

STUDY OF SOLUTION TOWARDS GROUND LEAKAGE CURRENT
VIA INVERTER SWITCHING IN DIFFERENT TOPOLOGIES
FOR GRID CONNECTED PV SYSTEM

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ABSTRACT

Renewable energy sources are major issues in order to address the energy problem. Among them, the PV (Photovoltaic) system will be dominant because its availability and reliability. One of the common problems that arise due to the formation of solar PV panels is capacitive ground current. Although transformer helps in reducing this problem, the poor side of having the transformer in PV systems is accounted to bulky in size and hard to install the entire PV system. Indirectly, the cost is higher and led to a lower efficiency due to higher losses of power. To solve this, transformerless inverter topology offers a solution for the efficiency, size and weight. The leakage current depends on both inverter topology and control strategy. In this report, different inverter topologies have been reviewed with respect to ground current formation due to inverter switching that causes varying common mode voltage that will excite the resonant circuit as well as causes the leakage current phenomenon. The transformerless inverter topologies that are considered are Bipolar H-Bridge, Modified HB-ZVR and NPC. In order to study the effect of having a transformer in eliminating the ground current, Bipolar H-Bridge inverter with transformer also include in this project. All proposed topologies are modelled and simulated to compare the pattern and behavior of ground leakage current with other existing topology. By comparing the pattern of the output from the simulation, a conclusion is given which proves that NPC topology are suitable for PV application due to low leakage current compared with other two topologies.

ABSTRAK

Sumber tenaga boleh diperbaharui adalah isu-isu utama dalam usaha untuk menangani masalah tenaga. Antaranya, sistem PV (photovoltaic) yang akan menjadi dominan kerana ketersediaan dan kebolehpercayaan. Salah satu masalah biasa yang timbul akibat pembentukan panel solar PV arus kapasitan bumi. Walaupun pengubah membantu dalam mengurangkan masalah ini, keburukan mempunyai pengubah dalam sistem PV menyumbang kepada saiz yang besar dan sukar untuk memasang keseluruhan sistem PV. Secara tidak langsung, kos adalah lebih tinggi dan membawa kepada kecekapan yang lebih rendah disebabkan oleh kerugian kuasa yang lebih tinggi. Untuk menyelesaikan ini, topologi penyongsang tanpa pengubah menawarkan penyelesaian untuk kecekapan, saiz dan berat. Kebocoran arus bergantung kepada kedua-dua topologi penyongsang dan strategi kawalan. Dalam laporan ini, topologi penyongsang yang berbeza telah dikaji berkenaan dengan pembentukan arus bumi kerana pensuisan penyongsang yang menyebabkan pelbagai voltan mod biasa yang akan merangsang litar salunan serta menyebabkan fenomena kebocoran arus. Topologi penyongsang tanpa pengubah yang dipertimbangkan adalah Dwikutub 'H-Bridge', 'Modified HB-ZVR' dan 'NPC'. Dalam usaha untuk mengkaji kesan mempunyai pengubah dalam menghapuskan arus bumi, penyongsang Dwikutub "H-Bridge" dengan pengubah juga termasuk dalam projek ini. Semua cadangan topologi adalah model dan simulasi untuk membandingkan corak dan tingkah laku kebocoran arus bumi dengan topologi lain yang sedia ada. Dengan membandingkan corak keluaran dari simulasi, kesimpulan yang diberi membuktikan bahawa NPC topologi adalah sesuai untuk aplikasi PV kerana kebocoran arus rendah berbanding dengan lain-lain dua topologi

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LIST OF SYMBOLS AND ABBREVIATIONS

ϵ_0	-	Permittivity, Physical Constant : $8.85 \times 10^{-12} \text{ As/Vm}$
ϵ_r	-	Permittivity Number
I_D	-	Diode current (A)
I_{SC}	-	Short circuit current (A)
K	-	Boltzman constant, $1.38 \times 10^{-23} \text{ J/(K mol)}$
q	-	Elementary charge, $1.602 \times 10^{-19} \text{ (C)}$
R_S	-	Series resistance (Ω)
R_{SH}	-	Shunt resistance (Ω)
T	-	Absolute temperature (K)
V_{dc}	-	DC voltage (V)
V_g	-	Grid Voltage (V)
C_p	-	Parasitic capacitance
I_{max}	-	Maximum current
V_{max}	-	Maximum voltage
V_{cm}	-	Common mode voltage
I_{cm}	-	Common mode current
f_{sw}	-	Switching frequency
AC	-	Alternating current
DC	-	Direct current
CSI	-	Current source inverter
VSI	-	Voltage source inverter
MPP	-	Maximum power point
NPC	-	Neutral point clamped
PWM	-	Pulse width modulation
HB-ZVR	-	Half bridge-zero voltage rectifier
UniTL	-	Unipolar Transformerless

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CHAPTER 1

INTRODUCTION

This chapter presents the introduction of the thesis including with a short overview of grid-connected PV systems. Furthermore, it details the aims of the project, continuing with the objective as well as the scope of the project and finishing with the outline of the thesis.

1.1 Introduction

Protecting the energy and environment becomes a major problem for humans due to the worsening the world energy shortage and environmental pollution problems. Therefore, solar, wind, fuel cells, tides, and geothermal heat, and etc. are getting more interactive in development and the use of clean renewable energy. Renewable energy sources are major issues in order to deal with energy problems. Solar energy will be dominant among them because of its availability and reliability [1].

Photovoltaic (PV) power generation has become one of the main ways to use solar energy. Inverter is the medium in which the renewable energy is typically interfaced to the grid based on distributed generation systems (DG) as shown in Figure 1.1. Thus developing a photovoltaic grid connected inverter system is important for the mitigation of energy and environmental issues.

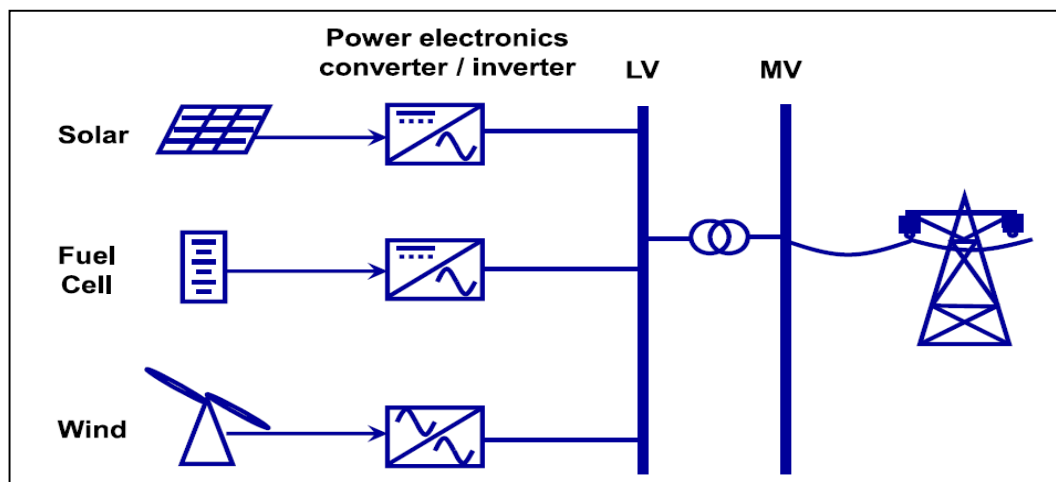


Figure 1.1: Renewable energy based distributed generation system [1]

Quite often, commercially used inverters include a transformer to ensure galvanic isolation for safety reason. Transformer used in PV systems is large in size depending on rated power and complicate to assemble the whole PV system. Furthermore, the cost is higher and led to a lower efficiency due to higher loss of power [2]. Therefore, more improved efficiency, smaller size and weight as well as more reducing cost are obtained in the transformerless topologies.

However, the absence of transformer caused some safety issues due to the solar panel parasitic capacitance. This situation causes the common mode voltage to appear and forming leakage currents (common mode currents) to flow through the stray capacitance between the PV array and the ground [3]. The ground current can cause severe (conducted and radiated) electromagnetic interferences, distortion in the grid current and additional losses in the system. These leakage currents can be avoided or at least limited, by including damping passive components in the resonant circuit [2]. In order to avoid common mode currents, different inverter topologies have been proposed. Furthermore, it strongly reduces the leakage current between the PV system and the ground, ensures that no continuous current is injected into the grid, and can be used to increase the inverter output voltage level.

1.2 Objective of the Project

The main goal of this project is to design a model for single phase transformerless PV inverter systems with respect to the leakage current phenomenon. It is summarized in two points as stated below:

- (i) To design the bipolar or unipolar pulse width modulation (PWM) switching technique for each inverter topology.
- (ii) To observe and compare ground current pattern with three different inverter topologies as well as determine the most effective topology that will minimize the leakage current.

1.3 Problem statement

According to [4], the line transformer in grid connected PV guarantees galvanic isolation between the grid and the PV systems, thus providing personal protection and avoiding leakage currents between the PV system and ground. Additionally, it significantly reduces leakage currents between the PV and system and the ground as well as ensures that no direct current (DC) is injected into the grid. However because of its low operating frequency (50 Hz), the transformer is big, heavy and expensive.

Because of these factors, it becomes desirable to remove the transformer in the PV system. This will result in improving the efficiency and reducing the cost and size, but on the other hand, the ground current problem due to ground current capacitance will appear. To avoid these leakage currents, it is important to use an inverter topology that can avoid common mode voltage and have higher efficiency [3]. The thriving technology allows the use of inverters without line transformer and without any impact on the system characteristic concerning personal safety and grid integration.

1.4 Scope of project

The scope of this project is to study and analyze the ground current pattern for the different transformerless PV inverter topologies in single phase as stated below:-

- (i) Bipolar H-Bridge transformerless inverter topology.
- (ii) Modified HB-ZVR transformerless inverter topology.
- (iii) NPC transformerless inverter topology.

The switching pattern of the inverter is controlled using Pulse Width Modulation (PWM) - Bipolar for H-Bridge inverter topology while Unipolar for NPC and Modified HB-ZVR inverter topology. The proposed topology has been verified in the simulation based on MATLAB SIMULINK®.

1.5 Thesis Outline

This report is arranged and distributed into five chapters. Chapter 1 has presents a brief introduction of the project mainly about PV and a problem that cause leakage current, the problem statements, the objectives of the project and its scope, and the limitations identified using the proposed approach.

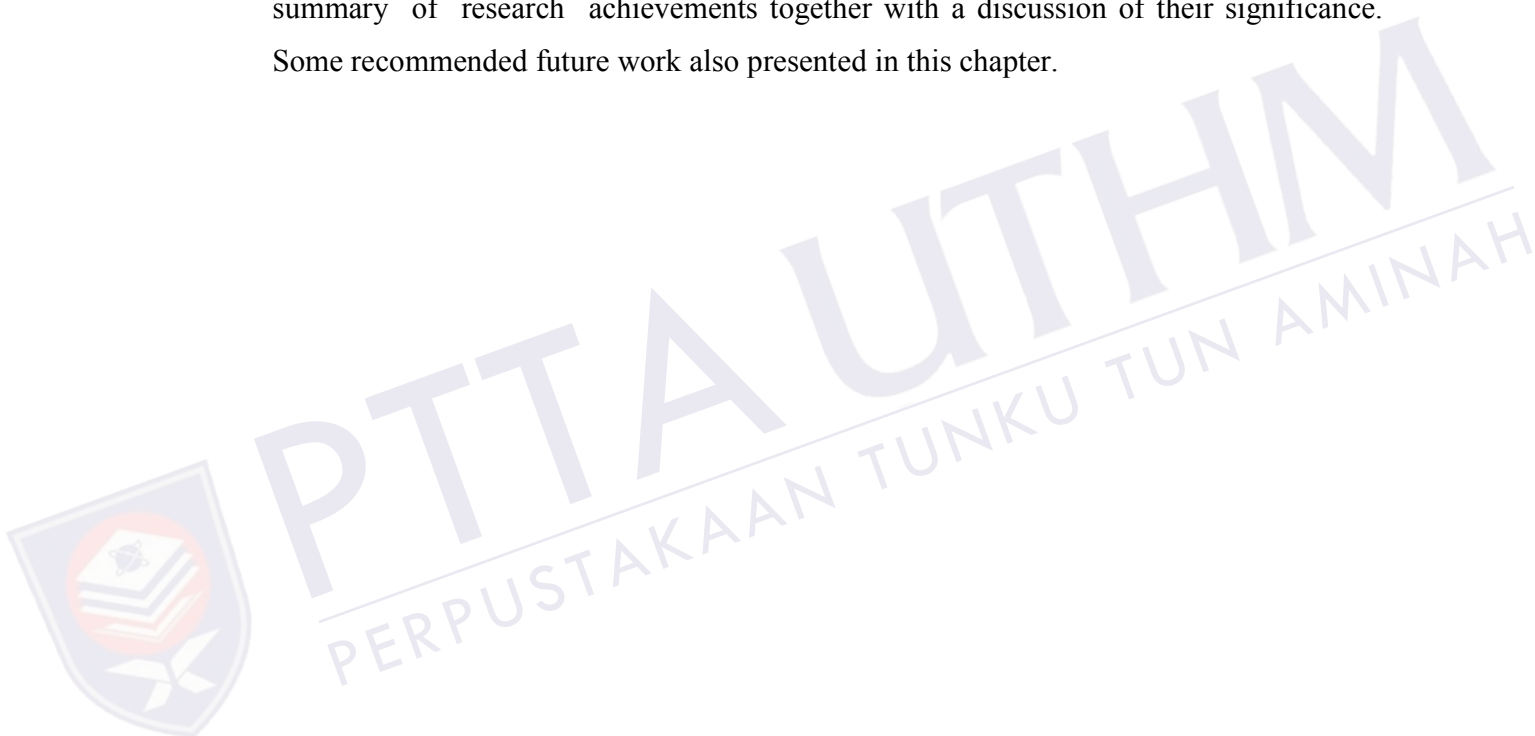
Chapter 2 of the dissertation includes literature survey related to this project as per referred to previous studies and results obtained by past researchers. It also contains some important findings from past researchers such as a review of existing inverter control and switching strategies. Their respective advantages and disadvantages, with specific reference to single phase photovoltaic systems, are discussed.

Together with the literature review carried out in Chapter 2, has helped with the search for inverter control features that could potentially improve performance and cost. Chapter 3 provides methodology in how this project is conducted in sequence. It also includes the development and progress of transformerless PV circuitry, dedicated

controller and PWM design. Details in the circuitry are explained and description is provided in this chapter

Chapter 4 contains the results and findings of the project. A simulation is run on construction circuit for three transformerless topology which is H-Bridge transformerless bipolar switching inverter topology, NPC transformerless inverter topology and Modified HB-ZVR transformerless inverter topology. Simulation result is analyzed and studied.

Lastly is chapter 5 where this chapter concludes the dissertation. It presents a summary of research achievements together with a discussion of their significance. Some recommended future work also presented in this chapter.



CHAPTER 2

LITERATURE REVIEW

2.1 Photovoltaic

Solar energy is considered to be one of the most useful natural energy sources because it is free, abundant, pollution-free, and most widely distributed. Electricity can be produced from sunlight through a process called photovoltaic (PV). “Photo” refers to light and “voltaic” refer to voltage. Because the source of light is the sun, usually they are called solar cells [4]. Indirectly, photovoltaic (PV) grid-connected generation system is the trend of solar energy application. While the world’s power demand increases, grid connected PV systems is expected to become increasingly prevalent in the near future since they process power from renewable energy source. The price of the PV modules is now much lower than that in the past due to the increasing production capacity; therefore a cost reduction for the grid-connected inverter has great significance in making PV-generated power more attractive.

An electrical field is created near the top surface of the cell where these two materials are in contact (the P-N junction). When the sunlight strikes the surface of a PV cell, this electrical field provides momentum and direction to light-stimulated electrons, resulting in a flow of current when the cell is connected to an electrical load [8]. PV offer the ability to generate electricity in a clean, quiet and reliable way. Therefore, the

photovoltaic is “producing electricity directly from sunlight”. One of the major advantages of PV technology is that it has no moving parts. Therefore, the hardware is very robust; it has a long lifetime and low maintenance requirements. And, most importantly, it is one solution that offers environmentally friendly power generation [2].

Nowadays, PV panels are not only used in space applications, but they are present in everyday life: powering wrist watches, small calculators, supplying loads in remote sites and, last but not least, they are connected to the public grid, generating the green power of the future [7]. In the current market, photovoltaic system is divided into two major categories which are grid connected PV system and stand alone PV system.

2.1.1 Grid Connected PV

This is currently the most common PV installation. All energy that can be generated by the array is delivered to the public utility grid as shown in Figure 2.1. Compared to the other PV system, the grid connected PV in term of power system design criteria shows the reliability means no blackouts i.e. always have the capability to generate more energy than will actually be used.

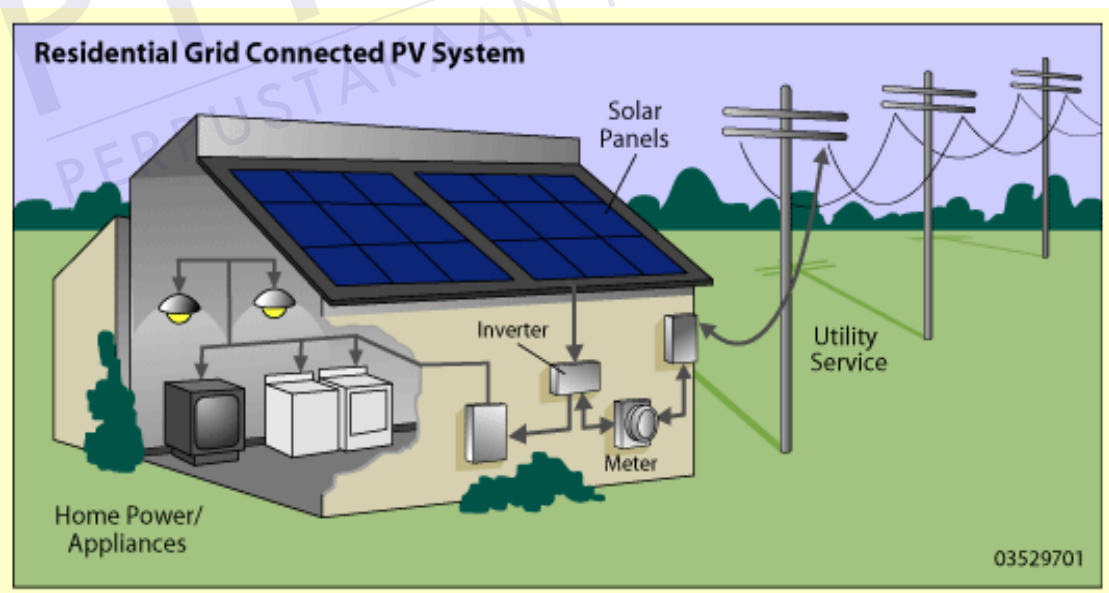


Figure 2.1: Grid connected PV system [19]

When using grid-connected systems solar photovoltaic, electricity is fed into the grid. As the electricity generated by a PV module is in the form of direct current (DC), the electricity needs to be converted to alternating current (AC) for which an inverter is required. Energy surplus will be fed into the grid, while in times of shortage (e.g. At night) energy will be consumed from the grid. The other option is utility scale, central station PV fields, managed by the utilities in the same way as other electric power plants.

All DC output of the PV field; which is generally in the megawatt range, is converted to AC and then into the central utility grid after which is distributed to the customers. In a grid-connected power system the grid acts like a battery with an unlimited storage capacity.

2.1.2 Standalone PV

Stand alone application basically operates independently of the grid network. Stand alone applications relate mainly to rural areas of developing countries and the majority of grid-connected application relates to industrialized countries.

The areas of application for standalone PV system (also called off-grid applications) consist of:

- (i) Isolated facilities (cottages, coastal cottage settlements, fish farms, hunting lodges, etc.)
- (ii) Telecommunication systems (transmitters, repeaters, base stations) .
- (iii) Street lighting, bus stops, parking lots, various signaling.
- (iv) Mobile Units, camping cottages, campers and boats .
- (v) Systems for automatic acquisition and tracking data.

The standalone system as in Figure 2.2 is very useful for application such as outdoor activity or travel. Since PV only able to store energy provided when sunlight is available, this required a battery bank to store charge for guarantee few hours an even up to a few days of energy capacity to overcome the unavailability of energy storage during

night time. To protect the battery, a charge controller is implemented to regulate the charge and prevent the battery from excessive charge and discharge.

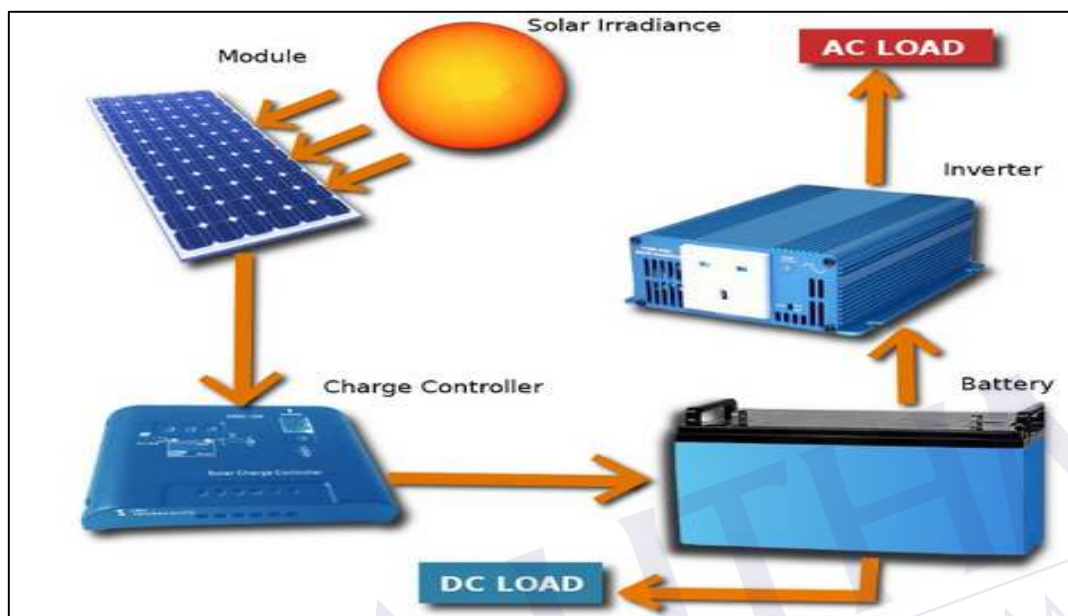


Figure 2.2: Stand alone PV system [11]

Nevertheless there are some advantages of standalone PV system where it is easy installation due to photovoltaic modules is lightweight and portable as well as system scalability, longevity, no maintenance and complete energy independence. This system also can protect the environment and has no electricity bills.

2.1.3 Hybrid System

Aside from grid connected and standalone system, another PV system is the one shown a very high reliability by combining of two renewable energy or implement the used of backup generator in a PV system. A hybrid system based on photovoltaic is considered an effective option to electrify remote and isolated areas far from the grid. This is true for areas that receive high averages of solar radiation annually.

Using a diesel generator as a standby source will make utilization of hybrid systems more attractive. An economic feasibility study and a complete design of a hybrid system consisting of photovoltaic (PV) panels, a diesel generator as a backup power source and a battery system is shown as Figure 2.3. AC generator will allow the batteries to regenerate charge when they achieve a certain discharge point. Ideally, the AC generator will be used as little as possible for noise and pollution control, but it is necessary in the event the load is simply too high.

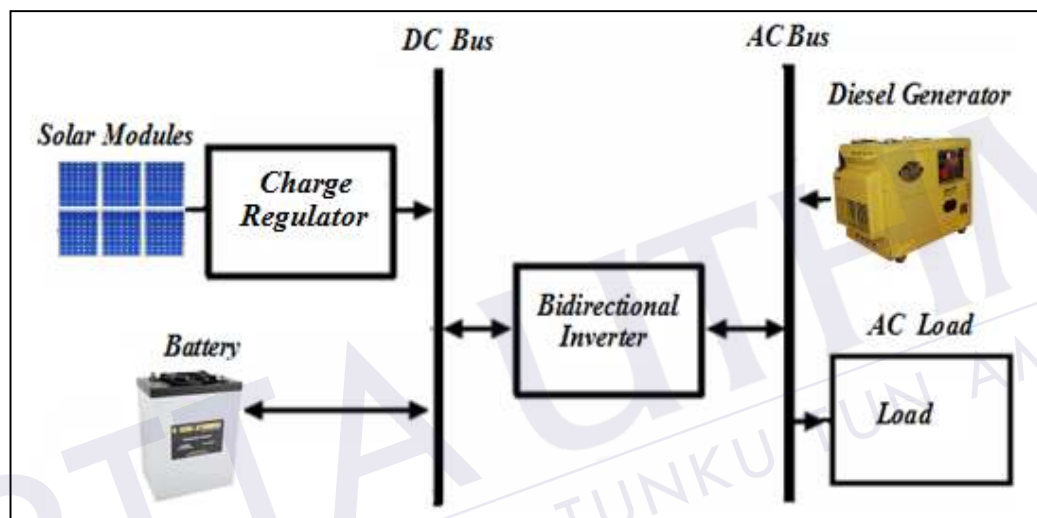


Figure 2.3: Block diagram of the hybrid system [16]

2.1.4 Equivalent circuit for solar cell

A solar cell can be electrically represented as in Figure 2.4, where the non-ideal characteristic is shown. The solar cell is placed as a source in parallel with a diode. The series resistance R_s , gives a more precise shape between the maximum power point (MPP) and the open circuit voltage (V_{oc}). The shunt resistor R_{sh} , in parallel with the diode which corresponds to the leakage current to the ground. The output of the solar cell is proportional due to the lighting fall on the cell. More solar irradiance on solar cell, more the output will be produced.

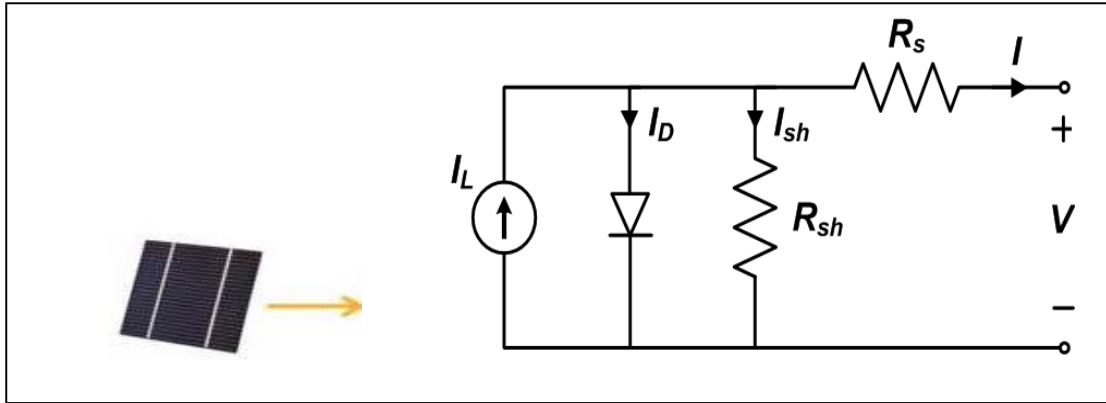


Figure 2.4: Solar cell equivalent circuit [12]

The equation (2.1), of the solar cell is given by:

$$I = I_L - I_D - I_{sh} \quad (2.1)$$

The diode current I_D can be expressed by the Schokley equation and current I_{sh} through R_{sh} can be solved by Ohm's law. Then the current from a solar cell can be given by the following equation (2.2):

$$I = I_L - I_0 \left\{ e^{\frac{q(V + IR_s)}{nKT}} - 1 \right\} - \frac{V + IR_s}{R_{sh}} \quad (2.2)$$

Where

I_L = photo generated current (A)

I_0 = saturation current (A),

n = the diode ideality factor (1 for ideal diode)

q = electronic charge (1.6×10^{-19} C)

K = Boltzmann's constant (1.38×10^{-23})

T = cell temperature ($^{\circ}\text{C}$)

I = cell current (A)

V = cell voltage (V)

2.1.5 Current-Voltage I-V Curve for Solar Cell

The I-V (current-voltage) curve of a PV string (or module) describes its energy conversion capability at the existing conditions of irradiance (light level) and temperature. Conceptually, the curve represents the combinations of current and voltage at which the string could be operated or 'loaded', if the irradiance and cell temperature could be held constant.

Figure 2.5 shows a typical I-V curve, the power-voltage or P-V curve that is computed from it, and key points on these curves. The span of the I-V curve ranges from the short circuit current (I_{sc}) at zero volts, to zero current at the open circuit voltage (V_{oc}). At the 'knee' of a normal I-V curve is the maximum power point (I_{mp} , V_{mp}), the point at which the array generates maximum electrical power. In an operating PV system, one of the jobs of the inverter is to constantly adjust the load, seeking out the particular point on the I-V curve at which the array as a whole yields the greatest DC power [16].

At voltages well below the maximum power voltage, V_{mp} the flow of solar-generated electrical charge to the external load is relatively independent of output voltage. Near the knee of the curve, this behavior starts to change. As the voltage increases further, an increasing percentage of the charges recombine within the solar cells rather than flowing out through the load. At V_{oc} , all of the charges recombine internally. The maximum power point, located at the knee of the curve, is the (I,V) point at which the product of current and voltage reaches its maximum value.

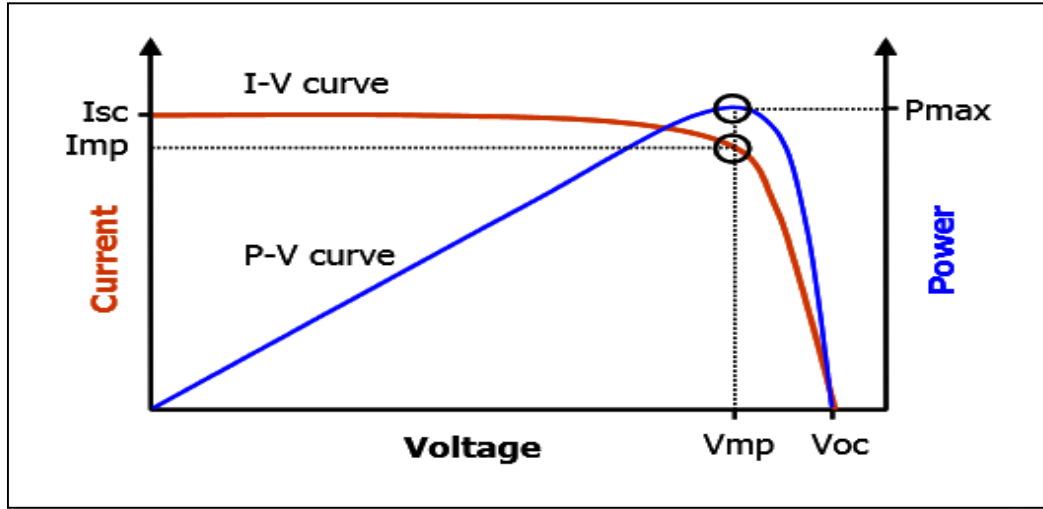


Figure 2.5: I-V Curve for solar cell [16]

The fill factor (FF) can be determined from the I-V curve as well. It shows the performance of PV cell towards power production. The fill factor (FF) and the conversion efficiency (η) are metrics used to characterize the performance of the solar cell. The fill factor is defined as the ratio of P_{\max} divided by the product of V_{oc} and I_{sc} , given in (2.3). The conversion efficiency is defined as the ratio of P_{\max} to the product of the input light irradiance (E) and the solar cell surface area (A) as given in (2.4) [16].

$$\text{Fill Factor, } FF = \frac{P_{\max}}{I_{sc} * V_{oc}} = \frac{I_{mp} * V_{mp}}{I_{sc} * V_{oc}} \quad (2.3)$$

$$\text{Conversion efficiency, } \eta = \frac{P_{\max}}{E * A} = \frac{V_{oc} * I_{sc} * FF}{E * A} \quad (2.4)$$

2.1.6 Open Circuit Voltage and Short Circuit Current

Short circuit current, I_{sc} is the maximum value of current generated by a solar cell. It produces by the short circuit conditions. The short-circuit current can be measured by exposing the device to sunlight and measuring current with an ammeter or multimeter. The measuring procedure depends on the actual current and the type of meter. If the short-circuit current is less than the fused current rating of the meter (typically 1 A or 10 A), the test leads can be connected to the output terminals. The meter short-circuits the PV device with a very small resistance and measures the resulting current [10]. If the current is expected to be closer to or higher than the meter rating, this in-line method should not be used. Instead, a conductor with a switch is used to short-circuit the output terminals and a clamp-on ammeter is put around the conductor to measure the resulting current [4].

The open circuit voltage, V_{oc} is the maximum voltage drop across the diode and generated current $I = 0$. Since there is no current at the open-circuit voltage, the power output is also zero. The open-circuit voltage is used to determine maximum circuit voltages for modules and arrays. The open-circuit voltage of a PV device can be measured by exposing the device to sunlight and measuring across the output terminals with a voltmeter or a multimeter set to measure DC voltage [4]. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light generated current as given by (2.5) [15].

$$V_{oc} = \frac{kT}{q} \ln \left(\frac{I_L}{I_o} + 1 \right) \quad (2.5)$$

2.1.7 PV Cell, Module and Array

There are several types of photovoltaic cells available on the market. Different types of solar cells have different efficiency. Solar cells can be represented by an electrical equivalent circuit. A single solar cell cannot provide an adequate amount of voltage and current to power up electrical equipment. Connecting solar cells in series and parallel produces higher current and voltage. These combinations of solar cells are called solar panels.

It is to be noted that, connection of each single PV cell in series makes up a PV module. Connection of PV module with another PV module can be in either parallel or series and the combination of them results in a PV array. PV array aims to achieve desired voltage, contrarily by having PV module connected in parallel will leads the system to achieve a greater current or in the other hand is to provide sufficient charge to charge the battery bank. Their relationship can be illustrated as Figure 2.6.

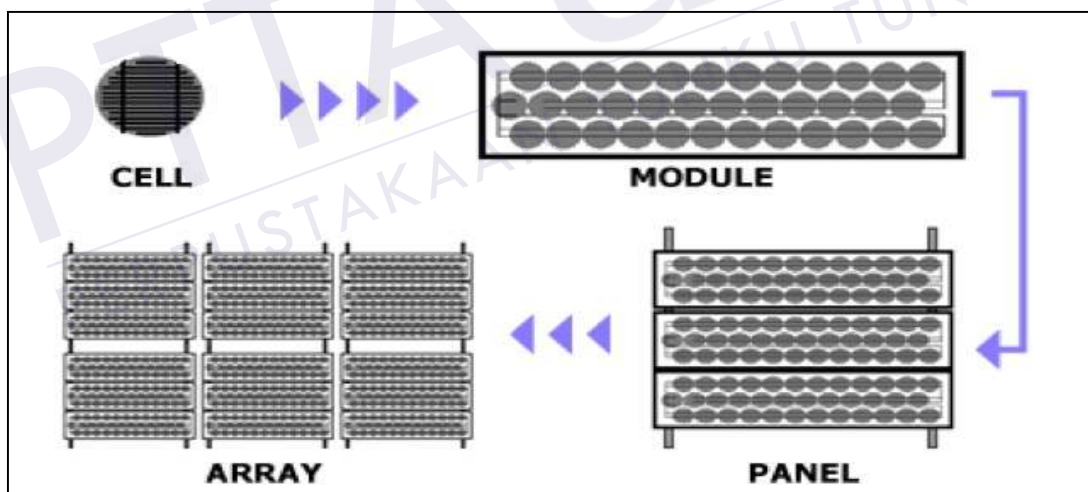


Figure 2.6: PV cell, PV Module and PV Array relationship [15]

2.1.8 Types of PV Cell

PV cells can be categorized into 4 types namely Monocrystalline Silicon Cells, Multicrystalline Silicon Cells, Thick-film Silicon and Amorphous Silicon. The images can be differentiated as shown in the table 2.1.


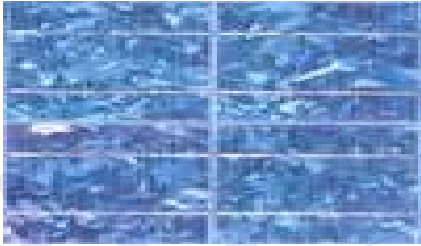
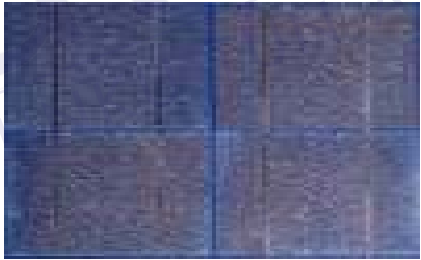
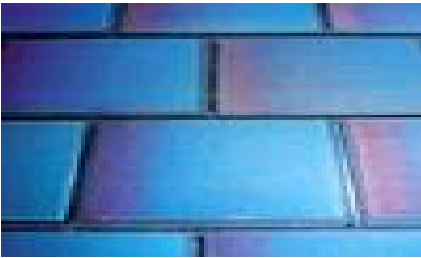
For Monocrystalline Silicon Cells, this silicone is made using cells saw-cut from a single cylindrical crystal of silicon where this is the most efficient of the photovoltaic (PV) technologies. The principle advantage of monocrystalline cells is their high efficiencies, typically around 15%, although the manufacturing process required to produce monocrystalline silicon is complicated, resulting in slightly higher costs than other technologies [12].

Multicrystalline Silicon Cells are made from cells cut from an ingot of melted and recrystallised silicon. In the manufacturing process, molten silicon is cast into ingots of polycrystalline silicon; these ingots are then saw-cut into very thin wafers and assembled into complete cells. Multicrystalline cells are cheaper to produce than monocrystalline ones, due to the simpler manufacturing process. However, they tend to be slightly less efficient, with average efficiencies of around 12%, creating a granular texture [12].

Thick-film Silicon is another multicrystalline technology where the silicon is deposited in a continuous process onto a base material giving a fine grained, sparkling appearance. Like all crystalline PV, this is encapsulated in a transparent insulating polymer with a tempered glass cover and usually bound into a strong aluminium frame.

Amorphous Silicon cells are composed of silicon atoms in a thin homogenous layer rather than a crystal structure. Amorphous silicon absorbs light more effectively than crystalline silicon, so the cells can be thinner. For this reason, amorphous silicon is also known as a "thin film" PV technology. Amorphous silicon can be deposited on a wide range of substrates, both rigid and flexible, which makes it ideal for curved surfaces and "foldaway" modules. Amorphous cells are, however, less efficient than crystalline based cells, with typical efficiencies of around 6%, but they are easier and therefore cheaper to produce [12].

Table 2.1 : PV cell image [12]

Type of PV Cells	Images
Monocrystalline Silicon Cells	 A photograph of a monocrystalline silicon solar cell. It features a dark blue, square surface with a grid of thin, light-colored lines forming a pattern of smaller squares. The corners of the cell are rounded, and there are small, light-colored diamond-shaped features at the corners of the grid.
Multicrystalline Silicon Cells	 A photograph of a multicrystalline silicon solar cell. It shows a dark blue surface with a grid of thin, light-colored lines. The surface has a mottled, textured appearance with various shades of blue and purple, indicating the presence of multiple crystal grains.
Thick-film Silicon	 A photograph of a thick-film silicon solar cell. It displays a dark, textured surface with a grid of thin, light-colored lines. The texture is more pronounced than in the other types, with visible grain boundaries and a slightly uneven appearance.
Amorphous Silicon	 A photograph of an amorphous silicon solar cell. It shows a dark, textured surface with a grid of thin, light-colored lines. The texture is more uniform than in the other types, with a slight blue tint and a fine, granular appearance.

2.2 Inverter

The electricity generated by a PV module is in the form of direct current (DC). Transformation of direct current to alternating current (AC) required by many common appliances and for grid connection is achieved with an inverter. The efficiency of inverters is generally greater than 90%. Inverters connected directly to the module (as opposed to through a battery) incorporate a Maximum Power Point Tracker (MPPT), which continuously adjusts the load impedance such that the inverter is always extracting the maximum power from the system.

Inverters fall into two main categories which are line-commutated and self-commutated. In line-commutated inverters, thyristors as switching elements are used. Line-commutated inverters are not suitable for use in standalone system because AC voltage is required to turn off thyristors. In self-commutated inverters, these can be operated without AC grid voltage. In these inverters IGBT, MOSFET or GTO (Gate Turn Off) thyristors are used. According to the inverter operation, voltage and current control scheme are distinguished [9].

Because of some advantages in grid connected inverters in most cases current control scheme is applied. The advantages are higher power factor, better transient current suppression and short circuit current are limited to rated AC current. Utilities require that inverters connected to the grid must contain suitable control and protection to ensure that systems are installed safely and do not adversely affect the power quality.

In a grid connected PV, inverter converts the DC power produce by PV Array into utility frequency AC before transmitted to the utility. Inverter performs conversion of DC to AC in the form of switching operation where the switch On and OFF in a dedicated sequence with respect to the square pulse applied to the switch gate in a dedicated interval pattern. Controlling the switches can be done in two modes, either using square pulse or Pulse Wave Modulation (PWM). However, PWM is to be more preferable due to the advantages offered over square pulse switches control scheme (PWM produces sinusoidal, low in ripple output waveform which consists less of harmonics)

To design an inverter, many power circuit topologies and voltage control methods are used. The most important aspect of the inverter technology is the output waveform. To filter the waveform (Square wave or Sine wave) capacitors and inductors are used. Low pass filters (LCL filter) as illustrated in Figure 2.7 below has good current ripple attenuation with small inductance values. If the inverter has adjustable output frequency, the filter must be tuned to a level above the maximum fundamental frequency.

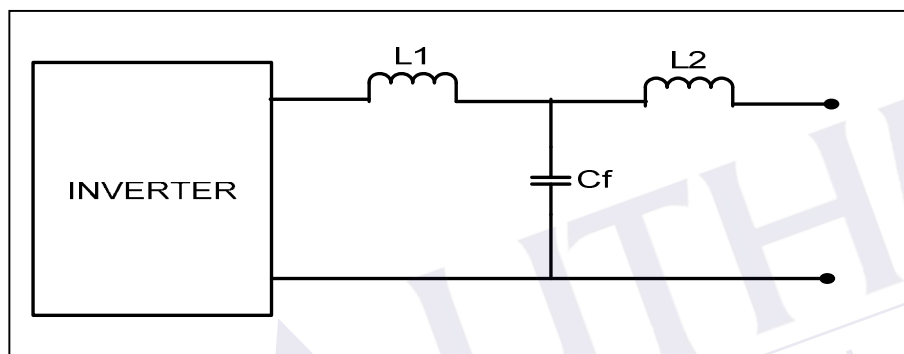


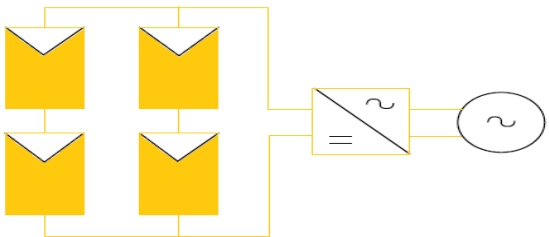
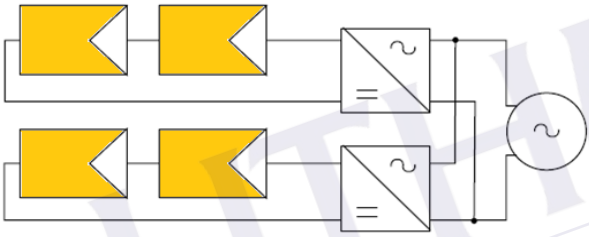
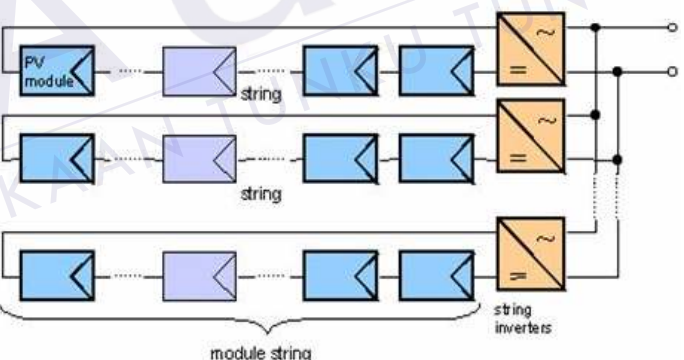
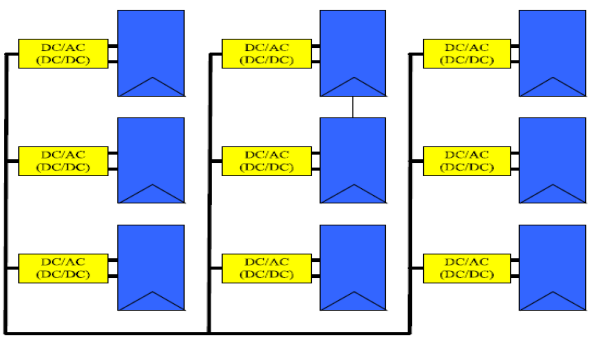
Figure 2.7: LCL Filter

2.3 Inverter for Photovoltaic Applications

In a PV system, inverter contributes only a fraction of the overall initial installation cost of PV systems. By referring to the percentage of initial cost distribution, inverter itself occupies only 10% of overall cost compare to 70% of module and 20% of installation and planning [9]. Even the value of inverter account is a small amount of cost but their roles in overall system performance must not take lightly. The inverter has the capability in the leading PV system towards a high efficiency, low cost and convenience in design (size).

As seen in currently market available PV system topology, string inverters capable of reduce in installation cost and higher input voltage [9]. Table 2.2 shows a PV system configurations namely Large Single Inverter (Centre inverter), Multi Small Inverter (String inverter), DC Bus (Multi-String inverter), and AC Module.

Table 2.2: Types of PV inverter/converter configurations [18]

Type of Inverters	Block Diagram
Centralized inverter	
String inverter	
Multi-String inverter	
AC Module	

2.3.1 Centralized inverter

Centralized inverter topology is the most common PV inverter topology which implemented widely in the high rated power system, typically for rated power of more than 10 kW. In central inverter, PV modules are connected in series to form a string and the string are placed in parallel to each other. Each string connected to only one inverter. Having only one inverter in the system contributed to both advantage and disadvantage. The advantage of having only one inverter in the system can greatly reduce the conversion losses which subsequently reduce the overall cost. Other than that, having only one inverter allows easy monitoring and maintenance to the system. However the list of its disadvantages is significant [18]:

- Need for high-voltage DC cables between PV panels and inverter
- Power losses due to common MPPT
- Power loss due to module mismatch
- Losses in the string diodes
- Reliability of the whole system depends on one inverter (the breakdown of a single inverter will affect the whole system)

2.3.2 String inverters

String inverters are slightly evolved from central inverters. The key difference is that they perform MPPT on strings rather arrays which may consist of multiple, parallel strings. A string inverter may literally be a self-contained inverter for just one (short) string of modules, so that multiple string inverters are needed for larger systems. In other words, a string inverter may be a central inverter that has multiple inputs, one for each string in the array. The advantages compared to the central inverter are as follows:

- No losses in string diodes (no diodes needed)
- Separate MPPTs for each string
- Better yield, due to separate MPPTs
- Lower price due to mass production

2.3.3 Multi-string inverter

The multi-string inverter configuration combines string inverter and central inverter concept into one configuration. The main advantage of this configuration is the independent individual MPPT. In multi-string inverter, a DC/DC converter is connected for each string and then connect to the one central inverter. By having this DC/DC converter, the input voltage will remain constant and the control scheme of the inverter becomes easier because of the MPPT is controlled by the DC/DC converter. The major disadvantage of this system is when the inverter is break down, the whole system will also fail to work [17].

2.3.4 Module-integrated inverter

The Module-integrated inverter known as AC modules is considered as new technology and is gaining popularity in the PV world. This is a major advantage since the MPPT mismatch is no longer a problem because the inverter (built-in MPPT system) controls the tracking of one module only. This will lead to maximum power for each module. Since each module has its own inverter, expansion of the system is rather easy. The output of the module can be directly connected to the grid, thus DC cabling can be reduced or eliminated. Installing the AC module is also easy, hence no expertise is needed. The AC module also eliminates the need for the bypass and string diode, therefore eliminating the associated losses.

The drawback of the AC module system is that the power per unit produced is low, with the DC boosting system inherent to the inverter adds to the losses. This reduces the efficiency of the systems. Another disadvantage of this configuration is that the inverter lifetime is shorter than the module, so bundling up the inverter to the module often leads to the failure of the module because they need to be able withstand the harsh environmental conditions. Since the AC module is still a new technology, the production cost remains high. New trends are observed where more and more inverters are proposed and designed for AC module configuration. This situation is a good sign for the AC

module to be expanded and widely used in the future. The simplicity of connection is the main reason for AC modules to draw users towards this technology. Cost, however, has been, and remains, one of the critical obstacles to further expansion of AC models in PV applications [18].

2.4 Classification of Inverters

The two major classifications of the inverter are the voltage source inverters (VSIs) and the current source inverters (CSIs). The VSI is the most commonly used in many applications. Figure 2.8 illustrates how the voltage source inverter and current source inverter can be used in a photovoltaic system. In the VSI, the capacitor in the DC link constitutes the actual voltage source, since the voltage across the capacitor cannot change instantly. The main task of the inductor is to isolate the high frequency components of the input current [11]. In some applications, the inductor is removed to reduce the size and cost of the inverter and to avoid the reduction of the maximum available output voltage due to the voltage drop across it.

The absence of the freewheeling diode across the switch is the obvious difference of the CSIs compared to the VSIs as well as reducing the size and weight of the inverter. The freewheeling diode becomes redundant if the inverter is supplied from a DC current source, since the current cannot change its polarity in any half-leg of the inverter. Therefore, it can only flow through the switches. The input current to the inverter is maintained at a constant level and the DC link inductor attenuates the current ripple [11].

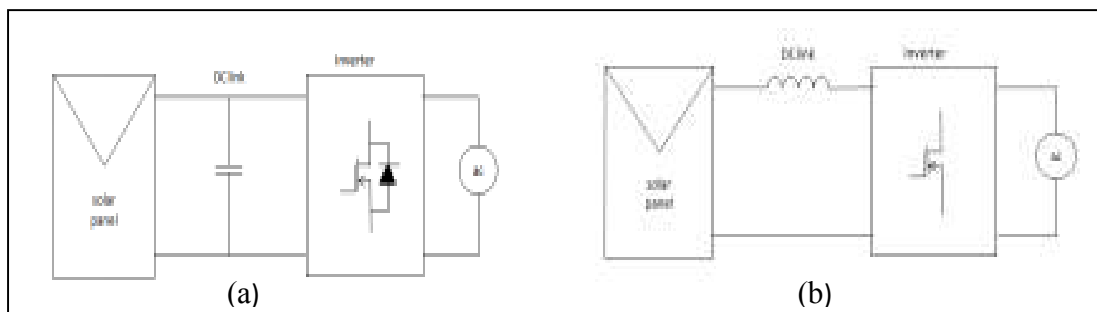


Figure 2.8: (a) Voltage source inverter and (b) Current source inverter [14]

2.5 Resonant Circuit

Low power PV application in single phase grid connected PV system allows the possibility of eliminating the implementation of transformer [12]. According to [13], leakage current tends to flow through the resonant circuit which consists of DC source (PV Array), input/output filter, inverter, parasitic ground capacitance and grid impedance as shown in Figure 2.9.

The galvanic connection between DC and AC side resulting from an absence of isolation transformers together with particular switching scheme with varying common mode voltage, will cause the resonant circuit to excite and results in the flow of leakage current. The grid itself, switching scheme with respect to converter topology and also the resonant circuit formed by the ground capacitance are the factors which will cause the leakage current to flow in the resonant circuit.

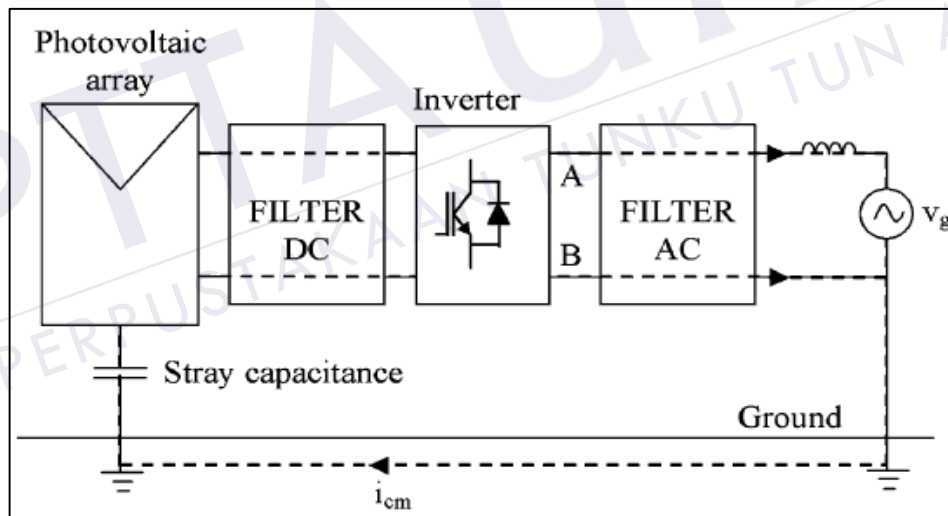


Figure 2.9: Leakage current flow in resonant circuit [5]

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