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FINAL YEAR PROJECT REPORT

DEVELOPMENT OF MICROGRID BASED PV-RESTORATION INCORPORATING DEMAND RESPONSE

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SUPERVISOR ENDORSEMENT

" I hereby declare that I have read through this report entitle "Development of Microgrid Based PV-Restoration Incorporating Demand Response" and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Industrial Power)"

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" I hereby declare that this report entitle "Development of Microgrid Based PV-Restoration Incorporating Demand Response" is the result of my own research except as cited in the reference. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree"

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ABSTRACT

Today's electrical grid was designed to operate as a vertical structure consisting of generation, transmission, and distribution with the supported of controls devices to maintain system reliability, stability, and efficiency. However, system operator are now facing new challenges including the penetration of renewable energy resources in the legacy system, rapid technological change, and different types of market players and end users. Technical challenges associated with the operation and controls of microgrid are immense. The microgrid need to optimize their performance during grid connected mode and island mode operation. Interruption of the main grid supply will cause the microgrid disconnect itself and microgrid will loss power. By making the microgrid operates in stand-alone operation, the microgrid need to isolate from the main grid and need a reference voltage to restore and deliver power among the microgrid. Ensuring stable operation during network disturbance, maintaining stability and power quality in the islanding mode of operation requires the development of sophisticated control strategies for microgrid inverter in order to provide stable frequency and voltage in the presence of arbitrarily varying loads. This project focuses on the protection for restoration of PV-connected microgrid incorporating demand response during grid supply interruption. The project aim to restore the power generate by PV system by using grid-tie inverter and pure sine wave inverter aided by battery storage. This project is done to develop a control strategy for restoration of PV-connected microgrid with load control algorithm. The control strategy was designed to be installed on the residential system that comprise of microgrid system with a PV source. The method of load control management was applied to obtain the voltage stability during islanded mode operation. The load control scheme is depend on the current generate by PV. According to the result from conducted experiment, the load control algorithm was operate to stabilize the microgrid voltage by controlled the load demand depend on the PV generation.

ABSTRAK

Grid elektrik hari ini telah direka bentuk untuk beroperasi secara menegak yang terdiri daripada penjanaan, penghantaran, dan pengagihan dan disokong dengan kawalan dan alat-alat untuk mengekalkan kebolehgunaan sistem, kestabilan, dan kecekapan. Walau bagaimanapun, pengendali sistem kini menghadapi cabaran baru termasuk penggunaan sumber tenaga boleh diperbaharui dalam sistem legasi, perubahan teknologi yang pesat , dan jenis pembekal dan pengguna akhir. Cabaran teknikal yang berkaitan dengan operasi dan kawalan microgrid adalah besar . Microgrid perlu mengoptimumkan prestasi mereka semasa mod bersambung dengan grid dan mod pulau. Gangguan bekalan grid utama akan menyebabkan microgrid terputus hubungan dengan grid dan microgrid akan hilang kuasa. Dengan membuat microgrid beroperasi bersendirian, microgrid perlu diasingkan dari grid utama dan memerlukan voltan rujukan untuk memulihkan dan menyampaikan kuasa di dalam microgrid. Pembangunan strategi kawalan yang canggih untuk micrgrid inverter semasa gangguan berlaku adalah diperlukan untuk mengekalkan kestabilan dan kualiti kuasa seterusnya menstabilkan frekuensi dan voltan dengan kehadiran beban yang berubah-ubah. Projek ini memberi tumpuan kepada perlindungan untuk pemulihan PV yang disambung ke microgrid bersama respon kawalan beban semasa gangguan bekalan grid. Projek ini bertujuan untuk mengembalikan kuasa oleh sistem PV dengan menggunakan grid-tie inverter dan inverter bergelombang sinus dibantu oleh penyimpanan bateri. Projek ini dijalankan adalah untuk membina strategi kawalan untuk pemulihan PV yang disambung ke microgrid dengan algoritma kawalan beban . Strategi kawalan telah direka untuk dipasang pada sistem kediaman yang terdiri daripada sistem microgrid dengan sumber PV. Kaedah pengurusan kawalan beban telah digunakan untuk mendapatkan kestabilan voltan semasa operasi mod pulau. Teknik kawalan beban adalah bergantung kepada bekalan yang dijana oleh PV. Menurut keputusan eksperimen yang dijalankan, algoritma kawalan beban telah berfungsi untuk menstabilkan voltan microgrid dengan mengawal beban yang bergantung kepada generasi PV.

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CHAPTER 1

INTRODUCTION

1.1. Motivation

Environment concern like greenhouse effect and pollutant are driving the need for increase interest in more deployment of renewable energy resources. In addition, the low voltage distribution systems need to be expanded horizontally. One proposed solution that may provide remedies for these issues is penetration of distributed energy resources into the next generation of electricity grid. This proposed solution promising the environmental friendly and efficient electricity generation and distribution. As a result, microgrids provide a unique opportunity for integrating the renewable resources into the distribution system [1].

Microgrids comprise low voltage distribution system with a group of interconnected load and distributed energy resources which can operate in both grids connected or island mode [2]. Microgrid are small-scale version of centralized electricity system where smaller scale distributed generator and renewable energy resources like wind turbines, solar panel and energy storage; provide power closer to the point. Microgrids are expected to provide environmental and economic benefits for end-customers, utilities and society. Microgrids need the capability to improve power quality, network efficiency, reliability and economic in order to reduces the environmental effect [3].

In typical microgrid, the microsources may be rotating generator or Distributed Energy Resources (DER) interfaced by power electronic inverter. The installed DERs may be biomass, fuel cells, geothermal, solar or wind turbine. Microgrid systems operate at low voltage distribution and consist of several distributed energy resources. The microgrid structure consists of Distributed Generation (DG); energy reserves from battery

(Distributed Storage/DS) and loads. One of the promising renewable energy sources is photovoltaic (PV). The interesting in PV-based sources is due to their many advantages such as ease of installation, less maintenance and long lifetime [4].

The microgrid-connected PV-sources comprise of PV module, inverter, storage and load. The PV module is use to convert the solar energy into DC electricity. The inverter is use to convert the DC supply from PV module or storage into AC supply. The system is either interconnected to main grid or operated in islanded mode. The difference between grid-connected and islanded mode is the operation of inverter. There are two types of inverter that typically used which is stand-alone and grid-tie inverter [5].

A microgrid can be operating in two modes which are grid-connected mode and island mode. In grid-connected mode, the microgrid is connected to the main grid. The power management system of grid-connected is stable because it sharing a power from the main grid. When the microgrid is connected to the microgrid, its excess power is supplied to the main grid and in the event that the demand surpasses the power being generated at a certain time, the extra power is provided by the main grid.

Under grid-connected mode, the frequency and voltage magnitude of the microgrid must be synchronizing with the main grid. For island mode operation, the distributed energy resources which connect to the DC/AC inverter must controlled in the load-following mode. The power management of island mode is different from the grid-connected mode. The operational in island mode must fulfilled two most important requirement which is good power balance between generation and consumption, and a proper control of the main parameter of the microgrid such as voltage magnitude and frequency [6].

The most important of these are the protection system which are installed to clear fault and limit any damage to the distributed equipment. In order to design a protection for any system, knowledge about the system is required before it can be developed. In order to obtain the optimum protection system, the protection arrangement for any power system must follow to the basic principle which is reliability, speed, selectivity and cost [7]. The disturbances can be found in the system during fault condition such as during a change of operation mode – going from grid-connected to islanded mode. The most common disorder is transients, voltage sags and swells, over-voltage and under-voltage as well as under-current and over-current fault. To overcome these protection issues in microgrid, various protection schemes are discuss [8]. The technique for PV restoration under island mode operation will increase the performance of microgrid during grid loss condition. The uses of demand response algorithm give an advantage for microgrid to deliver the optimal energy generate by PV to the load.

1.2. Problem Statement

Today's electric grid was designed to operate as a vertical structure consisting of generation, transmission, and distribution and supported with controls and devices to maintain reliability, stability, and efficiency. However, system operator are now facing new challenges including the penetration of renewable energy resources in the legacy system, rapid technological change, and different types of market players and end users. The next iteration, the microgrid, will be equipped with communication support scheme and real-time measurement techniques to enhance resiliency and forecasting as well as to protect against internal and external threats.

Technical challenges associated with the operation and controls of microgrid are immense. Ensuring stable operation during network disturbance, maintaining stability and power quality in the islanding mode of operation requires the development of sophisticated control strategies for microgrid inverter in order to provide stable frequency and voltage in the presence of arbitrarily varying loads.

The main problem is once the network disturbance, how to make the microgrid disconnect itself from the main grid and operate in islanded mode using PV source without battery storage. As the battery is too expensive and short lifespan, this project develops the protection scheme for PV-connected microgrid without battery as storage.

This project used a grid-tie inverter as a conversion to convert DC voltage from PV module to AC voltage supply. To operate this grid-tie inverter, it needs a reference in frequency and voltage. The use of Pure Sine Wave (PSW) inverter is to provide a reference to the grid-tie inverter. This project can prevent the wastage of energy during the high irradiation of sun that can handle some critical load. Therefore, to make the microgrid more efficient and safe, the development of PV restoration and protection scheme for PV-connected microgrid is needed to overcome this problem.

1.3. Objectives

The main project objective is to propose strategies for development of protection scheme for PV-connected microgrid. To achieve this goal, the aims of the research project were identified as:

1. Develop a control strategy for restoration of PV-connected microgrid during grid loss condition.
2. Develop load control algorithm to maintain supply and demand.

1.4. Scope

This project focuses on designing a PV restoration under off grid condition for PV-connected microgrid. The execution of this project includes the development of friendly interface. The protection scheme is designed to be installed on low voltage distribution system that comprise of microgrid system with a PV source.

The main function of this protection scheme is to isolate the microgrid from the main grid due to the grid failure. Then the microgrid will operate in islanded mode and give power supply to the critical load. The PSW inverter with battery storage is used to give a reference in voltage and frequency to the grid-tie inverter that connected from the PV module and will powered the critical load.

This protection scheme should disconnect the microgrid itself from the main grid due to occurrence of abnormal condition and to be shifted to islanded mode. In order to prevent the reverse power flow to the PSW inverter, a load control algorithm is used to protect the PSW inverter from reverse current. This protection scheme is very useful to critical appliances that need a power without a long interruption. This protection scheme also prevents the wastage of power that supplied from PV module especially when the PV captures high irradiation of solar energy that will produce high power to handle the critical load. Figure 1.1 shows the hourly PV generation profile.

Based on Figure 1.1, the PV starts to produce electricity at 9.00 a.m. Then, PV will increase the generation of electricity. The maximum irradiance occurs at 12.00 p.m. to 2.00 p.m. After this period, the irradiance will decrease until 6.00 p.m. However, the peak demand of PV are depends on weather [9].

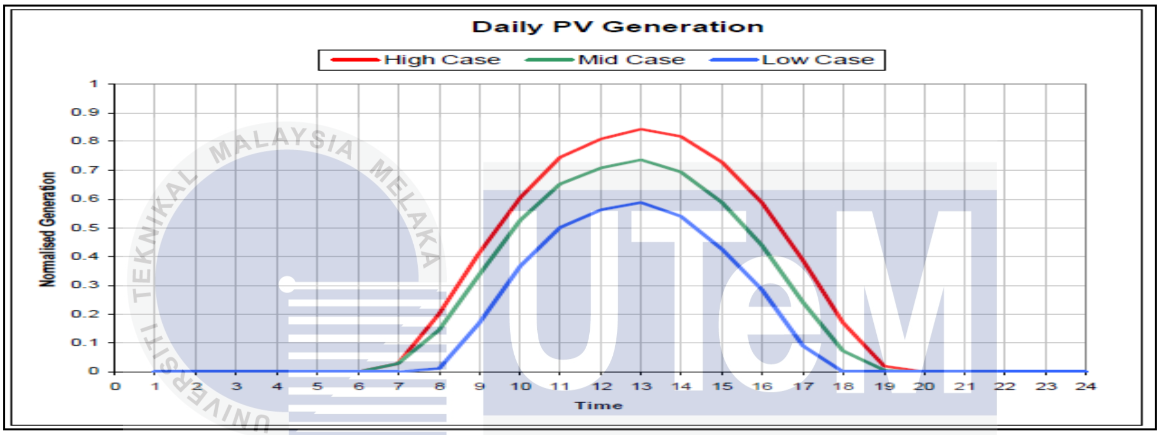

Figure 1.1: PV generation curve

This proposed project gives many benefits to consumer especially which consume high energy during the PV capture high irradiation of solar energy. The target audience to propose this project is the commercial building. The commercial building is referring to office building, government building, industrial building, retail, shopping mall and etc. During this period, their energy consumption is high because of lighting, cooling system and other appliances. Figure 1.2 shows the pattern average of daily energy consumption for office building [10].

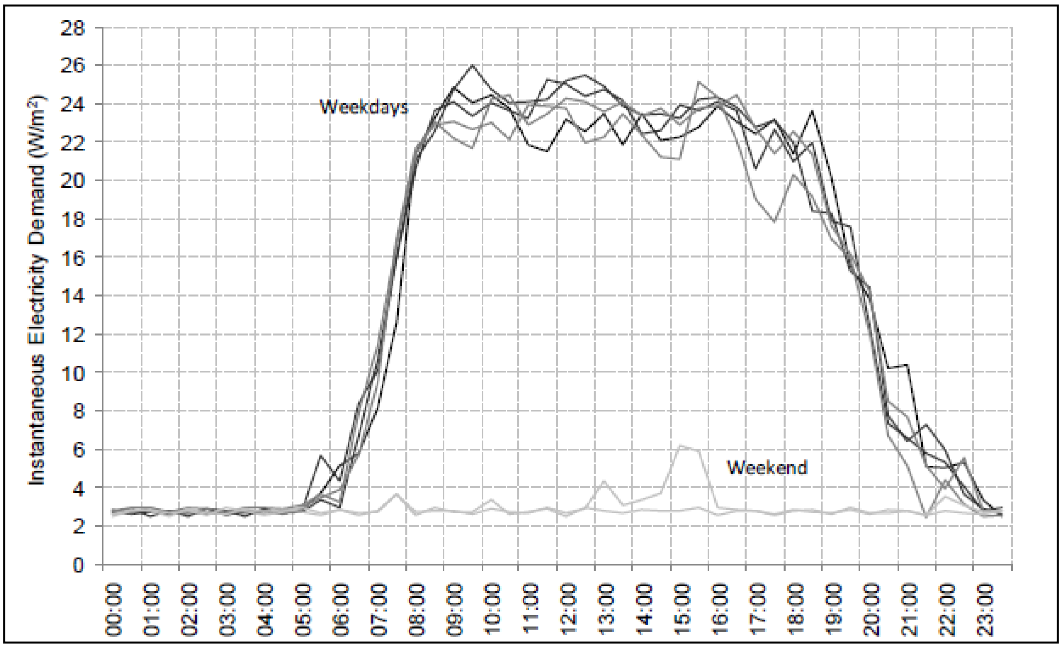

Figure 1.2: Average energy consumption

Figure 1.2 shows analysis of energy consumption for lighting and small power in office building. This daily energy consumption pattern is considered same as any office building [10]. Based on Figure 1.2, it shows the load is start from 7.00 a.m. until 9.00 p.m. The loads start to increase at 8.00 a.m. and reach maximum demand at 10.00 a.m. Then, load will decrease after 6.00 p.m. By comparing Figure 1.1 and Figure 1.2, the patterns are exactly same and can be combined. Therefore, the implementation of PV connected microgrid will give benefits to office building and other commercial building that has same pattern energy consumption.

CHAPTER 2

LITERATURE REVIEW

2.1. Basic Topologies

2.1.1. Microgrid

Microgrid means a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and that connects and disconnects from such grid to enable it to operate in both grid-connected or island mode [11].

A microgrid is a localized grouping of electricity generation, energy storage, and loads that normally operate connected to a traditional centralized grid. This single point of common coupling with the microgrid can be disconnected. The microgrid can then function autonomously. Generation and loads in microgrid are usually interconnected at low voltage. From the point of view of the grid operator, a connected microgrid can be controlled as if it were one entity.

Microgrid generation resources can include fuel cells, wind, solar or other renewable energy resources. Figure 2.1 shows typical microgrid architecture. The microgrid can operate either in grid-connected or island mode. In grid-connected mode, the goal of power management can be achieved by controlling the frequency and voltage profile of the inverter by referring to the main grid frequency and voltage profile. In the islanded mode, the microgrid operates in stand-alone using the DG.

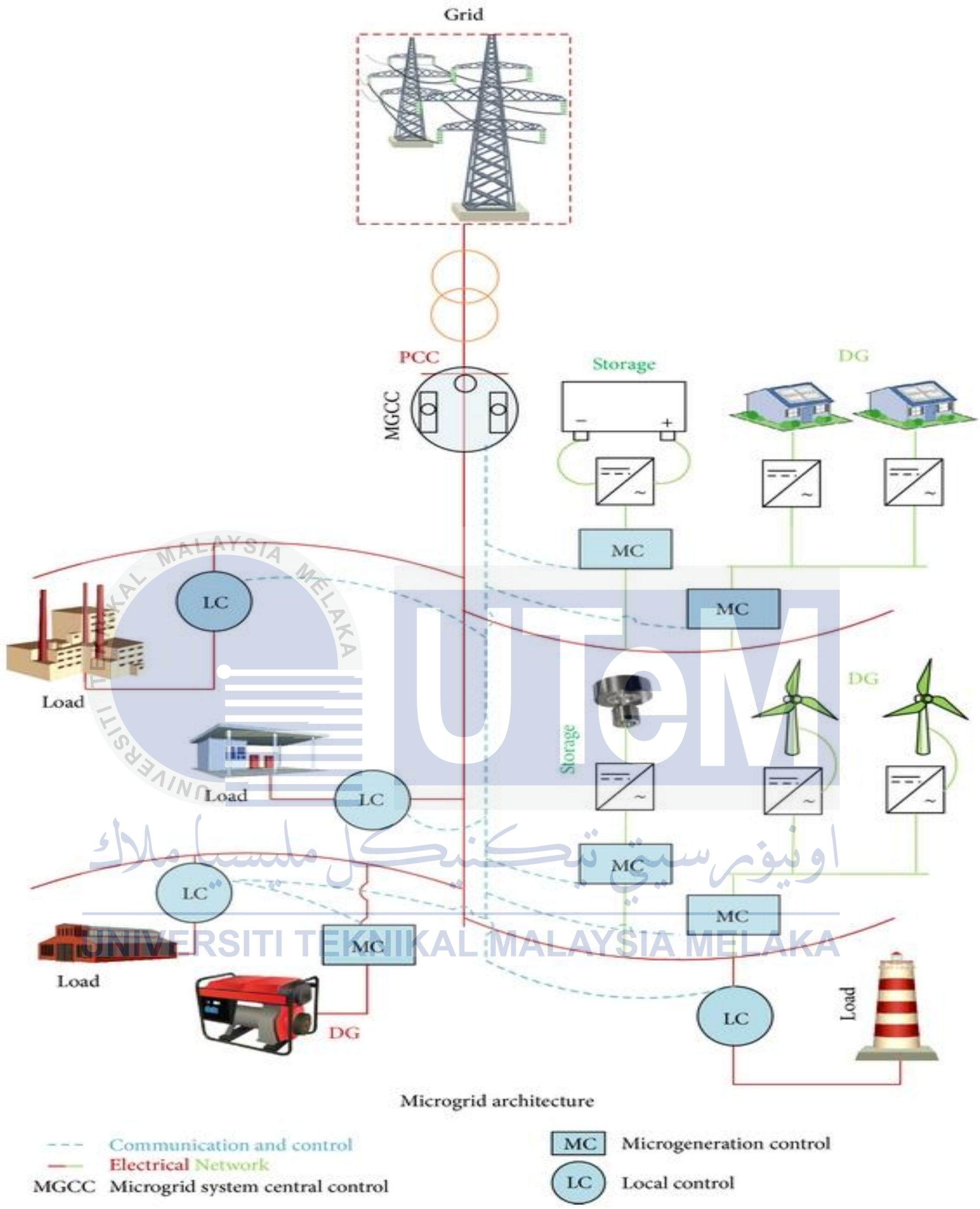

Figure 2.1: A simple microgrid structure

2.1.2. PV Generation

The conversion efficiency of a solar cell is defined as the cell-produced power (W) divided by the input light irradiance (W/m^2) in standard test conditions (STC: 1000 W/m^2 and 25°C) and the surface area of the solar cell (m^2). Thus, conversion efficiency depends on many factors such as irradiance levels and temperature. Manufacture processes usually lead to differences in electrical parameters, even within the same type of cells. In view of the foregoing, only the experimental measurement of the I-V and P-V curves allows to get to know with precision the electrical parameters of a photovoltaic cell, module and array. This measure provides very relevant information for the design, installation, and maintenance of PV systems. The experimental measurement of the I-V characteristic is of great importance, as it can be considered as a quality and performance certificate of every PV generator.

The main points of the I-V and P-V curve characteristics are the short-circuit current (I_{sc}) or the maximum current at zero voltage, and the open-circuit voltage (V_{oc}) or the maximum voltage at zero current. For each point in the I-V curve, the product of the current and voltage represents the output power for that operating condition. The MPP produced by the generator is reached at a point on the characteristic where the product I-V is maximum. Hence, $P_{mp}=I_{sc}$ x V_{oc}. Figure 2.2 shows the relation of I-V curve and P-V curve.

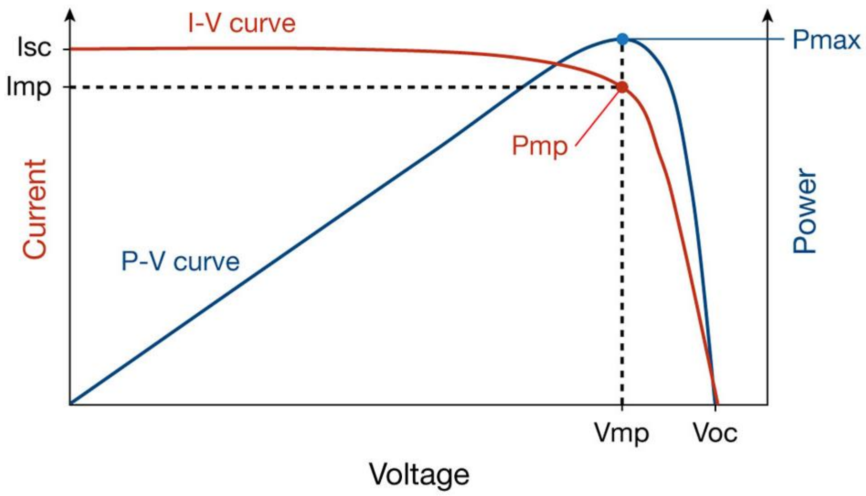

Figure 2.2: Normal I-V curve and P-V curve

2.1.3. Load Flow Studies in a Simple Radial System

Every distribution network operator has an obligation to supply its customers at a voltage within specified limits. This requirement often determines the design and capital cost of the distribution circuits and so, over the years, techniques have been developed to make the maximum use of distribution circuits to supply customers within the required voltages.

The connection of distributed generator will change the power flows in the distribution network hence the voltage profile. In grid connected mode, the voltage received by all customers will be regulated under specified limits. During minimum load, the voltage will increased below the maximum allowed. The most onerous case is likely to be when the customer load on the network is at minimum and the output of the distributed generator must flow back to the source.

For lightly loaded distribution network the approximate voltage rise (ΔV) caused by a generator exporting real and reactive power is given by Equation (1):

$$\Delta V = \frac{PR + XQ}{V} \quad (1)$$

Where:-

P = Active Power output of the generator

Q = Reactive power output of the generator

R = Resistance of the circuit

X = Inductive reactance of the circuit

V = Nominal voltage of the circuit

2.2. Review of Previous Related Works

A microgrid is formed when an electrical region capable of autonomous operation is islanded from the remainder of the grid. Formation of a microgrid due to an islanding process can be due to disturbances, such as a fault and its subsequent switching incidents or due to pre-plan switching events. Current utility practices do not permit autonomous microgrid operation. This requirement is imposed to address safety concerns and to comply with the existing control constraints of distribution system.

2.2.1. Protection Issues in Microgrid

For the protection issues, P.Anil Kumar, J.Shankar and Y. Nagaraju were discussed the protection issues in the International Journal of Applied Control, Electrical and Electronics Engineering (IJACEEE). The title of this paper is "Protection Issues in Microgrid". This paper discuss on the various protection scheme depends on the various protection issues. In microgrid application, the traditional power system protection strategies cannot be used. The integration of DG in microgrid system poses several technical problems in the operation of system protection. There is a various protection issues arises such as change in fault current level of network, possibility of sympathetic tripping, reduction in reach of distance relays, loss of relay coordination and unintentional islanding [12]. This paper also present the key of protection issues in microgrid which are:

i. Modification in fault current level
ii. Device discrimination
iii. Reduction in reach of impedance relays
iv. Reverse power flow
v. Sympathetic tripping
vi. Islanding
vii. Single phase connection
viii. Selectivity.

2.2.2. Voltage source inverter (VSI)

Inverter is a device that converts from DC supply to AC supply. The VSI means the inverter circuit has direct control over output AC voltage. The DC voltage input will be converting into AC voltage within the desired voltage magnitude and frequency. All VSI assume stiff voltage supply at the input. The magnitude of the AC output voltage is limited by the magnitude of DC input voltage. The output voltage is constant and the output current changing with the load. The VSI widely used in power supplies, Uninterruptible Power Supply (UPS), unified power quality conditioners, and distributed generation systems. Figure 2.3 shows the three level voltage source inverter topology. The VSI topology uses a diode rectifier to convert the AC voltage to DC voltage. The capacitor connected in parallel to regulate the DC bus voltage ripple and store energy for the system. The inverter is consists of insulated gate bipolar transistor (IGBT) semiconductor switches. The IGBT switches create a Pulse Width Modulator (PWM) voltage output that regulate the output voltage and frequency.

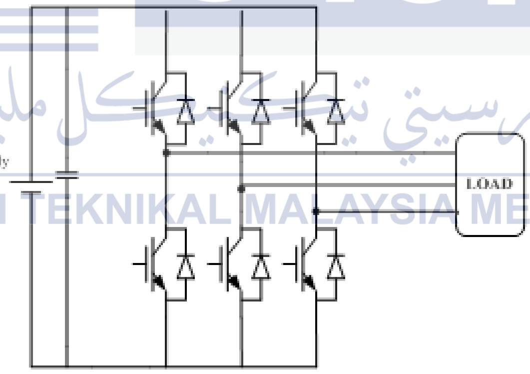

Figure 2.3: Voltage source inverter topology

2.2.3. Current source inverter (CSI)

The current source inverter means the inverter circuit has direct control DC input over output AC current. The load current magnitude is controlled by varying the input DC voltage to the large inductance; hence inverter response to load changes is slow. The output current is nearly constant but the voltage will varies with the load. The current source inverter is an electronic circuit that delivered a current which independent of the voltage across it. Figure 2.4 shows the current source inverter topology. The converter uses silicon-controlled rectifiers (SCRs), gate commutated thyristor (GCTs) or symmetrical gate commutated thyristor (SCGTs) to convert from AC voltage to DC voltage. The DC link uses inductors to regulate current ripple and store energy for the system. The inverter consist of gate turn-off thyristor are turned on and off to create a PWM output regulating the output frequency.

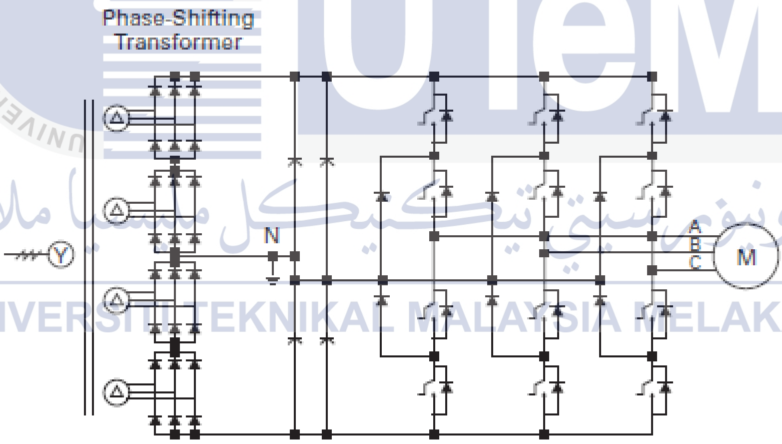

Figure 2.4: Current source inverter

2.2.4. Restoration of microgrid

Under normal operating condition, a microgrid is synchronizing to the main grid. During the general blackout, the microgrids need to isolate from the main grid. Therefore, C. L. Mooreira, F. O. Resende and J. A. Pecas Lopes were proposed a sequence of action to restore the operation of microgrid in islanded mode operation. In order to ensure system stability, many consideration and action should be take off such as voltage and frequency control approaches, inverter control mode and storage device.

In order to make a restoration of power during general blackout, a step by step procedure must be considered based on predefined guidelines and operating procedure [13]. The restoration procedure is focused on the plant preparation for restart, network energization, and system rebuilding. Depending on system characteristics, a choice must be made between a strategy of energizing the bulk network before synchronizing most of the generators and a strategy of restoring islands that will be synchronized later [14].

Frequency and voltage is very important during the islanded operation of microgrid. The inverter should be responsible to control the stability of the entire system. A cluster of MS operating in islanded mode requires at least a master inverter to define the voltage and frequency references for the entire network [15]. This means that a general frequency and voltage control strategy should be followed in order to operate the MG in islanded mode. Combining the inverter control techniques, two main strategies are possible [15], [16]. Figure 2.5 shows the proposed scheme of microgrid which consists of a single-shaft microturbine, PV generator, wind generator and load.

- Single Master Operation: A single VSI is used to provide the reference voltage for the islanded system.
- Multi Master Operation: Two or more inverters are operated as VSI; eventually, other PQ controlled inverters may also coexist.

In this paper, the author was listing the sequence of action that should be performing after general blackout. The following sequence of action is described to perform service restoration in islanded mode operation [17].

i. The microgrid should be sectionalize around each microsource to energize the load according to the sectionalize area and each sectionalize area will be synchronize later which helps to stabilize the operation of microgrid.

ii. Small islands synchronization which was already operating in standalone operation then should be synchronizing with the LV network to share the power among each small island.

iii. Connection of controllable load in order to avoid the large frequency and voltage deviation of the entire system during load connected.

iv. Connection of non-controllable microsource such as PV and wind generator to share more power among the entire isolated system.

v. Load increase depending on the generation capability.

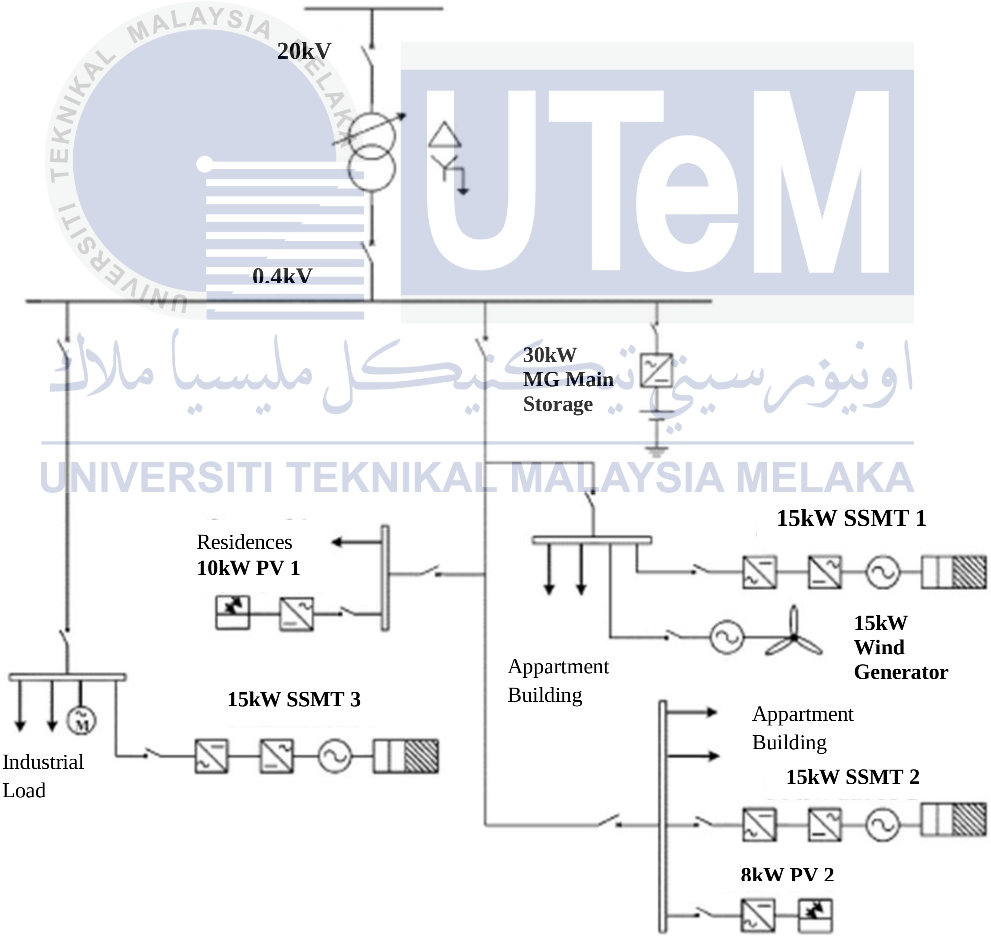

Figure 2.5: Proposed design of microgrid

As the conclusion, the control strategies to be adopted for microgrid black start and subsequent islanded operation prove the feasibility of such procedure and show that the storage device are absolutely essential to implement successful control strategies during all restoration stage.

2.2.5. Load Control Management

A control scheme for standalone photovoltaic system has been proposed by J. Faxas-Guzman, G. Roa and A. Urbina in their article of "A priority load control algorithm applied to a standalone PV system". The objective is to propose an optimal energy management in a standalone PV system. The idea is by control the load depends on the energy availability and battery state-of-charge (SOC). The control scheme is classified the load into two categories which is critical loads and non-critical loads. The purpose is to protect the batteries from overcharge or over discharge and to keep the critical load always connected.

The algorithm keeps connected the priority loads until battery reach its minimum state-of-charge. The non-priority loads will be switch ON and OFF depending on battery status. If the battery has low state-of-charge, and low solar power is available, loads will be disconnected in order to preserve battery energy. Conversely, with enough energy is available, all loads will be supplied. The experiment objective is to compare the result between using a load priority control and without using a load priority control. Figure 2.6 shows the result of the experiment through 275 days.

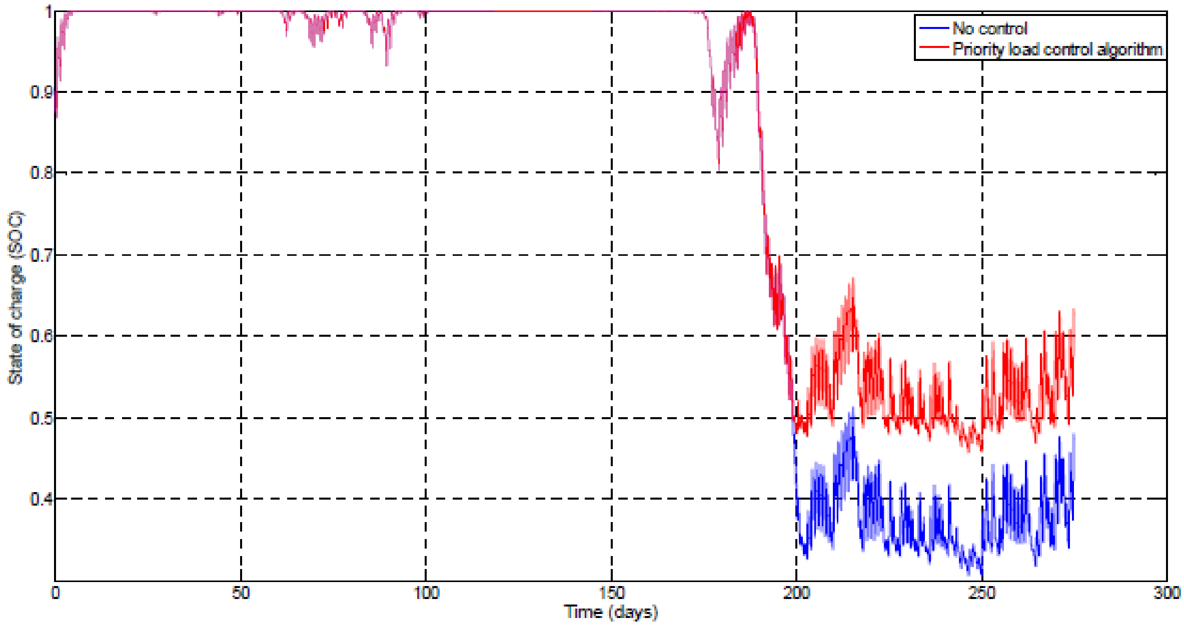

Figure 2.6: Battery state-of-charge evolution through 275 days

The Figure 2.5 represents the state-of-charge evolution through 275 days. The blue line represents the SOC behavior without using a load priority control and the red line represents the SOC behavior by using a load priority control algorithm. From the analysis, the SOC of the battery storage is higher by using a load priority load control algorithm compare to the SOC of the battery storage without using load control algorithm. As a result, a load priority control algorithm gives an optimal management of loads and battery storage [18].

2.3. Summary and Discussion

There are a lot of design has been showed in developing a protection scheme for microgrid. Each design has their strengths and weakness depend on the fault to be cleared. Each design uses the same parameter in detection circuit which is voltage and current signal. The difference is the method use to process the data in order to follow the basic principle of protection which is reliability, speed, selectivity and cost. Based on the literature review, a few things need to be considered to develop a protection scheme. For the purpose of this project, a load management is the important issue that to be considered. In order to give an optimal use of energy, the load need to be control depend on the generation. This also can prevent the wastage of energy that generate. And the most important thing is the restoration of the microgrid. Although if there has a source to convert into power, it also need to synchronize with other source generation such as PV and wind generator. The use of grid-tie inverter is very practical to be use for synchronizing each system. However the combinations of source give an effect to the voltage and frequency of the entire system. Therefore, the loads need to be control in order to follow the generation.

CHAPTER 3

PROJECT METHODOLOGY

3.1. Project Methodology

Figure 3.1 shows the project methodology. The project methodology was constructed before the project start. The project consists of several process which is planning, design, implementation testing and evaluation. The initial process is planning which involves the definition phase and literature review. This process finding using different sources such as journal, articles, internet and books and need to be analyzed in a proper way. This process give a better understanding about the project and the concept will be used to achieve the project objectives.

Then the projects proceed with design process. Design process can be divided into two parts which is hardware and software. The hardware development starts with designing the circuit. This process involves choosing the right component to be including in the system. The hardware is combination of electronic circuit and power device. The component used in this project is current transducer, relay, electronic component, LCD and Arduino. The circuit is then will be test to ensure the functionality of each component to reach the desired operation. The process is same with the programming development. After both of the development work well, the next process is implementation. In project implementation process, the hardware and software were combined together. The program coding is burn into microcontroller. The following process is essential to ensure the program works well with the hardware as desired objectives. At the next process, testing will be carried out to ensure the system work perfectly. And the last process is evaluation process which use to achieve second objective.

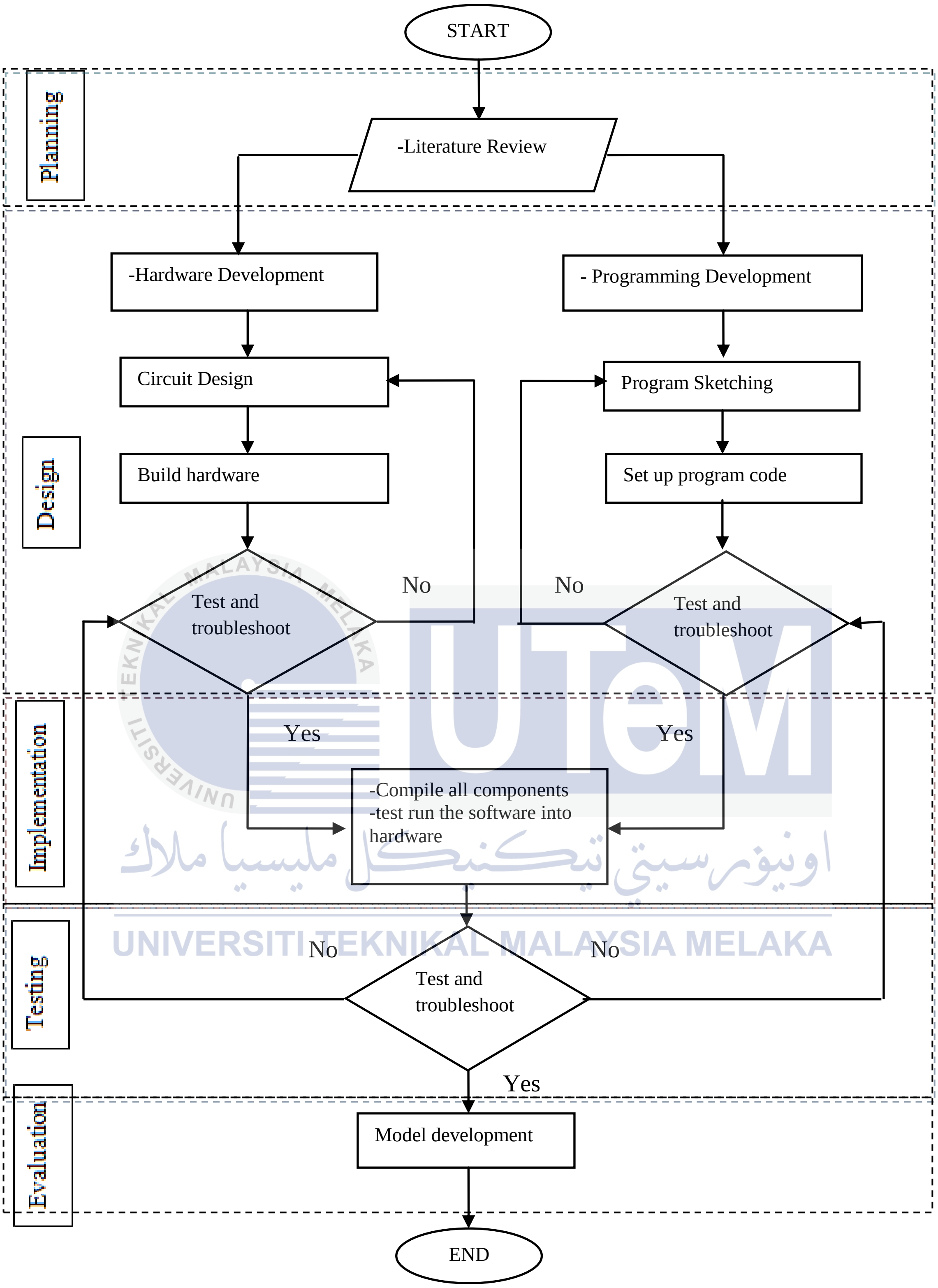

Figure 3.1: Project methodology

3.1.1. Operation of Protection Scheme System

The flowchart in Figure 3.2 shows the operation of the system. When the supply is injected to the system the microcontroller initialize all involved ports and initialize the LCD. The voltage transformers measure the voltage profile of the main grid. The value of voltage in rms and frequency will be calculated by the microcontroller. The value is display in the LCD. The measured value will be compare with the threshold value that has been set up in the microcontroller. If the measured value is within the threshold, the contactors that connect between microgrid and main grid will be energized. Therefore, the microgrid is operating in grid-connected mode.

If the measured value is above or under the threshold, the contactor will disconnect the power lines and start-up the backup generator. The contactors that connect to main load and PV also will be disconnected. At the same time, the voltage profile and frequency of the backup generator are measured. The measured value is calculated and compare to the threshold that set up in the microcontroller. If the measured value is within the threshold, the contactors that connect to the generator and PV are connected. Therefore, the microgrid is operating in island mode until the main grid supply back to normal. The system will always monitor and check the condition of the main grid.

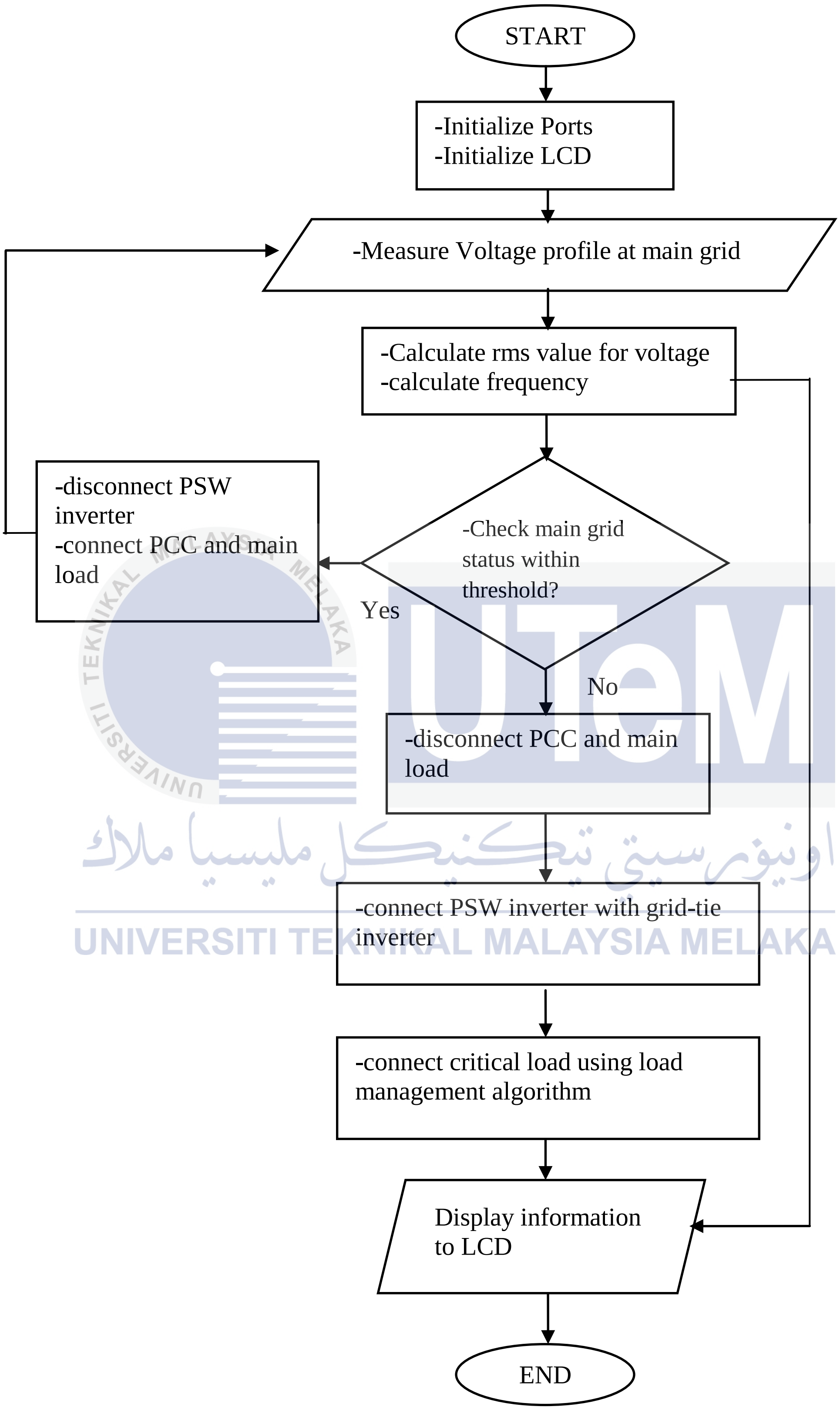

Figure 3.2: Flowchart of the system

3.2. Experimental Setup

The first experiment is about the microgrid under grid connected mode. The purpose for the first experiment is to analyze the behavior of the load voltage due to the PV generation. The experiment was conducted in FKE Solar Lab. The experiment was conducted using PV panel, grid-tie inverter, isolation transformer, and pure resistive load bank. Figure 3.3 shows the single line diagram of this experiment. The PV panel gives DC supply to the grid-tie inverter. The grid-tie inverter that use in this experiment is SB 2000-HF. The SB 2000-HF is a current source inverter type. This inverter can produce 2000 Watts for the maximum output power. In order to turn ON this grid-tie inverter, the supply from main grid was use to give a reference to the grid-tie inverter. However, the isolation transformer is needed to prevent the system trip because of the neutral current that flow from grid-tie inverter to the main grid. The pure resistive load bank is use as loads to absorb power generate and analyze the effect of voltage magnitude due to the load current and generation.

The second experiment is about the microgrid under island mode operation. For the second experiment, the purpose is to analyze the voltage stability when the microgrid is operating in island mode operation with the load control algorithm. The island mode operation in this experiment is continuity of the first experiment. Figure 3.4 shows the single line diagram of microgrid operated in islanded mode. The experiment consists of PV generation, voltage source generator, current transducer, microcontroller and pure resistive load. The PV generation captures from PV panel and produce DC voltage. The grid-tie inverter is use to convert the DC supply into AC supply. The grid-tie inverter used in this experiment is a current source inverter. The inverter used is SB 2000-HF which can generate 2000 Watts maximum power. The rating for this inverter is shown in Appendix A. For the voltage source generator, a 1200 Ampere-hour battery was used and connected in series to a 300 Watts pure sine wave (PSW) inverter. The solar inverter used in this project is SRINVT PSW-300 manufactured by Job Solar Energy. The inverter can produce 300 Watts maximum powers. The datasheet for SRINVT PSW-300 was attached in Appendix B. The PSW inverter was connected in parallel with the grid-tie inverter and loads.

This PSW inverter is a voltage source inverter that converts the DC supply from battery into AC supply. The PSW inverter used to give a reference in voltage magnitude and frequency to the grid-tie inverter. To measure the current from grid-tie inverter and PSW inverter, two current transducers was used. The current transducer in grid-tie inverter side will measure current from the PV generation and is called as I_{pv}. The current transducer used in this project is ACS756 Fully Integrated, Hall Effect-Based Linear Current Sensor IC. The datasheet for the current transducer was attached in Appendix C. The current transducer in PSW inverter side was used to measure the reference current and is called as I_{ref}. This current measurement will be processed by the microcontroller to control the load. The microcontroller was used to control the load based on the PV current and reference current. Arduino Mega 2560 was used as microcontroller to process the load control algorithm. The datasheet of Arduino Mega 2560 was attached in Appendix D. The microcontroller will process current measurement based on the designed load control algorithm to control the relay module indirectly will control the load. The relay used in this experiment is 20 units to control the loads which consist of 20 units of 100W tungsten bulb.

3.2.1. Grid-connected system

In order to analyze the behavior of voltage and frequency in islanded mode, an experiment was conducted. During grid-connected mode, the voltage and frequency must be regulating within its threshold. According to Tenaga Nasional Berhad (TNB), the normal power supply that provides to customer is 230V for voltage and 50Hz frequency. However, there is a tolerance that was defined by TNB. Table 3.1 shows the specification of supply that supplied by TNB to customer [19].

Table 3.1: Specification of supply

Item	**Specification**
Voltage	230V with -6% & +10%
Frequency	50Hz with ±1%

During islanded mode, the operation is standalone which means the voltage and frequency is not control by the main grid. The voltage and frequency in islanded mode will change depend on the power generation. This will cause any damage to equipment that cannot operate below or above their rating operation. Besides that, the use of PSW inverter to give a reference to the grid-tie inverter will cause a reverse power flow that will damage the PSW inverter.

Therefore, an experiment was conducted to analyzed the effect of current generate by PV due to the voltage. Figure 3.3 shows the single line diagram for this experiment. The experiment was conducted using a source from the main grid to give a reference in voltage and frequency to the grid tie inverter. The pure resistive load bank is set as 1000W. The purpose of the isolation is to isolate the grounding system. The important of isolation is to prevent neutral current that can go through the main system. This will cause unbalance fault to the main system and the system will trip.

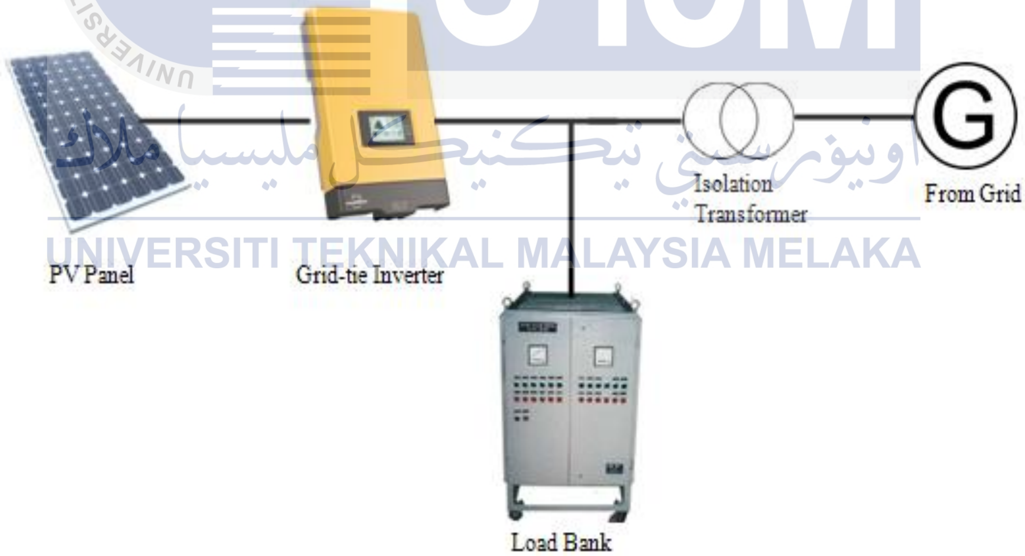

Figure 3.3 : Grid-connected system

3.2.2. Islanded operation

One method to be used to protect the PSW inverter is by control the load depends on the power generated by PV. This method gives benefits by using the power that generate by the PV without any wastage of power. During grid connected mode, the power can be export to the grid when the power generate by PV is larger than power consume by the load. In standalone operation, the power generates by PV cannot be export. By using a generator as a reference to the grid-tie inverter, the generator can be control to stabilize their voltage and frequency. But, for PSW inverter, the AC voltage is depends on the input voltage. The output voltage of PSW inverter cannot be regulated.

During island mode operation, the voltage stability and frequency is depends on the generation and load demand. The voltage and frequency not be regulated by the main grid. Such in grid-connected mode, the microgrid is connected to the main grid to get a reference in voltage magnitude and frequency for the purpose of grid-tie inverter. However, the microgrid will be disconnected during island mode. Figure 4.3 shows the single line diagram for microgrid operated in island mode. In this experiment, battery and PSW inverter was used to give a reference to the grid-tie inverter. For the purpose of protection to the PSW inverter, a load control algorithm was designed to make the demand response during island mode operation. The load control algorithm will control the load demand depend on the PV generation.

Figure 3.5 shows the proposed load control algorithm. The load control algorithm will be controlled by a microcontroller. The microcontroller will measured the PV current and reference current from the PSW inverter. The PV current was labeled as I_{pv} and the reference current was labeled as I_{ref}. The microcontroller only measured I_{pv} and I_{ref} during island mode operation. The n terms will represent number of relay. Initially, the microcontroller was set number of relay, n is equal to zero and all loads is turn OFF. The microcontroller will measured I_{pv} and I_{ref}. The microcontroller will calculate the summation of I_{ref} and the assumption load current. The summation is labeled as $I_{desired}$. If I_{pv} is greater than $I_{desired}$, number of relay, n will increase and the load will turned ON one by one until the microcontroller sense that I_{pv} is smaller than $I_{desired}$. The load current should be higher than PV current for the safety purpose. The other loads current that cannot supply by PV then take over by the reference source. When $I_{desired}$ is greater than I_{pv}, the microcontroller will calculate the difference between $I_{desired}$ and I_{pv}. The difference between $I_{desired}$ and I_{pv} is labeled as I_{del}. If I_{del} is greater than 0.45A, the number of relay, n will decrease and will turn OFF the loads one by one. The value of 0.45A is the measured current for 100 Watts tungsten bulb.

To solve this problem, a load management algorithm has been proposed. The algorithm is depends on the current generate by PV and PSW inverter. The load will be controlled due to the current from PV. As the current generate is higher than the desired load current, the load also increase.

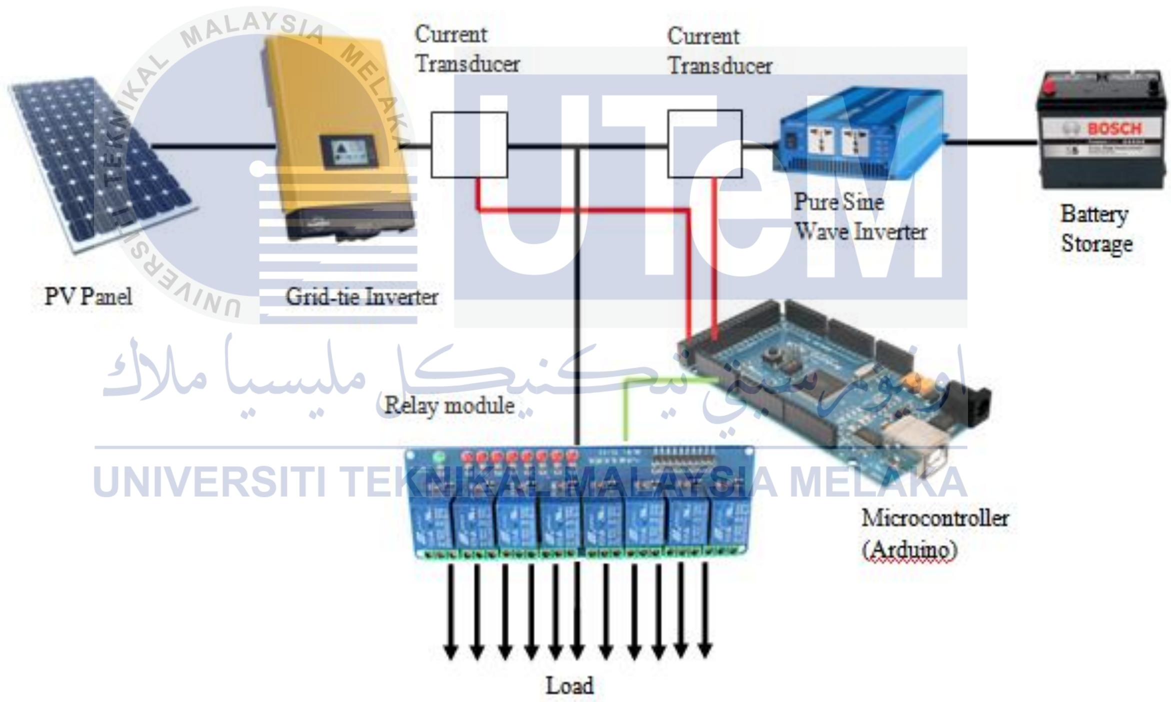

Figure 3.4: Proposed Load Management Scheme

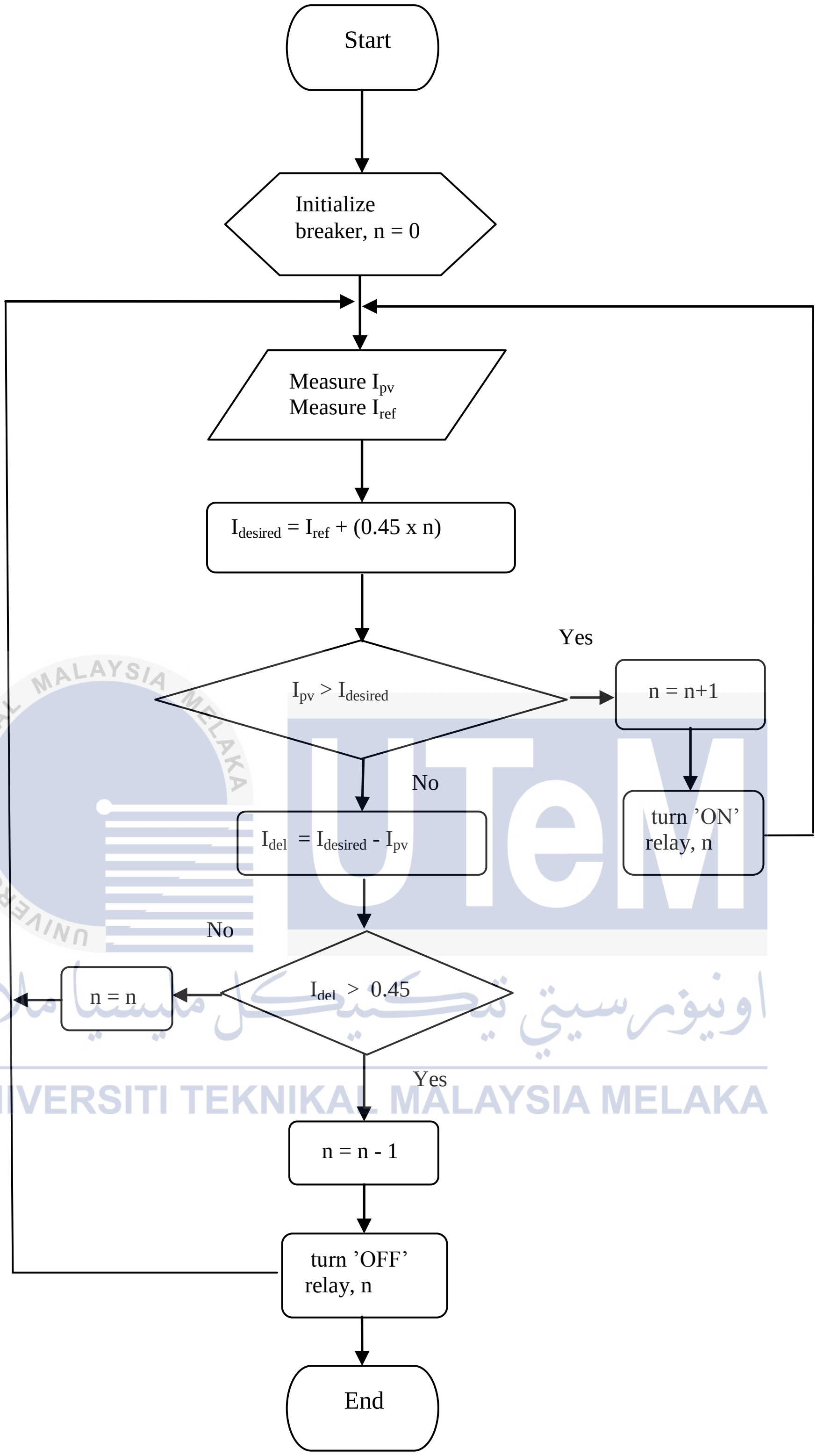

Figure 3.5: Load control algorithm

CHAPTER 4

RESULT AND DISCUSSION

4.1. Grid Connected System

The intentional islanding mode is very important in order to provide power to a load among the microgrid during grid loss. The distributed generation units supposedly have to operate independently without any interruption to provide power to critical load. During grid connected mode, each DG unit must operate with power flow control which is the voltage and frequency from the DG units must synchronize with the main grid. When the power outage of the main grid, the microgrid should be disconnected and each DG units have to switch its control scheme from power flow control to voltage control mode and provide a constant voltage to local load. Appendix E shows the experimental data for grid connected system.

4.1.1. Voltage Stability

By having a PV as a DG units, the generation of electricity is depends on the irradiance from the sunlight. The power produce is proportional with the irradiance. In order to prevent the microgrid from under voltage or over voltage, the load need to be control depends on power produce by PV unit. Figure 4.1 shows the behavior of current and voltage from 9.00 a.m. until 6.00 p.m. The generation is according to the irradiance. As long as the current generate is higher, the voltage also increase.

This system is connected to the constant pure resistive loads which absorb 1000W. By using the main grid as a reference to the grid-tie inverter, the voltage will be stabilized by the main grid. Figure 4.2 shows the relationship between PV current, load voltage and load. When the PV current increase, voltage will increase. The rated current for 1000W pure resistive load is about 4.1A. If PV current is more than 4.1 A, the load voltage will increase. If PV current is less than 4.1 A, the load voltage will decrease.

From the Figure 4.2, the voltage will drop when the current generated by the PV is low. When the current generated by the PV is 2A, the grid voltage dropped until 235V. For current generate by PV is around 4A, the grid voltage was maintained at 240V. The grid voltage increased until 253V when the current supplied by the PV is 7A. The current generated by PV was delivered to the grid when the current generated by PV not required by the load. However, there is a voltage drop between PV voltage and load voltage. This is because of the losses in the isolation transformer.

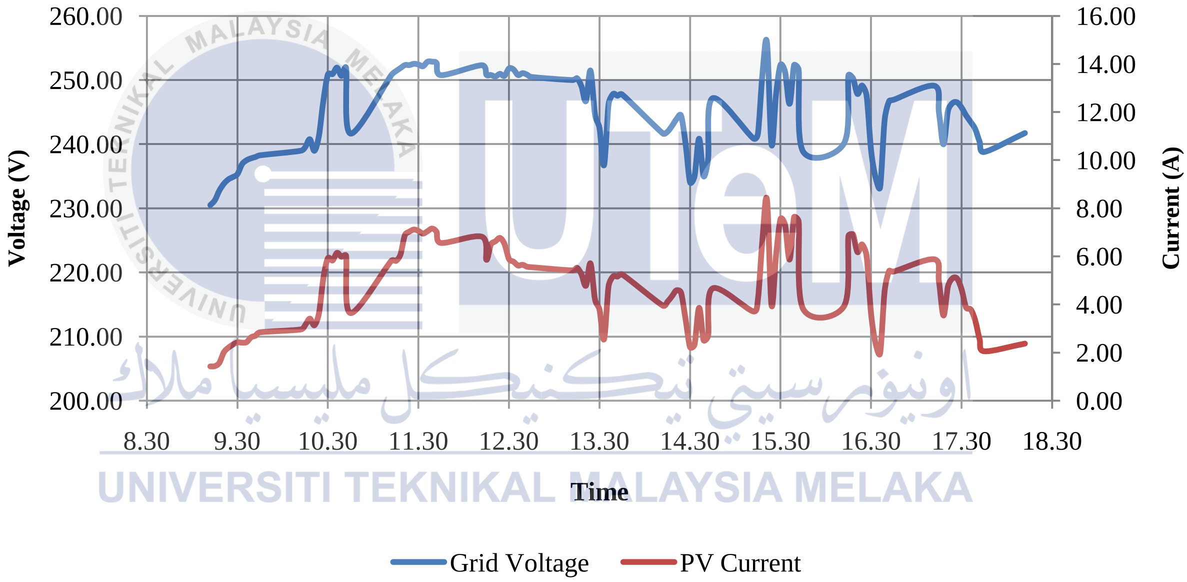

Figure 4.1: Voltage and current measurement

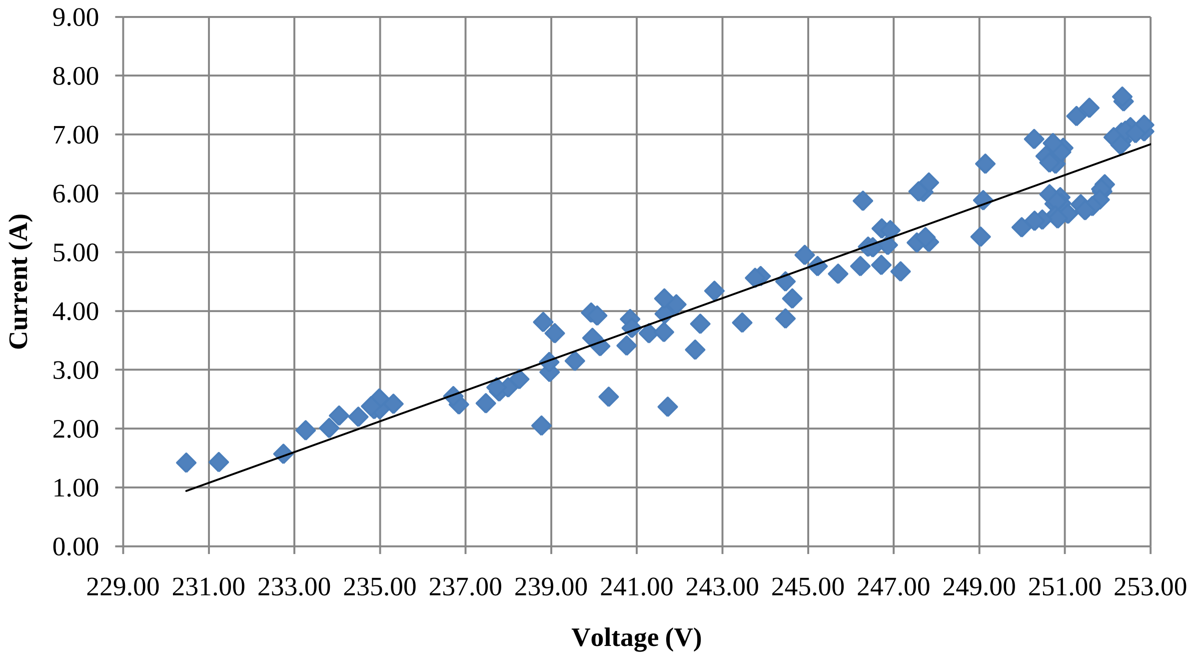

Figure 4.2: Voltage vs current graph

4.1.2. Import and Export Power of Microgrid

Based on the experiment, Figure 4.3 shows the relationship of PV current, reference current and reference voltage. The experiments conduct using a PV generation with grid-tie inverter and 1000 W of pure resistive load. Figure 4.3 shows the diagram of the experiment. The main grid is use as a generator to give a reference in voltage and frequency to the grid-tie inverter. The purpose of this experiment is to prove that if the source current increase, voltages also increase. For 1000 W pure resistive load, it draw a current about 4.1 A.

As the PV current generates more than 4.1 A, the voltage is directly proportional increase. The residual current that generates by PV will be exported to the grid. If PV generates low power, then the load will draw a current from the grid and the grid voltage will decrease. The reference voltage will maintain at 240V when the power generate by the PV is equal to the power consume by the load.

The Figure 4.4 shows the relationship between power produce by PV and load voltage. When the power produce by PV is increase, the voltage will increase. The power is directly proportional to the load voltage. The voltage is increase because of the active power feed-in to the main grid. In condition of constant power load, the power generate by PV will change the voltage. From the Figure 4.4, when the power produce by PV is greater than power consume by the load, the voltage become increase. The power will be delivering to the main grid and this will cause increasing in the main grid voltage. As the power that can be deliver to the main grid increase, the voltage will directly increase and this will cause over voltage to the system.

When the power generate by the PV is less than power consume by the load, the load will deliver their consume power from the main grid. As the power generate by PV decrease, the power deliver from the main grid will increase. The increasing power absorb from the grid will cause decreasing in voltage of the main grid. Therefore, intelligent load management algorithms need to be implemented in a microgrid system to stabilize the load voltage. The load must be control depend on the power generate by PV.

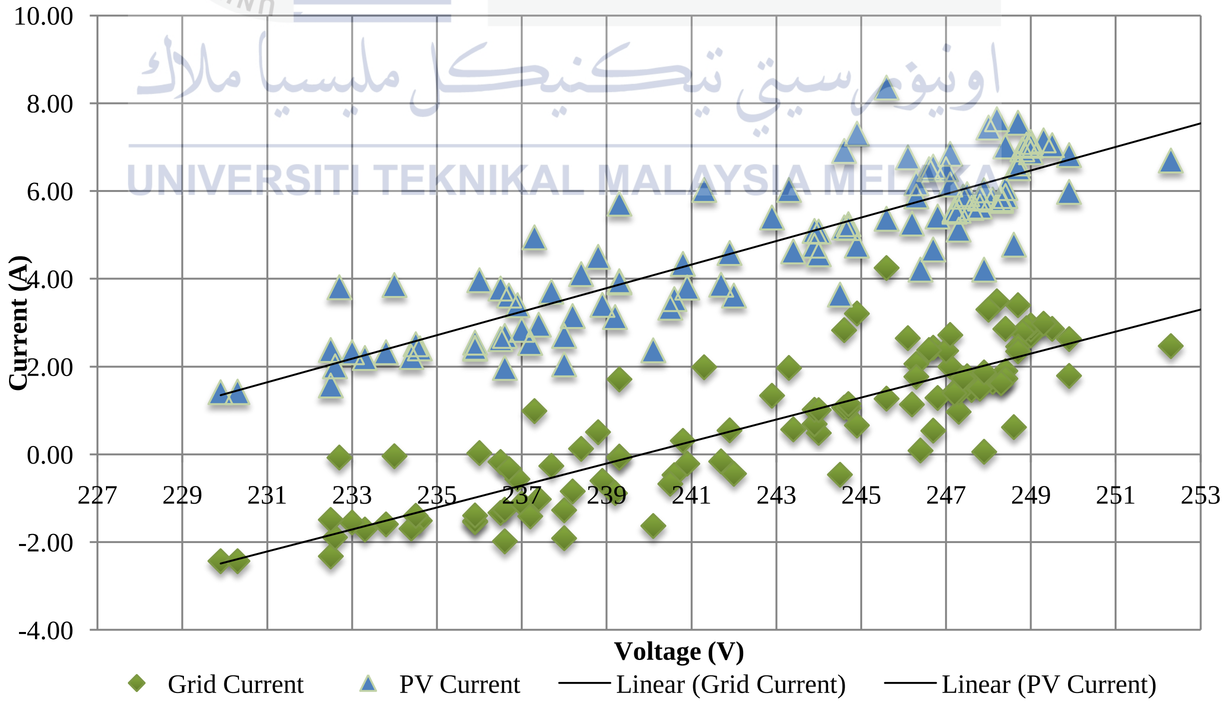

Figure 4.3: Relationship between PV current, reference current and voltage

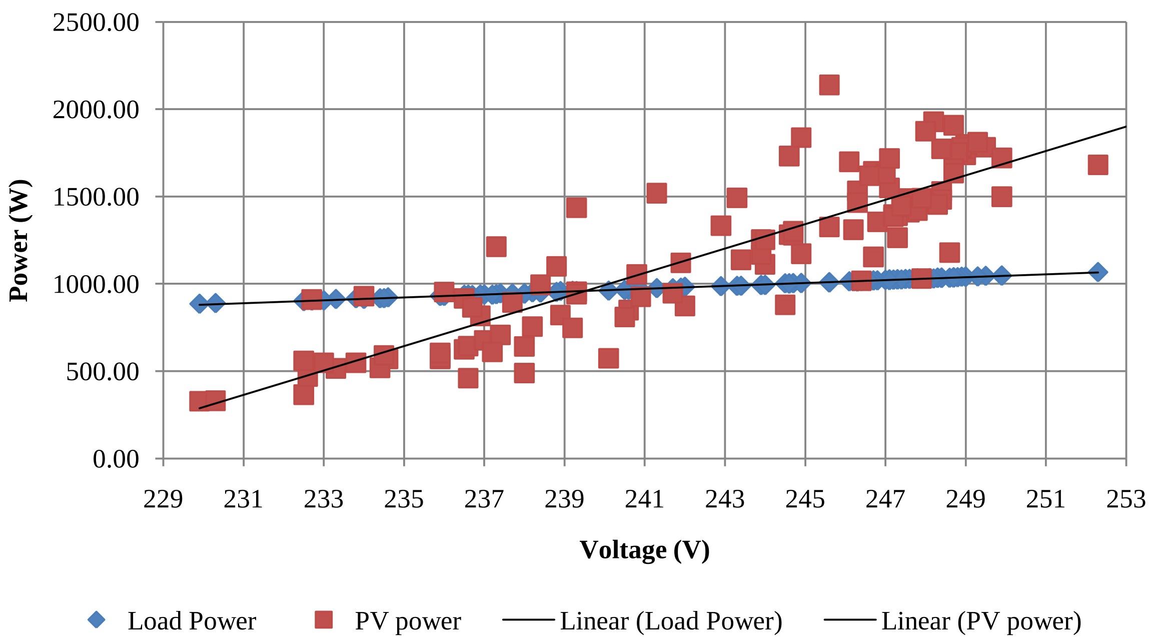

Figure 4.4: Import and export power of microgrid

4.2. Island Mode Operation

One method to be used to protect the PSW inverter is by control the load depend on the power generate by PV. This method gives benefits by using the power that generate by the PV without any wastage of power. During grid connected mode, the power can be export to the grid when the power generate by PV is larger than power consume by the load. In standalone operation, the power generates by PV cannot be export. Appendix F shows the experimental data for island mode operation.

4.2.1. Voltage stability

Figure 4.5 shows the result for PV current, load current and voltage. The graph shows the relationship between PV current, load current and voltage. When the current generated by PV increased, the voltage also increased. However, the microcontroller increased the load due to the designed load control algorithm. The voltage was stabilized by the absorption of power generated by PV to the load. Since the load current is higher than PV current, the load will draw current from the PSW inverter. The draw current from PSW inverter caused the voltage decreased.

In the morning, the power generated by PV is low until 10.30 a.m. There was a changing in voltage magnitude due to the changing power generated by PV. After 10.30 a.m. the power generated by PV was increase and the load also increased. At 10.30 a.m. the voltage magnitude was increased before the load increased. This is because of the current generated by PV is higher than load current. After the microcontroller increased the load, the voltage was stabilized. At 11.20 a.m. the voltage was increased dramatically. This is because of the PV current also increased dramatically before the load increased. By comparing to the load control algorithm that was designed, the load needs to increase. This is because the PV current is higher than load current. After 1.00 p.m. the load increased dramatically because the PV current also increased dramatically. However, the PV current is little much lower than load current that will cause the voltage decreased. The voltage remained lower after 2.00 p.m. because the voltage supplied from battery was decreased. This will cause the output AC voltage from PSW inverter which used to give a reference voltage also decreased.

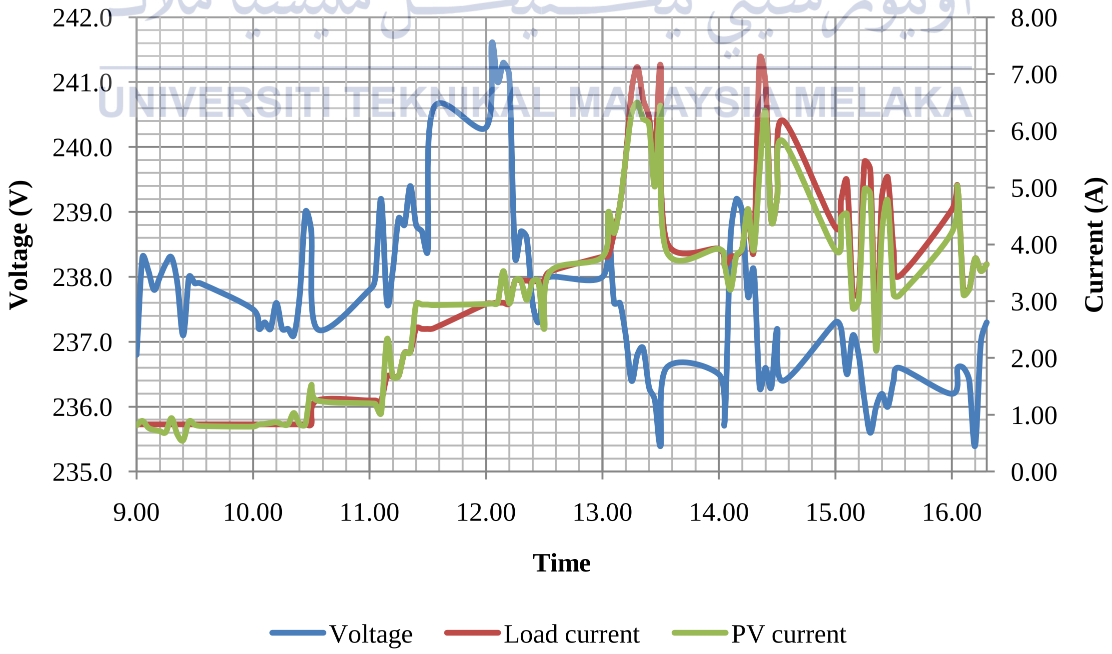

Figure 4.5: PV current, load current and voltage in microgrid island mode operation

Figure 4.6 shows the relationship between voltage and the direction of current. From the graph, the voltage magnitude changed due to the magnitude and direction of current. The positive current magnitude represented the direction of current flow from PSW inverter to the load and grid-tie inverter. In other words, the load absorbed power from the PSW inverter because the power generated by PV is lower than the load demand. The voltage was decreased until 236V because the current draw from the PSW in higher. The larger the current draw from the PSW inverter, the lower the voltage of the microgrid.

The negative current magnitude represented the direction of current flow from the grid-tie inverter to the load and PSW inverter. In other words, the power generated by PV is higher than the power consumed by the load. This will cause a reverse power flow and reverse current to the PSW inverter that can damage the PSW inverter. The voltage was increased due to the increasing in current magnitude. In the designed algorithm, this situation should not occur. The algorithm was designed to protect the PSW inverter from reverse current.

However, there was a problem while using the ACS756 current transducer. The sensitivity of the current transducer is low. The rating for this current transducer is 0 A to 50A for input and the output is 0V to 5V. The resolution is 10A per volt. But, the current used in this system is below than 10A.

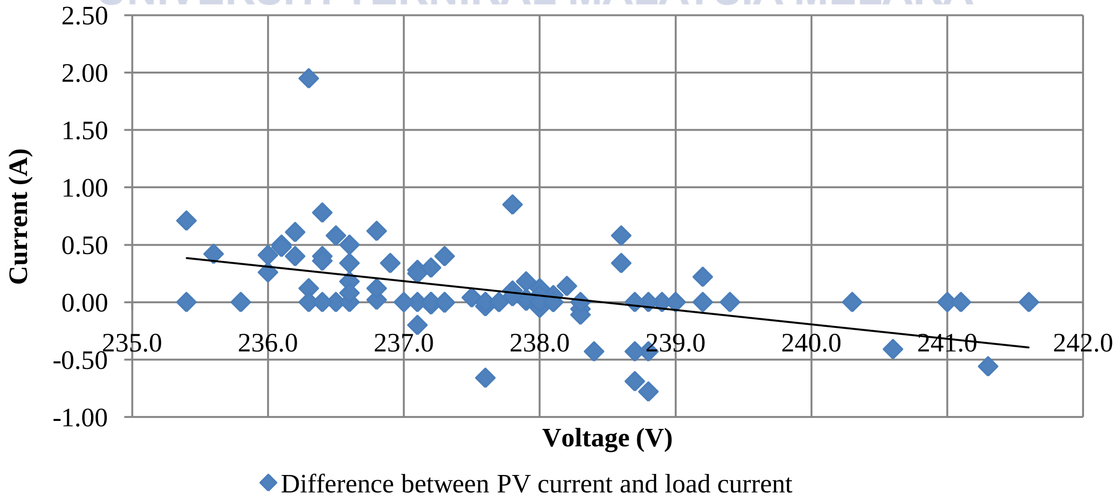

Figure 4.6: Voltage stability due to current flow

4.2.2. Power use in microgrid

By using a generator as a reference to the grid-tie inverter, the generator can be control to stabilize their voltage and frequency. But, for PSW inverter, the AC voltage is depends on the input voltage. The output voltage of PSW inverter cannot be regulating. To solve this problem, a load management algorithm has been proposed. The algorithm is depends on the current generate by PV and PSW inverter. The load will be control due to the current from PV. As the current generate is high, the load also increase.

For the algorithm that proposed in this project, the load will be control based on the current generate by PV and the current from PSW inverter. In this algorithm, the current generate by PV is labeled as I_{pv} and for current from PSW inverter is labeled as I_{ref}. Basically, this proposed algorithm was design to manage the load and also as a protection to the PSW inverter from reverse current.

The algorithm was design to increase the load when I_{pv} is greater than I_{ref} and will decrease the load when I_{pv} is less than I_{ref} . However, the loads will always change because when the I_{pv} greater than I_{ref}, the load will be turn ON. As a load is turn ON, it will absorb power and necessarily the load needs to draw current. If the current generate by PV is lower, the load will draw current from PSW inverter and this will cause increasing current in I_{ref}. As I_{ref} is greater than I_{pv}, the load will turn OFF. This process is done repeatedly and causes the unstable in switching thus effect the voltage stability.

To prevent the unstable load switching, the algorithm need to change. If I_{pv} is greater than I_{ref}, one load will turn ON. Initially, I_{pv} was design to be larger than I_{ref}. Therefore, one load will be turned ON in the initial condition. This is because to reduce and prevent the reverse current to the PSW inverter. When I_{pv} is less than I_{ref}, this algorithm will measure the difference between I_{pv} and I_{ref}. The difference between I_{pv} and I_{ref} is called as I_{del}. The load will decrease when I_{del} is greater then the pre determine current value for one load. The pre determine current value is depending on the current that absorb by one load. In the experiment that was conduct, the 100W tungsten lamp was use for one load. The current draw from the 100W tungsten lamp is 0.45A. Therefore, the predetermine value is set as 0.45A. If I_{del} is greater than 0.45A, the load will turn OFF.

Figure 4.7 shows the result for the load control algorithm. When the power generate by PV increased, the load also will increased. The result shows the load is low in the morning from 9.00 a.m. until 10.30 a.m. because at that time it was raining. After 10.45 a.m. the raining has stopped and the power generated by PV started to increased. The load also increased due to the power generated by PV increased. At 1.00 p.m. the increased dramatically because the PV panel was captured high irradiance from sunlight. The PV generated power more than 1600 Watts and the microcontroller was turned ON 17 relays which means 1700 Watts of tungsten bulb was turned ON. At 1.40 p.m. the PV generation decreased because the irradiance captured by PV panel is lower and the load also decreased. The PV generation started increased after 2.20 p.m. and the load also increased. In the evening, the irradiance captured by PV panel was decreased and the PV generation also decreased. As the power generated by PV decreased, the load also decreased.

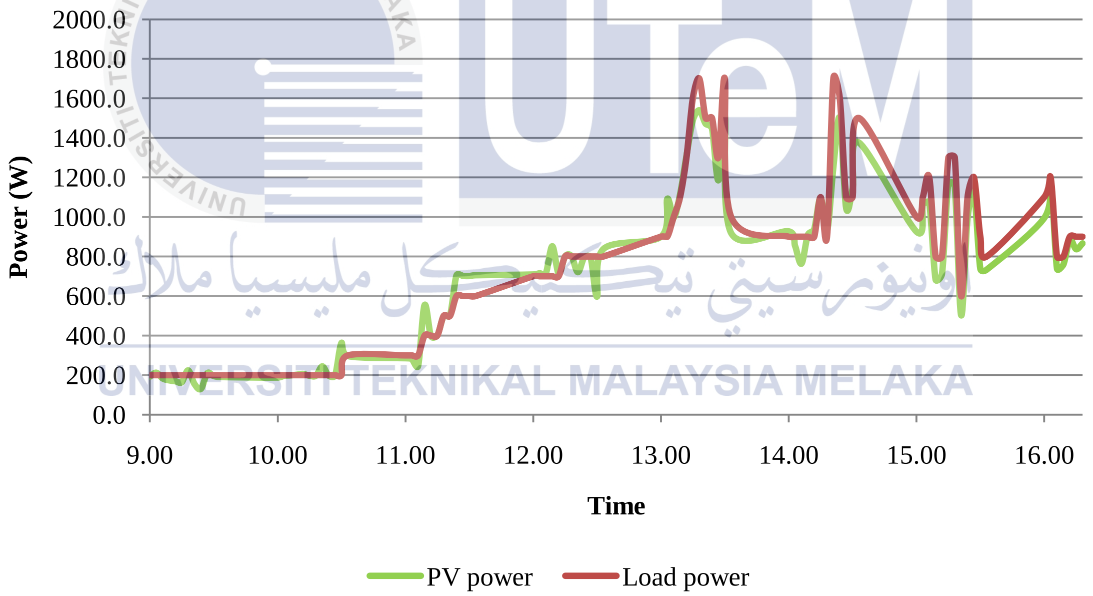

Figure 4.7: PV power and load power

CHAPTER 5

CONCLUSION & RECOMMENDATION

The use of renewable energy will reduce the effect of using conventional generator. This will reduce the fuel consumption to generate electricity and then can reduce the gas emission and greenhouse effects. As the fuel consumption increase, the fuel production will decrease because the fuel is a limited source. Based on the project objective, the implementation of the project of PV Restoration Incorporating Demand Response for PV connected microgrid will increase the reliability of the microgrid system. This protection scheme is supposed to provide a power to customer during interruption of the main grid. The restoration method that use in this project will increase the performance of the microgrid in the future. The combination of PSW inverter and grid-tie inverter will make the microgrid operate independently although during interruption of the main grid. The uses of PSW inverter provide a constant voltage to the microgrid system and the grid-tie inverter provide a power to the critical loads. The purpose by using the demand response will optimize the uses of energy that generate by distributed generation system. In other words, the load demand will follow the generation. The load control by using microcontroller gives advantages to the performance and stability of microgrid. The voltage in the microgrid during island mode can be regulated using the demand response depend on the power generated by PV. Besides that, the purpose of demand response indirectly provide as a protection to the PSW inverter. The load control algorithm will protect the PSW inverter from reverse current that can damage the PSW inverter.

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APPENDIX A

13 Technical data

13.1 Sunny Boy 2000HF

DC Input

Maximum DC power at cos φ = 1	2 100 W
Maximum input voltage*	700 V
MPP voltage range	175 V ... 560 V
Rated input voltage	530 V
Minimum input voltage	175 V
Start input voltage	220 V
Maximum input current	12.0 A
Maximum input current per string	12.0 A
Number of independent MPP inputs	1
Strings per MPP input	2

* The maximum open circuit voltage, which can occur at a cell temperature of − 10 °C, must not exceed the maximum input voltage.

AC Output

Rated output power at 230 V, 50 Hz	2 000 W
Maximum AC apparent power	2 000 VA
Rated grid voltage	230 V
AC nominal voltage	220 V/230 V/240 V
AC voltage range*	180 V ... 280 V
Nominal AC current at 220 V	9.1 A
Nominal AC current at 230 V	8.7 A
Nominal AC current at 240 V	8.3 A
Maximum output current	11.4 A
Total harmonic distortion of output current at AC THD voltage < 2 % AC power > 0.5 nominal AC power	≤ 3 %
Rated grid frequency	50 Hz
AC grid frequency*	50 Hz/60 Hz
Operating range at AC grid frequency 50 Hz	45.5 Hz ... 54.5 Hz
Operating range at AC grid frequency 60 Hz	55.5 Hz ... 64.5 Hz
Power factor at rated power	1
Feed phases	1
Connection phases	1

APPENDIX B

	MODEL/ITEM	SRINVT PSW200	SRINVT PSW300	SRINVT PSW600	SRINVT PSW1000	SRINVT PSW1500	SRINVT PSW2000	SRINVT PSW3000	SRINVT PSW5000	SRINVT PSW8000
Inverter	Output Power(Continuous Watts)	200	300	600	1000	1500	2000	3000	5000	8000
	Output Power(Peak Watts)	360	600	1200	2000	3000	4000	6000	10000	16000
	Nominal Input Voltage(DC)	12(11-15V)/24V(21-30V)/48V(42-60V)								
	Nominal Ouput Voltage(AC)	115V AC/230V AC, (Regulation:5%~10%)								
	Frequency	50Hz								
	Output Waveform	Pure Sine Wave (THD<3%)								
	Low Battery Alarm(V)	10.4-11VDC/20.8-22VDC /41.6-44VDC								41.6-42VDC
	Low Battery Shutdown(V)	9.9-10.5VDC/19.8-21VDC/39.6-42VDC								39.6-42VDC
	High Voltage Shutdown(V)	15-16VDC/30-32VDC/60-64DVC							60-64VDC	
	Efficiency	85-90%								
	Thermal Protection	-30℃ - 70℃								
	Overload	Shutdown & Red LED light								
	Battery Polarity Reverse	By Fuse								
	Output Short	Output Short Circuit Protection								
	With Cooling Fan	Yes, Auto-operation fan (temperature or load)								
	AC Output	1AC Outlet	U.S.A. Type:2AC Outlets European Type:1AC Outlet				U.S.A. Type:4 AC Outlets European Type:2 AC Outlet, AC hardwire terminal block			
	Product Dimension(LXWXH)cm	15.5x8x5.8	16x15x5.3	26.5x15x7	29.5x15x7.2	37.5x15x8.8	41.5x21x10.3	48.5x21x12.7	56.5x21x16	61x26.5x18
	Weight(KGS)	0.5	1.1	2.16	2.68	4.5	6.36	9.12	14	21.5

APPENDIX C

Fully Integrated, Hall Effect-Based Linear Current Sensor IC with 3 kVRMS Voltage Isolation and a Low-Resistance Current Conductor

Features and Benefits

- Industry-leading noise performance through proprietary amplifier and filter design techniques
- Total output error 0.8% at $T_A = 25°C$
- Small package size, with easy mounting capability
- Monolithic Hall IC for high reliability
- Ultra-low power loss: 130 µΩ internal conductor resistance
- 3 kV_{RMS} minimum isolation voltage from pins 1-3 to pins 4-5
- 3.0 to 5.0 V, single supply operation
- 3 µs output rise time in response to step input current
- 20 or 40 mV/A output sensitivity
- Output voltage proportional to AC or DC currents
- Factory-trimmed for accuracy
- Extremely stable output offset voltage
- Nearly zero magnetic hysteresis

TÜV America
Certificate Number:
U8V 09 05 54214 021

Package: 5 pin package (suffix PFF)

Additional leadforms available for qualifying volumes

Description

The Allegro ACS756 family of current sensor ICs provides economical and precise solutions for AC or DC current sensing in industrial, automotive, commercial, and communications systems. The device package allows for easy implementation by the customer. Typical applications include motor control, load detection and management, power supplies, and overcurrent fault protection.

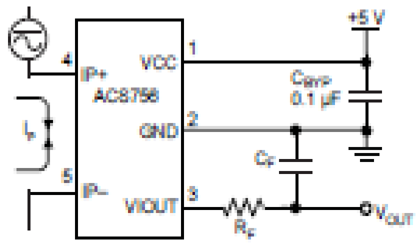
The device consists of a precision, low-offset linear Hall circuit with a copper conduction path located near the die. Applied current flowing through this copper conduction path generates a magnetic field which the Hall IC converts into a proportional voltage. Device accuracy is optimized through the close proximity of the magnetic signal to the Hall transducer. A precise, proportional voltage is provided by the low-offset, chopper-stabilized BiCMOS Hall IC, which is programmed for accuracy at the factory.

The output of the device has a positive slope ($>V_{CC}/2$) when an increasing current flows through the primary copper conduction path (from terminal 4 to terminal 5), which is the path used for current sampling. The internal resistance of this conductive path is 130 µΩ typical, providing low power loss.

The thickness of the copper conductor allows survival of the device at up to 5× overcurrent conditions. The terminals of the

Continued on the next page...

Typical Application



Application 1. The ACS756 outputs an analog signal, V_{OUT}, that varies linearly with the uni- or bi-directional AC or DC primary sampled current, I_P, within the range specified. C_F is for optimal noise management, with values that depend on the application.

APPENDIX D

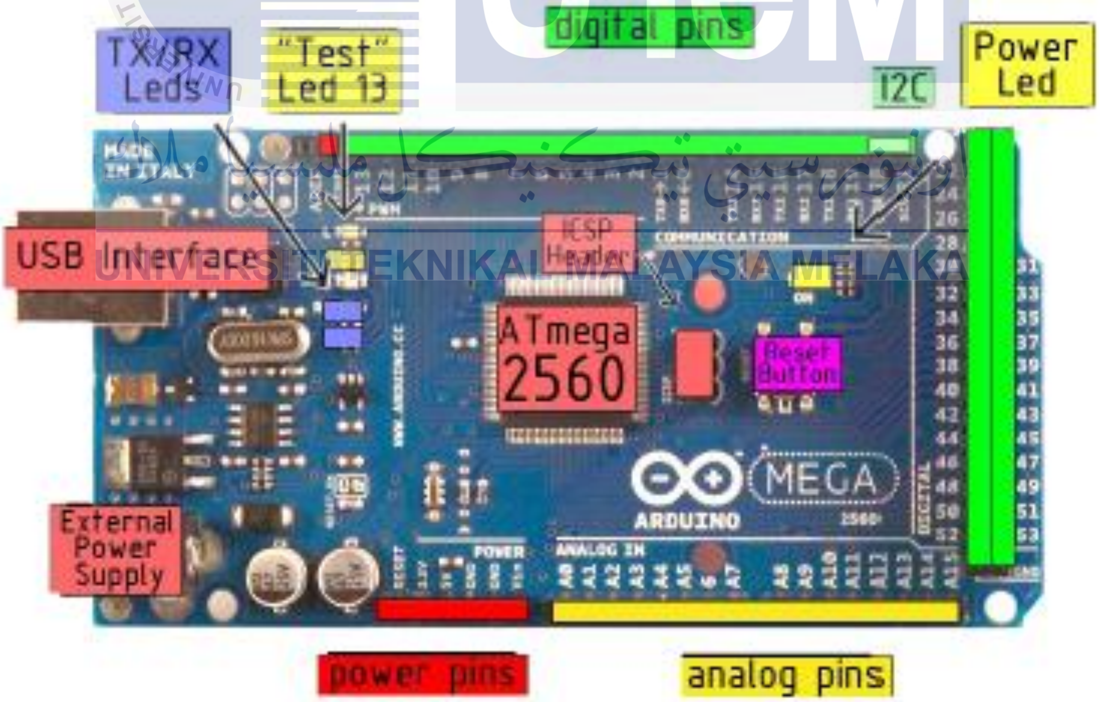
Technical Specification

EAGLE files: arduino-mega2560-reference-design.zip Schematic: arduino-mega2560-schematic.pdf

Summary

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 14 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

the board



RS radiospares RADIONICS

APPENDIX E

Time	Voltage	Current (A)			Power (W)	
		Load current	Grid Current	PV Current	PV power	Load Power
9.00	229.9	3.85	-2.43	1.42	327.27	885.12
9.05	230.3	3.86	-2.43	1.43	330.66	888.96
9.10	232.5	3.89	-2.32	1.57	365.40	904.43
9.15	232.6	3.90	-1.89	2.01	469.96	907.14
9.20	233.3	3.91	-1.71	2.20	515.88	912.20
9.25	233.8	3.92	-1.59	2.33	547.22	916.50
9.30	234.6	3.93	-1.51	2.42	569.45	921.98
9.35	235.9	3.95	-1.54	2.41	570.78	931.81
9.40	235.9	3.95	-1.52	2.43	577.05	931.81
9.45	236.5	3.96	-1.33	2.63	625.36	936.54
9.50	236.6	3.96	-1.26	2.70	642.57	936.94
9.55	237.0	3.96	-1.12	2.84	676.63	938.52
10.00	237.4	3.98	-1.02	2.96	707.32	944.85
10.05	238.2	3.99	-0.84	3.15	754.58	950.42
10.10	238.9	4.01	-0.60	3.41	820.99	957.99
10.15	239.2	4.01	-0.88	3.13	747.91	959.19
10.20	242.0	4.06	-0.44	3.62	873.43	982.52
10.25	247.3	4.15	0.97	5.12	1263.92	1026.30
10.30	247.5	4.15	1.78	5.93	1487.78	1027.13
10.35	247.8	4.16	1.67	5.83	1462.81	1030.85
10.40	247.1	4.15	2.00	6.15	1549.37	1025.47
10.45	249.9	4.19	1.79	5.98	1498.83	1047.08
10.50	241.3	4.04	1.99	6.03	1518.78	974.85
10.55	244.5	4.10	-0.46	3.64	879.53	1002.45
11.00	248.3	4.17	1.65	5.82	1459.42	1035.41
11.05	248.1	4.16	1.65	5.81	1460.46	1032.10
11.10	248.4	4.17	1.90	6.07	1528.73	1035.83
11.15	249.0	4.18	2.71	6.89	1738.55	1040.82
11.20	249.0	4.18	2.85	7.03	1773.81	1040.82
11.25	249.0	4.18	2.94	7.12	1798.01	1040.82
11.30	248.9	4.18	2.88	7.06	1782.01	1040.40
11.35	248.8	4.17	2.78	6.95	1752.37	1037.50
11.40	249.5	4.19	2.86	7.05	1782.59	1045.41
11.45	249.3	4.18	2.98	7.16	1810.41	1042.07
11.50	248.4	4.16	2.86	7.02	1773.60	1033.34
11.55	246.7	4.13	2.43	6.56	1644.92	1018.87
12.00	249.9	4.19	2.63	6.82	1720.69	1047.08
12.05	247.8	4.15	1.71	5.86	1469.75	1028.37

12.10	247.0	4.14	2.36	6.50	1630.07	1022.58
12.15	248.7	4.17	2.46	6.63	1661.15	1037.08
12.20	246.1	4.12	2.65	6.77	1699.00	1013.93
12.25	248.7	4.17	2.35	6.52	1634.17	1037.08
12.30	248.4	4.16	1.73	5.89	1483.16	1033.34
12.35	248.3	4.16	1.62	5.78	1454.48	1032.93
12.40	247.6	4.15	1.47	5.62	1409.33	1027.54
12.45	247.8	4.15	1.50	5.65	1418.55	1028.37
12.50	247.2	4.14	1.43	5.57	1397.12	1023.41
12.55	247.3	4.14	1.41	5.55	1390.11	1023.82
13.00	246.8	4.13	1.29	5.42	1354.95	1019.28
13.05	247.2	4.14	1.39	5.53	1384.10	1023.41
13.10	246.2	4.12	1.14	5.26	1309.90	1014.34
13.15	248.6	4.16	0.62	4.78	1179.27	1034.18
13.20	239.3	4.00	1.71	5.71	1435.89	957.20
13.25	247.9	4.15	0.06	4.21	1029.89	1028.79
13.30	236.5	3.95	-0.17	3.78	916.57	934.18
13.35	235.9	3.94	-1.39	2.55	603.61	929.45
13.40	244.9	4.10	0.66	4.76	1172.01	1004.09
13.45	244.6	4.10	1.07	5.17	1281.23	1002.86
13.50	244.7	4.10	1.06	5.16	1277.31	1003.27
13.55	244.7	4.10	1.15	5.25	1300.64	1003.27
14.00	239.3	4.00	-0.05	3.95	954.52	957.20
14.05	238.4	3.98	0.13	4.11	994.29	948.83
14.10	240.8	4.03	0.31	4.34	1053.80	970.42
14.15	241.9	4.04	0.55	4.59	1119.46	977.28
14.20	238.8	3.99	0.51	4.50	1100.12	952.81
14.25	236.9	3.96	-0.56	3.40	816.48	938.12
14.30	234.4	3.91	-1.69	2.22	519.57	916.50
14.35	233.0	3.88	-1.55	2.33	547.53	904.04
14.40	234.0	3.90	-0.04	3.86	929.64	912.60
14.45	234.5	3.91	-1.40	2.51	589.80	916.90
14.50	238.0	3.97	-1.27	2.70	641.84	944.86
14.55	246.7	4.13	0.54	4.67	1154.24	1018.87
15.00	237.7	3.97	-0.26	3.71	893.66	943.67
15.05	246.4	4.12	0.09	4.21	1017.30	1015.17
15.10	252.3	4.23	2.47	6.70	1681.10	1067.23
15.15	245.6	4.11	4.25	8.36	2138.99	1009.42
15.20	236.0	3.94	0.03	3.97	952.52	929.84
15.25	247.9	4.15	1.87	6.02	1491.09	1028.79
15.30	248.7	4.16	3.40	7.56	1907.92	1034.59
15.35	244.9	4.10	3.21	7.31	1836.78	1004.09
15.40	247.4	4.14	1.73	5.87	1445.66	1024.24
15.45	248.2	4.15	3.49	7.64	1927.88	1030.03

15.50	248.0	4.15	3.30	7.45	1874.20	1029.20
15.55	232.7	3.88	-0.07	3.81	909.87	902.88
16.00	239.3	4.00	-0.08	3.92	941.07	957.20
16.05	247.1	4.13	2.72	6.85	1717.43	1020.52
16.10	244.6	4.09	2.83	6.92	1731.94	1000.41
16.15	246.3	4.12	2.06	6.18	1531.53	1014.76
16.20	246.6	4.12	2.38	6.50	1619.41	1015.99
16.25	243.3	4.06	1.97	6.03	1492.91	987.80
16.30	236.7	3.95	-0.33	3.62	865.47	934.97
16.35	232.5	3.87	-1.49	2.38	558.80	899.78
16.40	236.6	3.95	-1.98	1.97	459.52	934.57
16.45	244.0	4.07	0.49	4.56	1111.55	993.08
16.50	242.9	4.06	1.34	5.40	1332.29	986.17
16.55	245.6	4.10	1.27	5.37	1325.96	1006.96
17.00	246.3	4.11	1.77	5.88	1464.65	1012.29
17.05	237.3	3.96	0.99	4.95	1212.35	939.71
17.10	240.6	4.01	-0.47	3.54	849.46	964.81
17.15	243.9	4.07	0.69	4.76	1167.25	992.67
17.20	243.9	4.07	1.02	5.09	1254.18	992.67
17.25	244.0	4.07	1.01	5.08	1252.27	993.08
17.30	243.4	4.06	0.57	4.63	1137.59	988.20
17.35	241.7	4.03	-0.16	3.87	946.10	974.05
17.40	240.9	4.01	-0.21	3.80	925.15	966.01
17.45	240.5	4.01	-0.67	3.34	809.48	964.41
17.50	237.2	3.95	-1.41	2.54	610.46	936.94
17.55	238.0	3.96	-1.91	2.05	489.48	942.48
18.00	240.1	4.00	-1.63	2.37	572.88	960.40

APPENDIX F

Time	Voltage	Current (A)		Power (W)	
		Load current	PV current	Load power	PV power
9.00	236.8	0.83	0.81	196.5	191.8
9.05	238.3	0.83	0.89	197.8	212.1
9.10	238.1	0.83	0.77	197.6	183.3
9.15	237.8	0.83	0.73	197.4	173.6
9.20	238.0	0.83	0.71	197.5	169.0
9.25	238.2	0.83	0.69	197.7	164.4
9.30	238.3	0.83	0.94	197.8	224.0
9.35	237.9	0.83	0.65	197.5	154.6
9.40	237.1	0.83	0.55	196.8	130.4
9.45	238.0	0.83	0.88	197.5	209.4
9.50	237.9	0.83	0.82	197.5	195.1
9.55	237.9	0.83	0.80	197.5	190.3
10.00	237.5	0.83	0.79	197.1	187.6
10.05	237.2	0.83	0.83	196.9	196.9
10.10	237.3	0.83	0.84	197.0	198.5
10.15	237.2	0.83	0.85	196.9	202.0
10.20	237.6	0.83	0.87	197.2	205.9
10.25	237.2	0.83	0.83	196.9	196.9
10.30	237.2	0.83	0.83	196.9	196.9
10.35	237.1	0.83	1.03	196.8	244.2
10.40	237.7	0.83	0.83	197.3	197.3
10.45	239.0	0.83	0.83	198.4	198.4
10.50	238.7	0.83	1.52	198.1	362.8
10.55	237.2	1.25	1.25	296.5	296.5
11.00	237.8	1.25	1.20	297.3	285.4
11.05	238.0	1.25	1.19	297.5	283.2
11.10	239.2	1.25	1.03	299.0	246.4
11.15	237.6	1.67	2.33	396.8	553.6
11.20	238.1	1.67	1.67	397.6	397.6
11.25	238.9	1.68	1.68	401.4	401.4
11.30	238.8	2.09	2.09	499.1	499.1
11.35	239.4	2.10	2.10	502.7	502.7
11.40	238.8	2.52	2.95	601.8	704.5
11.45	238.7	2.51	2.94	599.1	701.8
11.50	238.4	2.51	2.94	598.4	700.9
11.55	240.6	2.52	2.93	606.3	705.0
12.00	240.3	2.95	2.95	708.9	708.9
12.05	241.6	2.96	2.96	715.1	715.1

12.10	241.0	2.97	2.97	715.8	715.8
12.15	241.3	2.97	3.53	716.7	851.8
12.20	241.1	2.96	2.96	713.7	713.7
12.25	238.3	3.36	3.36	800.7	800.7
12.30	238.7	3.36	3.36	802.0	802.0
12.35	238.6	3.36	3.02	801.7	720.6
12.40	237.6	3.35	3.35	796.0	796.0
12.45	237.3	3.35	3.35	795.0	795.0
12.50	237.8	3.36	2.51	799.0	596.9
12.55	238.0	3.52	3.52	837.8	837.8
13.00	238.0	3.78	3.78	899.6	899.6
13.05	238.8	3.79	4.57	905.1	1091.3
13.10	237.6	4.20	4.20	997.9	997.9
13.15	237.6	4.69	4.69	1114.3	1114.3
13.20	237.1	5.52	5.52	1308.8	1308.8
13.25	236.4	6.70	6.30	1583.9	1489.3
13.30	236.8	7.12	6.50	1686.0	1539.2
13.35	236.9	6.55	6.21	1551.7	1471.1
13.40	236.3	6.24	6.12	1474.5	1446.2
13.45	236.1	5.52	5.02	1303.3	1185.2
13.50	235.4	7.14	6.43	1680.8	1513.6
13.55	236.6	4.06	3.88	960.6	918.0
14.00	236.5	3.92	3.92	927.1	927.1
14.05	235.8	3.62	3.62	853.6	853.6
14.10	238.6	3.78	3.20	901.9	763.5
14.15	239.2	3.80	3.80	909.0	909.0
14.20	239.0	3.93	3.93	939.3	939.3
14.25	237.7	4.62	4.62	1098.2	1098.2
14.30	238.1	3.90	3.90	928.6	928.6
14.35	236.3	7.25	5.30	1713.2	1252.4
14.40	236.6	6.84	6.34	1618.3	1500.0
14.45	236.3	4.42	4.42	1044.4	1044.4
14.50	237.2	4.82	4.82	1143.3	1143.3
14.55	236.4	6.18	5.82	1461.0	1375.8
15.00	237.3	4.30	3.90	1020.4	925.5
15.05	237.2	4.78	4.48	1133.8	1062.7
15.10	236.5	5.11	4.53	1208.5	1071.3
15.15	237.1	3.13	2.88	742.1	682.8
15.20	236.8	3.13	3.01	741.2	712.8
15.25	236.1	5.45	4.97	1286.7	1173.4
15.30	235.6	5.31	4.89	1251.0	1152.1
15.35	236.0	2.39	2.13	564.0	502.7
15.40	236.2	4.83	4.22	1140.8	996.8
15.45	236.0	5.18	4.77	1222.5	1125.7

15.50	236.4	3.90	3.12	922.0	737.6
15.55	236.6	3.44	3.10	813.9	733.5
16.00	236.2	4.61	4.21	1088.9	994.4
16.05	236.6	5.01	5.01	1185.4	1185.4
16.10	236.6	3.20	3.12	757.1	738.2
16.15	236.4	3.21	3.21	758.8	758.8
16.20	235.4	3.75	3.75	882.8	882.8
16.25	237.0	3.53	3.53	836.6	836.6
16.30	237.3	3.65	3.65	866.1	866.1