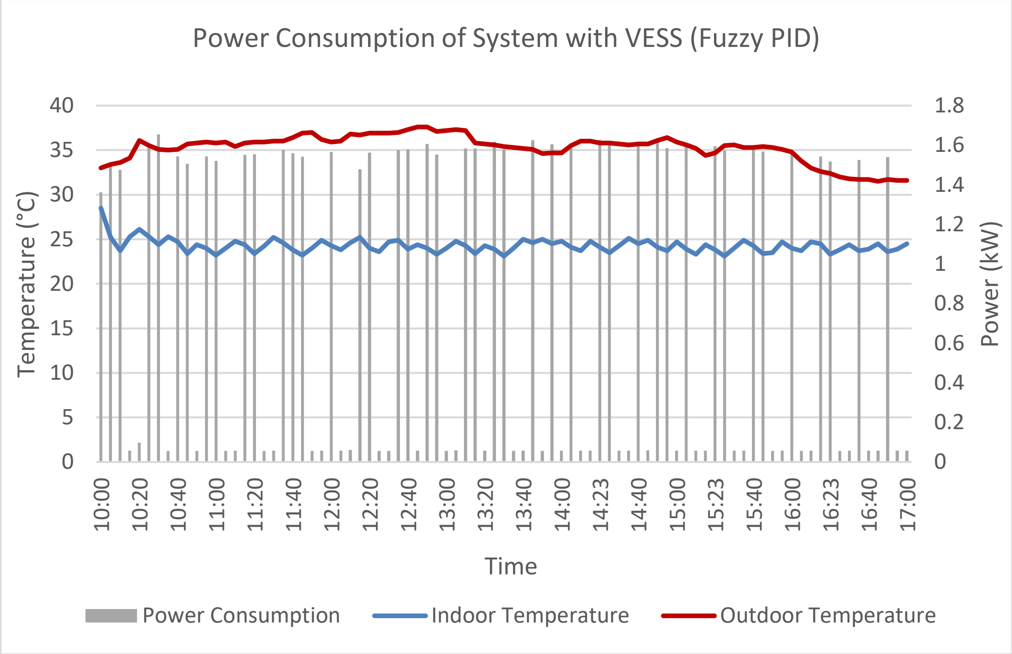

Figure 4.10: Power Consumption of System with VESS (Fuzzy PID, Summer)

4.2.5 Case Study Comparison

By merging the information from 4 separate case studies, the daily energy consumption range of the cooling system at different conditions is visualized in Figure 4.11. The graph presents the daily energy consumption in terms of minimum, maximum and average values, ensuring a more thorough depiction of the data examined. According to Figure 4.11, the energy consumption of the cooling system without VESS during raining season can be surprisingly low. Nevertheless, the cooling system without VESS will consume an additional 20% of energy on average during the summer season. This problem can be solved by implementing the VESS to the cooling system. The data had shown that both PID and Fuzzy PID controllers successfully reduce the summertime energy consumption of the cooling system. In fact, the potential daily energy saving by utilizing VESS is demonstrated in Figure 4.12 based on the minimum, maximum and average percentages. The PID-based VESS achieves a potential energy saving within the range of 17.13 % to 44.9 % whereas Fuzzy PID-based VESS accomplishes 11.91 % to 44.12 % energy saving.

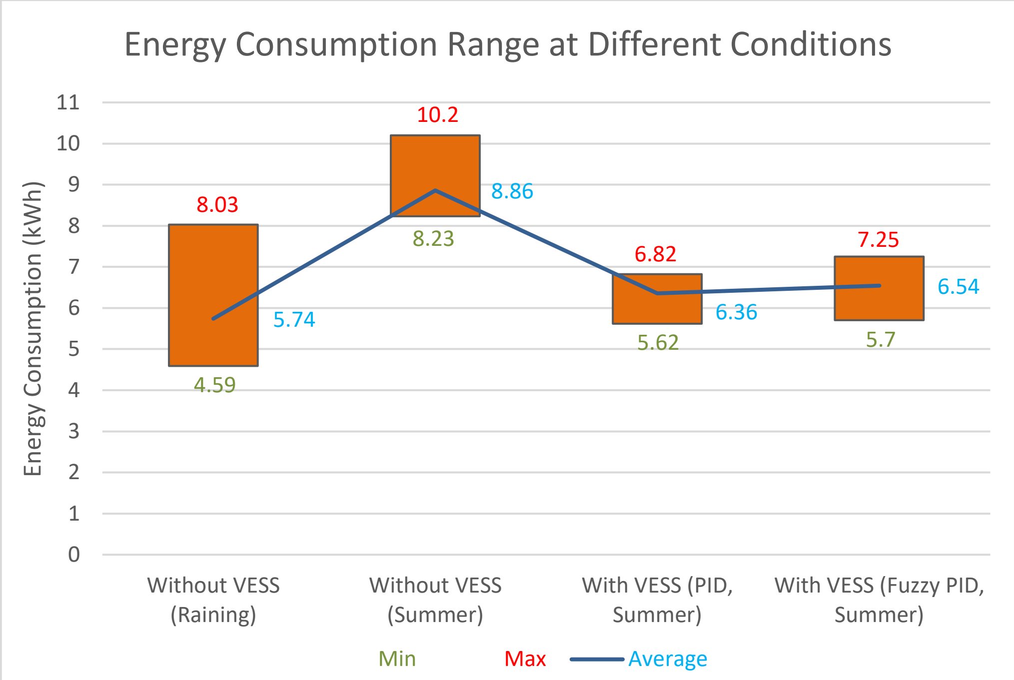

Figure 4.11: Energy Consumption Range of Cooling System at Different Conditions

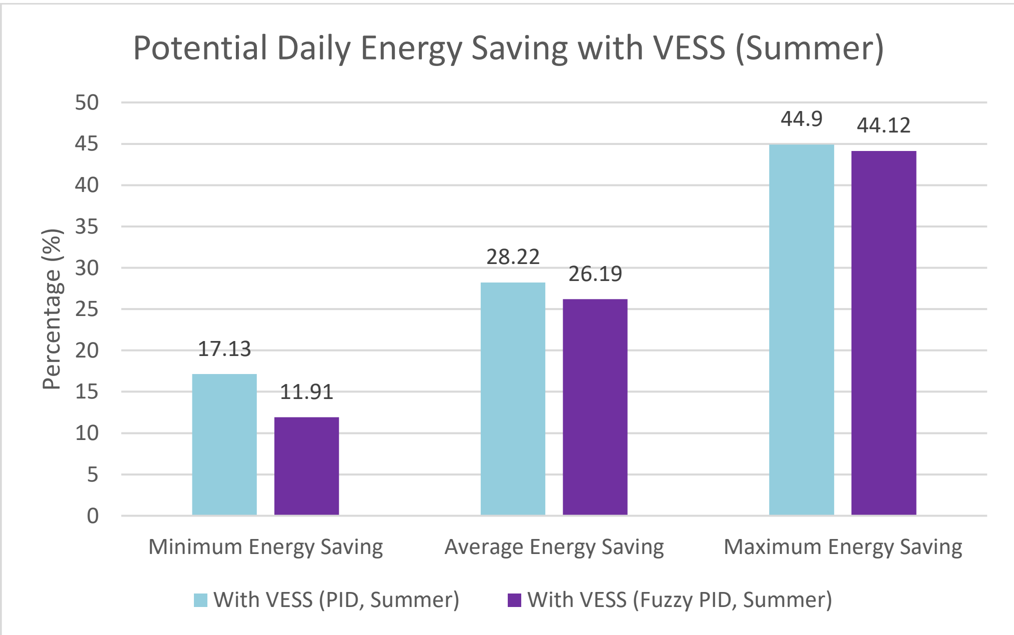

Figure 4.12: Potential Daily Energy Saving with VESS (Summer)

Apart from that, two graphs are presented to examine the efficacy and stability of the PID and Fuzzy PID controllers in order to better assess their performance. According to Figure 4.13, Fuzzy PID controller can achieve the desired temperature which is 24 °C in approximately 8 minutes while PID controller requires 15 minutes to reach the temperature set point. Hence, Fuzzy PID controller has a lower rise time as compared to the PID controller. This implies that Fuzzy PID controller preserves a faster response to the input signal received. In addition, the measured indoor temperature for the two controllers is demonstrated in Figure 4.14. Based on the observation, the fluctuation of the indoor temperature value is smaller when using the Fuzzy PID controller. This suggests that Fuzzy PID controller can maintain the desired indoor temperature with greater consistency.

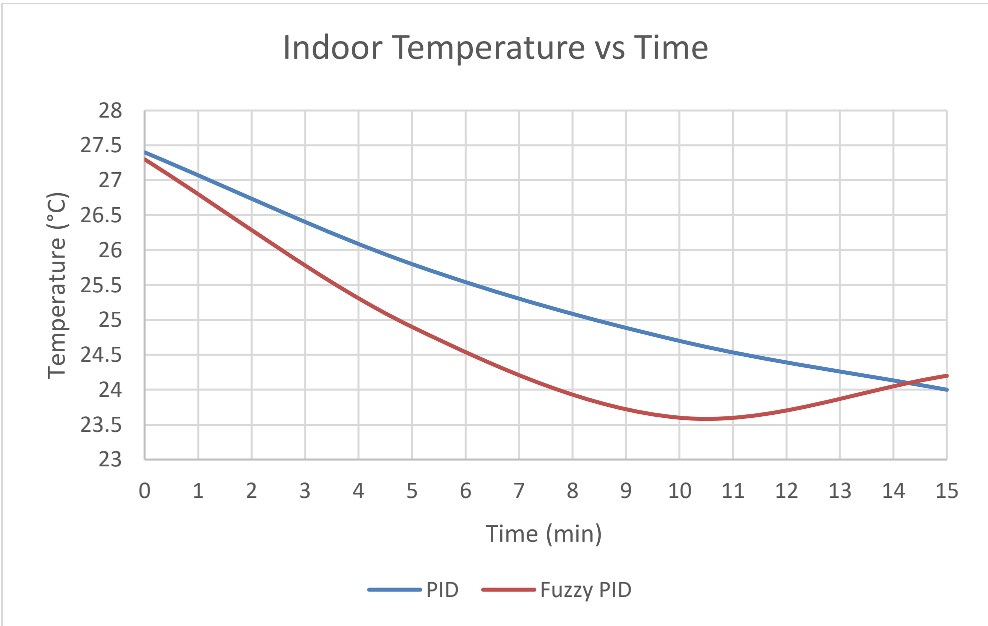

Figure 4.13: Indoor Temperature vs Time for Different Controllers

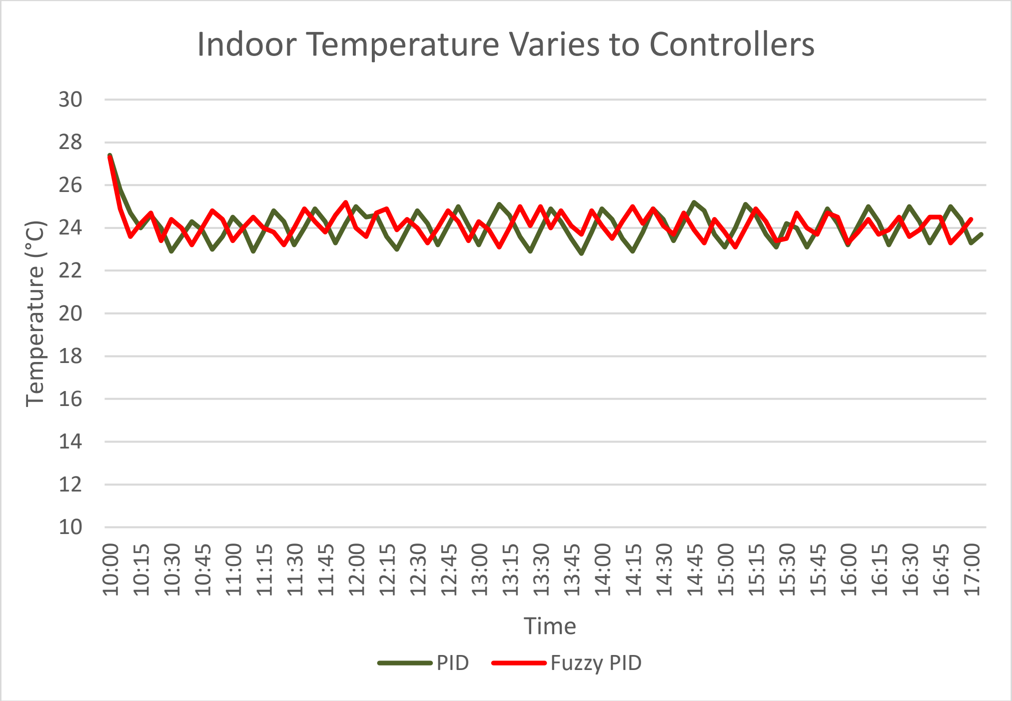

Figure 4.14: Indoor Temperature Varies to Controllers

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In the nutshell, the purpose of this project is to plan a strategy for a cloud-based virtual energy storage system (VESS) for achieving energy saving. The novel concept of VESS aims to overcome the limitations of the conventional energy storage system (ESS). In order to enhance the efficiency of VESS, cloud computing and internet of things (IoT) play a crucial role in providing the real-time analysis and ensuring the reliability of assets.

The VESS in this project consists of a single-board computer (SBC) and three subsystems: data acquisition subsystem, outdoor temperature measurement subsystem and indoor load controller subsystem. The control technique used in this project is chosen to be the hybrid Fuzzy-PID algorithm due to the high flexibility, quick response time and low computational complexity. Moreover, MQTT protocol is utilized to conduct the wireless communication between the subsystem and SBC.

Last but not least, the results indicate that the first objective of this project which is developing an IoT monitoring system for the cooling system is achieved by using the smart energy meter and Node-RED. The monitoring system enables the user to visualize the data acquisited and store the historical data in csv file for future usage. Additionally, the case studies prove that the outdoor temperature has a high chance in affecting the energy consumption of the cooling system. By implementing the VESS, both PID-based and Fuzzy PID-based controller successfully reduce the energy consumption within 17.13 % to 44.9 % and 11.91 % to 44.12 % respectively. The performance analysis also suggests that Fuzzy PID controller has a smaller rise time and higher consistency in preserving the desired indoor temperature when compared to PID controller.

5.2 Recommendations for Future Work

According to the outcomes of the project, a few recommendations for future work can be suggested to enhance the effectiveness of VESS in energy saving. First of all, a temperature and humidity sensor with higher accuracy is essential in providing more precise measurements of the actual scenario, ensuring higher reliability of the data collection. Hence, the advanced sensors can be utilized in the project to improve the performance of the system designed. Besides, the number of temperature sensors is suggested to be increased particularly in the indoor spaces. As the measured indoor temperature at different areas of the experimental environment may have slight difference, the thermal comfort will vary depending on the location of temperature sensor as well. Thus, the present of multiple indoor temperature sensors positioned at various areas enables a more thorough examination of the entire indoor temperature.

Apart from that, a comprehensive study on the parameter tuning technique of the PID and Fuzzy PID controllers can be carried out to further analyze and determine the most appropriate parameters for the targeted cooling system. As the rise time, settling time and overshoot percentage will greatly influence the performance of the controllers, the fine tuning process of the controllers plays a crucial role in improving the response time and stability of the controllers.

Lastly, the advanced control strategy like model predictive control (MPC) is recommended to be developed and implemented for the project. Due to the high complexity of the advanced control strategy, the system robustness can be improved as the complex control strategy is capable of stronger adaptive control and higher predictive accuracy. Thus, the performance of the VESS can be optimized by incorporating the advanced control strategy.

In summary, the recommendations place a strong emphasis to enhance the accuracy of data collection and develop a more efficient and advanced VESS system.

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APPENDICES

Appendix A: Technical Specifications of DHT22 Temperature Sensor

Model	DHT22
Power supply	3.3-6V DC
Output signal	digital signal via single-bus
Sensing element	Polymer capacitor
Operating range	humidity 0-100%RH; temperature -40~80Celsius
Accuracy	humidity +-2%RH(Max +-5%RH); temperature <+-0.5Celsius
Resolution or sensitivity	humidity 0.1%RH; temperature 0.1Celsius
Repeatability	humidity +-1%RH; temperature +-0.2Celsius
Humidity hysteresis	+-0.3%RH
Long-term Stability	+-0.5%RH/year
Sensing period	Average: 2s
Interchangeability	fully interchangeable
Dimensions	small size 14*18*5.5mm; big size 22*28*5mm

Appendix B: Pin Overview of ESP32 Devkit V1 (DOIT Version)