DEMAND SIDE MANAGEMENT: DEVELOPMENT OF BUILDING POWER MONITORING DEVICE AND LOAD CURTAILMENT ALGORITHM

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A project report submitted in partial fulfilment of the requirements for the award of the degree of Bachelor (Hons.) of Electrical and Electonics Engineering

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May 2014

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 **"DEMAND SIDE MANAGEMENT: DEVELOPMENT OF BUILDING POWER MONITORING DEVICE AND LOAD CURTAILMENT ALGORITHM"** was prepared by **CHOK EU-TJIN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of (Hons.) Electrical and Electronics at Universiti Tunku Abdul Rahman.

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Specially dedicated to

my beloved grandparents, mother and father

ACKNOWLEDGEMENTS

I would like to thank everyone who had contributed to the successful completion of this project. I would like to express my gratitude to my research supervisor, Mr. Chua Kein Huat for his invaluable advice, guidance and his enormous patience throughout the development of the research.

In addition, I would also like to express my gratitude to my loving parent and friends who had helped and given me encouragement throughout the duration of this project. I would also like to especially thank my course mates Alvey Hau and Nicoline Saw for helping me throughout the duration of this project. Their insights and input has enabled me to further understand the different scopes involved in this project.

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ABSTRACT

Demand for energy has increased significantly for the past few decades. The main method of electricity generation is through the burning of fossil fuels, which are depleting at an alarming rate. The oil crisis of the past has lead to the introduction of Demand Side Management (DSM), which is even more relevant in for the consumers of electricity today. DSM strives to flatten the load curve through techniques such as load shifting, valley shifting, peak clipping, as well as load curtailment. In flattening the demand load curve, electricity consumers will benefit financially through the reduction of peak demand charge. Peak demand charge is imposed by the utility on the consumers, in order for the right of consumer to have a specific energy capacity available to them anytime. Peak reduction will also benefit the utility as it will stall the need for further expansion of more power plants in order to cater for the increment of peak demand. When peak demand decreases, the need to operate back-up power plants which operates at a higher cost and lower efficiency will decrease as well. This project describes DSM as a whole, and investigates how the different methods and techniques of DSM can be applied in the application of load curtailment of a building. A building power data acquisition and monitoring device is developed to monitor the power consumption of a building in UTAR. An air conditioner load curtailment algorithm is developed and simulated in LabVIEW.

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LIST OF SYMBOLS / ABBREVIATIONS

AC	Admission Controller
CT	Current Transformer
DLC	Direct Load Control
DRM	Demand Response Manager
DSM	Demand Side Management
HVAC	Heat Ventilation Air Conditioning
ILC	Indirect Load Control
LB	Load balancer
LF	Load Forecaster
AC	Air Conditioner
R	Room

CHAPTER 1

INTRODUCTION

1.1 Background

The last few decades have seen a significant growth in demand for energy, not only from the industries, but also from domestic household users. Energy is needed for a wide range of human activities, from the power up of small consumer appliances, and even up to its usage in driving industrial machines. One cannot deny that electricity has become an integral part of our lives, and its significance and impact towards our well-being has become more profound as time passes by. The energy crises during 1973 and 1979 for instance, have shown our dependence on fossil fuels in the generation of electricity. Today, after over 40 years from the energy crisis, we are still at a point where we are still highly dependent on fossil fuels for electricity generation, although major advancements have been made in the area of renewable energy generation technology, with sources of electrical energy generation depleting fast.

It is the concern over the energy usage efficiency that has brought about the introduction of Demand Side Management (DSM), during the energy crises in the 1970s. Other than increasing demand for electricity, and other problem which is present is the fluctuation in demand. The fluctuating demand results in low generation efficiency, as well as increased minimal grid requirements (A. Molderink, 2010). In (C. W. Gellings, 1985), DSM is defined as the planning, implementation, as well as monitoring of the utility operation taken, in order to bring about targeted changes in the load curve of the utility; a load shape in which time pattern and load magnitude is positively altered. Popular forms of load management involved in the DSM include: peak clipping, valley filling, load shifting, and load curtailment. Although DSM relatively new in Malaysia compared to other countries, it has potential to develop, in line with Malaysia's energy policy of supplying energy with the lowest cost coupled with high energy efficiency. Essentially, DSM strives to minimize energy (kWh) usage, reduce peak demand (kW) for total energy (kWh) consumed, and also to advocate the use of 'eco-watts'; the usage of electricity which results in lower fossil fuel consumption, and hence reduce greenhouse gas emissions (M. Ibrahim, 1993).

Air conditioning plays a vital role in maintaining thermal comfort within indoor environments, especially for buildings situated in region with hot and humid climate. Air conditioning systems in general contributes to a large portion of the total power consumption in buildings and facilities, where it can exceed 50% of the total energy consumption for those in tropical climates.

Despite the various new technologies in the area of air conditioning systems, it is normally not feasible to replace existing AC systems due to financial factors, considering the amount of effort involved. Hence, various studies have been done in order to incorporate intelligent air conditioner management system into existing air conditioners. This fact in itself provides a motivation to incorporate air conditioning systems as part of the DSM strategy.

1.2 Aims and Objectives

The aims and objectives of this project are presented below:

1. To design and develop a data acquisition system to collect, monitor and analyze power parameters for a building
2. To design and simulate an air conditioner load curtailment control algorithm

1.3 Potential Benefits

Through DSM energy users will be able to see reductions in electricity bill due to reduced electricity consumption. For large users of electricity, the electricity cost reduction will be very significant, due to savings in terms of peak demand surcharge; an imposed surcharge which is usually a few times higher than the normal electricity tariff. From the point of view of the utility, reduction in peak demand would mean lower generation cost. This is happens as the utility needs to operate its gas-powered power plant in order to cater for the peak demand, where electricity generation through gas is evidently much more expensive than the conventional generation through coal. Besides that, gas-powered plants also run at a lower efficiency than coal-powered ones, thus increasing the cost of electricity generation. All these makes even more sense when we realize the fact that electricity is a commodity than cannot be stored or kept. Hence, wastage occurs when there is over generation of electricity where in the end, the wastage is in a way retrieved through implementation of peak demand surcharge towards industrial users. Other than that, efficiency of energy usage will delay or even prevent the need for expensive investments to be made for new power plants as well as upgrading of the current transmission and distribution lines. Another benefit of DSM is that it reduces transmission and distribution losses (A. Nourai, 2008), in the context of having a lower peak demand or a shifted load. This is because at off-peak periods, transmission and distribution cables have lower resistance due to a lower temperature in the cables.

1.4 Scope of project

The scope of this project involves performing research on DSM as a whole, understanding the different types of techniques and methods in realizing DSM. The literature review in this report investigates different methods of DSM, as well as how it can be related and implemented in the sense of load curtailment within a building. The importance of DSM, types of load control, and load classification method is also presented in the literature review section. Works of other researches were carefully studied and its potential in terms of its usage in load curtailment. Other than that, this project involves the construction of a power diagnostic tool which enables electrical measurement within the electrical network of a building. The design and construction of the hardware is in the methodology section of this report. The main platform which the power diagnostic tool runs on, the National Instruments sbRIO embedded control and acquisition is configured to perform load curtailment of air conditioners (AC) within the campus building. In this project the cooling and heating characteristic of the classroom will be identified by using the program developed in LabVIEW, for use on to the sbRIO. Once this characteristic has been acquired, the data is implemented in the AC load curtailment program. This project will also cover the design and simulation of an air conditioner load curtailment control algorithm which is programmed using LabVIEW. In order to perform this, this project will also involve data acquisition of room temperature in order to predict the heating/cooling characteristics of the room, which is to be used in the simulation.

CHAPTER 2

LITERATURE REVIEW

2.1 Demand Side Management

Demand Side Management (DSM) is defined as the planning, implementation, and monitoring of activities of the utility, created to affect the way electricity is consumed by the consumer (C. W. Gellings, 1985). This is done in a way that will produce desired changes in the load shape of the utility, such as changes in magnitude of utility's load over a period of time. DSM is further noted as activities which are in performed order to alter consumer's demand of electricity, a form of intervention done by the utility. In saying this, the purchase of energy-efficient electrical appliances by customers is not seen as DSM, although the end product is bring desired positive changes to the utility load shape.

Iterating further, Gellings introduced six categories of objectives which alters the load-shape. This takes into account of the fact that the load shape is dictated by daily and seasonal electricity demands over period within a day, period within a week, and period over a season. These categories include peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape. Figure 2.1 illustrates the various categories of DSM.

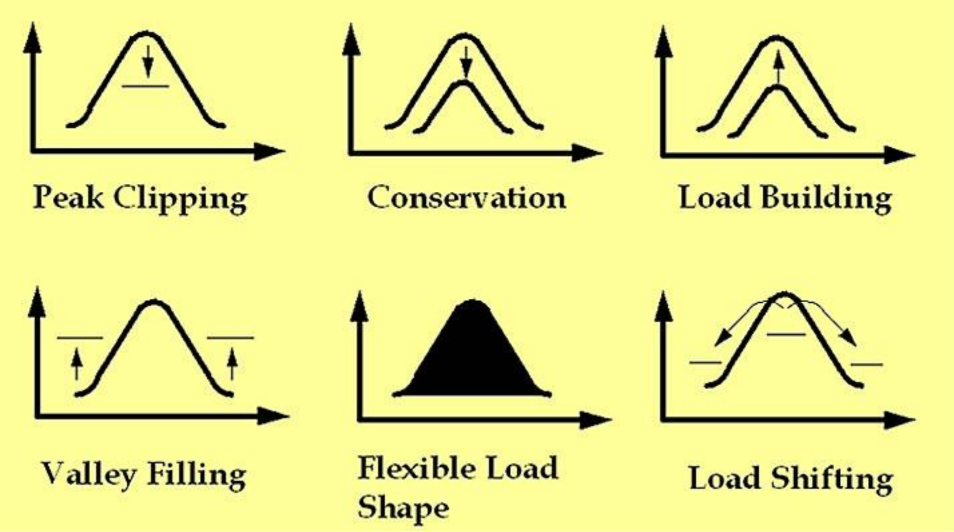


Figure 2.1: Categories of DSM

2.1.1 Peak Clipping

As the name suggests, peak clipping means the reduction of peak loads, and is one of the most classic method of load management. Peak clipping is generally done by using direct load control, which is one common form of utility intervention in the form of control of customer's appliances. This form of control is normally done in system peak load is forecasted to occur during certain periods of time. An example of the use of peak clipping is the application of interruptible or curtailable rates for commercial and industrial customers.

2.1.2 Valley Filling

Valley Filling is another classic form of load management, coming after Peak Clipping. This form of load management deals with increasing off-peak loads. This may be sought after where long-run incremental cost is lower than the mean cost of electricity. Properly priced off-peak load in those situations lowers the average cost of electricity for the customer. A well known application of such method is by the implementation of thermal energy storage systems, replacing loads served by fossil fuels.

2.1.3 Load Shifting

This is part of the three classic forms of load management, which involves shifting or moving loads from on-peak period to off-peak periods. Applications include the usage surrounding heating and cooling processes, such as storage water heating, coolness storage, and consumer load shift of miscellaneous electrical appliances. One such modern application involves the charging of batteries at night when it is an off-peak period, as opposed to charging it during the day, when it is an on-peak period.

2.1.4 Strategic Conservation

This method changes the load shape through utility-stimulated or utility-backed programs which is aimed at altering the end-use consumption. The load-shape change shows the altering of load shape, which is a product of reduction in sales as well as alteration in pattern of use. An important aspect of this is the evaluation of the cost-effectiveness of the planned utility program to bring forth these actions, while considering what conservation would happen naturally. It is therefore a need that distinctions between naturally occurring and induced changes in consumption pattern are noted.

2.1.5 Strategic Load Growth

Load growth programs are aimed at improving productivity of the customer and compliance to environmental standards while increasing the sale of electricity of the utility. Load growth involve increased portion of loads served by other types of fuels. This increased market share will enable the increase of load peaks as well asthe filling of valleys. Programs related to load growth will potentially a motivation towards improvement of productivity through reduction in fossil fuel and raw material usage.

2.1.6 Flexible Load Shape

Once load shape is forecasted and supply side choices are outlined, the utility presents different options to consumers as to the loads which are willing to be surrendered to utility to be controlled during critical periods, in exchange for different types of incentives (Tianyu Luo, 2010). Programmes involved can be in terms of curtailable/ interruptible load, where load shape of the consumer can be flexible.

2.2 The need for Demand Side Management

Considering all types of Demand Side Management (DSM) techniques, load shifting is a simple way in reducing peak load, as it does not require any additional hardware or any installation of additional equipments. Essentially, it only involves proper management of loads with respect to time, where activities that are supposed to take place for a particular time are put off to a time which does not fall into the peak load period. Although such is the advantage, this approach in DSM is not feasible in the context of a building where academic activities take place, say, a university building. It is not possible to shift lectures, tutorials, and practical laboratory sessions which takes place during office hours, to a later time. Hence, DSM would have to take place in other form, where in this project, is the load curtailment of electrical appliances. Medium voltage commercial users such as universities are categorized as C1 type consumer. C1 consumers are not only charged with the total energy usage in terms of kWh, but also require to pay an additional charge called the maximum demand surcharge which is based on the highest energy demand within a time cycle, in terms of kW.

For C1 type of energy users, monthly price for each kilowatt of maximum demand is fixed at RM 25.90 per kW, while consumption tariff is 31.2 sen per kWh. This means that users falling under category would need to pay a maximum demand charge which is 81 times higher than the price of energy per kWh, which easily translates into a significantly high portion of additional cost. Table 2.1refers to the electricity cost for a particular month in UTAR:

Table 2.1: Electricity cost breakdown in a particular month for UTAR

	Units	Unit Price (RM)	Electricity cost (RM)
Electricity (kWh)	208,501	0.312	65,052
Maximum Demand per Month (kW)	1002	25.90	25, 952
Monthly Electricity Bill			91,004

It can be seen that the maximum demand charge is RM 25, 952, which is a high 39.89% of the price of the total electricity used. This scenario itself provides a motivation to perform DSM in the buildings within UTAR Setapak campus.

2.3 Direct Load Control

In the beginning, DSM programs were conducted by utilities, where implementation was done using data communication and are operated by the utility themselves. The control and management over the power consumption was done through direct load control (DLC), a technique where customers willingly allow the utility to disconnect supply to certain appliances whenever there is a need (C. W. Gellings, 1985), which is hard for energy users to accept, should their comfort level be compromised. However, in the scenario within a building where there are a large number of appliances, DLC is not a suitable approach, although it being an efficient and easy method. With that being said, control should not be limited over a certain number of appliances, but should be done towards all the appliances within the system. Since it is technically not feasible to connect all of these appliances directly to energy network, an approach using decentralized control at the demand side or the consumer's side can be used, as mentioned in (G.T. Costanzo, 2012). Decentralized control allows consumers to manage and handle the load control locally, with the utility playing its part to influence the consumer through price adjustments, in order to modify their own load curve.

The research conducted in (G. T. Costanzo, 2012) not only addressed the problem surrounding DLC, but it also proposed a layered structure architecture for load management in buildings for DSM to be performed. Inspired by real-time computing scheduling approach, this system uses online scheduling strategies for appliance load control. The system consists of:

1. Admission Controller (AC)- acts as a medium between other layers and the physical equipments, to perform real-time load control.
2. Load Balancer (LB)- manage demand response and admission control by spreading load to reduce operational cost according to the capacity parameter and size decided by DRM., for each physical electrical appliances. This means that for a particular time period, total energy cost is at minimum for particular capacity constraints.
3. Demand Response Manager (DRM)- the onset into the DSM system which acts as a connecting medium between the system to the grid. Obtain capacity limit and cost of energy for the utility.
4. Load Forecaster (LF)- provide LB and DRM with information and data regarding energy pricing and energy consumption efficiency.

Such layered structure provides ease of integration, modularity, as well as well as high inter-operability. As a scalable and extensible system, the said architecture can be used for a wide range of consumer, from homes, buildings, factories, or even islanded energy grids. Simulation results of such an architecture have shown that within a given capacity constraint, it is able to schedule burst load appliances in such a way that is able to stay within capacity limit while in the required time scale. When such action is not able to be done, the system is able to reduce operation time above the capacity limit, at a minimal level.

2.4 Indirect Load Control

Other than the direct load method (DLC), another method of control in DSM is the indirect load control (ILC). In this method of control, the customer is responsible in manually controlling and managing power consumption of loads, as opposed to DLC where control is done by the utility regardless of the user's preference or input. Besides that, ILC can be done automatically using appliances while taking note of current electricity tariffs and other real-time parameters in the power system. In (N. Lu, 2012), the author researched on the potential of load balancing on HVAC loads, using a DLC algorithm. The author fed a simplified HVAC model into the central controller for the forecasting of ambient room temperature every minute, and used continuous 15 minute interval room temperature measurements to correct the forecast.

All this was done while considering that HVAC usage is dependent on the ambient temperature values, providing a properly modelled HVAC. Results showed that the system performed at an acceptable level without greatly compromising user's comfort. The rate at which the forecasting and forecasting is done also helps to reduce the calculation and communication burden of the system. Such a forecast and update mechanism decreases data congestion between each managed HVAC unit and the central controller.

2.5 Transmission network

The modern power transmission grid is a complicated network which can be broken down into a few subsystems, namely the generation plants, transmission lines, sub-power stations, distribution grids, and also the energy users. All of these interdependent parties exist coherently and can be grouped (I. Atzeni, 2010) into three main categories:

1. Supply-side- this includes the utility, which consists of energy producers and providers, as well as the electricity transmission network.

2. Demand side- it consists of the end users behind the energy transmission lines which are the energy consumers, as well as the energy distribution network.
3. Central unit- this is the administration which has power and control over the regulation and coordination over the grid optimization process.

2.6 Load Classification

In order for an effective and well planned load management, it is essential and important to appropriately classify different modes of power consumption and their corresponding categories. Basically, we can power loads can be grouped into three categories, based on the type of electrical appliances used (G. T. Costanzo, 2012):

1. Baseline load- involves the power consumption by appliances which must be instantly served at any period, at the point of demand. Appliances which fall under the baseline load category include lighting, networking and computing tools.
2. Burst load- appliances that run or operate within a given period, or a specific time frame. Such appliances include washing machine, laundry dryer or the dishwasher. Management of burst load is of a critical importance as the accumulation of such loads will bring about a significant rise in peak load, impacting power consumption efficiency.
3. Regular load- the energy required by electrical appliances which constantly operate for a long duration of time. Examples of such appliances include the HVAC (Heat Ventilation Air Conditioning) system, water heater, and the refrigerator. The appliances related to this category can be stopped or interrupted at irregular time intervals, depending on the current circumstances in which the appliances currently operate in.
4. The understanding gained in classifying these modes of consumption also helps us in developing the Load Priority Technique (LPT) mentioned in (P. Ravibabu, 2008).

Basically, these the loads can be further classified in terms of interruptible and non-interruptible loads. Non-interruptible loads are connected to the power supply continuously without interruption, while interruptible loads are those which can be disconnected from the power supply depending on the level agreed beforehand, and also at a level which is comfortable for the consumer. In saying this, we can say that non-interruptible loads are high-priority loads while interruptible loads are low priority loads. This classification of high and low priority loads will help to provide a distinction between loads which can be affected through DSM method of load curtailment, and loads which cannot be affected. In the context of load curtailment, the category of power consumption that we will deal with is the regular load, which includes the HVAC system in the campus building.

2.7 Air Conditioner Systems

In the area of HVAC system, this project will focus on the air conditioning system in performing load curtailment. The air conditioning system is essential and also of a high importance in many buildings in Malaysia, due to the country's generally hot and humid climate throughout the year. In this case, the UTAR campus building is no exception.

2.7.1 Type of Air Conditioner Systems

In the market today, there are basically a few types of air conditioner systems available to the consumer. They are the Split Air Conditioner System, Window Air Conditioner System, as well as the Central Air conditioner System. They type of air conditioning systems installed within a building or a premise is highly dependent on factors such as: the size of the space to be cooled, heat dissipation within the space to be cooled, as well as the structure design of the area to be cooled.

2.7.1.1 Split Air Conditioner

The Split Air Conditioner (SAC) comprises of two main parts, namely the outdoor unit and the indoor unit:

1. Outdoor unit: This unit is installed outside of the area or space which is to be cooled, and is illustrated in Figure 2.2. The outdoor unit stores the vital components of the air conditioner. These include the compressor, condenser coil, and the expansion coil.
2. Indoor unit: The indoor unit is the unit which is installed within the walls of the area which is to be cooled, and is illustrated in Figure 2.3.This unit houses the air filter, evaporator coil, and the long blower. The chilled Freon fluid from the outdoor unit enters the evaporator coil, and the blower blows the hot filtered air from the room, onto the evaporator coil. The filtration of air before it is passed to the evaporator is done by the air filter, which ensures that dirt particles of the room are removed, before eventually reintroducing cooled air into the room. The air which is passed over the evaporator coil has a lower temperature, and it is effectively the air which will cool down the temperature within the space. The distribution of this cooled air is performed by the blower, which not only suck hot air as it rotates, but also passes cool air from out of the indoor unit to the area to be cooled.

Figure 2.2: SAC Outdoor Unit

Figure 2.3: SAC Indoor Unit

Split air conditioners are usually installed for use in small rooms, and also when one does not wish to make huge modification to the room wall sections, or when there are no windows available in the room. An advantage of SAC is that since the compressor is located outdoors, it basically means that it makes very little noise, ensuring no disruption to the occupants within a room.

2.7.1.2 Central Air Conditioner

Another type of air conditioning system is the Central Air Conditioner (CAC) System, which is usually used in applications involving large space areas, such as hotels, large buildings, complexes, hospitals, etc. It is such that when these large areas are to be completely air conditioned. It is economically more viable to have CAC over SAC or WAC if there are many individual rooms within a large building to be air conditioned, as installation cost of these SAC or CAC units in each and every room would be very huge.

In a CAC system, there exists a large plant room which houses the compressor, condenser, evaporator, expansion valve, and the thermostat. Such a system functions similarly as how a normal conditioning system would, with the exception being that these components are made much larger and have a higher cooling capacity. Chilled air is passed through ducts which runs in all room and spaces, and is distributed via opening on the ducts. This essentially means a noise-free air conditioning experience in each of these spaces to be cooled, as AC components are located far away from these areas.

Concerning the CAC system, one type of technology in the air conditioning system today is the Variable Air Volume (VAV) system, found in the Air Handling Unit (AHU) of the air conditioning system and plays its role in the distribution of conditioned air to occupied spaces. In such a system, the supply air flowrate is proportional to the thermal load. The fan speed varies as the demand for air flowrate in increased or decreased (M. Kotaki, 2006). Such a control method produces a considerable amount of energy consumption reduction. This is in contrast with Constant Air Volume (CAV) system where constant supply of air volume is brought through the distribution system, regardless of the parameter of the thermal load. CAV systems have been used from the time air-conditioning was introduced while VAV systems have been used since the 1960s. One of the main reason that VAV system is more popular than CAV systems in commercial and industrial premises is the energy saving properties of the VAV system (M. A. Aktacir, 2009).

2.8 Air Conditioner Load Curtailment

In the area regarding load-shedding in air conditioning systems, one method proposed is through automatic people counting in an indoor environment, in order to obtain an appropriate setting for air conditioners within the indoor environment (Q. Ye, 2010). Results from the study have shown that the system developed has a high recognition rate, and is practically viable due its low hardware requirement, in which it needs only a single camera and a commercial computer. This is an approach which is currently not found on any air conditioning systems available in the market, and could prove to be a significant addition to future air conditioning products.

In (Y. Wu, 2013), the paper proposed a low cost monitoring and control system for the purpose of energy management of aggregated air conditioners. The system, which utilizes web-based infrared remote control technology, which proves to be more cost-effective than an equivalent ZigBee based system, capable of controlling the same amount of classrooms. In the study, the authors performed tests within a university building which houses 28 classrooms, and a total of 56 split ACs. The system, which controls aggregated ACs in a non-invasive manner, consists of microcontroller-based IR modules are placed in every room.

The control strategy of the system utilizes a simple algorithm, where classrooms on a particular floor are designated cycles of 15 minutes each, considering 3 floors within the building. Within these 15 minute cycles, the will be a 5 minute segment of the cycle where the AC will in cooling mode, for a particular floor. Concurrently, ACs on other floors would be in fanning mode. After the 5 minutes have passed, the AC which was previously turned on in a particular floor will operate in fanning mode, while AC which was in fanning mode previously, will now be in cooling mode. This process continues for ACs for the next floor in order, where eventually, ACs for all the floor levels would have a chance to be turned on for 5 minutes at every 15 minute cycles. The demand control strategy is a s shown in Figure 2.4.

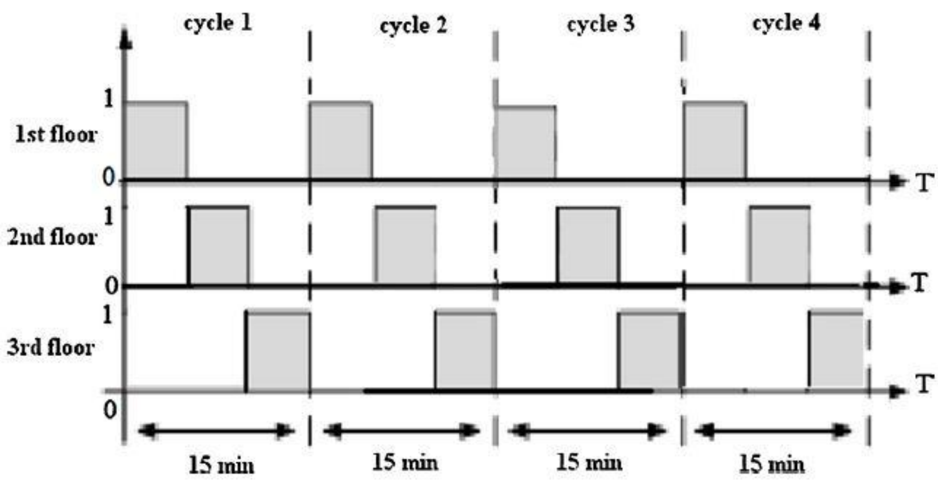


Figure 2.4: Demand Control Strategy for air conditioner

In another study,(Y. Wang, 2011) presented a non-invasive Zigbee wireless controller for energy saving in air conditioners. The motivation behind the use of Zigbee protocol is due to the BACnet protocol of ASHRAE in 2008, which includes the Zigbee protocol. Other than that, being developed for sensor networks, Zigbee consumes low power while providing a reasonable working range. The results from the study showed energy savings of more than 50%, lowering energy use from 7.63kWh to 3.61kWh.

2.9 Thermal comfort

In the Standard 55a of the ASHRAE standard pertaining to thermal conditions for human occupancy in buildings, thermal comfort is defined as when the situation where a person has satisfaction on the surrounding environment's temperature.
(ANSI/ASHRAE Standard 55a, 1995). Thermal comfort is regarded as one of the factor with the highest importance when it come to the design of buildings, as thermal comfort will affect work efficiency and productivity. Fanger in the late 1960s proposed method known as the predicted mean vote (PMV) model, which can be used to assess the comfort level of occupants within buildings. The PMV model utilizes a standard scale which takes into consideration four physical variables which are air velocity, air temperature, relative humidity, mean radiant temperature, as well as two personal variables which are the clothing insulation and activity level. This means that, as contrary to popular belief, it is not ambient air temperature alone which affects the thermal sensation of occupants within a space. Fanger defines PMV further as the mean thermal sensation vote on a scale using the aforementioned variables for a large group of occupants. The PMV model is expressed through a 7-pont scale which is as shown in Table 2.2.

Table 2.2: ASHRAE 7-point sensation scale

Value	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Another name which can be used for PMV is the heat balance model, due to the fact that the thermal load of the human thermoregulatory is interdependent on the thermal sensation in PMV. Fanger explains that a person can attain thermal comfort when the body is in a state of heat balance, whereby average temperature of skin and sweating rates are kept within limits, and that no local discomfort is present in the environment. Local discomfort can be defined as temperature gradients within the environment, which basically means that high variation and fluctuations of temperature should be avoided in order to maintain thermal comfort. (J.V. Hoof, 2008)

Presently, the PMV model is applied worldwide in many types of buildings. Since the model was developed from studies done within the laboratory, it is such that the effect of building type on the PMV model outcome was not investigated. This issue is also important when considering building environments in different climates and geographical location. This in turn, could cause discrepancies between predicted and actual thermal sensations.

Another issue surrounding the PMV model is the validity of such data in representing the thermal satisfaction of groups of people. Results derived from the PMV model is what the 'average' person would feel, or the average reaction of a large group of occupants towards the thermal environment. It is also the case that there exists individual differences which are greater than 1.0 unit on the ASHRAE 7-point scale, which suggests that on normal basis for the same environment this large differences still occur . This means that it is almost impossible to predict thermal comfort for the particular group, since it is not reasonable to expect every occupant to be satisfied in a controlled environment, even if it means that the thermal condition meets standards pertaining to thermal comfort.

Other than that, another criticism deals with the argument of thermoneutrality versus preferred thermal sensation by the occupants. On the ASHRAE scale, votes for values from +1 to -1 are considered as the satisfaction of the occupants towards the provided thermal environment. It is said that thermal neutrality might not necessarily mean the preferred thermal sensation of an individual. It could be that some individuals prefer the environment to be slightly warm. (Humphreys and Hancock, 2007). It might be such that occupants in hot climates prefer a thermal sensation which is slightly cooler than the neutral sensation. Thus, it is argued that the PMV model might need certain modifications for groups of people across different climates.

In a field study done in (I. Hussein, 2009), the author conducted a PMV model test on air conditioned classrooms in a UNITEN campus building. It was found that the neutral temperature is 24.6°C, with a thermal comfort range between 20.8°C and 28.3°C. The results show that respondents in a hot-humid tropical climate such as Malaysia may have a higher tolerance towards heat, due to the fact that the respondents accepted thermal conditions which are beyond the ASHRAE standards.

2.10 LabVIEW Programming

LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) is a system design and growth platform used for the graphical programming language by National Instruments (National Instruments, 2011). Applications of LabVIEW include usage in instrumentation and control, data acquisition, as well as industrial automation. LabVIEW is available for use in popular platforms such windows, UNIX, LINUX, as well as Mac OS.

The programming language in LabVIEW is known as dataflow programming language, or G programming in short. Execution is done according to the way structure within the block diagram is wired, where one can connect wires between different function nodes. Once data is passed on and available on this particular node, the node executes, hence explaining the term dataflow programming where it is such that data flow from one node to another.

In terms of the programming syntax for low level language such as C, it is optimized to run instructions in a sequential manner, as fast as the host CPU can run the,. On the other hand, the graphical syntax of LabVIEW allows parallel execution of tasks which are constrained by real-world timing issues.

Programs in LabVIEW are known as virtual instruments (VI), since their appearance and functionality mirrors real-world physical instrument, such as multimeters and oscilloscopes. LabVIEW VIs are made up of three primary parts, which are the front panel window, block diagram, as well as icon/connector pane. The front panel acts as a user interface for the VI, and is the section where controls (input) and indicator (outputs) are placed. Figure 2.5 shows an example of a LabVIEW front panel.

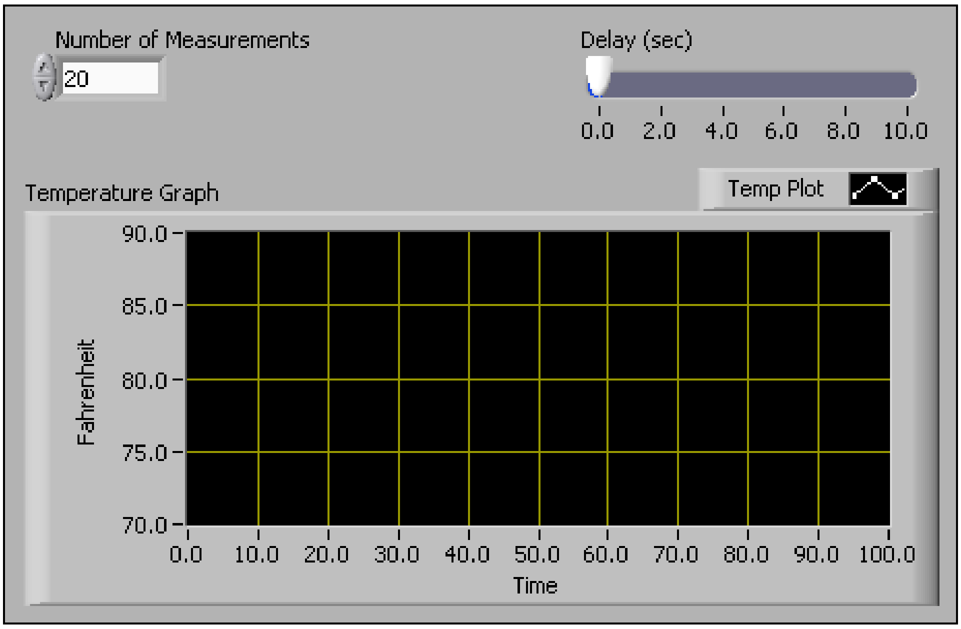


Figure 2.5: LabVIEW front panel

The block diagram is the section which contains the graphical source code. Objects of the front panel will appear as terminals in the block diagram. In the block diagram, one of the blocks available is terminal block. Terminals are entry/exit points which transfer data between front panel and the block diagram. Other than that there are nodes, which are basically objects within the block diagram that have inputs and outputs, and perform a specific function when the VI is run. Nodes come in the form of subVIs, functions, or structures. The function node is the basic operating element in LabVIEW, and a simple example of a function node is the addition function node. Figure 2.6 shows an example of a LabVIEW block diagram.

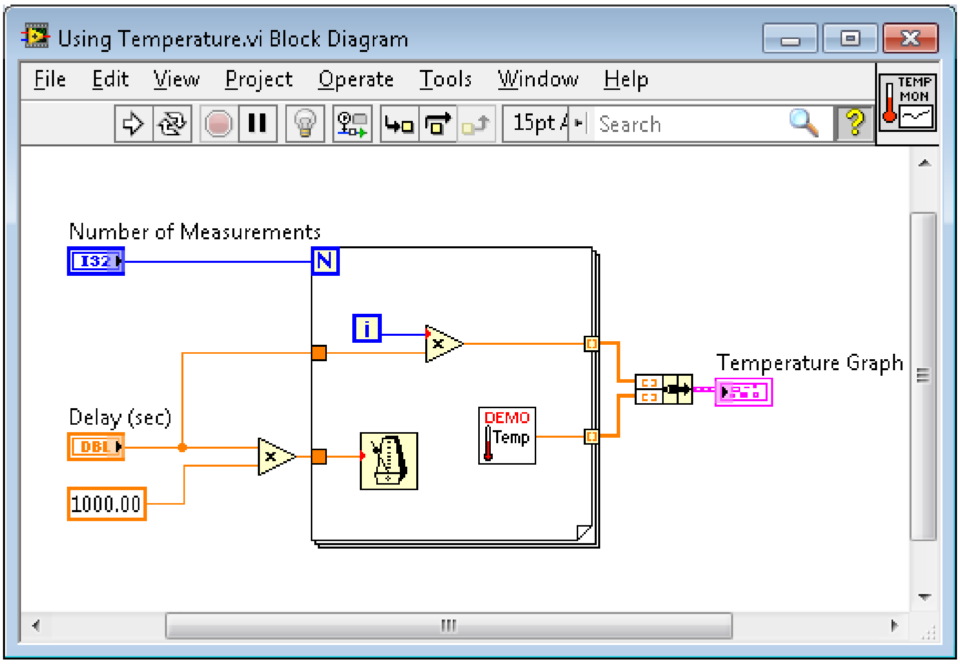


Figure 2.6: LabVIEW block diagram

The Icon is the graphical representation of a VI, while the Connector pane maps the input and output of the VI. Icons and connector panes are important when we want to use a VI as subVI, which is basically a VI within another VI. This is the same as a function in a text based programming language, where it can be called at any time and have it run tasks to produce a desired output.

CHAPTER 3

METHODOLOGY

3.1 Power Diagnostic Tool

In order to perform any DSM techniques or specifically load curtailment, it is essential to have in hand the data of the power consumption within a specific time period. Once this information is obtained, we can use statistical methods to carefully analyze the data. In analyzing the data, we will be able to know the amount of load that can be curtailed. In this part 1 of the final year project, the methodology involved is basically building and constructing the hardware needed to perform measurements of power consumption.

Figure 3.1 shows the flow chart of the design and building process of the power diagnostic tool for electrical network within a building, which is needed to collect data for DSM implementation. In the device design stage, the shape and the size parameters were planned, in reference to the size of the various components which would need to be fitted onto the hardware casing. The order and placement of the electrical components were also defined. In sourcing the materials, we have sourced and opted for 2.0 mm thick aluminium sheet as the material of our hardware casing. Aluminium was chosen over other type of materials as it is lightweight, strong, and can be easily shaped. The electrical components needed were also sourced.

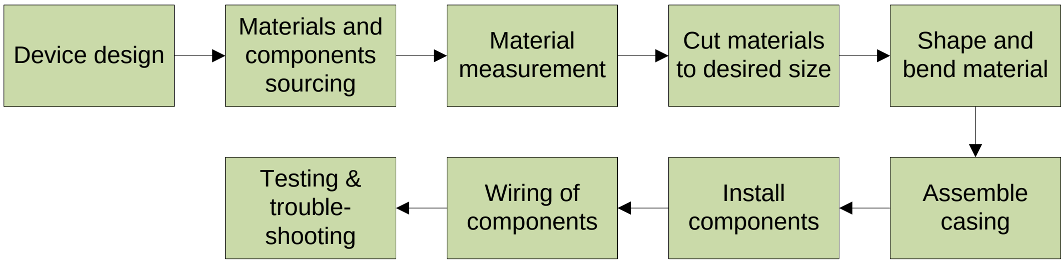


Figure 3.1: Design methodology flow chart of the hardware

The next step involves the measurement of aluminium sheet according to the design plan, to prepare it for the cutting process. After correct lengths were marked out onto the aluminium sheet, it was then cut accordingly, using machineries and tools available for use in the university's mechanical lab. Next, the cut aluminium sheet was shaped and bent using tools, in order for it to attain the designed shape. Suitable holes and slots were also made onto the casing for placing the components. In the stage of casing assembly, the casing was secured using a selection of screws and rivets. By the end of this stage, the aluminium sheet would now look like a cube shaped case. The case is painted using aerosol spray paints in order to protect and improve longevity of the case. After this was complete, the components were installed onto the hardware. The components involved are the cam switch, single pole double throw switch, single and three phase miniature circuit breaker (MCB), residual current device (RCD), single and three phase electrical plug slots, and female pin jacks.

Next, the components were all connected and wired together according to the schematic in Figure 3.3. Distinction in terms of cable colours were made to differentiate the different phases of energy flow through the wires. The tip of the wires were reinforced and strengthened by soldering them. When the wiring has been completed, additional tests were conducted to ensure that the components are wired correctly to each other, using a multimeter. The finished device is as shown in Figure 3.2.

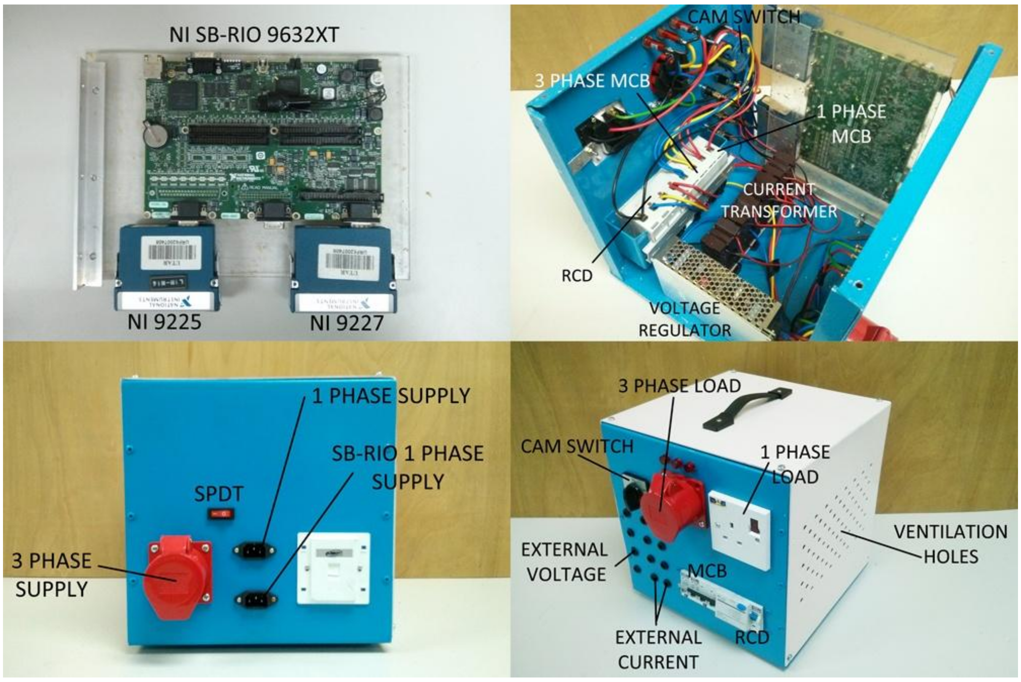


Figure 3.2: The completed hardware design of the power monitoring and data acquisition device

3.1.1 Schematic Design

The electrical schematic of the design is as shown in Figure 3.3. The main component behind this power diagnostic tool is the NI sbRIO 9632XT which is a powerful hardware with many advanced features and is capable of being a central controller. This off-the-shelf product is simply the best fit for this kind of application. The reason is because the NI sbRIO utilizes the NI LabVIEW programming platform, which is in a graphical programming manner. Graphical programming enables its users to simply drag and drop function block in order to produce a desired function on any NI products. This means that tedious long lines of code writing can be eliminated, which is a sure-happen, should we decide with other types of existing hardware in the market.

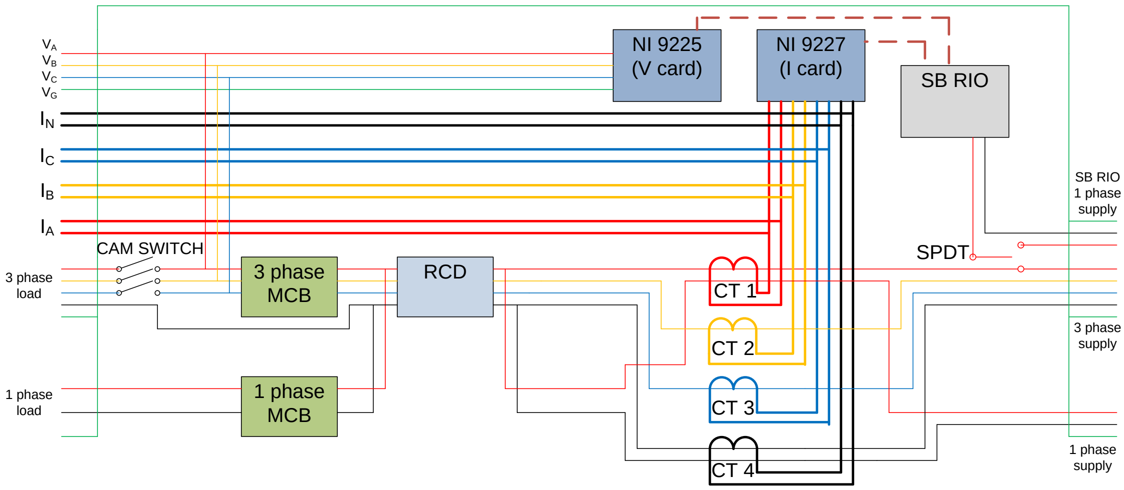


Figure 3.3: Schematic diagram of all the components

The NI sbRIO is connected to two measurement cards, which are the NI 9225 voltage input measurement card, as well as the NI 9227 current input measurement card. Both the NI 9225 and NI 9227 enables voltage and current input to be read, and then fed into the NI sbRIO for further monitoring, analysis, and control of voltage and current levels, as well as any other power related parameters. The input to the NI 9225 can be either from external voltage tap points indicated as V_A, V_B, V_C, and V_G, or from the 3 phase lines towards the load. Meanwhile, NI 9227 receives current input from the current transformers CT 1, CT 2, CT 3, and CT 4 respectively. All of these CTs step down the values of current going through them, and feeds these values into the NI 9227.

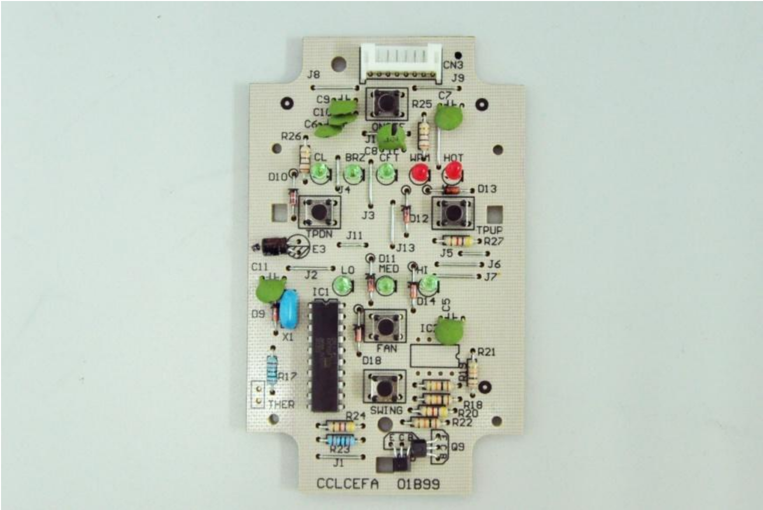
The points I_A, I_B, I_C, I_N are jack pin points which enable external current to be measured, through the connection of external clip-on CTs, mainly in the application of measurement in a power switch room. The Single Pole Double Throw (SPDT) switch enables the selection of either power from a 3phase source or from a 1 phase source to be fed into the NI sbRIO as a power supply source. This application is especially useful, when this diagnostic tool is to be operated in an area without any 1 phase wall plug points, such as the power switch room. The Miniature Circuit Breaker (MCB) and Residual Current Device (RCD) act as protection devices, and break the continuity of the electricity flow in wires whenever there are any abnormal imbalances in current within the device, mitigating harm from the user.

3.2 Data acquisition

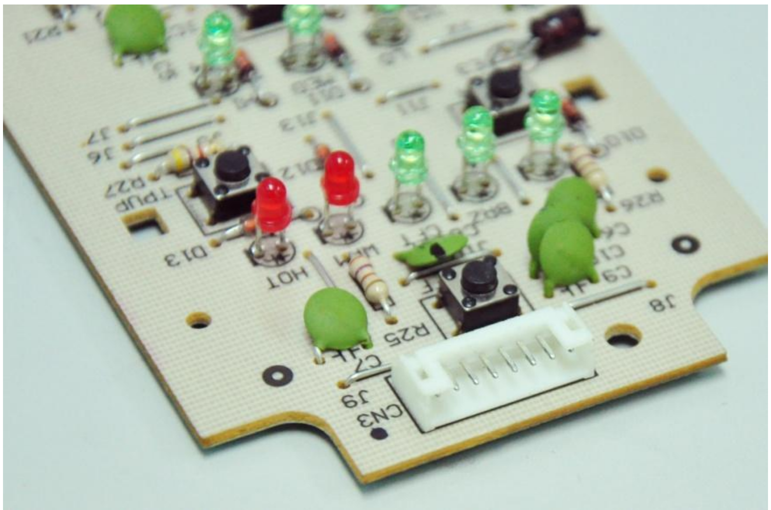
3.2.1 Air Conditioner control signals

In order to proceed to design of a control algorithm for the AC, we first will need to perform tests in order to identify the various characteristic of the AC unit. The first step in this section involves identifying the control signals given off by the AC controller, which is connected directly to the AC circuit within the indoor unit of the AC. In order to do so, the plastic enclosure of the controller was dismantled. It can be seen that the cable which connects the AC controller circuit and AC circuit consists of a group of 8 signal-carrying wires. Whenever a button is pressed on the controller, different sets of signals will be sent to the AC circuit, through this group of wires. Figure 3.4 illustrates the AC controller in its different state.

(a)



(b)



(c)

Figure 3.4: AC controller (a) with plastic enclosure (b) without plastic enclosure (c) circuit 8 data pins

The different combination of signals need to be identified in order to generate control signals to be used in the AC control algorithm. A device known as the National Instruments MyDAQ, which is a low cost, portable data-acquisition (DAQ) device is used for the purpose of identifying the signal. MyDAQ has multiple software instruments built in, and includes the Digital Multimeter, Oscilloscope, Function Generator, Bode Analyzer, Dynamic Signal Analyzer, Waveform Generator, Digital Reader, as well as the Digital Writer. These tasks are realised through the two analog input and output at 200 kS/s and 16 bits, as well as eight digital input and output lines.

Here, the Digital Reader function of the MyDAQ was used to read the signal emitted by the AC controller, every time a button is pressed. The hardware connection for this purpose is such that essentially, MyDAQ's 8 digital input port connection is tapped to the 8 wires of the controller cable. The hardware connection is a shown in Figure 3.5, while the program interface for the digital reader function in MyDAQ is as shown in Figure 3.6. In figure 3.6, a LED which is lighted up indicates a logic high, while a LED which does not light up indicates a low.

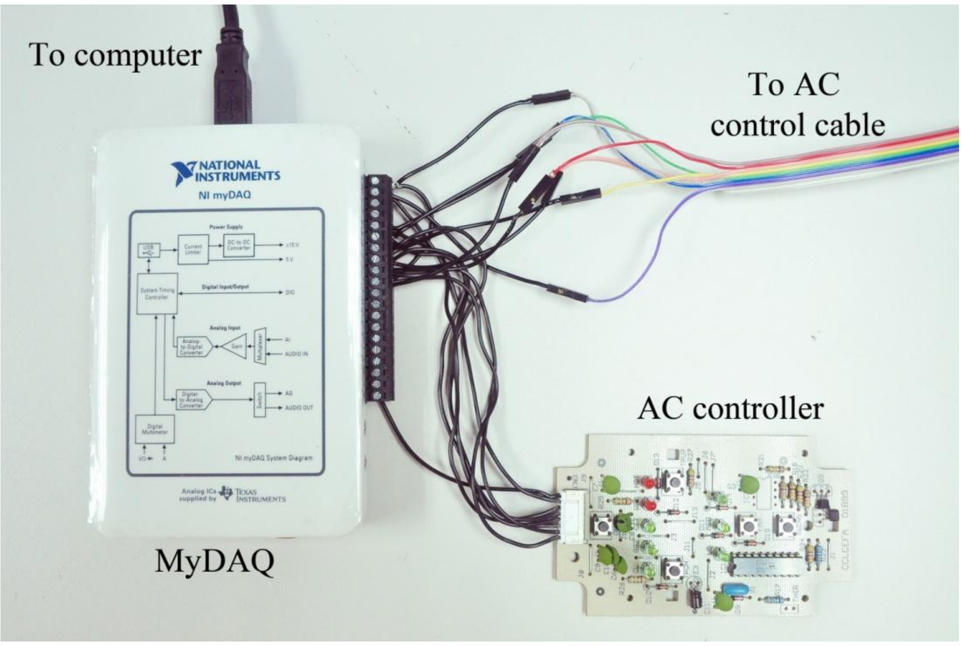


Figure 3.5: Hardware setup for AC controller signal identification

Figure 3.6: Digital Reader interface for MyDAQ.

3.2.2 Control Signal Identification results

The control signal for different combination of AC setting is identified and the results are tabulated as shown in Table 3.1, where '1' represents a logic high while a '0' represents a logic low.

Table 3.1: AC Control signals for various settings

	Port 0	Port 1	Port 2	Port 3	Port 4	Port 5	Port 6	Port 7
On	0	1	1	1	1	0	0	1
Off	0	0	0	1	0	0	0	1
Fan low	0	1	0	0	0	0	0	1
Fan medium	0	0	0	0	0	0	0	1
Fan high	0	0	0	1	0	0	0	1

3.2.3 Air conditioner on/off state

Besides identifying the signals emitted by the controller unit, the current drawn by the outdoor AC unit was also noted. This was done by using a commercial current clamp meter, which basically a device capable of measuring current flow through an electrical conductor. The device is designed with jaws that can open, thus enabling hassle-free current measurement without breaking the circuit. It was found that whenever the AC unit is turned on, regardless of any setting dialled onto the controller, the current reading on the live wire to the compressor unit remains at about 14Amperes. This also means that whatever temperature setting set on the controller, the current drawn by the compressor is the same at 14A. This infers that since compressor draws the same current value, the compressor is always working and rotates at a constant speed.

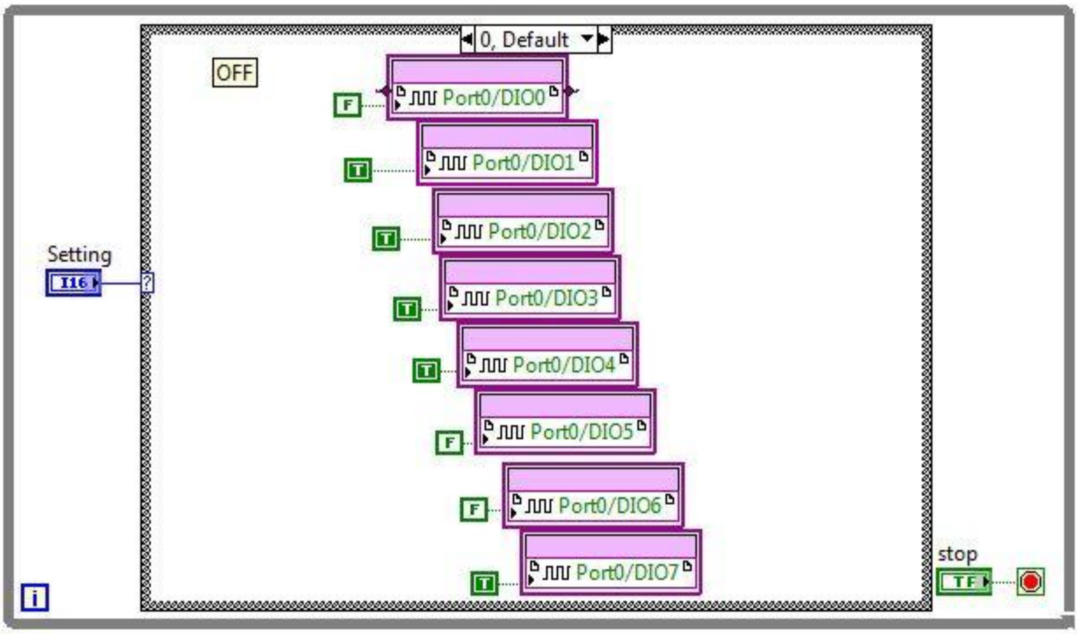
This situation could only mean one thing, and could be that by changing the temperature setting on the controller, this would produce a specific temperature set-point information for the AC circuit. Whenever the temperature sensor of the AC unit senses that the air temperature has already reached the temperature set-point, the compressor would be turned off. This is evident from testing through observation, where at setting 5 (highest temperature), the compressor would turn off after a certain period of time, and at low temperature settings, the compressor would run for a longer time, before eventually turning off. For the controller's fan control setting, it was found that manipulating it has little to no effect to the power consumption of the AC unit.

After the signals are identified, a program was created in LabVIEW in order to control the AC so that the these functions can be done: on-off control, and indoor unit fan speed control. When the program was run, it is verified that the AC unit performs all the function specified by the LabVIEW program.

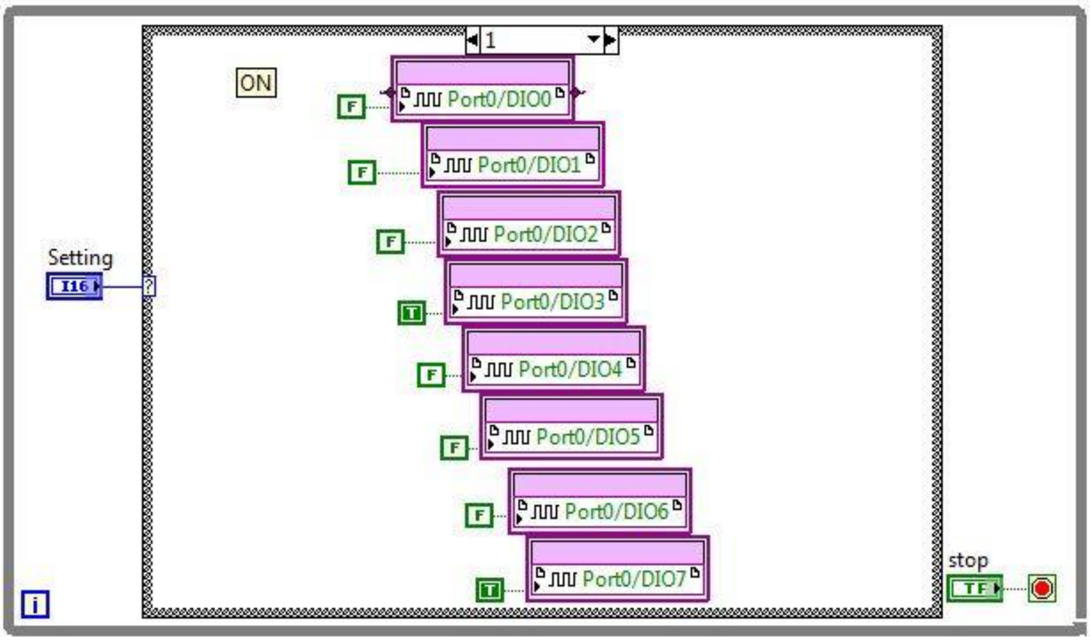
Figure 3.7 below shows a snippet of the front panel of the AC on/off state control program. This simple program aims to show the functionality of the sbRIO in controlling the running state of the AC. As can be seen from the figure, there are a total of 5 available settings available, which are OFF, ON, LOW FAN, MID FAN, and HIGH FAN. These settings have a corresponding setting number which can be keyed in onto the ‘Setting’ control. Basically, any number from 0 to 4 can be dialled onto it, and the sbRIO will send a signal out to the AC unit in order to perform the various setting controls.

Figure 3.7: AC on/off state control front panel

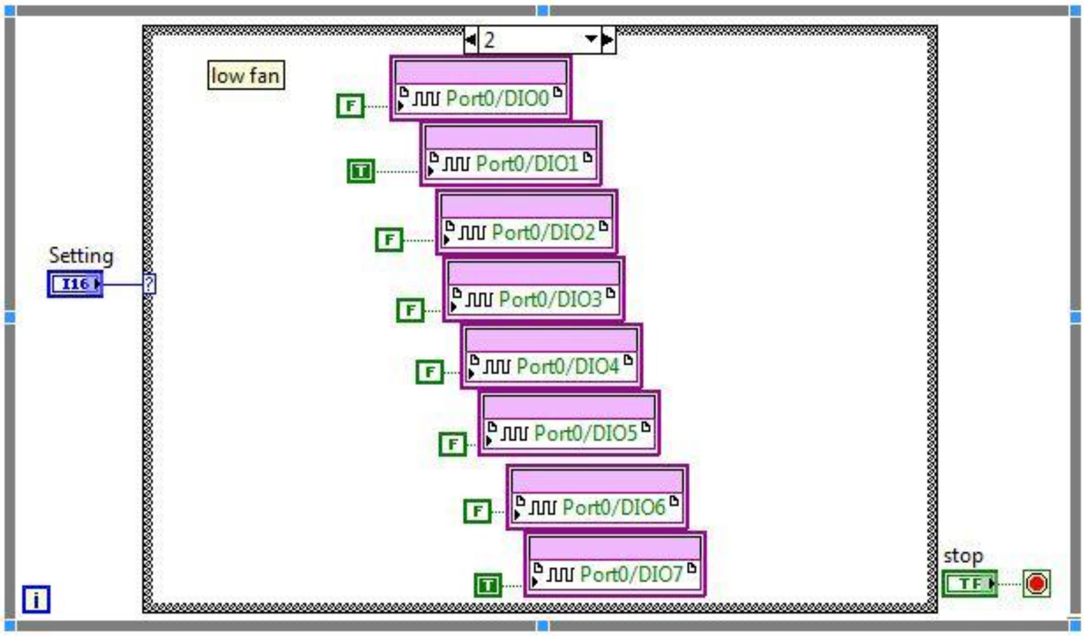
Figure 3.8 shows the block diagram of the LabVIEW program. Basically, the outer structure is a while loop which loops continuously until the ‘stop’ button is pressed. Inside this while loop is a case structure which are made up of case 0 for setting 0, case 1 for setting 1, up to case 4 for setting 4. The case structure will execute the different cases according to the ‘Setting’ input. Inside the case structure, there are a total of 8 DIO (Digital Input Output) nodes which receives different sets of Boolean logic TRUE or FALSE (indicated by block ‘T’ or ‘F’), according to the type of setting selected. Figure 3.8 shows the Boolean logic signal combination for setting 0 (OFF) for DIO0 up to DIO7. Figure 3.9 and 3.10 shows the block diagram for ON setting and LOW FAN setting respectively.


0, Default
OFF
Port0/DIO0
Port0/DIO1
Port0/DIO2
Port0/DIO3
Port0/DIO4
Port0/DIO5
Port0/DIO6
Port0/DIO7
Setting
I16
stop
TF

(a)


1
ON
Port0/DIO0
Port0/DIO1
Port0/DIO2
Port0/DIO3
Port0/DIO4
Port0/DIO5
Port0/DIO6
Port0/DIO7
Setting
I16
stop
TF

(b)



(c)

Figure 3.8: Block diagram for (a) OFF setting (b) ON setting (c) LOW FAN setting

Once the Boolean signals are sent to the DIO nodes, these sets of signal will be sent through the AC controller cable to the AC control circuit. The AC unit will then perform functions as specified by this control signal. Figure 3.9 shows the hardware setup to perform this program. The LAN cable from the sbRIO is connected to a host computer, which displays the front panel of the program. Figure 3.10 shows a close-up image of the 8 data wires (DIO0 to DIO7) which carries data from the sbRIO to the AC control cable, while Figure 3.11 shows the 8 data wires from sbRIO connected to the AC control cable.

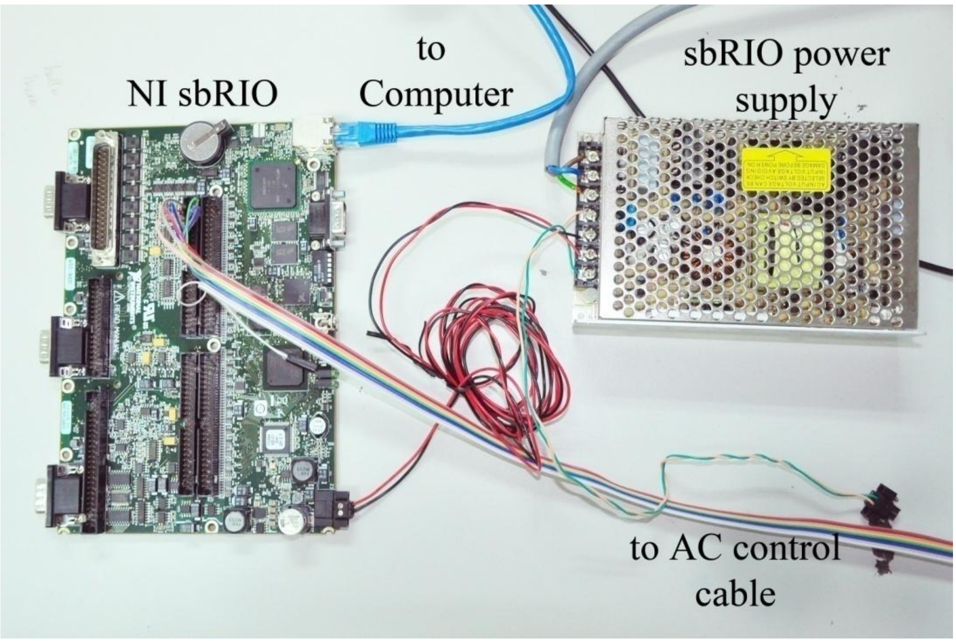


Figure 3.9: Hardware setup to perform AC control

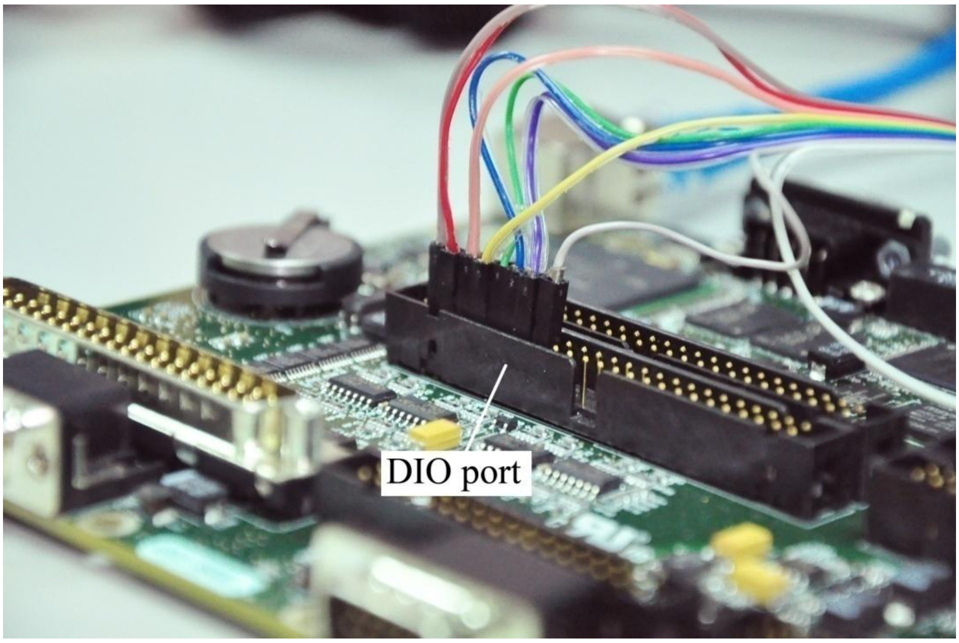


Figure 3.10: Close up of NI sbRIO DIO port

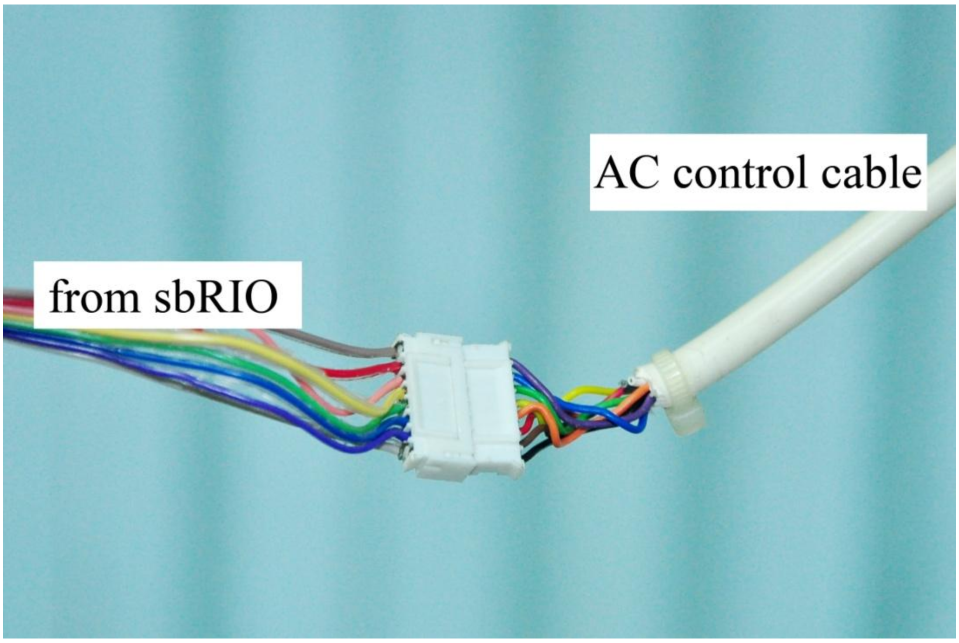


Figure 3.11: Connection between 8 data wires from sbRIO and AC control cable

3.3 Room heating/cooling characteristics

It is vital in our case, that we know the cooling characteristic curve of the room when the AC is in operation. It is important to know the duration of time that the AC is turned on, to the resultant room temperature. To do so, data acquisition set up has been prepared, which functions to measure the relationship between time, temperature sensed by thermistor in the AC, room ambient temperature, on-off state of the AC compressor. This set up serves two functions, with one being identifying at which temperature and time the AC compressor will be shut down, as well as room ambient temperature as a function of time.

3.3.1 Field Test Environment

In this project, the area within the campus building that is dealt with is one of the block, called the SE block, which houses a total of 10 tutorial rooms, all situated within level 1 of the block. There are two classroom sizes available, but this study will assume all the classrooms to be of the same size, measuring 808 x 795 x 362 cm (L x W x H). The justification behind this was so that the simulation/programming section of this study will be kept simple. In each of the classrooms, there are two units of split air conditioners installed within them as shown in Figure 3.12. The AC on the right side of the room is referred to as AC1, while AC on the left side of the room is referred to as AC2. These air conditioners are powered by compressors with the specifications in Figure 3.13, which states that the power consumption is 3kW each.

Figure 3.12: AC 1 and AC 2 inside the classroom

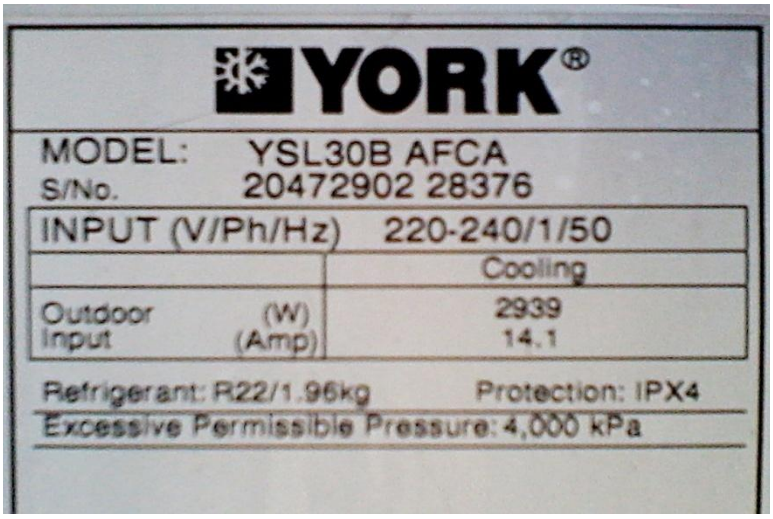


Figure 3.13: Air conditioner compressor specification

3.3.2 Room heating/cooling data acquisition

3.3.2.1 Data acquisition hardware

The set-up for the purpose of data acquisition of the room heating/cooling consists of the following:

1. NI sbRIO 9632xt- sbRIO functions as the central processing unit used in testing, control, as well as monitoring of the system. Advanced features such as integrated analog and digital I/O, real-time controller, reconfigurable FPGA and C series module connector which are built-in to this board simplifies the system design and data acquisition. It is illustrated in Figure 3.14.

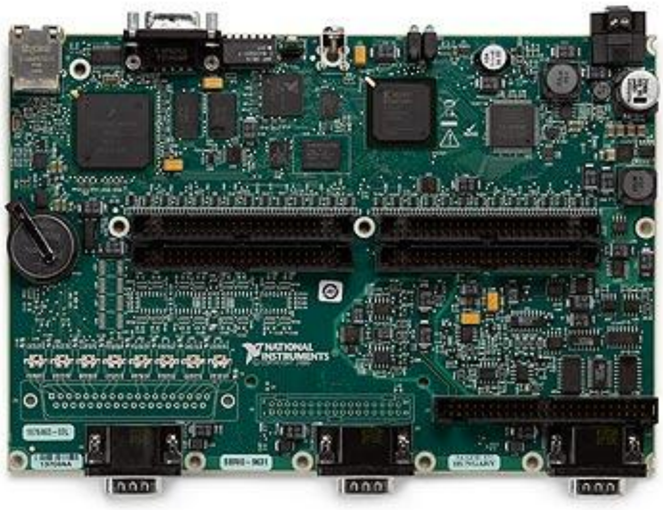


Figure 3.14: NI sbRIO 9632xt

2. LM35 temperature sensor- precision temperature sensor in an IC package, which has an output linearly proportional to the temperature reading in Centigrade value. The LM35 does not require external calibration, and is able to achieve accuracy of ±¼°C at room temperature. Besides that, it is also be used in applications involving temperature range of −55°C to +150°C. A total of 4 LM35s were used in this test. The LM35 temperature sensor is as shown in Figure 3.15.

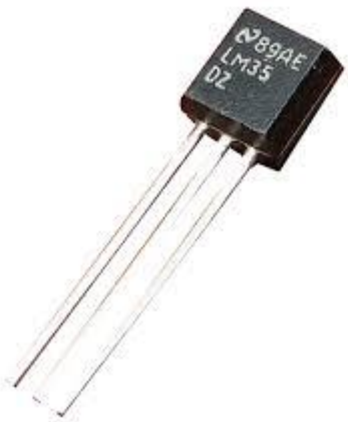


Figure 3.15: LM35 temperature sensor

3. Current transducer- A current transducer is used to measure the magnitude of the current drawn by the AC outdoor unit when AC is turned on. The current transducer is connected to the NI MyDAQ, which reads the magnitude of the

current consumed by the AC outdoor unit. The current transducer, which outputs 0.35mV/A, is as shown in Figure 3.16.

Figure 3.16: Current transducer

4. NI myDAQ- low cost, portable data acquisition device, with build in analog input port. This was used here in to read the stepped-down current value provided by the current probe. A myDAQ was used for this application in order to read the Voltage value outputted by the current probe. It is shown in Figure 3.17.

Figure 3.17: National Instrument MyDAQ data acquisition device

5. Capacitor and resistor- Capacitors of 1μF and resistors of 75Ω were used. These components are needed in order to reduce the fluctuations due to noise in the reading of the temperature and current values. In a way, the connection with the

capacitor and resistor forms a RC damper circuit and filter which will improve the readings measured by both the sbRIO and the myDAQ. A RC damper circuit is needed for each individual LM35 connection, as well as for the measurement by the myDAQ. The RC damper circuit is as shown in Figure 3.18.

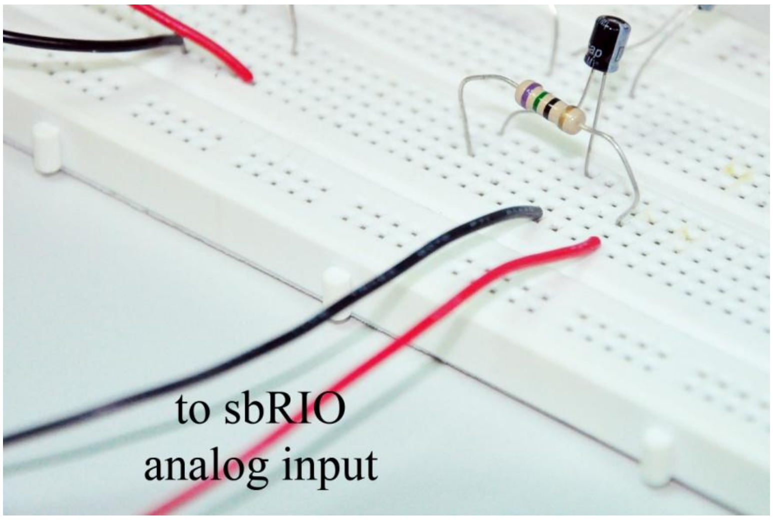


Figure 3.18: RC damper circuit

Since there is a built in thermistor in each of the cavity (Figure 3.19) within the indoor unit of the AC, it is important to place the LM35 temperature sensor in close proximity to the thermistor, in order to sense the temperature measured by the thermistor. The LM35 temperature sensor was placed in both the ACs the classroom. LM35 was placed in such a way as we want to identify the temperature set-points for different settings of the AC. LM35 was placed in close proximity as shown in Figure 3.20 so that it senses the temperature sensed by thermistor more accurately

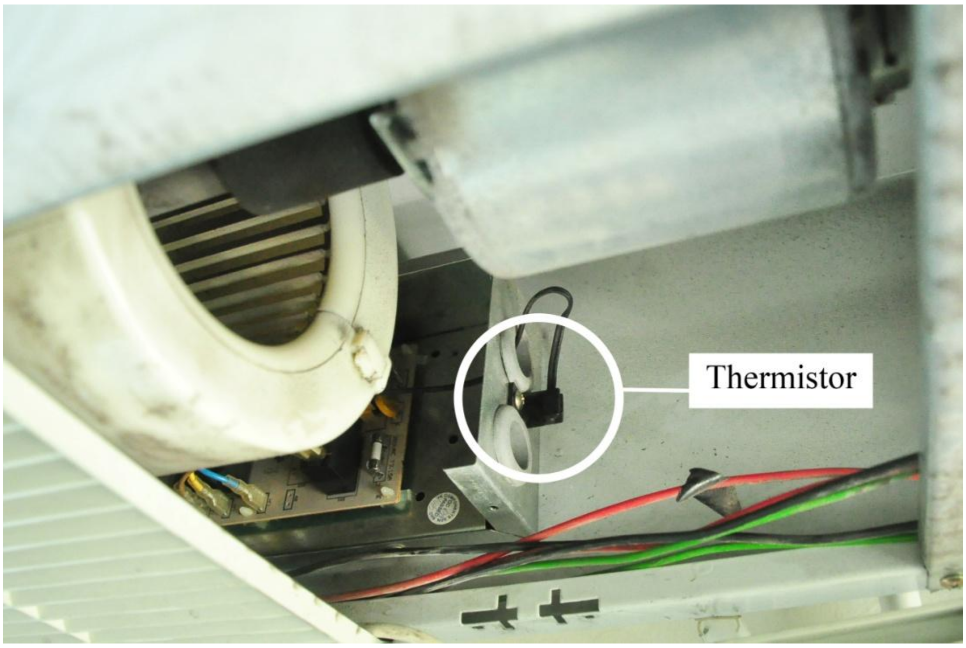


Figure 3.19: Thermistor placed inside of the AC indoor unit

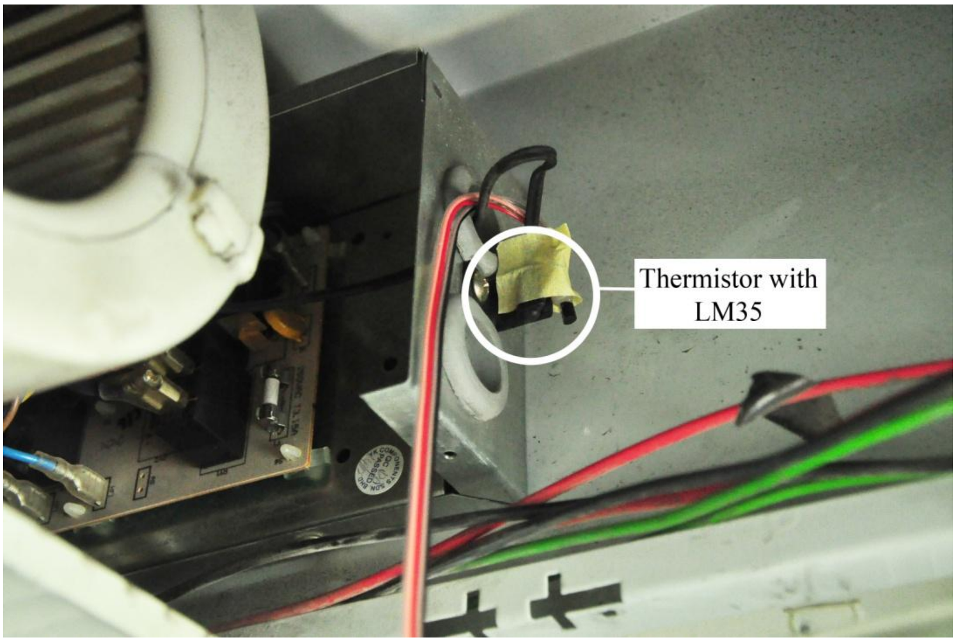


Figure 3.20: LM35 placed in close proximity to AC thermistor

When the LM 35 was first tested for use with the sbRIO, the readings were found to be fluctuating. A solution pertaining this was later found in the datasheet of the LM35 sensor, which involves the use of resistor and capacitor to form a simple RC damper circuit. The circuit connection is as shown is Figure 3.21.

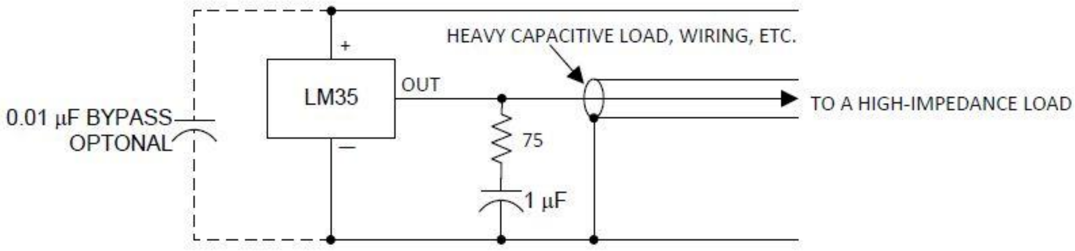


Figure 3.21: RC damper circuit for LM35

The legs of the LM35 sensor were sealed off using hot glue in order to prevent heat transfer through the legs, instead of the plastic head, as shown in Figure 3.22.

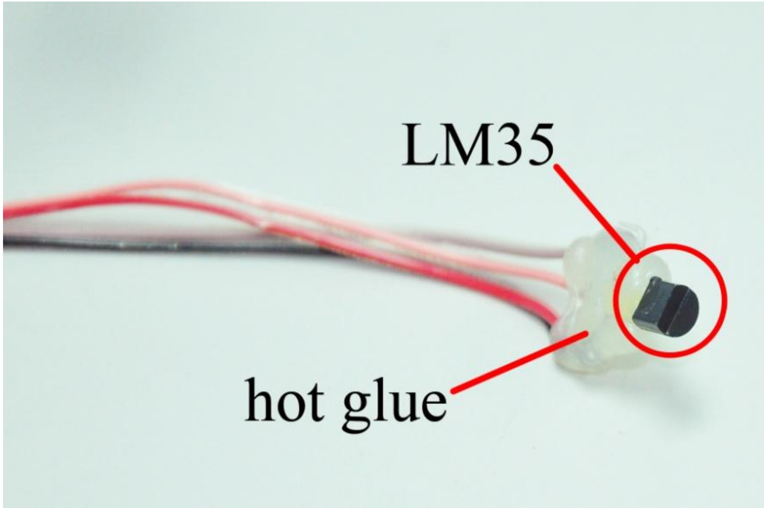


Figure 3.22: LM35 temperature sealed with hot glue

The test was conducted in the room SE106 of the SE block, which has 2 units of split type air conditioner installed. The current transducer was placed in such a way that it measures the current magnitude of the live wire which is connected to the AC outdoor unit, as shown in figure 3.23.

Figure 3.23: Current measurement using current transducer

3.3.2.2 LabVIEW Programming

A simple data acquisition program was developed in LabVIEW which functions to acquire the data of room temperature, AC1 (AC on right side of the room) temperature , AC2 (AC on left side of the room) temperature, Outdoor Temperature, AC current, in relation to time. The program is made up of two main while loops, illustrated in figure 3.24 and figure 3.25.

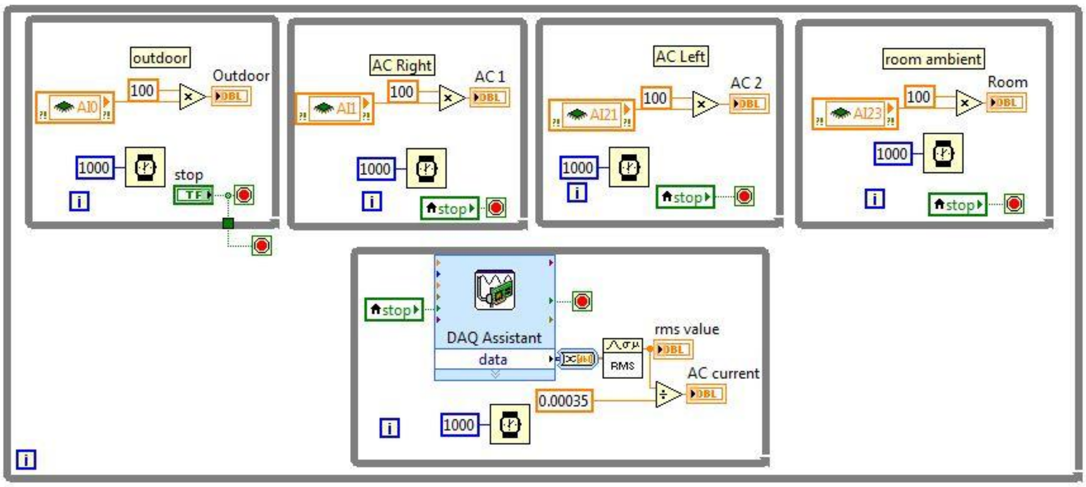


Figure 3.24: while loop 1- data acquisition and display

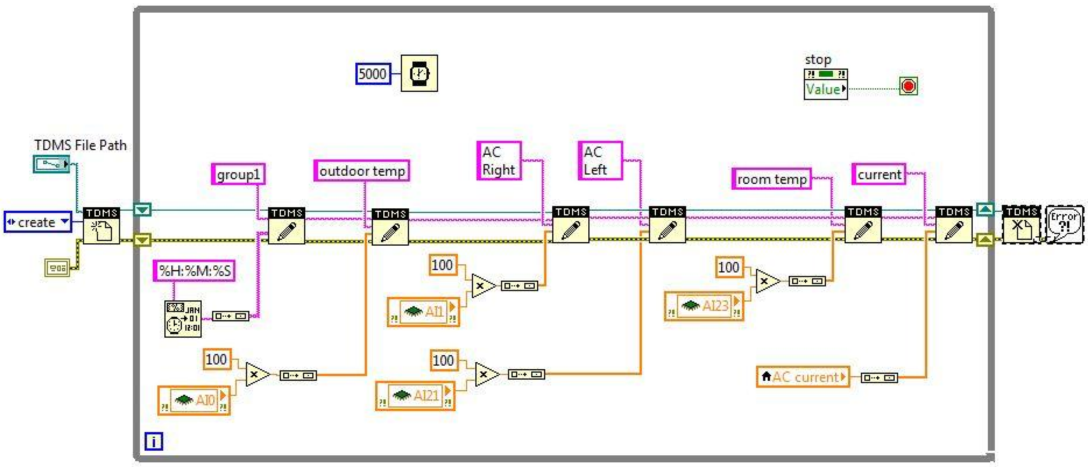


Figure 3.25: while loop 2- data acquisition and data write

While loop 1 illustrated in Figure 3.24 contain 4 individual while loops which functions to acquire temperature data from the analog input (AI) pin of the sbRIO. In figure 3.26, it shows the while loop which continually reads data from AI1 (Analog Input 1) node, which corresponds to AI1 pin on the sbRIO. This data is the output from the LM35 after it has passed through the RC damper circuit. This output is multiplied by 100 because the LM35 temperature sensor outputs linearly a + 10mV reading per °C sensed. The multiplied data is then connected to indicator ‘AC 1’, which displays the current temperature value onto the VI. A constant of 1000ms (1s) is wired to the ‘wait’ function so that data from AI 1 is acquired every 1 second, as temperature data need not be acquired at a high clock rate. This loop ends when the user clicks on the ‘stop’ button on the front panel.

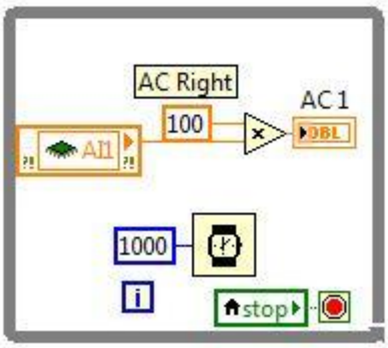


Figure 3.26: Read data from analog input node

Other than acquiring temperature data, while loop 1 also functions to acquire and display current values which is drawn by the outdoor unit. The magnitude of the current will help to determine whether the compressor is actually turned on or off.
In the Figure 3.27, a DAQ Assistant Express VI in placed inside the while loop which acquires AC current data. This Express VI enables continuous data measurement using the MyDAQ. Data from DAQ Assistant is connected to the RMS function block which converts the data into a Root Mean Square value, as indicated by the indicator 'rms value'. At this point of time, data in 'rms value' is still a voltage value. This rms value is then divided by 0.00035 to obtain the Air Conditioner (AC) current value, since the current probe outputs 0.35mV per 1A of current measured.

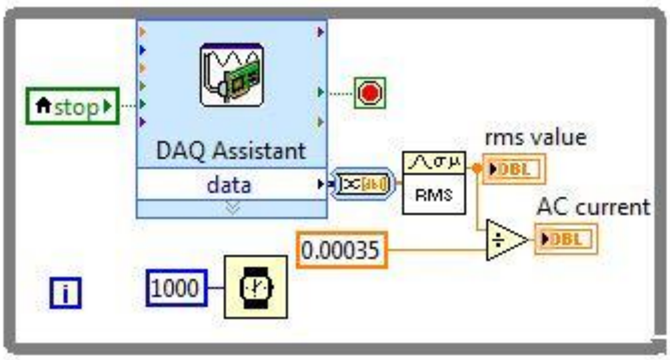


Figure 3.27: Current data acquisition while loop

The second while loop as shown in Figure 3.25 involved in this program deals with acquiring data and writing those data to perform data logging. Data logging is done primarily by a flexible data model known as Technical Data Management Streaming (TDMS). The TDMS data model is unique in such a way that it enables the user to attach descriptive information to measurement data seamlessly while writing the data onto disk, as well as providing the ability to scale project requirements.

TDMS is most useful when used in application which requires string of measurement data which comes in the form of arrays. TDMS files can be used to store data types such as Boolean data, string, or numbers. TDMS files can be created with data structuring in mind, where data within a file can be organized into multiple channel groups containing properties which store information or even other channels.

This simplifies viewing and analysis the data, thus increasing efficiency when dealing with a large number of data. There also is a TDM Excel Add-in Tool which enables TDMS files to be loaded to Microsoft Excel.

Figure 3.28 show a snippet of figure where there is a ‘TDMS Open’ function outside of the while loop, where it is initialised to create a new .tdms file for writing. A ‘file path’ block is also wired to ‘TDMS Open’ which enables the user to specify the path of the created file. In Figure 3.29, there are two ‘TDMS write’ function where the first function specifies the group of the data and the data input is wired to obtain system time in the format of Hour, Minute, and Second. The second ‘TDMS write’ function writes the temperature data from AI0 node onto a channel name called the ‘outdoor temperature’. This AI0 is the same as the one found in the first while loop which deals with acquisition and display of data, illustrated in Figure 3.30. As it can be seen from Figure 3.31, the following ‘TDMS write’ function creates the channel AC right, AC left, room temperature, which are temperature values, as well as the channel current, which writes AC current data onto the file. When the user presses the stop button, the while loop stops running and ‘TDMS close’ function will be executed, which will create the TDMS file.

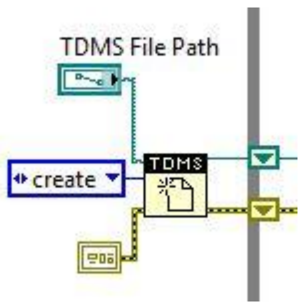


Figure 3.28: TDMS Open function

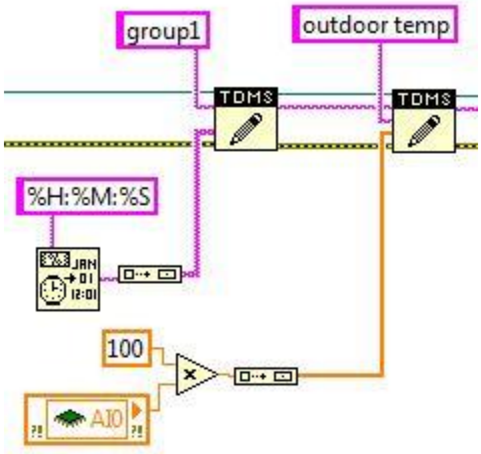


Figure 3.29: TMS Write function to specify group and channel

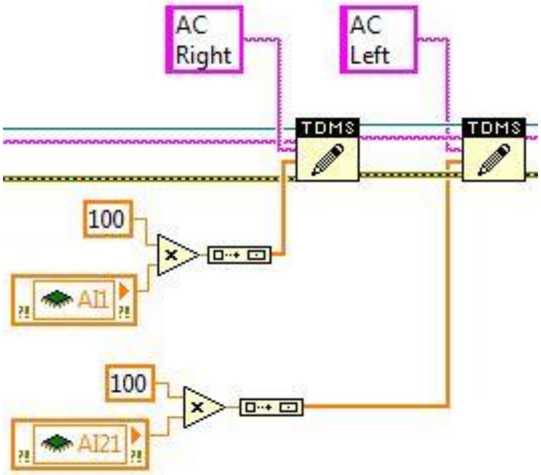


Figure 3.30: TDMS Write function to specify channels AC Right an AC left

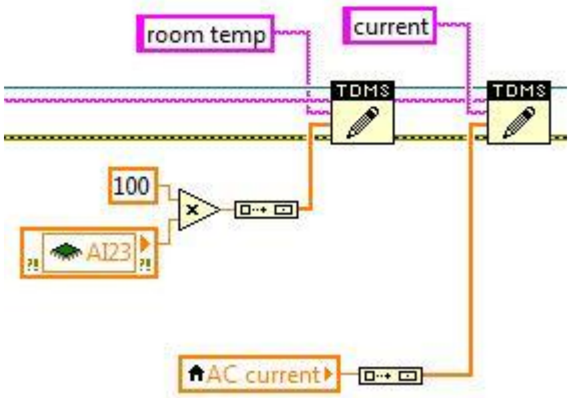


Figure 3.31: TDMS Write function to specify channels Room Temperature and AC Current

3.3.2.3 Data Acquisition procedure

The test was conducted in two different scenarios, with the first having only one AC turned on, and the other scenario both ACs turned on. While data acquisition was done, one thing which remained constant for both types of scenario is that:

1. There is only one person present in the classroom, which is the project student himself.
2. Both ceiling fans within the classroom are turned off during the data acquisition period.
3. All the fluorescent ceiling lights are turned on during data acquisition period, together with a laptop computer needed for the data acquisition process.
4. Only one current transformer is used throughout the period, and it is used on the right side AC, known as AC 1.

Figure 3.32 below illustrates the 5 different settings available on the AC controller unit. The different settings are indicated by Setting 1 (S1), Setting 2 (S2), Setting 3 (S3), Setting 4 (S4), as well as Setting 5 (S5). S1 is the setting with the lowest temperature set-point, while S5 is the setting with the highest temperature set-point. Data acquisition was done based on different settings of the AC controller, from S5 to S1.

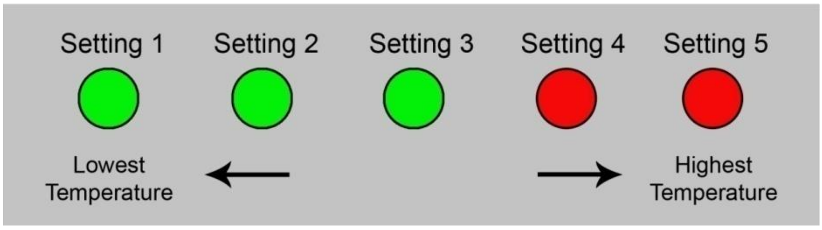


Figure 3.32: AC controller settings

Once data acquisition has been done, the data in is opened in Microsoft Excel for analysis. For every combination of number of AC turned on and AC setting, the data acquired was converted into chart format for analysis, in which will be made available in the results section of this report.

3.4 Air conditioner load curtailment programming

3.4.1 Room Temperature prediction

Results obtained from the room temperature data acquisition program is presented in Section 4.1 of this report. In that section the equations for the situation when 1 and 2 air conditioners are turned on is presented. Equation 3.1 shows the room temperature equation when 1 AC is turned on, while Equation 3.3 shows the room temperature equation when 2 ACs are turned on. Equations 3.2 and 3.4 are derived from Equations 3.1 and 3.3 respectively, where y represents temperature value in °c and x represents unit time in seconds divided by constant of 5.

$$y = 0.1668\ln(x) + 21.667 \quad (3.1)$$

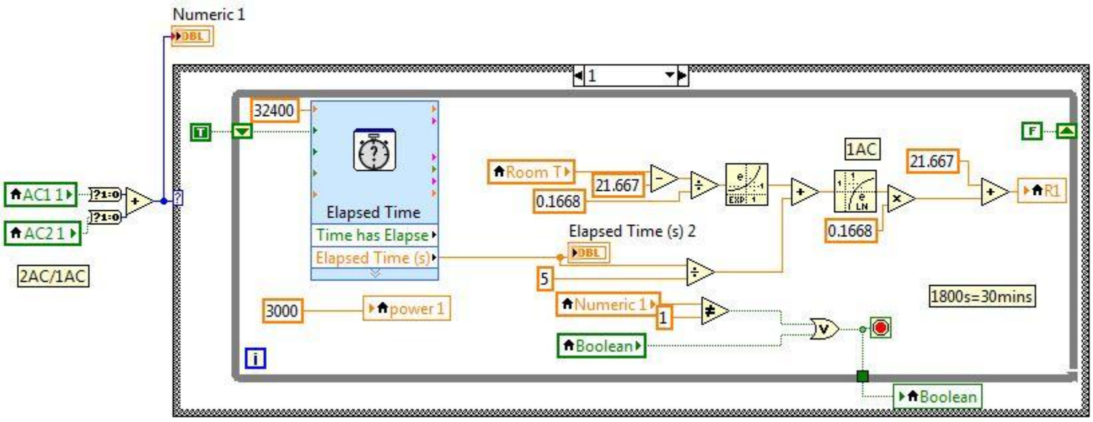
$$x = e^{\frac{y-21.667}{0.1668}} \quad (3.2)$$

$$y = -0.567\ln(x) + 25.99 \quad (3.3)$$

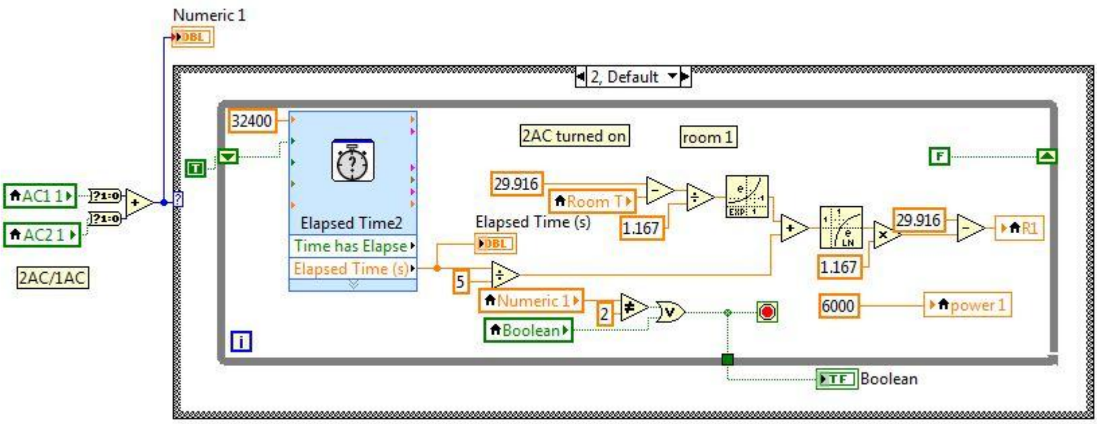
$$x = e^{\frac{25.99-y}{0.567}} \quad (3.4)$$

These equations enable the prediction of room temperature to be done in LabVIEW programming. Figure 3.33(a) shows the case structure for the case when 1 AC is turned on, while Figure 3.33(b) shows the case structure when 2 ACs are turned on. These two cases are a part of a single case structure. This case structure simulates the room temperature, depending on whether 1 or 2 ACs are turned on. The variables ‘AC1 1’ and ‘AC2 1’ represent the on/off status of AC1 and AC2 inside room 1. The boolean value of these variable are summed up and displayed as ‘Numeric 1’, which shows the number of AC which is turned on in a particular room, and in this case room 1. The case structure will execute either case 1 or case 2 based on the value of ‘Numeric 1’. When ‘Numeric 1’ has a value of 1, case 1 will be executed and while ‘Numeric 2’ has value of 2, case 2 will be executed. The variable ‘power 1’ in Figure 3.33 represents the AC power consumption for room 1.

The 'Elapsed Time' function specifies the time elapsed when a case is executed. The elapsed time is given in seconds and is divided by 5, since the value x in Equation 3.1, 3.2, 3.3 and 3.4 is time in seconds divided by 5. This is because the room temperature data acquisition program used writes the every data in intervals of 5 second. Hence, every point on the equation represents a time unit block of 5 seconds.



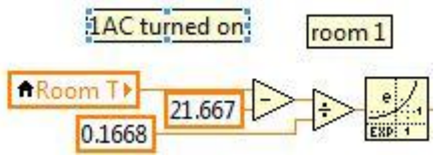
(a)



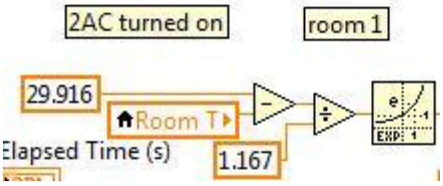
(b)

Figure 3.33: Room temperature prediction for (a) 1 AC turned on (b) 2 ACs turned on

Equations 3.2 and 3.4 is realised through the snippet of code illustrated in Figure 3.34. These snippets are found in case 1 and 2 respectively. Basically the function of this is that given a certain room temperature, we will be able to know at what x-point the temperature is currently at on the temperature curve.



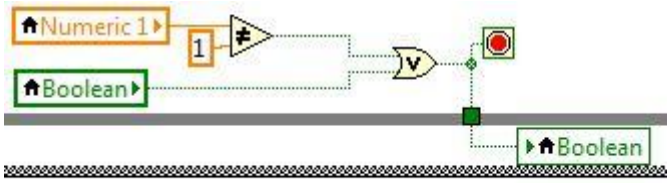
(a)



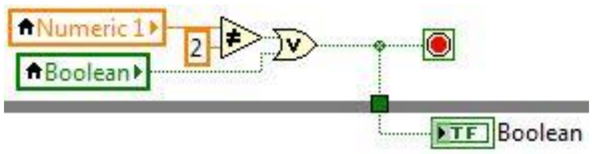
(b)

Figure 3.34: x value calculation for (a) 1 AC turned on (b) 2 ACs turned on

Referring to Figure 3.33 presented earlier, once the previous x-value is obtained from Figure 3.34, it is added to current x-unit in order to obtain the total x-value. The x-value is then applied to Equation 3.1 and 3.3 respectively, which outputs a temperature value from the variable ‘R1’. All these is done inside a while loop structure. The code snippet in Figure 3.35 shows a group of codes which functions to detect whenever there is a change in the number of ACs turned on. The ‘Boolean’ value is initialized as ‘false’, outside of the case structure. This means that whenever ‘Numeric 1’ is changes, and ‘true’ value will be sent to the OR function, producing an output of ‘true’ which will stop the while loop. Then, ‘Boolean’ will be reinitialized to a ‘false’ value again.



(a)



(b)

Figure 3.35: Number of ACs turned on detection change for (a) 1 AC turned on (b) 2 ACs turned on

In Figure 3.36, the variables ‘power 1’ up to ‘power 10’ is summed up, and the total power consumption is displayed in the form of numeric value as well as in a chart form. The variable ‘power 1’ refers to power consumed by AC in room 1, each room is designated such a variable.

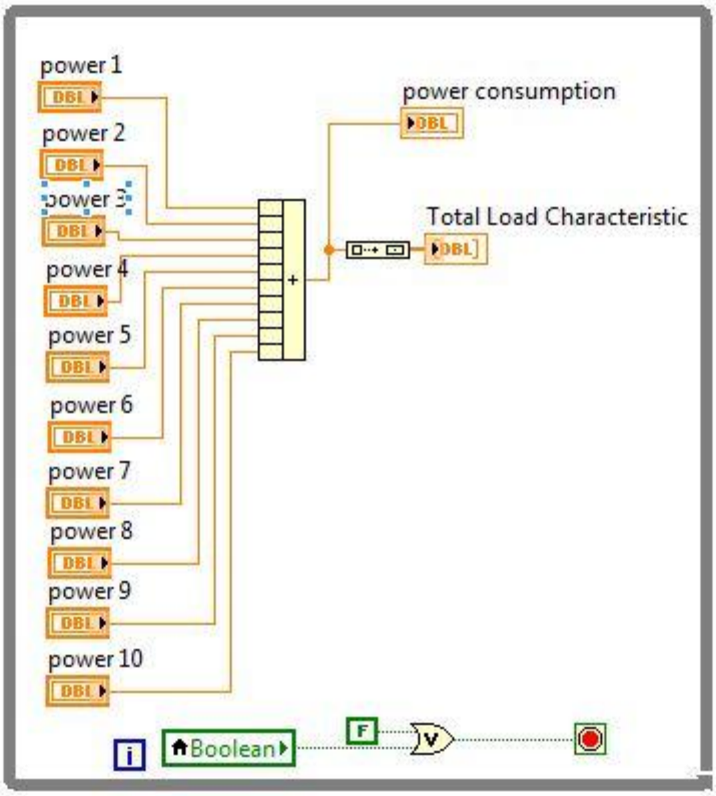


Figure 3.36: Total Power Consumption display

Figure 3.37 shows a code snippet which takes the AC setting from the variable ‘Room AC setting’ and converts it into Boolean form, with either ‘true’ or ‘false’ value available. Whenever there is a setting change in ‘Room AC setting’, a true value will terminate the while loop, and will in terminate all the other while loops which contain the variable ‘Boolean’. A Shift Register which is added to the while loop holds the Room AC setting value and compares it with the one from the previous iteration, in order to detect setting changes.

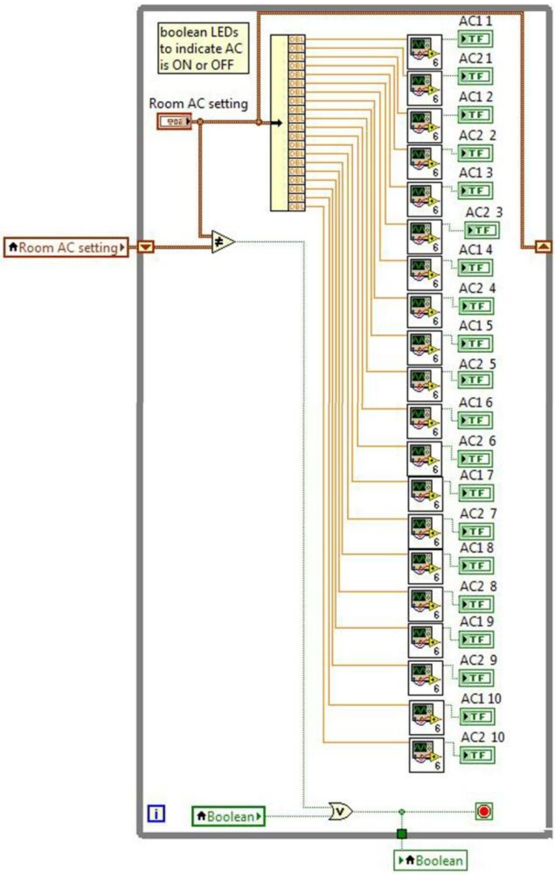
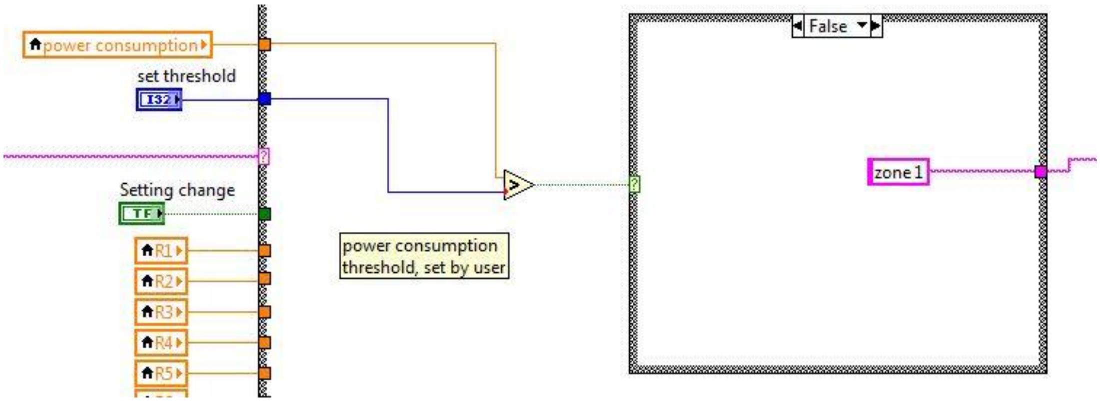
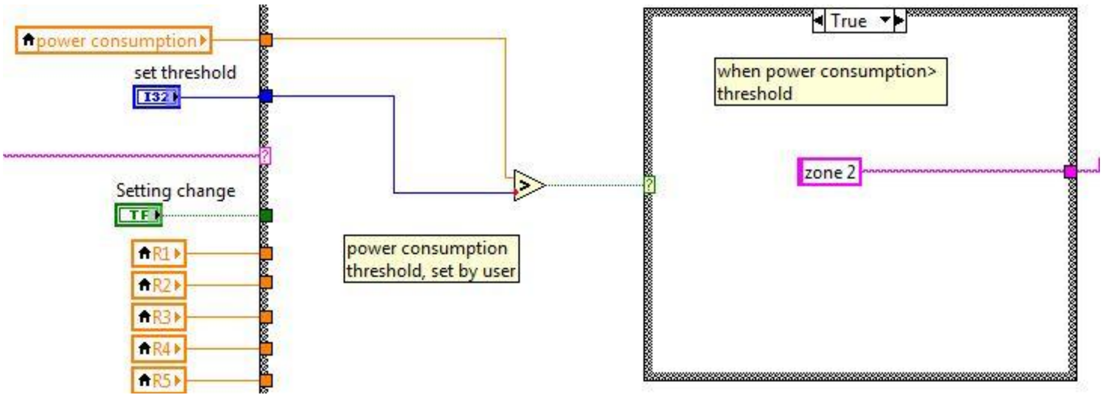


Figure 3.37: Room AC setting change detection

Another part of the programming is made up of a case structure within a while loop. The case structure is made up of 4 different cases, which is represented by the case ‘zone 1’, ‘zone 2’, ‘zone 3’, and ‘zone 4’. These cases indicate the current process that the program is doing. Figure 3.38 shows the code snippet when the program is running in zone 1. At zone 1, the total power consumption of all the AC (‘power consumption’) is compared with the power threshold set by the user, shown as the variable ‘set threshold’. When ‘power consumption’ is less than the threshold, the next process to be executed is ‘zone 1’, illustrated in Figure 3.38(a). When ‘power consumption’ is more than the threshold, the next process to be executed will be ‘zone 2’.



(a)



(b)

Figure 3.38: Process 'zone 1' of program (a) power consumption less than threshold (b) power consumption more than threshold

Figure 3.39 show the code snippet for the process 'zone 2'. In this process, the number of ACs needed to be shutdown in order to achieve the threshold is calculated. This number is indicated by the variable 'AC to OFF'. If 'AC to OFF' is more than 5 ACs, then a case structure is used to limit the 'AC to OFF' to a maximum number of 5 ACs. The value of 5 is just a reference, and can be adjusted according to the user. After this process, the program will proceed to 'zone 3'.

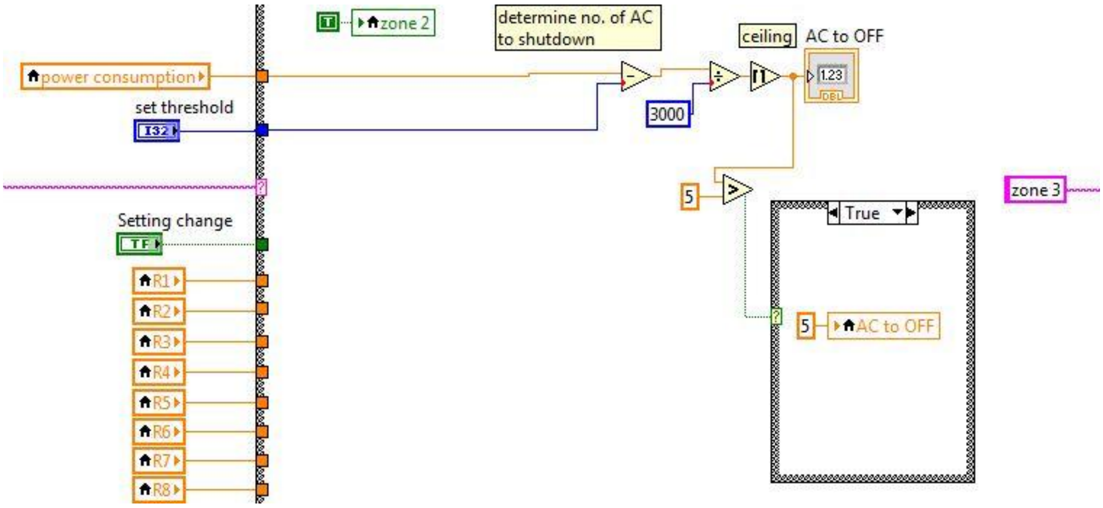


Figure 3.39: Process 'zone 2' of program

The process 'zone 3' contains 2 sections, with the first section illustrated in Figure 3.40. The function of the section is to arrange the rooms according to its temperature, from high to low temperature. This section is made up of a nested loop, with the outer loop being a while loop and inner loop being a for loop. The values of room temperature is obtained, which the variable 'R1' up to 'R10', which is made to form an array. Another array consisting of strings 'R1' to 'R10' is also formed. Both of these arrays are fed into the nested loop. Once inside the loop, the temperature array elements are compared with values of temperature array from previous iteration. This compare algorithm will run for i number of time. This means that this for loop runs for 10 iterations, and by the end of iteration, the highest value of room temperature will be kept at shift register and outputted as an index array outside of the while loop. While this is done, the 'Delete From Array' function deletes the highest temperature value from the array, as well as the room name with highest temperature from the string array. This step of deleting is needed so that the inner for loop will be able to always output the element with highest temperature value associated with it, including the room name with highest temperature. Once an element is deleted, the i value will also decrease accordingly.

This means that at the following iteration, i is 9, and the inner for loop will execute only for 9 times. The same process repeats, where it will output the highest room temperature element, as well as the room name element associated with it. These 2 elements will be deleted from the string array as well as the room temperature array. By the end of this code snippet, we will obtain 2 arrays, one being a room temperature array with elements arranged from highest to lowest temperature (orange in colour), as well as a string array which stores the name of the room from the one with highest temperature to lowest temperature (pink colour). The temperature array is reversed using a 'Reverse 1D Array' function so that we can display the array from lowest to highest temperature on the front panel.

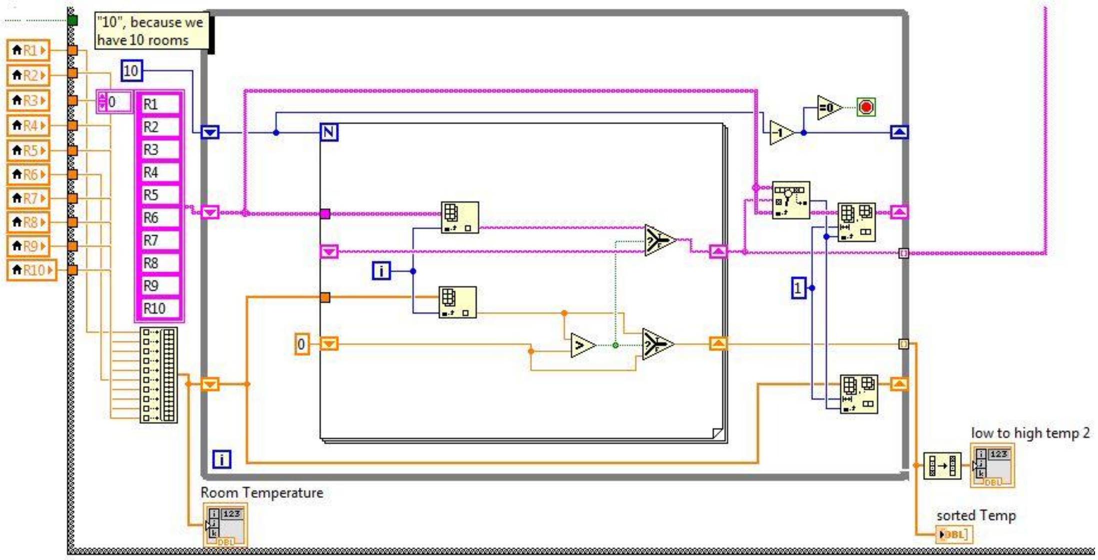


Figure 3.40: Sorting of room temperature

After the array of room with highest to lowest temperature obtained, it is reversed. Then, the resultant array is passed through a series of nested case structure which outputs an array in the form of numeric number instead of string names, as shown in Figure 3.41. This is done while maintaining the hierarchy of the rooms according to their room temperature. The program will then proceed to the process 'zone 4'.

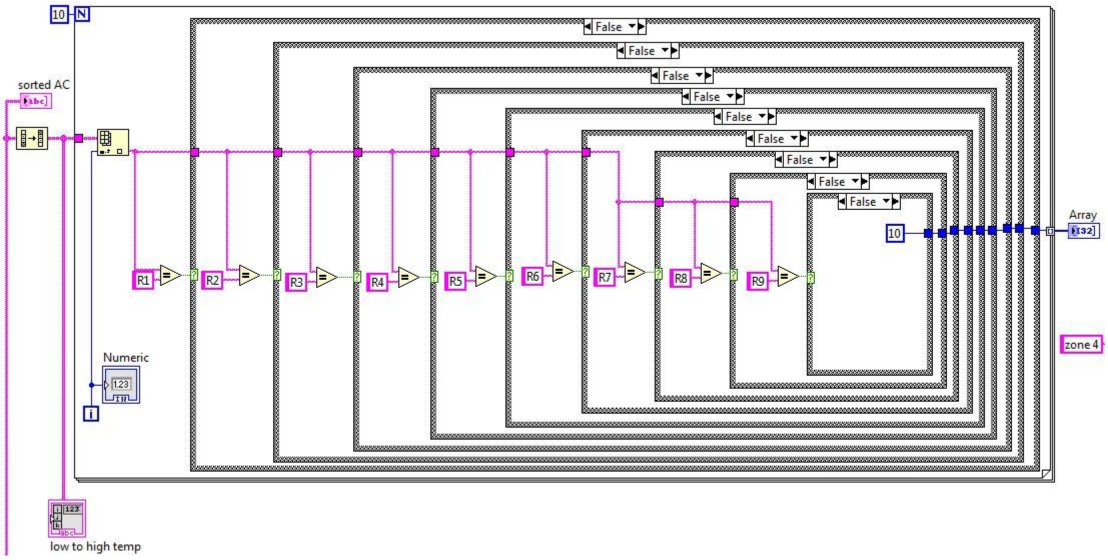
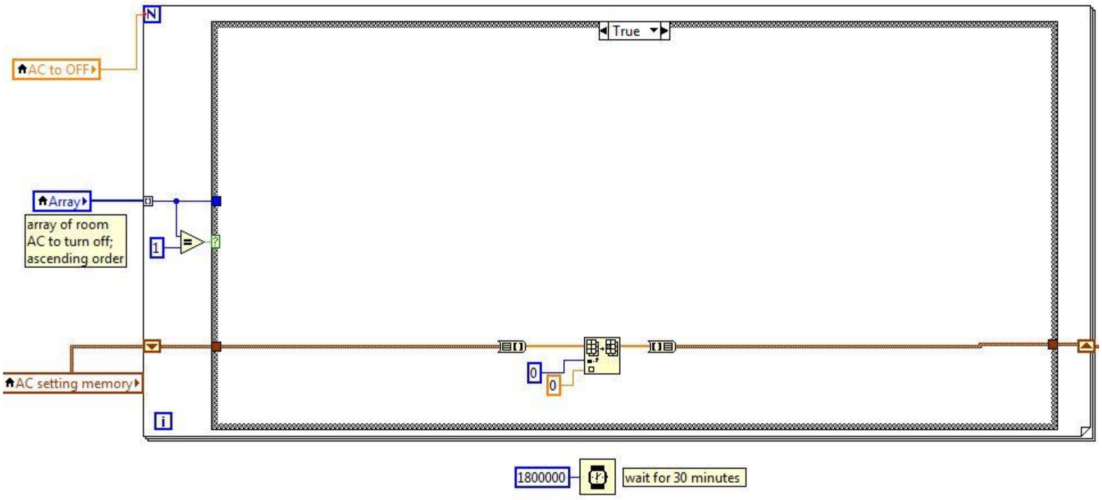
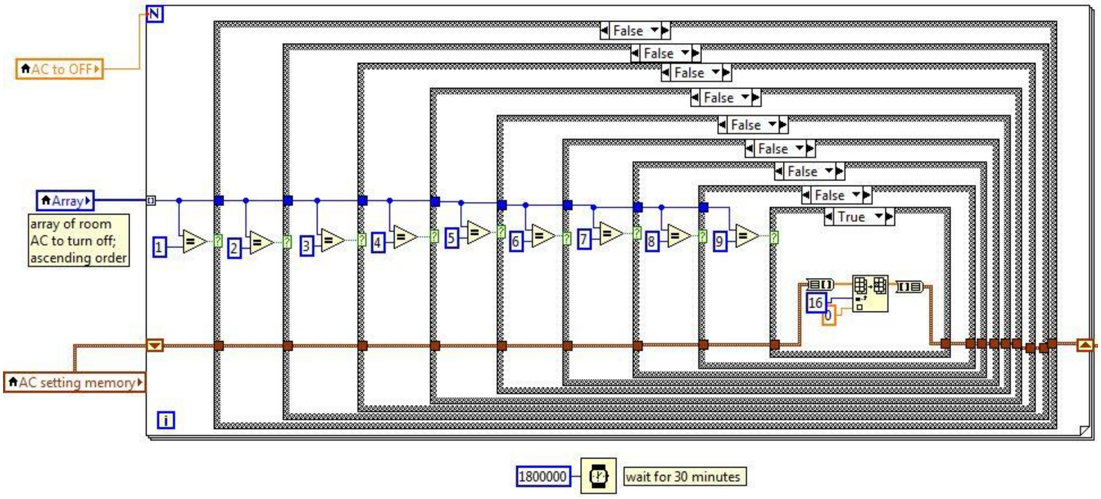


Figure 3.41: Convert string array to numeric array

Now, we move on to the process ‘zone 4’. The main task of this process is to shut down the ACs based on the variable ‘AC to OFF’, starting from rooms with the lowest temperature as indicated in the variable ‘Array’. This process is illustrated in Figure 3.42, where ‘Array’ is fed into a for loop which iterates according to the variable ‘AC to OFF’. The for loop structure consists of a series of nested case structure. The elements in ‘Array’ will constantly be compared to numeric 1 to 9, in order to shut down AC belonging to rooms which are placed in the beginning of the array. In Figure 3.42(a), the element form ‘Array’ is compared to value 1, which represents room 1. If both the element and the value is equal, the program executes the ‘true’ case, where at index 0 of ‘AC setting memory’ a value of 0 will replace the value of the previous element. This value of 0 indicates setting 0, which will turn of the particular AC. It should be noted that only 1 AC will be turned off in any of the rooms, and that is for a duration of 30 minutes. Another design fact is that for any rooms, the AC which will be affected for the purpose of load curtailment would be AC1, which is the AC at right side of the classrooms. In Figure 3.42(b), when element in ‘Array’ is 9, the AC setting element 16 which corresponds to AC1 of room 9 is turned off by setting the element to be 0.



(a)



(b)

Figure 3.42: (a) AC off at room 1 (b) AC off at room 9

After ‘AC setting memory’ is modified, this variable is then updated to ‘Room Ac setting’. ‘AC setting memory’ serves as a buffer which remembers the AC setting, in order for the process in Figure 3.42 to take place. This variable is then unbundled and is used to update the AC status variables, so that the room temperature prediction code can execute according to new changes in the AC setting. Figure 3.43 shows the code to update the AC setting. When this is done, the program will go to the process ‘zone 3’ again to calculate the array according to ascending room temperature. This is needed as the changes brought forth by ‘zone 4’ will change the behaviour of the room temperature as well, with room temperature either increasing (1 AC turned on) or decreasing (2 AC turned on).

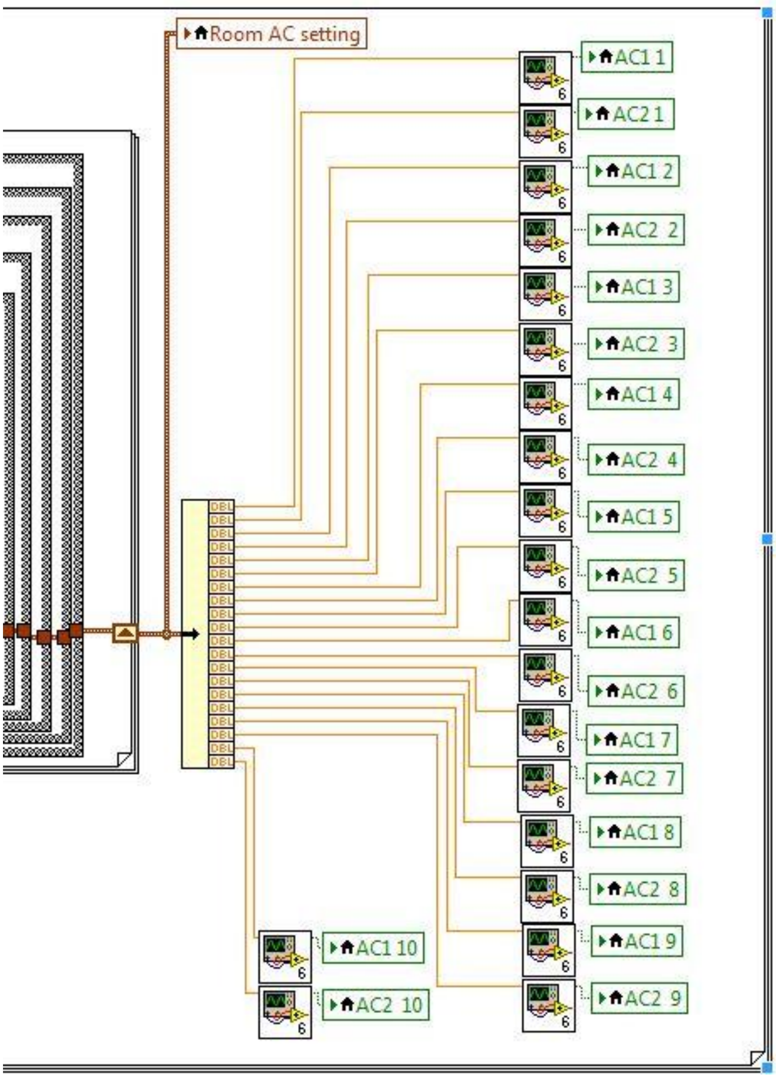


Figure 3.43: Update AC setting

Figure 3.44 illustrates the front panel of the load curtailment program, where the placement of buttons and indicator are such that it is intuitive and easy to use for the user, which is done through clear labelling of each of the sections. Figure 3.45 shows the flow chart of the AC load curtailment program.

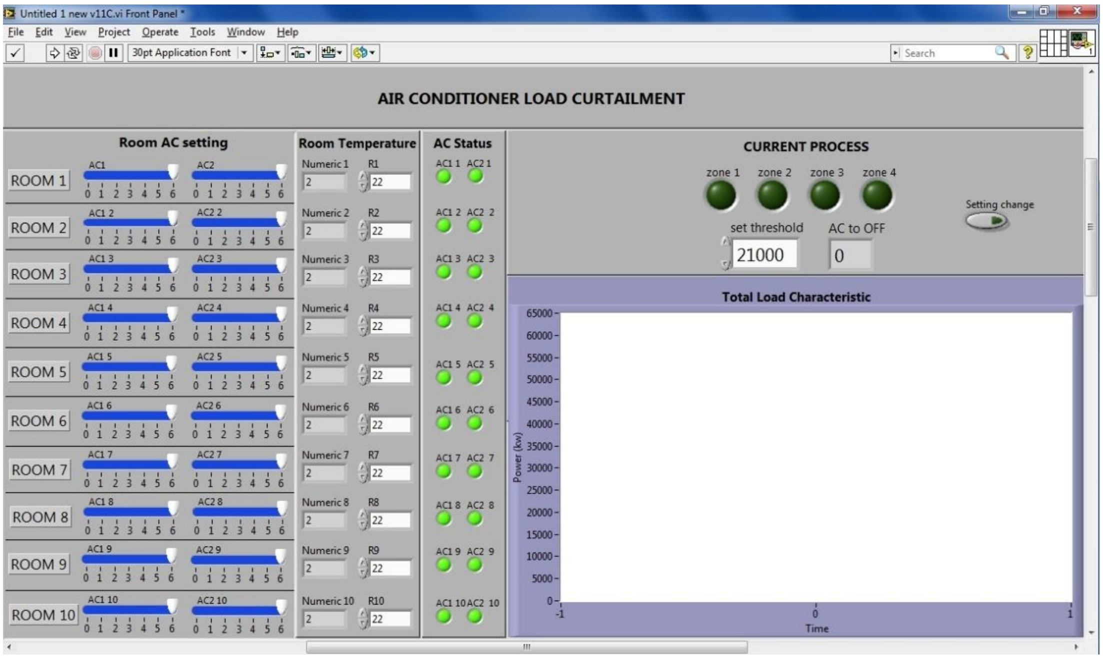


Figure 3.44: Front panel (UI) of the AC load curtailment program.

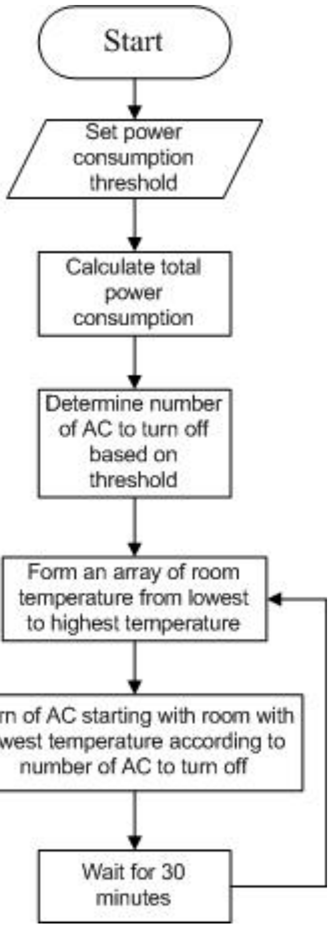


Figure 3.45: Program flow chart

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Room heating/cooling data acquisition

Based on the room temperature data acquisition program in Section 3.3, a series of room temperature data was obtained. The data is important, as it allows the modelling of the room temperature characteristics, where we will be able to predict the room temperature at a particular AC in relation to time. The data acquisition was done by manipulating the following variables: number of AC turned on and AC setting, which can be set from setting 1 to setting 5. For the variable of number of AC turned on, it can be the either 1 or 2 AC turned on.

4.1.1 Two air conditioners turned on

Figure 4.1 shows the chart when 2 ACs are turned on at setting 5. The primary Y-axis on the left represents the temperature given off by the LM35, while the secondary Y-axis represents the current consumed by AC, which is represented by the data series 'AC on'. Whenever the value of 'AC on' is greater than 5A, this indicates that the AC compressor is turned on, while a value of less than 5A indicates that it is turned off. 'Outdoor' refers to the outdoor temperature, 'AC right' refers to temperature sensed by the AC at the right side of the room, 'AC left' refers to temperature sensed by the AC at the left side of the room, and 'Room' refers to the ambient room temperature. The X-axis represent the time, in the format of hour, minutes, and seconds.

For 2 ACs turned on at setting 5, the final room temperature is 27.79 °C from initial room temperature of 28.05 °C . The AC was turned on for duration of 2 minutes before the compressor shuts itself down. For this setting, the temperature threshold of the AC is 26.79 °C, which is as sensed by AC right.

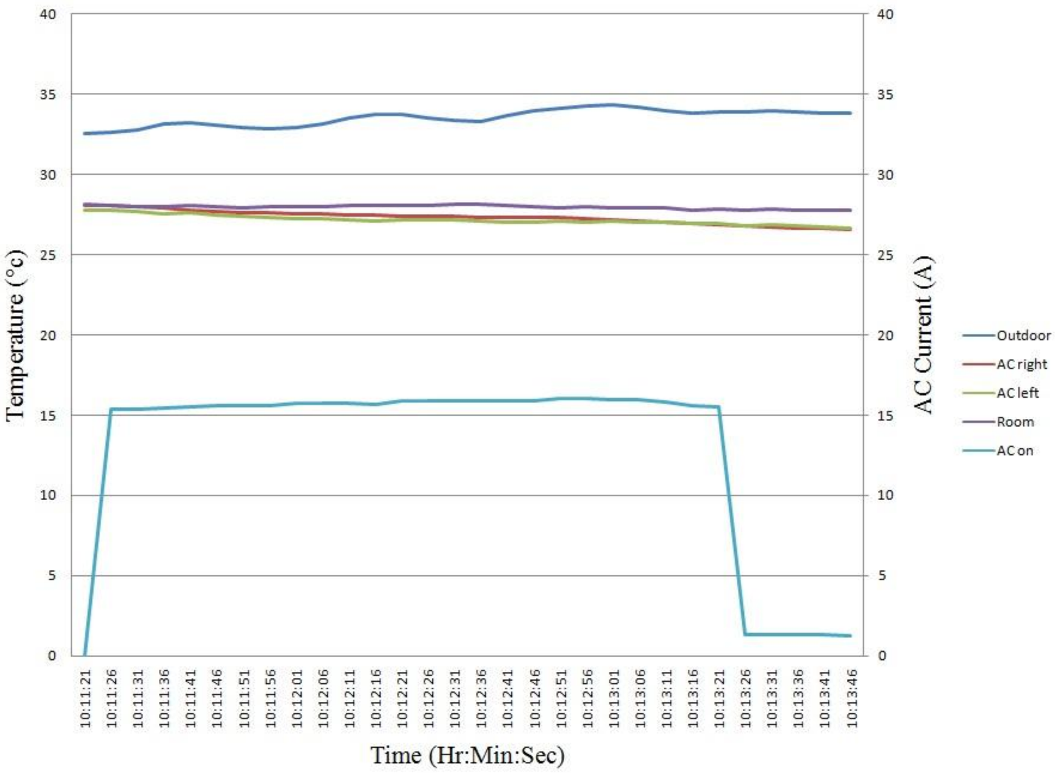


Figure 4.1: AC setting 5, two AC turned on

Figure 4.2 shows the chart when 2 ACs are turned on at setting 4. For 2 ACs turned on at setting 4 the final room temperature is 27.17 °C from initial room temperature of 28.37 °C. The AC was turned on for duration of 6.25 minutes before the compressor shuts itself down. For this setting, the temperature threshold of the AC is 25.22 °C, which is as sensed by AC right.

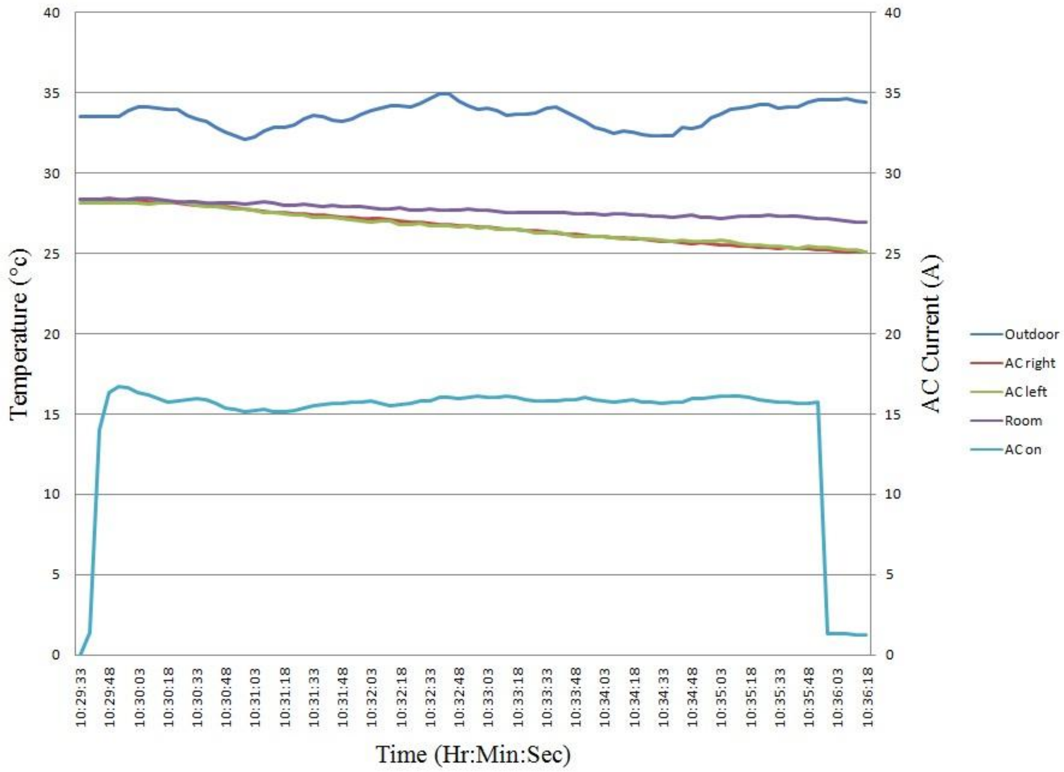


Figure 4.2: AC setting 4, two AC turned on

Figure 4.3 illustrates the data when 2 ACs are turned on at setting 3. For 2 ACs turned on at setting 3, the final room temperature is 25.39 °C from initial room temperature of 27.85 °C . The AC was turned on for duration of 15.83 minutes before the compressor shuts itself down. For this setting, the temperature threshold of the AC is 23.36 °C, which is as sensed by AC right.

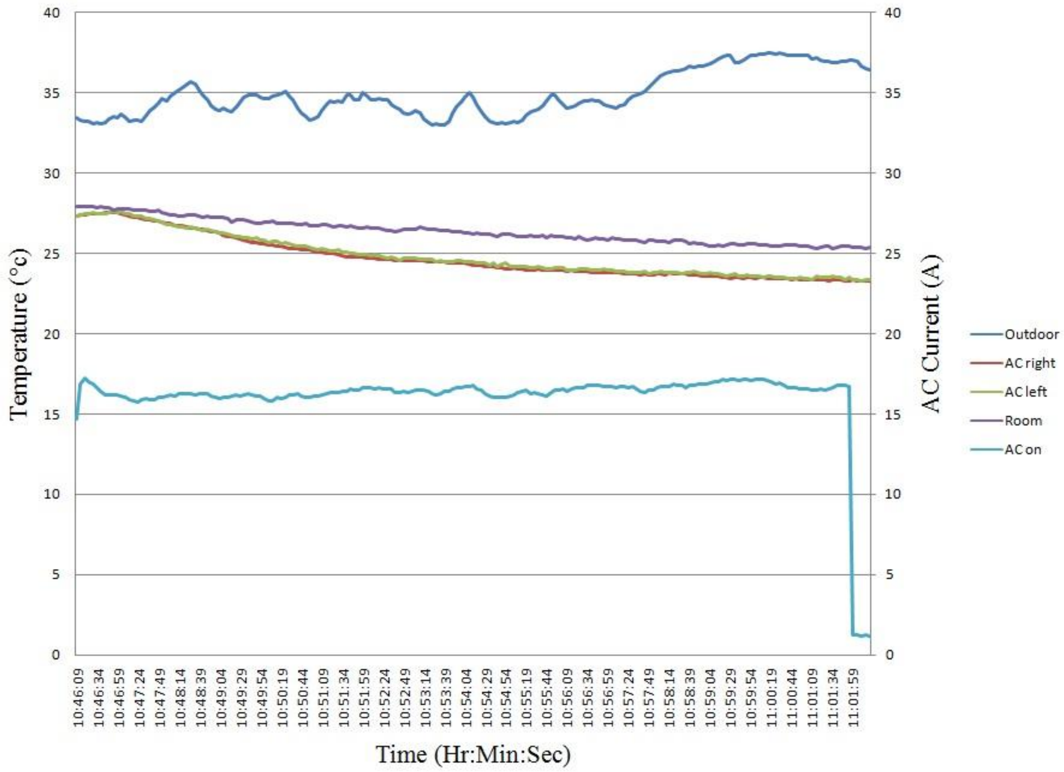


Figure 4.3: AC setting 3, two AC turned on

As illustrated in Figure 4.4, for 2 ACs turned on at setting 2, the final room temperature is 23.87 °C from initial room temperature of 26.82 °C. The AC was turned on for duration of 38.67 minutes before the compressor shuts itself down. For this setting, the temperature threshold of the AC is 22.10 °C, which is as sensed by AC right.

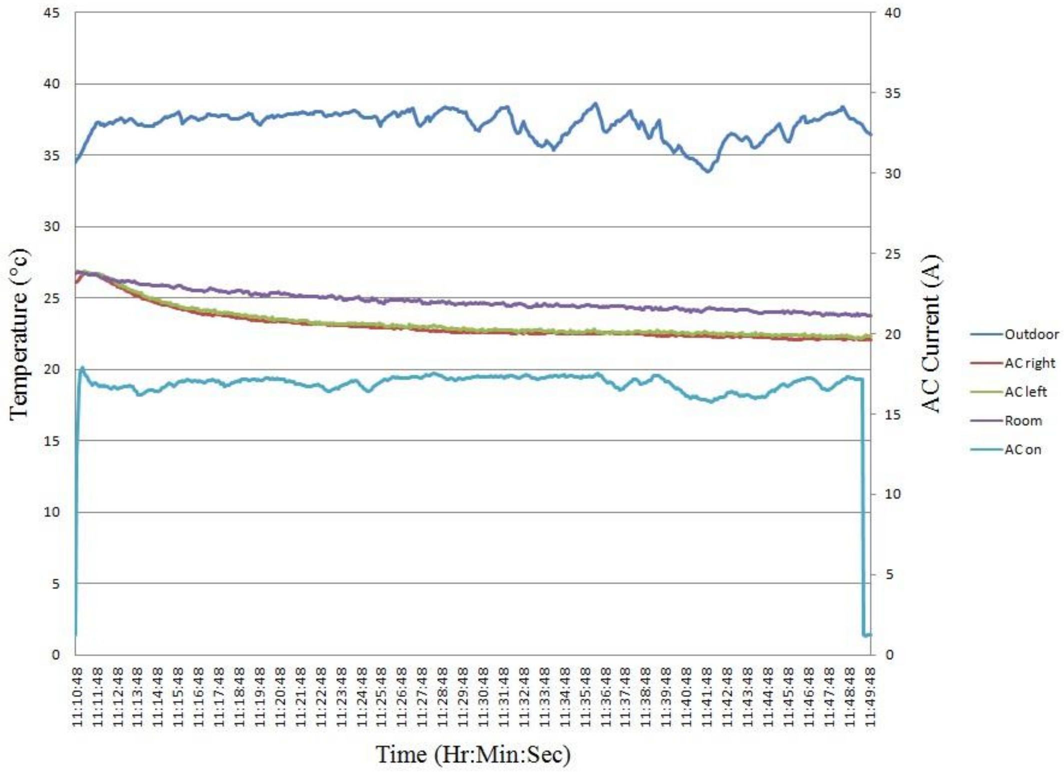


Figure 4.4: AC setting 2, two AC turned on

For 2 ACs turned on at setting 1 as illustrated in Figure 4.5, the final room temperature is 21.66 °C from initial room temperature of 25.65 °C. The AC was turned on for duration of 5 hours 22 minutes before the compressor shuts itself down. For this setting, the temperature threshold of the AC is 20.56 °C, which is as sensed by AC right. It is noted that at setting 1, the compressor turns on for a long duration of time, due to the low temperature threshold that the AC needs to attain. The line equation for the room temperature is obtained to be $y= -0.567\ln(x) + 25.99$, and is the equation to be used in the program for the purpose of room temperature prediction when two AC is turned on.

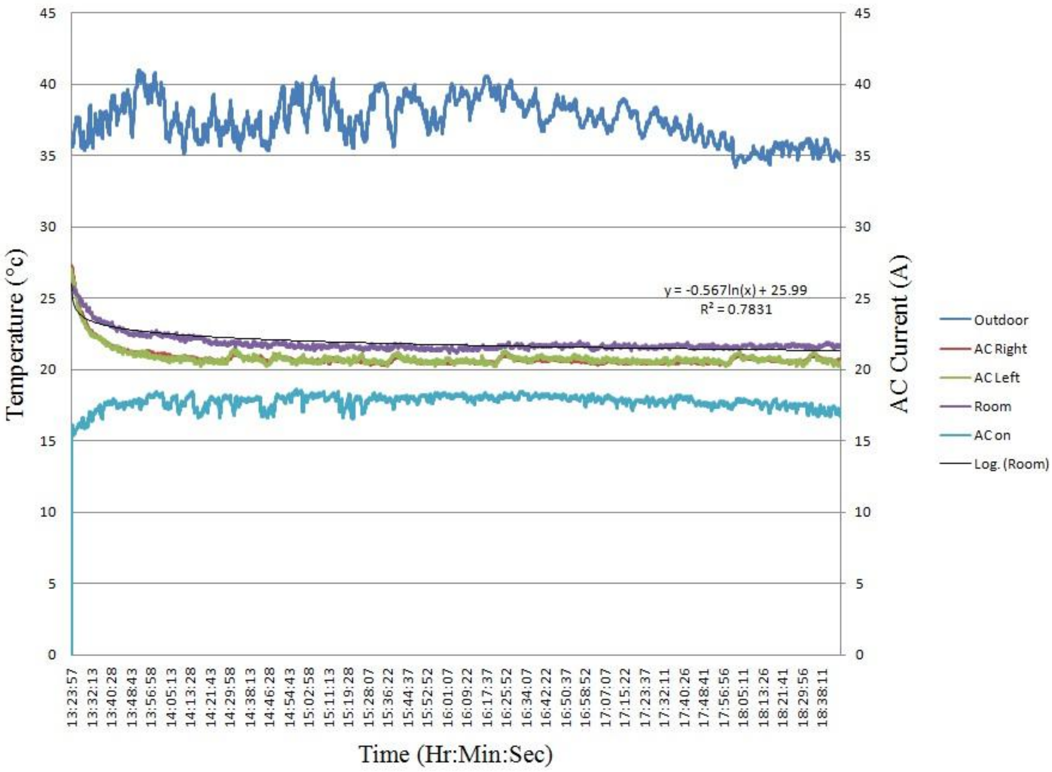


Figure 4.5: AC setting 1, two AC turned on

4.1.2 One air conditioner turned on

For 1 AC turned on at setting 5, the final room temperature is 26.07 °C from initial room temperature of 26.33 °C. The AC was turned on for duration of 4.1 minutes before the compressor shuts itself down. For this setting, the temperature threshold of the AC is 26.92 °C , which is as sensed by AC right. This is as shown in Figure 4.6.

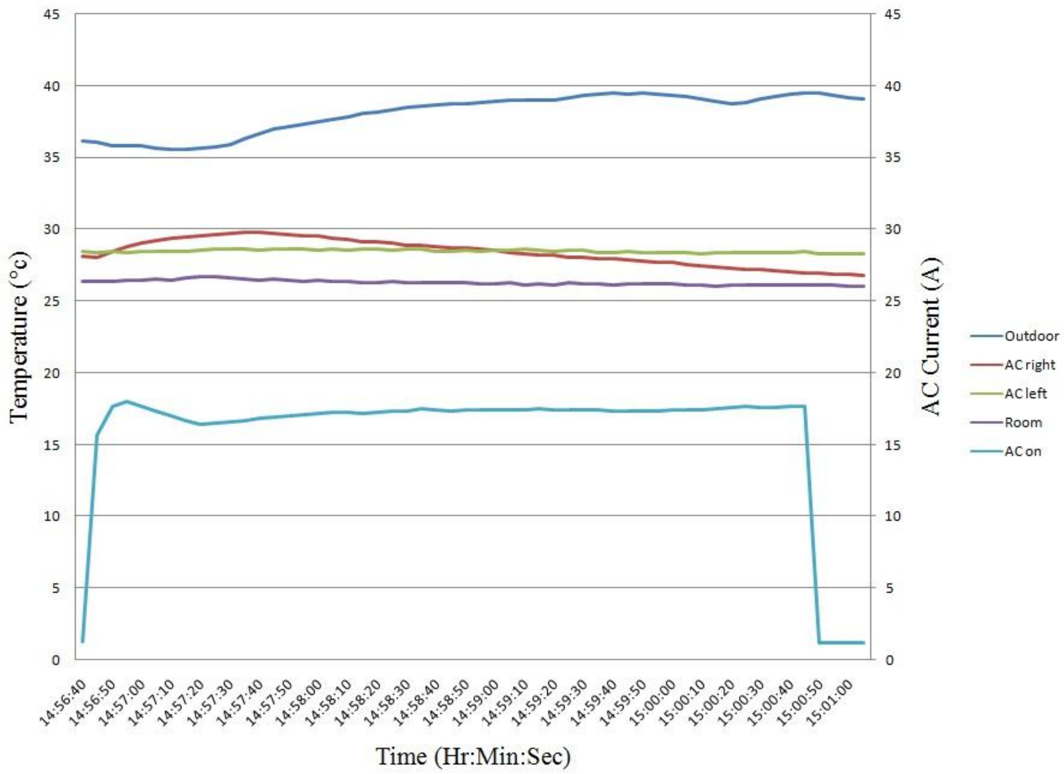


Figure 4.6: AC setting 5, one AC turned on

For 1 AC turned on at setting 4, the final room temperature is 26.46 °C from initial room temperature of 26.26 °C. The AC was turned on for duration of 11.33 minutes before the compressor shuts itself down. For this setting, the temperature threshold of the AC is 25.31 °C, which is as sensed by AC right. This is as shown in Figure 4.7.

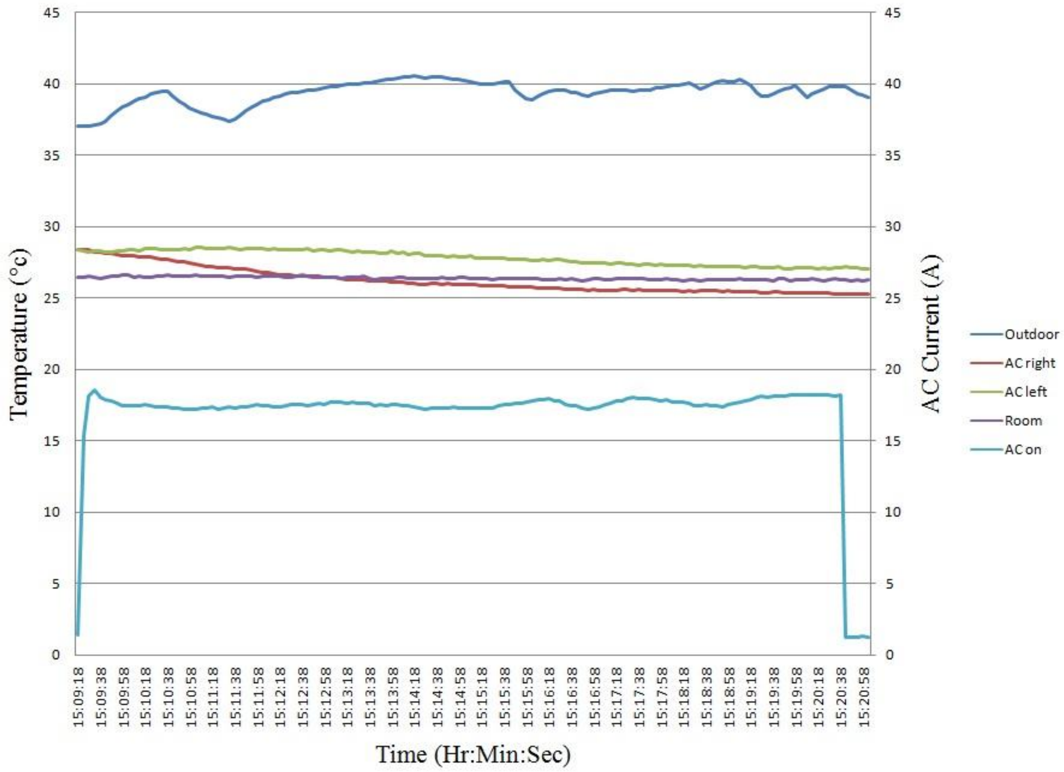


Figure 4.7: AC setting 4, one AC turned on

For 1 ACs turned on at setting 3 shown in Figure 4.8, data acquisition was done for 1 hour 25 minutes, and it was found that the compressor did not shut down by itself. The final room temperature at the end of this period is 23.02 °C from initial room temperature of 21.85 °C. It is noted that at setting 3, the compressor turns on for a long duration of time, due to fact that only one AC is turned on. The line equation for the room temperature is obtained to be $y= 0.1668\ln(x) + 21.667$, and is the equation to be used in the AC load curtailment program for the purpose of room temperature prediction when one AC is turned on.

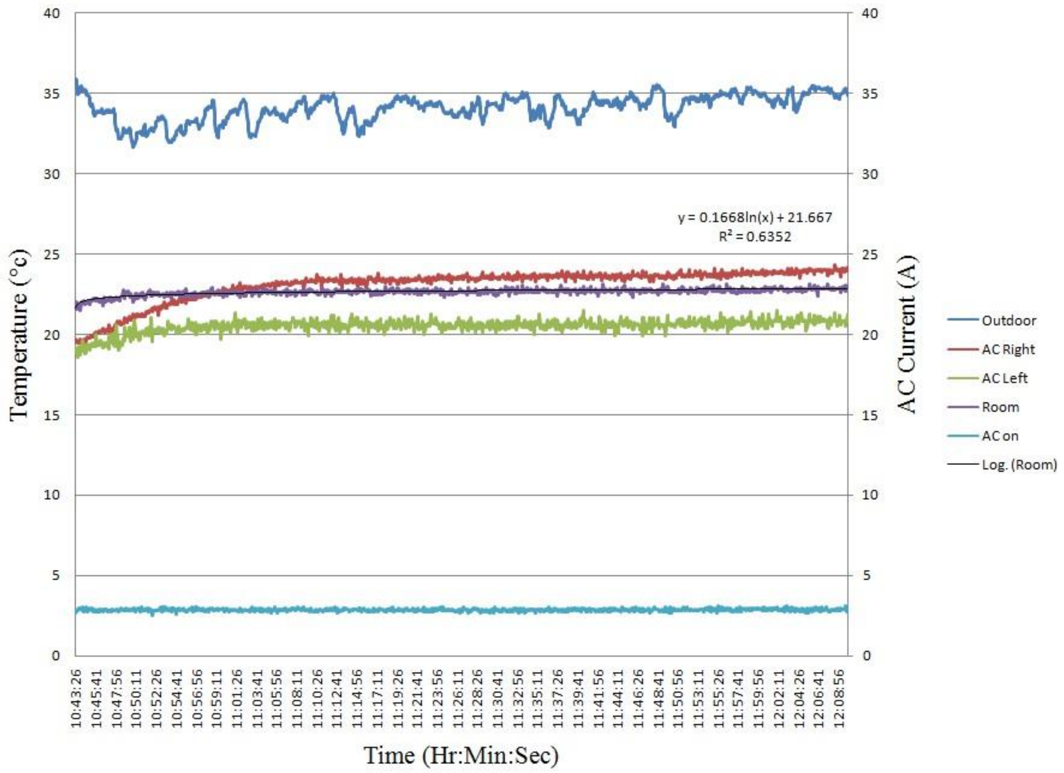


Figure 4.8: AC setting 3, one AC turned on

4.2 Air Conditioner Load Curtailment Program

The results of the AC Load curtailment algorithm are presented here. For the purpose of this demo, the time delay for 'zone 4' is set to be 5 seconds instead of 30 minutes. Figure 4.9 show the program before it runs and room temperature was initialized to 22 °C.

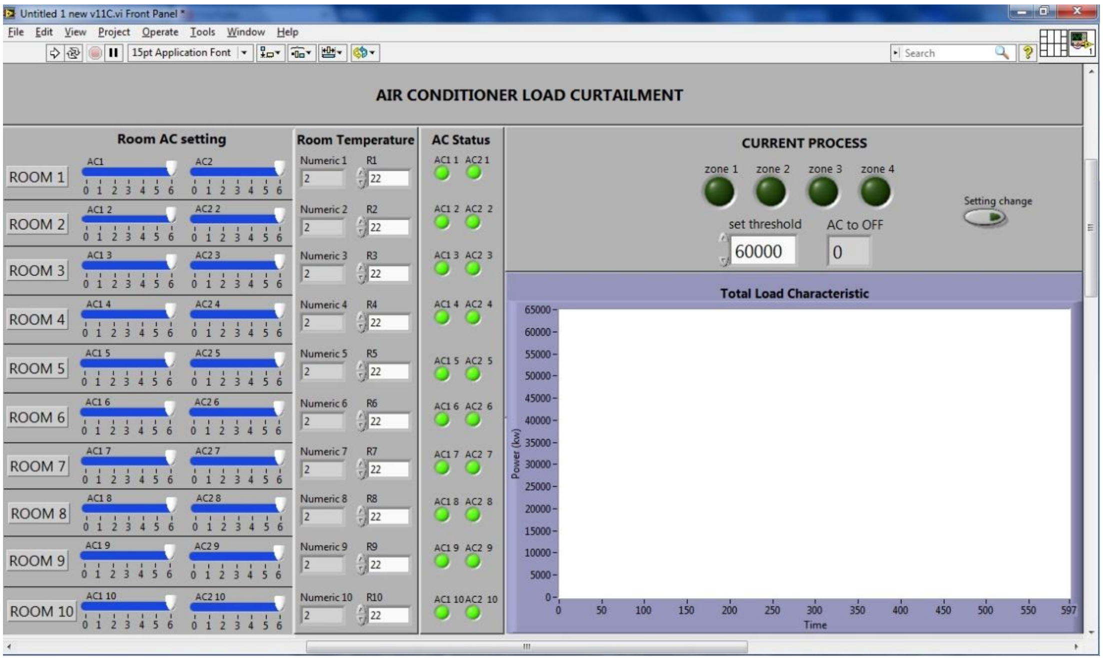


Figure 4.9: Initialize settings before starting program

When the program runs, it will execute 'zone 1', where it compares the total AC power consumption with the threshold set by the user. Since power consumption is not greater than threshold, the program will continue to be in process 'zone 1'.

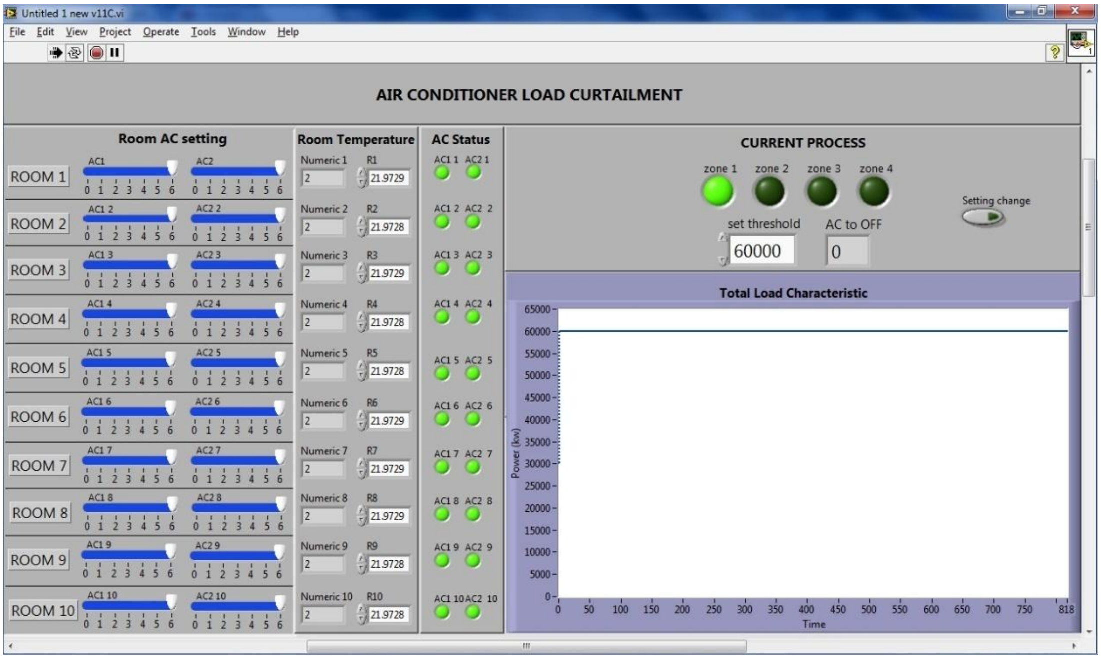


Figure 4.10: Executing process 'zone 1'

When the threshold is set to be 50000kW as shown in Figure 4.11, the program will execute ‘zone 2’ as power consumption is greater than threshold, a comparison done in ‘zone 1’. Process ‘zone 2’ calculates the number of AC to turn off, and in this case it is 4 ACs to turn off in order to for the power consumption to stay below the threshold. Figure 4.13 below shows the process where the room temperature array is calculated at ‘zone 3’.

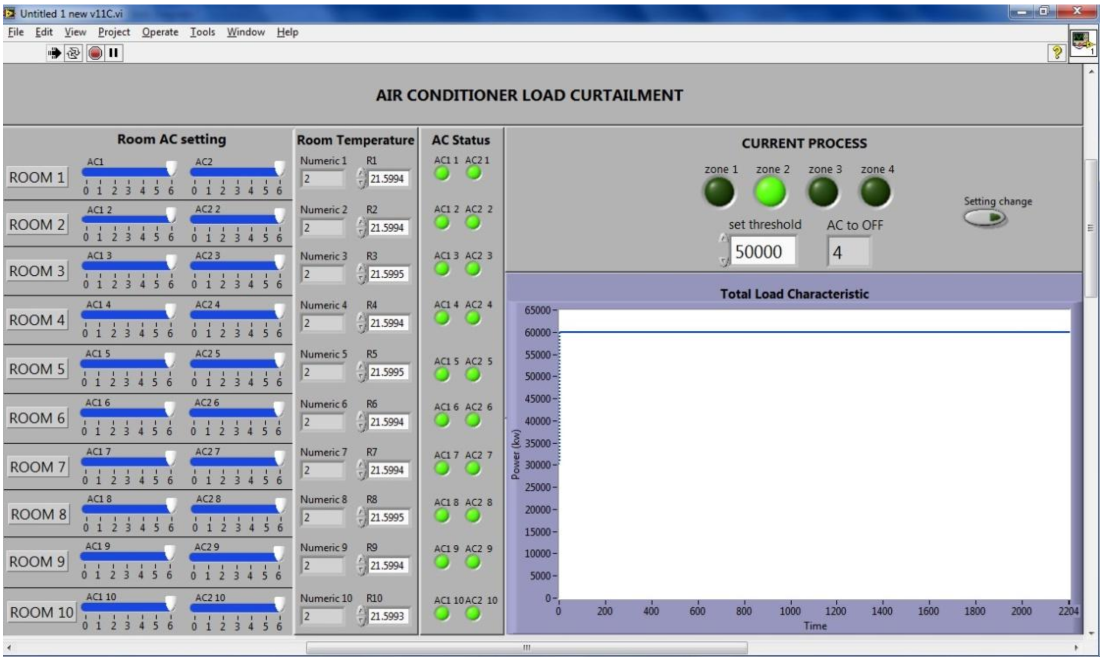


Figure 4.12: Executing process ‘zone 2’

Figure 4.13: Executing process ‘zone 3’

Figure 4.14 shows the program in ‘zone 4’, where it starts to turn off the 4 ACs situated in rooms with the lowest temperature. As it can be observed, the Total Load Characteristics chart shows a power reduction from 60,000kW to 48,000kW. At the ‘Room AC setting’ of the front panel, we can see that AC1 5, AC1 6, AC1 8, and AC1 10 are set to 0, which means that they are turned off. The ‘Room temperature’ section displays the number of ACs turned on within a room through the indicator ‘numeric’ and the temperature values are also presented. The status LED at ‘AC status’ lights according to the on/off state of the AC.

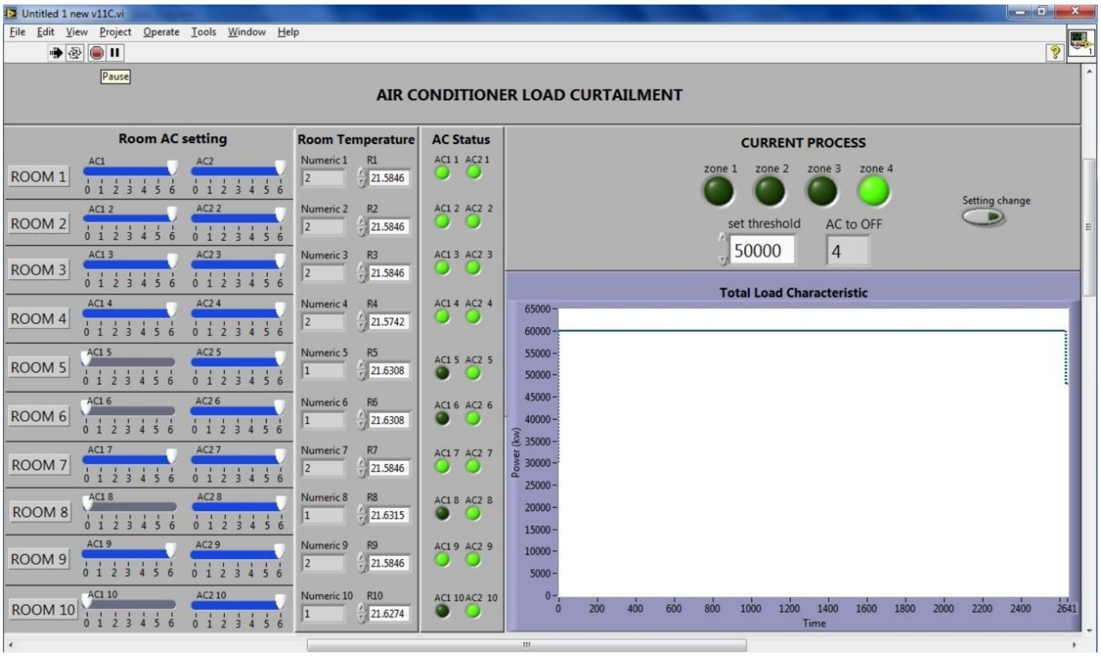


Figure 4.14: Executing process 'zone 4'

Once 'zone 4' is complete, the program executes process 'zone 3' again in order to obtain a new set of temperature array, as shown in Figure 4.15. The process repeats and will execute according to Figure 4.16. In this case, we see that Rooms 1, 2, 3 and 4 has the lowest temperature and this causes AC1 1, AC1 2, AC1 3, and AC1 4 to be turned off. Figure 4.17 shows a chart which indicates a successful AC load curtailment process, where total power consumption of the ACs is reduced to 48,000kW, from the initial power consumption of 60,000kW.

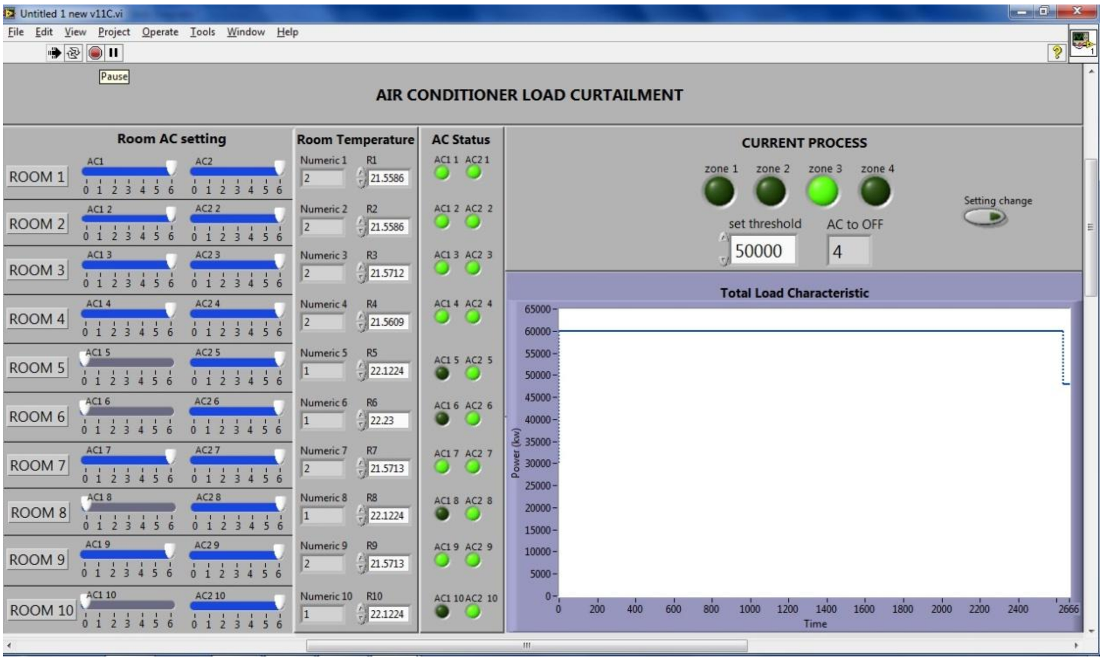


Figure 4.15: Executing ‘zone 3’ to obtain new set of array

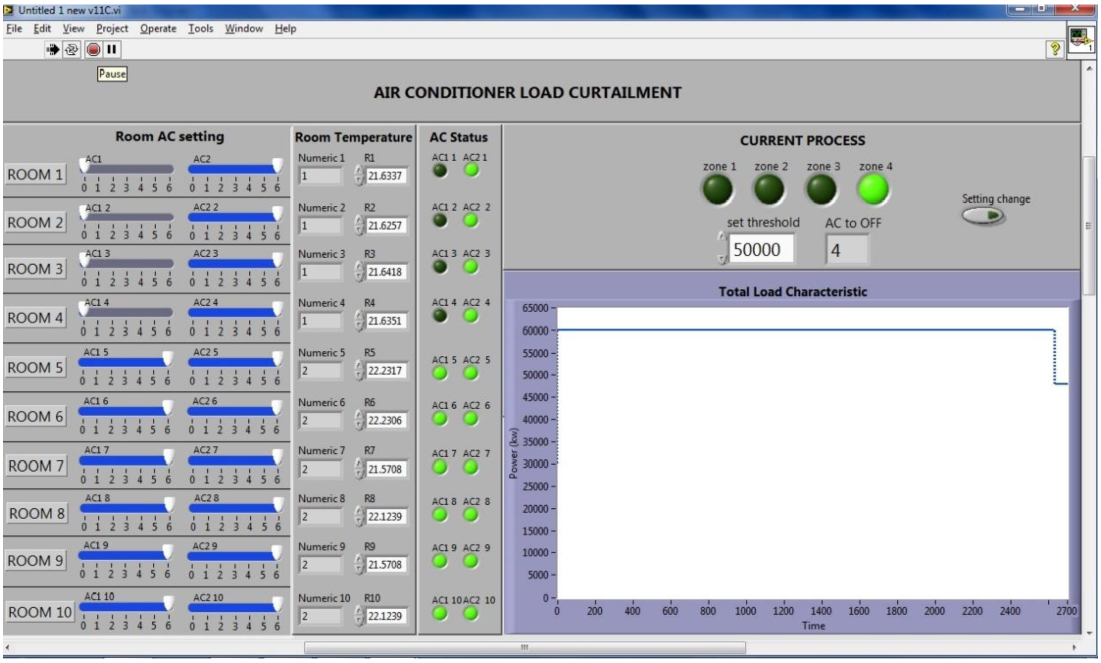


Figure 4.16: Executing ‘zone 4’ according to new set of array

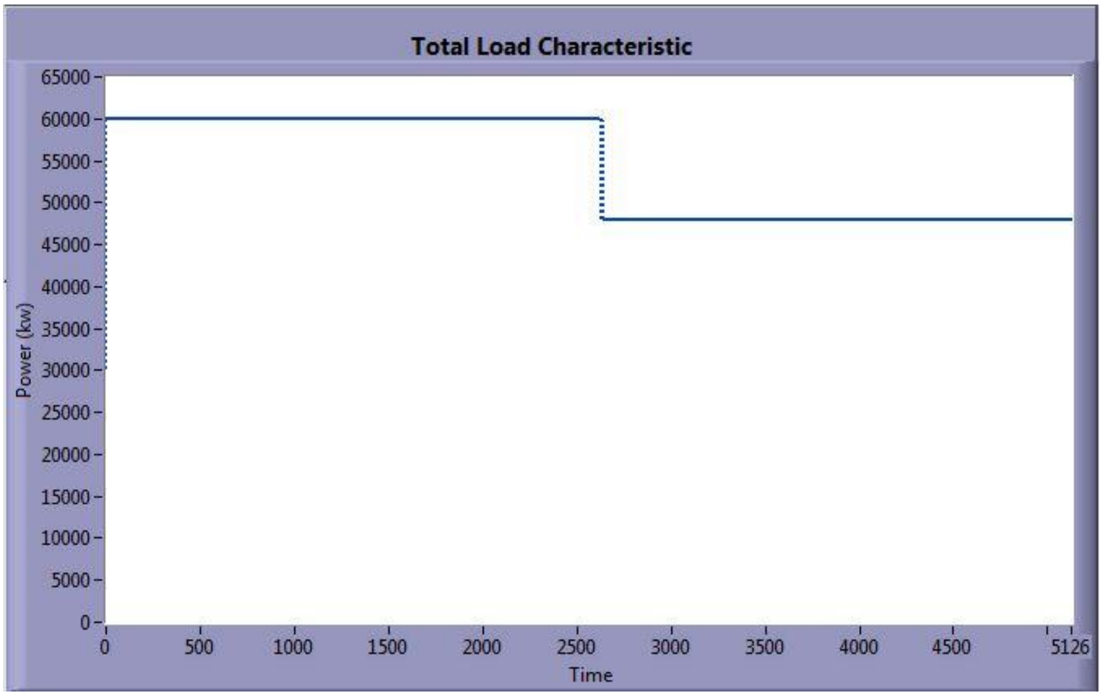


Figure 4.17: Successful AC load curtailment

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The demand for energy in buildings worldwide will only continue to increase in the future, and the need to properly manage energy consumption within buildings is greater than ever. Demand Side Management (DSM) which was introduced as a solution to bring about energy usage efficiency, strives to flatten load curves through techniques such as load shifting, valley filling, peak clipping, as well as load curtailment. Peak demand negatively affects the utility and commercial energy consumers, where operating cost is high for both parties. Where energy consumption is concerned, DSM will help reduce the peak demand charge for commercial energy consumers.

In this project, a building power monitoring device was successfully developed in order to perform Demand Side Management (DSM), where it can be used to collect, monitor and analyze power parameters within a building. The analyzed parameters can be used to bring about targeted changes for energy consumption within a building in order to perform DSM. Other than that, a simulation of air conditioner load curtailment algorithm was also successfully developed. In developing the load curtailment program, the room heating/cooling characteristic was investigated through a simple data acquisition program, in order to obtain a function curve which will enable the prediction of each individual room temperature. The air conditioner load curtailment program, which is developed in LabVIEW has a intuitive graphical user interface which enables easy operation of the software. Simulation results from the air conditioner load curtailment algorithm have shown that it is capable to perform load curtailment tasks as intended, reducing the energy consumption according to the energy threshold set by the user. In essence, this project is capable of helping to reduce a significant portion of the monthly electricity bill for commercial energy consumers.

5.2 Recommendations

The present load curtailment algorithm in this project is only limited to air conditioner (AC) control via physical data cables. In order to improve upon the air conditioner load curtailment algorithm, it is suggested that the algorithm is implemented with additional hardware modules which will enable wireless control of each individual AC in rooms within a building. Doing so will reduce installation charges and complexities associated with the connection of AC control cables from each individual ACs to the sbRIO, which is the central control unit for load curtailment algorithm. This wireless control capability can be realised through options such as the ZigBee or Radio Frequency modules.

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