

# **AN IMPROVED BUS CONNECTED PV SYSTEM FOR MARINE SHIPS**

A Dissertation submitted in fulfilment of the requirements for the Degree  
of

**MASTER OF ENGINEERING**

*in*

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*Submitted by*

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# CERTIFICATE

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I hereby certified that the dissertation entitled, “AN IMPROVED BUS CONNECTED PV SYSTEM FOR MARINE SHIPS” which is being submitted by Sourav Dhiman in fulfilment of the requirements for the award of M.E. (Power Systems) in EIED, Thapar Institute of Engineering and Technology, Patiala, is a bona-fide record of the candidate’s own work carried out by him under my supervision and guidance. The matter contained in this dissertation has not been submitted. neither in part nor in full to any other university or institute for award of any degree.

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This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge and belief.

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# ABSTRACT

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Photovoltaic (PV) systems convert the solar energy falling on them directly into electricity. In this thesis, an improved PV system connected with the electricity distribution system of marine ships is proposed. The proposed methodology will track the maximum power point (MPP) of PV array using hybrid MPPT technique and flyback DC-DC converter. The tracked maximum power is then converted into 3-phase AC power using a full bridge voltage source inverter controlled by space vector pulse width modulation (SVPWM) technique. This 3-phase power will feed the local load and the excess AC power is transmitted into the electricity distribution system of ship. Moreover, the system includes protection from different faulty conditions. As well, the necessary steps and key components needed to design and build an efficient, reliable and protective photovoltaic system are examined.

**Keywords:** Photovoltaic, MPPT, MPP, SVPWM, EDS, duty cycle, ship's bus

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*Sourav*  
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# LIST OF SYMBOLS

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$V_{PV}$	PV array's output voltage
$I_{PV}$	PV array's output current
$P_{PV}$	PV array's output power
$D$	Duty cycle of flyback converter
$V_{in}$	Input voltage to the chopper
$V_{out}$	Output voltage of Chopper
$V_{out}'$	Output voltage of chopper seen by the primary side
$N_P$	No. of turns in primary side of transformer
$N_S$	No. of turns in secondary side of transformer
$e$	Error signal

# LIST OF ABBREVIATIONS

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PV	Photo-Voltaic
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
DC	Direct Current
AC	Alternating Current
THD	Total Harmonics Distortion
VSI	Voltage Source Inverter
CSI	Current Source Inverter
PWM	Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation
IFEP	Integrated Full Electric Propulsion
EMI	Electromagnetic Interference
EDS	Electricity Distribution System
DG	Distribution Generator

# CHAPTER-1

## INTRODUCTION

---

### 1.1 INTRODUCTION

World energy demand is continuously growing at an exponential rate, the quest aimed for energy sources other than fossil fuels is gaining significance. Even if the fossil fuels offer a provisional solution on the way to overcome this energy crisis, they cause the emission of greenhouse gases and carbon dioxide which are injurious to the environment. Furthermore, Earth has a shortage of fossil fuels and it is expected that 80% of all the fossil fuels will be expended in our lifespan. For this reason, there is a growing requirement of renewable energy sources, as a result solar energy generation is acquiring more importance as a renewable source because of its numerous advantages such as, a lesser amount of running cost as there is no fuel requisite, tranquility, a lesser amount of wears and tears by the reason of nonexistence of any moving part, minute upkeep etc. According to the World Energy Outlook-2017 of International Energy Agency, there is a fast deployment and dropping costs of green energy technologies. In 2016, growth in solar PV capacity was superior than for any other form of generation. Since 2010, costs of new solar PV have come down by 70%, wind by 25% and battery costs by 40% [1]. Rather than its continental application, PV energy generation system can prove to be a breakthrough in marine application.

Electricity distribution system of a marine ship can be considered as a micro-grid. A study on the operation of a prototype microgrid system installed in the National Technical University of Athens, which contains a battery energy storage, PV generator, local load and a controlled interconnection to the LV grid is present in literature [2]. Photovoltaic (PV) systems contain PV modules, for converting eco-friendly solar energy into electrical power. The PV modules are made of a number of solar cells depending upon requirements, which transforms the sunlight energy straight into electrical energy and these modules are coupled, as required to deliver wanted levels of DC current and voltage. They harvest electricity caused by a quantum mechanical phenomenon well-known as the “photovoltaic effect” discovered by Alexander-Edmond Becquerel in 1839. However, first photovoltaic device

was made in 1939 by Russell ohl, by using a Silicon PN junction [3]. PV cells can be prepared from several types of semiconductor material by means of different engineering procedure. The foremost downside of these PV systems is their considerably high cost as equated to the conventional sources for instance fossil fuels and also, their energy generation efficiency is correspondingly low. But these PV systems facilitate to trap sun's energy which is getting wasted.

The requirement of inverters is significant because of the reason that PV panels transmit electrons as a DC output, and many equipment on marine vessels works on AC power.

Power semiconductor devices symbolize the core of the fresh power electronics. These devices are being widely inhabited in power electronic converters. These devices are practiced as a matrix of on/off switches and has advantage to transform power from one form to a different form. There are primarily four conversion functions that are employed, for instance DC – AC, AC - DC, DC - DC and AC - AC. DC to AC converter is one from the family of converters which is in the custom of altering DC input to AC output and it is also termed as inverter. Its AC output power is having symmetrical AC output voltage and current at preferred magnitude and frequency. The input of inverter can be acquired from the standing power supply setup, for instance wind energy system, photovoltaic system, battery, fuel cell or from any additional DC sources.

## **1.2 NEED ANALYSIS**

Environment protection policies and global warming have turn out to be a most happening issue in the international discussions in recent years. Urbanized countries are demanding to diminish their greenhouse gas emissions. In this situation, solar power generation systems have a significant starring role to play owing to the fact that it is a never ending and green energy source. The lone emissions accompanying the PV power generation is commenced by the manufacturing of its constituents. Afterwards their setting up, they produce electricity by absorbing solar irradiation lacking emission of environment injurious gases. PV systems harvest additional energy than that meant for their engineering in their lifespan. Furthermore, the places devoid of additional usage, such as deserts and roof tops can be used for their installed. PV system are able to harvest electricity for isolated localities with no power grid links. This style of setting up is acknowledged as off-grid PV system and sometimes these PV systems are the utmost cost-effective alternative to avail electricity in isolated localities. On the other hand, maximum of the total PV power is generated from grid-tied installations, where the excess power transmitted into the electricity distribution system.

Truthfully, PV system is an emerging business in technologically advanced countries for instance Germany which is world frontrunner in PV power generation tailed by USA, Japan, Italy and Spain. But then again by reason of the equipment requisites, PV power generation is further costly than other resources. That's why, Indian Administration is encouraging it with subsidies and feed-in tariffs, visualizing the growth of the economy. Also, in nearby future electricity generation and transmission will become deregulated as introduced in Electricity act 2003 [4]. Increasing the productivity of PV plants is a strategic plan to upsurge the power generation, as it will raise the profits, dropping the cost of the power generation and approaching the cost of the power generated using conventional sources.

### 1.3 AIM AND OBJECTIVES OF THESIS

The ambition of this dissertation is in the direction of study and implement a ship's bus-tied PV System with the help of MATLAB Simulink software which can help to feed local-load and transmit excess solar energy into the ship's bus in an optimum, reliable manner and,

1. Make the system to operate for different input voltage levels.
2. To provide electrical isolation between PV array and power converters
3. To apply an optimal MPPT algorithm to trace the MPP of PV array.
4. To utilize maximum DC output of PV array.
5. To cause very low THD in overall output of inverter.
6. To improve synchronization between inverter and ship's bus
7. To provide protection to the PV array, power converters and cause minimum disturbances to ship's electricity distribution system.
8. To reduce fluctuation in output voltage and to improve synchronization, DC bus voltage stabilization can be done.

### 1.4 ORGANISATION OF THESIS

This thesis is sub-grouped into 6 chapters:

**Chapter 1** contains the introduction, need analysis, aim and objective of the thesis.

**Chapter 2** presents the overview Indian energy scenario, literature survey and gap in study. This chapter also contains the formulation of objective and novelty of work done in this thesis.

**Chapter 3** contains the detail view on each component of the proposed bus-tied PV system for marine ships.

**Chapter 4** presents the details of design methodology, assumption, constraints and mathematical investigation of the proposed PV system.

**Chapter 5** contains the outcomes and discussions on the proposed PV system.

**Chapter 6** contains the conclusions of the proposed method and future scopes has also been discussed in this chapter.

# CHAPTER-2

## LITERATURE SURVEY AND PROBLEM FORMULATION

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### 2.1 OVERVIEW

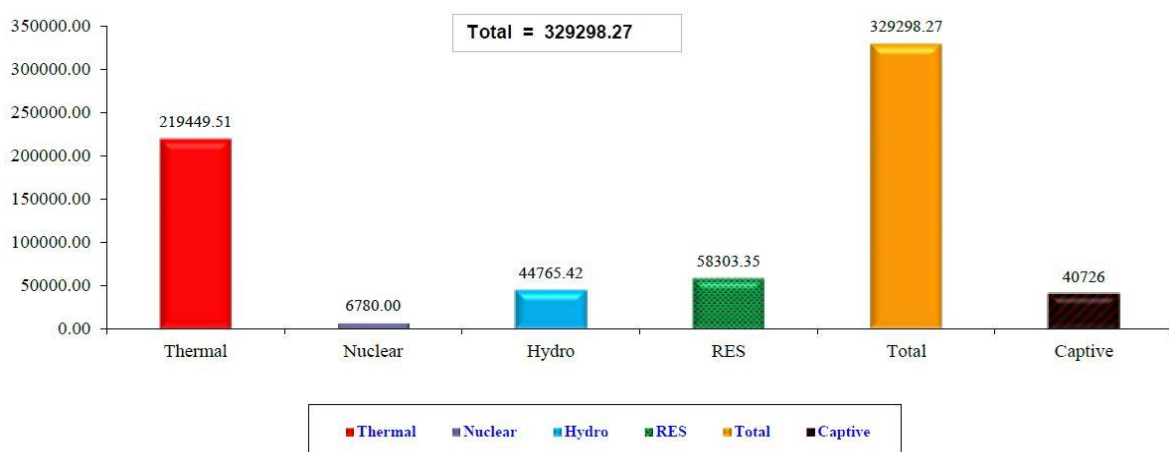
Without any uncertainty, the most recent decade was the terrific lifespan for the photovoltaic systems. The enormous number of technological advances on the research parts of photovoltaic (PV) panels, micro-grids, and power electronics has extended the usage of PV panels into frequent applications. The present PV systems are able to generate electricity that ranges from few Watts to MW. Portable solar chargers for portable devices such as calculators, cell phones, and laptops are very prevalent. Coupled arrangements of PV panels are helping to harvest electric power for isolated agricultural electric pumps, advertising signs, street lights, even small communities which are not linked to the power grid. Furthermore, fuel cell generators, wind power systems, PV systems, batteries, and other renewable energy generation structures can work collectively to establish reliable micro-grids [2], [5]–[7]. Nonetheless the utmost common PV applications are the power grid-tied systems, where lone PV panels or bulky scale PV plants supply secondary electric power to the power grid [7]–[9]. Although their stretched use for continental applications, the manifestation of PV systems in recent marine technology remains narrow, mostly working as supplying units for navigation units, small lighthouses, and battery chargers for the minor sailing ships [10]. Thanks to new environment protection policies, the transportation expenditures are growing because of the fuel prices, the growing limitations of NO<sub>x</sub> nitric oxides and CO<sub>2</sub> emission, and mostly the requirement for further environment friendly shipping. These were the motivations that forced the naval firms to reconsider the organized use of PV systems on bulky vessels [11], [12]. The photovoltaic systems can without a doubt be a surely cost-effective answer for ships. PV systems can turn as an ideal secondary power sources, liberated from the vessel's traditional electromechanical systems for the reason that they [13].

1. harvest electric power with lacking need carrying liquid fuel or transport gas,
2. cause no gas emissions or noise,
3. have low maintenance cost,
4. have very few or else no use of moving parts,
5. are made up of a small number of parts, with stress-free installation and easy replacement in the circumstance of malfunction or getting old,
6. have warranted performance for an acceptable lifespan, which is generally more than 80% as that of a new system after 25 years of operation,
7. can be positioned in unimportant exteriors with no everyday usage such as walls, roofs,

In this thesis, an investigation is done to answers that, how the utmost widespread technologies of the continental PV systems can be realised, and what qualifications must be achieved to design a PV system suitable for semi or completely electrical marine vessels.

## 2.1.2 Indian Energy scenario

According to Government of India Ministry of Power Central Electricity authority, New Delhi, Jan-2017 [14]. By the completion of September 2017, India had power generation dimensions of nearby 329298.27MW. Even by means of such an installed base, nearby 10% of the rural communities in India stand non-electrified, which would turn to around 125 million Indians. With a rising economy, the call for power is also rising at around 6% each year and the peak load demand is anticipated to reach 333500 MW by the end of 2017.



**Figure 2.1: All India installed electric power (MW) (30.09.2017)**

The Indian power division is exceedingly reliant on coal as a fuel, which makes 58.73% of the total set up generation volume being coal centered generation. Assuming the current

situation, consumption of coal by the power generation division is expected to extent level up to 545.9 million tonnes by 2017. According to Ministry of Coal, the current coal reserves are likely to last for only next 45 years.

### 2.1.3 Renewable energy scenario in India

In the present-day situation, renewable resources appear as the finest alternative. Among total installed generation capacity of India, renewable energy contributes for about 17.7% of 329298.27 MW. Wind-based generation system has most of the contribution with the portion of PV power being lone is about 22.49% of the total RES. India stands blessed of eco-friendly resources for instance wind, solar, hydro, biomass, and geo-thermal. Wind energy region has displayed a marvelous growth in the recent time and leads the renewable energy sector of India.

**Table 2.1: Status of RES in India in MW (30.06.2017)**

Micro Hydro Power	Wind Power	Biomass Power	Solar Power	Total Power
4384.55	32508.17	8295.78	13114.85	58303.35

India's mainland has plenty of solar radiation level, with the peninsula getting more than 300 sunlit days in a year. As the cost is continuously decreasing, solar systems have gradually become more eye-catching than other renewable energy sources. The several features leading to decrease in the cost comprises, enhancement in technology, introduction of mega plants, reducing material consumption and highly productivity of PV modules.

### 2.1.4 Earlier Works- An Overview

Photovoltaic (PV) systems are made up of PV modules which harvest electricity by reason of a quantum mechanical phenomenon recognized as the "photovoltaic effect" discovered by Alexandre-Edmond Becquerel in 1839. However, the first photovoltaic device was made in 1939 by Russell ohl, by using a Silicon PN junction [3]. PV cells can be made from several types of semiconductor material using different manufacturing procedure.

PV power generation is extra expensive than other resources. Indian Administration is encouraging it with subsidies and feed-in tariffs, visualizing the growth of the economy. Also, in nearby future electricity generation and transmission will become deregulated as introduced in Electricity Act: 2003 [4]. As per Electricity Act: 2003, section 7 & 8, in all

non-licensed activity, Electricity generation has been counted in, excluding hydro-electric power station having capital investment more than a certain expense.

IEEE declared a series of standards to assist power grid, to extract leftover electrical energy from other connected sources for instance “IEEE 1547: 2003 Standard for Interconnecting Distribution Resources with Electric Power System” [15]. The standards establish procedural necessities for the interconnection between electric power grid and distributed generators for instance photovoltaics, wind generators, fuel cells, large turbines, micro turbines and other connected generators.

Ambitious by the global demand for renewable sources, the photovoltaic market attained a significant volume of modernizations in the recent years concerning the productive operation and construction of power grid connected PV systems.

Samuel Vasconcelos Araújo et. al. [16] introduced a transformerless single-phase grid-tied photovoltaic inverter system. Author studied the most effective perceptions accessible in the market at that moment and proposed a latest inverter circuit. Its operation was calculated using experimental outcomes, and result showed the achievement of very high efficiency by means of an optimized semiconductor configuration. The three factors affecting the proficiency of a PV plant are PV panel’s efficiency (for commercial applications it is among 8-15%), inverter’s efficiency (95-98 %) and MPPT technique’s efficiency (more than 98%). Nonetheless, greater power losses are caused by the inverter’s operation at low input power levels which consequences the dramatical reduction in inverter’s efficiency.

The utmost freely available solar systems, perform well on sunny days with minute or no hindrance to incident light. Regular cloudy days and fractional hindrances for instance tree branches or neighbouring structures bound the productivity and reliability of solar power as a result of the nonlinear dependency of solar panel’s I–V curves on irradiance and temperature levels. H. M. Al-Masri [17] studied the PV module characteristic under different irradiance and temperature levels. MATLAB simulation outcomes illustrate that the addition in irradiance significantly upsurges the energy generation whereas big elevated change in temperature decreases the current which further decreases the output power. These outcomes are obtained from two fundamental curves that are, current characteristic curve (current versus voltage) and power characteristic curve (power versus voltage) [17]. Consequently, the operational current and voltage at which power output of PV panels is maximize, will alter according to the surrounding environmental conditions. With the aim of maintaining productive operation of PV array corresponding to the environmental variations, various maximum power point tracking (MPPT) techniques has been adopted [18]–[20]. These

MPPT techniques continuously tune the MPP, either by controlling output current or output voltage of PV array. Among the various available MPPT technique, 20 MPPT techniques are compared in literature by Eswam [19] on the bases of complexity, PV array dependency, sensed parameters, periodic tuning and convergence speed. Also, S. Jain [21] compared the dynamic and steady-state performance of 7 MPPT techniques applicable to grid connect PV systems

M. Abdulkadir et. al. [22] presented the modelling and simulation of a new maximum power point tracking algorithm with the help of MATLAB/Simulink software. This is the improved version of incremental and conductance MPPT technique modified with the integral regulator. Xiong Xiong et. al. [23] compared three techniques for instance P&O based on boost converter, INC based on boost converter and INC based on flyback converter. The outcome of these comparisons showed that the INC based on flyback converter method has better dynamic performance and fast response followed by INC based on boost converter and P&O based on boost converter.

PV systems, based on perturb and observe MPPT technique suffer from the oscillations in PV voltage. Nicola Femia et. al. [24] proposed a grid connected double-stage PV system to overcome the PV voltage oscillations caused due to the low frequency disturbances coming from the grid or due to the irradiance variations or due to the dynamics of the whole PV system.

With the advantages of string arrangement of PV panels there are some disadvantages too. Ricardo Alonso et. al. [25] examined two different topologies, namely the centralized topology, in which all PV modules are connected in series to a single inverter with a centralized MPPT, and the modular architecture, in which the PV array is arranged in a series string of intelligent PV modules with its own MPPT.

In direction of providing power to the crucial load through the power outages, the grid-tied-inverter ought to function in both grid-tied and off-grid modes. Furthermore, the shift sandwiched between these two manners ought to be seamless to diminish any unexpected voltage change across the crucial load or any unexpected current alteration into the grid. X. Liao et. al. [26] forecasted a seamless transmission between both modes.

Meanwhile maximum renewable sources are irregular, their power output, and later the generated ac power, differs significantly and arbitrarily. Several techniques for cultivating the productivity of PV systems have been testified in the work till now, utmost of which concentrate on evolving new topologies to accomplish higher productivities of PV system. Nonetheless, greater power losses are caused by the inverter's operation at low input power

levels which consequences the dramatical reduction in inverter's efficiency [16], [27]. To eliminate these losses at low input power, X. Liao et. al. [27] proposed a pulse-skipping control technique and it is widely used to control the inverter to halt nourishing the grid at low power input and store that power in the capacitor bank. As soon as the upper limit of dc bus voltage is attained, its maximum efficiency operating point the DC to AC inverter begin transmitting the energy kept in the dc bus capacitors to the grid, while waiting for the dc bus voltage to reduce beneath a defined lower limit.

By means of increased number of (DG) distribution generators, there is increase in alarm of unnoticed island formations. Islanding stands for a phenomenon according to which the power grid and the grid-tied distribution end generation system are disconnected. If this situation remains undetected and the distribution end generator remain operational such that DG continues to feed the power grid. This circumstance may become reason for the harm to the connected loads, inverter and it is a theoretically hazardous disorder for the maintenance workers. To improve anti-islanding detection, some methods are proposed in literature[23], [28], [29].

Marcel Istrate et. al. [29] presented a novel islanding prevention scheme. It includes the monitoring of dc-link voltage of VSI and analysis of islanding detection time in various relays for instance the frequency relays, the ROCOF relay, and respectively the dc-link voltage relay with the help of MATLAB/Simulink.

There are many different inverter topologies to convert DC power generated by solar array into AC power while maintaining the inverter phase angle and voltage level equal to main grid phase angle and voltage level [26], [28]. Varier et. al. [30] proposed a novel active anti-islanding protection scheme for interactive roof-top PV systems. To improve the inverter scheme, Tang et. al. [31] proposed a series connected Z-source inverter topology. Furthermore, Rajmohan et. al. [32] presented quasi Z source converter meant for reactive power compensation and harmonic mitigation in PV systems designed for marine applications. Among the various inverter controllers Zhengming et. al. [33] compared SPWM and SVPWM techniques.

Intended for a transformerless grid-tied system controlled by PWM (pulse width modulation) technique, during the design of filters, the important problems that should be eliminated are the leakage current, the electromagnetic interference (EMI) noise and the harmonics in grid-injected voltage and current. There are many filters to limit these components i.e. simple L-filter, LC, filter, LCL filter, LLCL filter [34]. Campanhol et. al. [34] proposed a universal filtering scheme applied to DG systems and AC.

As the DC voltage is fluctuating all the time to trace MPP, there are many sags and swells in the AC voltage output of inverter. To compensate this many compensation topologies being used. Agarwal et. al. [35] proposed a solar photovoltaic-DSTATCOM system.

Intended for large-scale photovoltaic (PV) systems, as equated with the traditional central inverter, the multistring configuration has become gradually more striking, in the meantime because of its better performance in maximum power point tracking which results in harvesting more energy. Between the standing solutions, Fuentes et. al. [36] proposed a single-phase test center prototype consisting of a single collector DC bus-bar with CHB (cascaded H-bridge) inverter, a striking topology with the experimental justification of the assembly on a compact dimension. This topology uses a single collector dc bus-bar with the cascaded H-bridge inverter which grants stable operation.

Nowadays, grid-connected photovoltaic (PV) technology has been well developed and widely applied in large PV power station, but its application on maritime ship is still at the stage of exploration. Xu-Jing et. al. [37] explored the power management system integrated in the PV system of the latest solar ship “COSCO Tengfei”, which is designed by the research group of New Energy Ship, Wuhan University of Technology (WUT) in 2013, It has a successfully integrated 143kWp PV system.

Moreover, a small-scale wind energy generation system can also be installed in parallel with PV system. Wang et al. [38] suggested an efficient and improved grid-tied small-scale wind energy generation system with a productive MPPT algorithm to trace the trail of maximum power point of the wind turbine.

P. Kotsampopoulos et. al. [39] studied the in-between gap of standardization of electromagnetic protection and emissions in the 2–150 kHz range. Electronic energy meters have been influenced by the electromagnetic interference by reason of PV inverters and additional power electronic devices. These interferences have directed the PV system to erroneous energy measurement in more than a few cases.

## **2.2 GAP OF STUDY**

1. Limitation of not to operate for different input voltage levels.
2. No isolation between PV array and power converters
3. Utilization of PV array’s DC output voltage can be increased.
4. To track the MPP, DC voltage level of PV array is variable. So, due to poor synchronization there is a voltage difference between inverter output and ship’s bus which causes circulating current.

5. DC bus voltage stabilization can be done to reduce fluctuation in output voltage and to improve synchronization.
6. EM interference of electronic devices led to inaccurate energy measurement. Standardization gap should be studied with the intention to solve this problem.
7. At low input the efficiency of inverter reduces dramatically.

## 2.3 FORMULATION OF OBJECTIVES

To design a system so that a PV array of around 50 solar modules with the capability of generating maximum 18 kW power, can feed the local load and transmit excess solar energy into ship's bus in an optimum and reliable manner.

Maximum power point of PV array is obtained when

$$\frac{dP_{PV}}{dV_{PV}} = 0 \quad 2.1$$

Where,

$$P_{PV} = V_{PV} \times I_{PV}$$

$$\frac{d(V_{PV} \times I_{PV})}{dV_{PV}} = I_{PV} + (V_{PV} \times \frac{dI_{PV}}{dV_{PV}}) \quad 2.2$$

The integral regulator minimizes the error

$$e = \frac{dI_{PV}}{dV_{PV}} + \frac{I_{PV}}{V_{PV}} \quad 2.3$$

Regulator output = chopper's Duty cycle correction

Inverter & inverter controller's design is such that

1. Inverter output voltage should be equal to ship's bus voltage at which system is connected.
2. Inverter output frequency should be equal to the frequency of ship's bus
3. Protection circuit should isolate the PV system at the time of fault.

## 2.4 EXPECTED DELIVERABLES

1. To be able to utilize maximum solar energy interacting with the panels by tracking MPPT of the solar panels.
2. The control scheme of inverter will help to utilize maximum DC output of the solar panels and help to synchronize PV inverter and ship's bus.
3. There will be less THD in the output as the inverter control scheme is efficient.
4. Frequency and output voltage of the inverter will match the ship's bus frequency and voltage.

5. In time operation of protection circuit and circuit breaker.

## **2.5 NOVELTY OF WORK**

1. High power flyback converter is providing electrical isolations b/w PV array & power converters and helps to operate for different input voltage levels.
2. High power flyback converter controlled by incremental conductance with integral regulator MPPT is helping in efficiently tracking MPP and cause very few oscillations around actual MPP.
3. SVPWM is successfully able to synchronize PV inverter with the electricity distribution system of ship. As study in literature it is utilizing 15% more DC-bus voltage and a cause smaller amount of THDs when equated with SPWM.
4. Isolation transformer has been used to electrically isolate PV inverter and ship's bus.
5. Anti-islanding protection circuit is able to sense over voltage, under voltage, over current, under current, THD, frequency deviations and provides ON/OFF signal to circuit breaker and prevent the PV system from feeding ship's electricity distribution system during the formation of island.

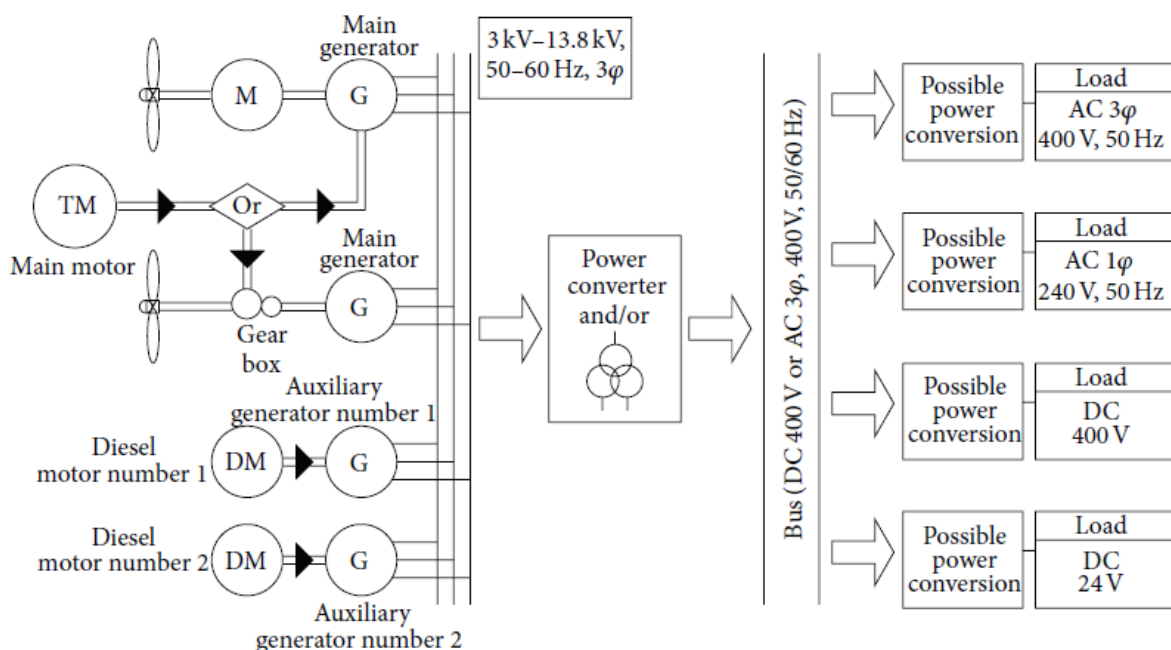
## CHAPTER-3

# THEORY, STANDARDS AND CONSTRAINTS

### 3.1 SHIP'S ELECTRICITY DISTRIBUTION SYSTEM

A marine ship can be well-thought-out as a mobile power plant. Utmost of the mechanisms are driven electrically, which accordingly makes for a vast electrical power request. This results in an electrical power system of marine ship to be very significant.

Four distinct areas can be well-known in the electric system of a classical ship are, the generators, the main propulsion engine, the loads, and the main distribution bus. Figure 3.1 presents a plan of a typical electrical system for a marine ship.



**Figure 3.1: Ship's typical electrical system**

A thermal motor utilizing weighty fuel such as diesel or oil works as a prime mover. Its revolving movement can be used to run either both electric generation and propulsion, or completely for electric power generation.

Firstly, the generator is attached to the shaft by using a step-up gear. It is recognized as shaft generator to the worldwide directory. Its purpose is not only to harvest electric power

intended for the marine ship but as well to function as a propulsion motor and support the main motor engine in certain conditions.

Secondly, thermal engine's mechanical power is devoted only to run the main generator. The generator at the same time drives an electric motor coupled to the propeller and supplies electric power to the ship. This propulsion system is recognized as integrated full electric propulsion (IFEP) configuration, and its core characteristic is to minimize shaft system, if not entirely eliminated.

Above and beyond the main generator, to providing with electric energy, at minimum two additional diesel powered auxiliary electrical generators are coupled to the electrical grid. Furthermore, at the time of breakdown or high load cases (fault in main generator and/or main motor) they have to tolerate the minimum operational standards of the marine ship.

Agreeing to the studies, the output voltages of the diesel and main generators fluctuates. Usual values of output voltage magnitudes are 13.8 kV, 6.6 kV, 6 kV, 4.16 kV, 3.3 kV and 3 kV whereas, frequency is 50Hz to 60Hz [13], [40], [41]. With the assistance of transformers and power converters, the generated power is delivered to an internal bus which helps to transfers the power to every load on-board the ship. The bus can be whichever AC or DC. The DC buses are extra widespread to the modern marine ships whereas the AC ones to passenger ships and cargo. Nevertheless, the research investigates the most gainful solution for the bulky marine vessels. Usual voltage and frequency standards for a 3-phase AC bus are 400V, 50Hz or 60Hz respectively and for a DC bus, voltage is 400V.

Electrical load is the end part of the ship's (EDS) electricity distribution system. There are various types of connected loads, however the utmost mutual are the DC 400V and 24V, the single-phase AC at 230V, 50Hz and the 3-phase AC at 400V, 50Hz loads.

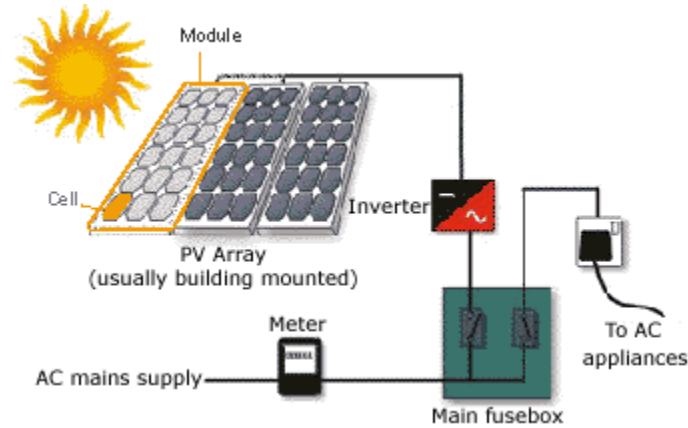
Along with the above-mentioned fragments of the ship's electric system, the PV systems can also be coupled with the distribution bus.

## **3.2 SHIP'S BUS-TIED PV SYSTEM**

### **3.2.1 Working principle of solar inverter**

A PV inverter, transforms the continuously varying DC output of a photovoltaic solar panels into an alternating current (AC) output, keeping the voltage and frequency synchronized with the power grid's voltage and frequency that can feed the load connected to it and transmit excess electricity into the ship's electricity distribution bus. It is a most important component in a PV system, allowing the usage of regular commercial appliances.

PV inverters have distinct functions adapted for use with photovoltaic arrays, together with MPPT (maximum power point tracking) and protection against the faults and formation island. A typical solar inverter scheme is presented in Figure 3.2.



**Figure 3.2: Solar Inverter Schematics**

### 3.2.2 Solar Inverter types

Solar inverters can be categorized into three general types.

1. Electricity distribution network tied solar inverters
2. Standalone solar inverters
3. Battery Backup solar inverters

#### 3.2.2.1 Standalone Inverters

Standalone inverters, draw its DC input energy from batteries charged by means of photovoltaic array and are implemented for isolated systems. A lot of standalone inverters has added in integral battery chargers to refill the battery from another AC source, when accessible. Generally, these types of inverters do not interact in any way with the utility distribution network, so do not require to have protection against any faults of distribution network and formation of island.

#### 3.2.2.2 Electricity distribution network tied solar inverters

These are the inverters, which are connected to the distribution network in a synchronized manner so as to feed load connected to it and transfer excess electricity into distribution network. These inverters are intended to automatically shut down upon the loss of power supply of distribution network, for protection motives. They are not being responsible for backup power to distribution network during power outages.

### 3.2.2.3 Battery Backup Inverters

These inverters, are distinct inverters which are engineered to pull energy from a battery, cope the battery charge via an implanted charger, and pass on leftover energy to the electricity distribution network. These inverters are proficient of supplying AC energy to designated loads during a power outage and are mandatory to have protection against islanding.

### 3.2.3 Application of photovoltaic system

Following are the advantages of ship's bus-tied photovoltaic system.

1. Saving the fuel, decreasing the running cost of the marine ships.
2. It can be used as a standby power supply for local loads in instance of grid's power supply failure.
3. Environmental friendly
4. Ever green energy system

## 3.3 COMPONENTS OF SHIP'S BUS-TIED PV SYSTEM

Following are the Components of ship's bus connected PV System

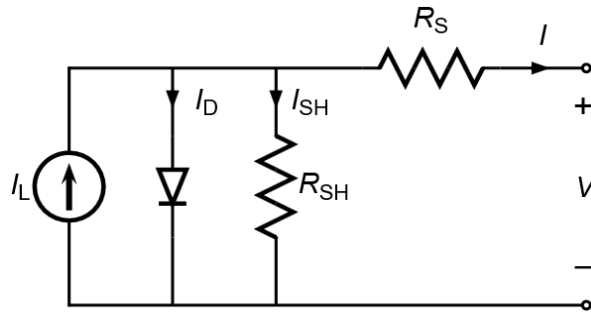
1. PV array
2. Maximum Power Point Tracking System
3. DC-DC converter
4. AC-AC converter
5. Inverter's control scheme
6. Filter
7. Protection circuit
8. Circuit breaker
9. Electricity distribution system of ship

## 3.4 PV ARRAY

Photovoltaic panels and array transform the solar energy into DC electricity. A photovoltaic array is a system made up of several solar panels electrically held together to form a considerably larger PV installation called an array and overall, the electricity produced by the solar panels is directly proportional to the surface area of PV panels. Characteristics of PV cells is dependent on irradiance and temperature of incident light as shown in Figure 3.5 & Figure 3.6.

### 3.4.1 Working principle

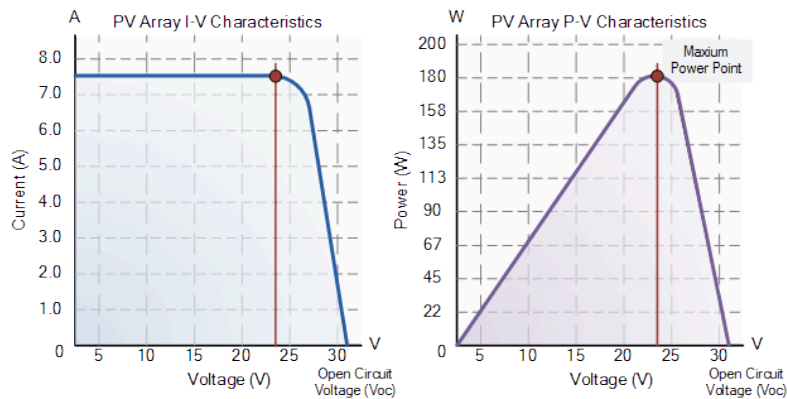
The fundamental component of photovoltaic panels is solar cell. These can be made from semiconductor materials such as silicon. Solar cell works on the phenomenon acknowledged as photoelectric effect, which is the capability of more or less semiconductors to transform Sun’s irradiation directly into direct-current electricity. The incident radiation generates charged particles which conveniently generate an electrical current as a result of a proper design of the arrangement of the solar cell as illuminated in literature [3]. The equivalent circuit diagram of solar panel is presented in Figure 3.1.



**Figure 3.3: Equivalent circuit of solar panel**

$$I = I_L - I_o \left( e^{\frac{q(V-IR_S)}{AKT}} - 1 \right) - \frac{V-IR_S}{R_{SH}} \tag{3.1}$$

Where, V and I stands for solar cell’s output voltage and current respectively,  $I_o$  represents the dark saturation current, q represents the charge of an electron, A stand for diode quality factor, also identified as ideality factor, k and T symbolizes the Boltzmann constant and absolute temperature respectively,  $R_{SH}$  and  $R_S$  symbolizes the shunt and series resistances of the solar cell. For an ideal circumstance  $R_{SH}$  would be infinite and  $R_S$  would be zero. The voltage versus current characteristics and power versus voltage characteristics of PV array are given below in Figure 3.4.



**Figure 3.4: VI & PV characteristics of PV cell**

### 3.4.2 Irradiance and temperature effect

Two significant influences that has to be taken care of are the temperature and the irradiation. They intensely affect the output characteristics of solar cells [17]. Accordingly, the MPP fluctuates throughout the day and this is the key motive because of which the MPP must be continuously tracked and make certain that the solar panels harvest maximum obtainable power. The influence of the irradiance and temperature on the V-I (voltage-current) and V-P (voltage-power) characteristics is illustrated in Figure 3.5 and Figure 3.6 respectively. These characteristics are observed using the  $I_{SC}$  and  $V_{OC}$  respectively, with the intention of better clarification of the impact of the temperature and irradiance on the V-P and V-I curves. There is direct proportion between short circuit current and irradiance, and inverse proportion between open circuit voltage and temperature.

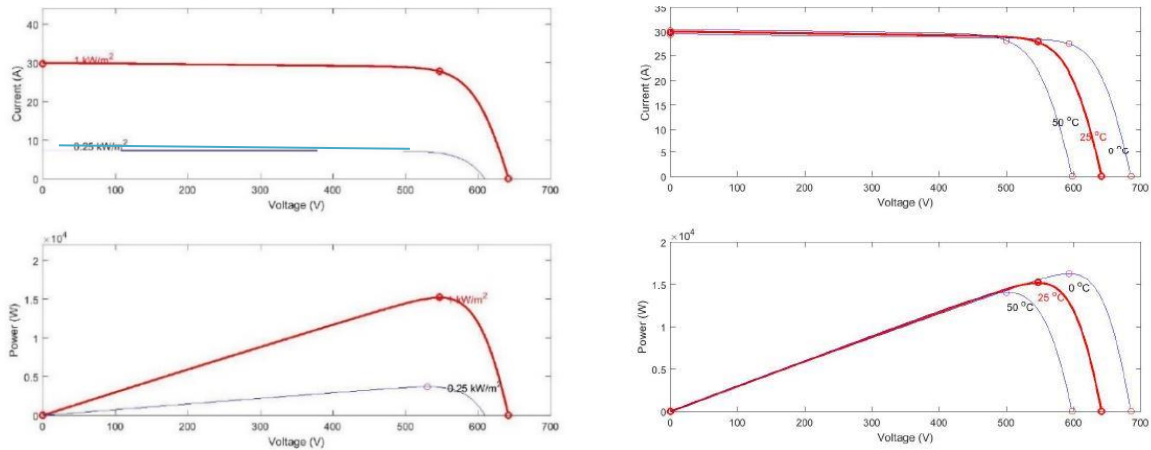


Figure 3.5: VI & PV char. with variable irradiance    Figure 3.6: VI & PV char. with variable temperature

## 3.5 FLYBACK CONVERTER

Flyback converter is a device used as a DC to DC converter and has galvanic isolation amid input and output. The flyback converter stands a modified version of a buck-boost converter in which inductor is fragmented to be used as a transformer. The working of flyback transformer is different from typical transformer as the low voltage and high voltage windings of the flyback transformer do not carry current at the same time [23].

Flyback converter is used to set-up or step-down the voltage depending upon the ON and OFF time period of the switch  $S$  per cycle. The representation of a flyback converter is presented in Figure 3.7. Its operating principle is very similar to that of typical buck-boost converter.

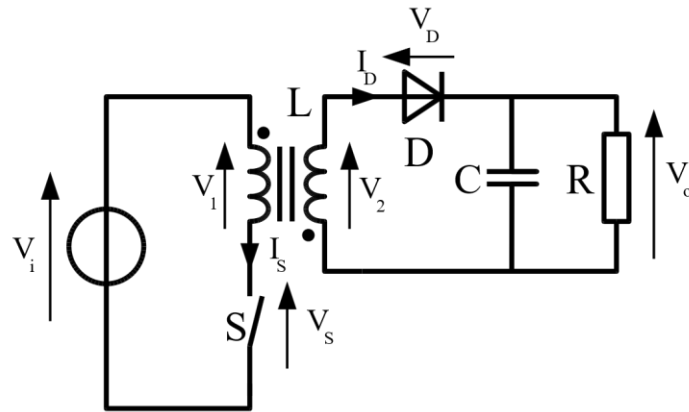


Figure 3.7: Schematic of a flyback converter

Flyback converter operates in two modes which are,

**Mode-1:** As soon as the switch S is closed, the PV panel side winding of the transformer is unswervingly connected to the PV array's output. In this case, transformer stores energy, PV panel side winding's current and its magnetic flux in the transformer escalates. By means of the opposite polarity of transformer winding, the voltage persuaded in the inverter side winding is negative, hence the diode D is reverse biased. Only the inverter side capacitor's energy participates to feed to the output load.

**Mode-2:** As soon as the switch S is opened, the transformer starts releasing stored energy therefore PV panel side winding's current and its magnetic flux descends. The inverter side voltage is positive, which forward-biases the diode, permitting current to stream from the transformer in the direction of load. The energy deposited in the transformer revives the capacitor to supply the load.

If the closing time of switch S is more than the opening time period, consequently the output voltage is greater than input voltage. On the other hand, if closing time is less than that of opening time period for switch S then the output voltage is less than that of input voltage. In the configuration presented in Figure 3.7 the output voltage polarity is opposite to the input voltage polarity. The ratio of output voltage to the input voltage is shown in equation 3.2. The ratio of ON time period to the total time period of switch S for a cycle is represented by duty cycle (D) as given in equation 3.3.

$$\frac{V_o}{V_i} = \frac{-D}{1-D} \quad (3.2)$$

Where,

$$D = \frac{T_{ON}}{T_{ON}+T_{OFF}} \quad (3.3)$$

Here D is Duty cycle.

For the reason of some applied limitations, the flyback converter is rarely used for output more than few hundred watts. Single-switch topology is adapted in Flyback converters but high breakdown voltage requirement of transistor is the downside of this topology. The commonly available IGBT transistor have 1200 V rating but they are very sluggish for the result of a productive flyback converter. To have fast operation MOSFETs are used instead of IGBTs. But for high voltage rated MOSFETs ON-state resistance is high which result in too much ON-state power loss in high-power applications.

Taking care of these draw backs of simple flyback converters, new MOSFETs are emerging, which are known as Silicon Carbide (SiC) MOSFETs. SiC MOSFETs has usually 1200 V voltage rating. The ON-state resistance of these converters is low (considerably lower than  $1 \Omega$ , generally about  $1 \Omega$ ) and very high switching speed. These MOSFETs are very efficient for high power flyback converters. The product number C2M0025120D in the standard TO-247 package of Cree industries has a breakdown voltage around 1200 V having  $0.025 \Omega$  ON-state resistance and drain current at  $100^\circ\text{C}$  is nearby 60 A. The ON/OFF switching times is around 50 ns [42].

Also, the switching frequency of these SiC MOSFETs can be increased beyond 100 kHz for high power outputs. This increased frequency result in the requirement of low valued output capacitors. The common belief is that the flyback transformers are big in size but with proper design and by means of the help of high switching frequency the size of flyback transformers can be decreased even for high power outputs, for example ETD4917 core, with top view dimensions of  $(48.5 +1.3, -0.9) \times (16.7 \pm 0.8)$  mm.

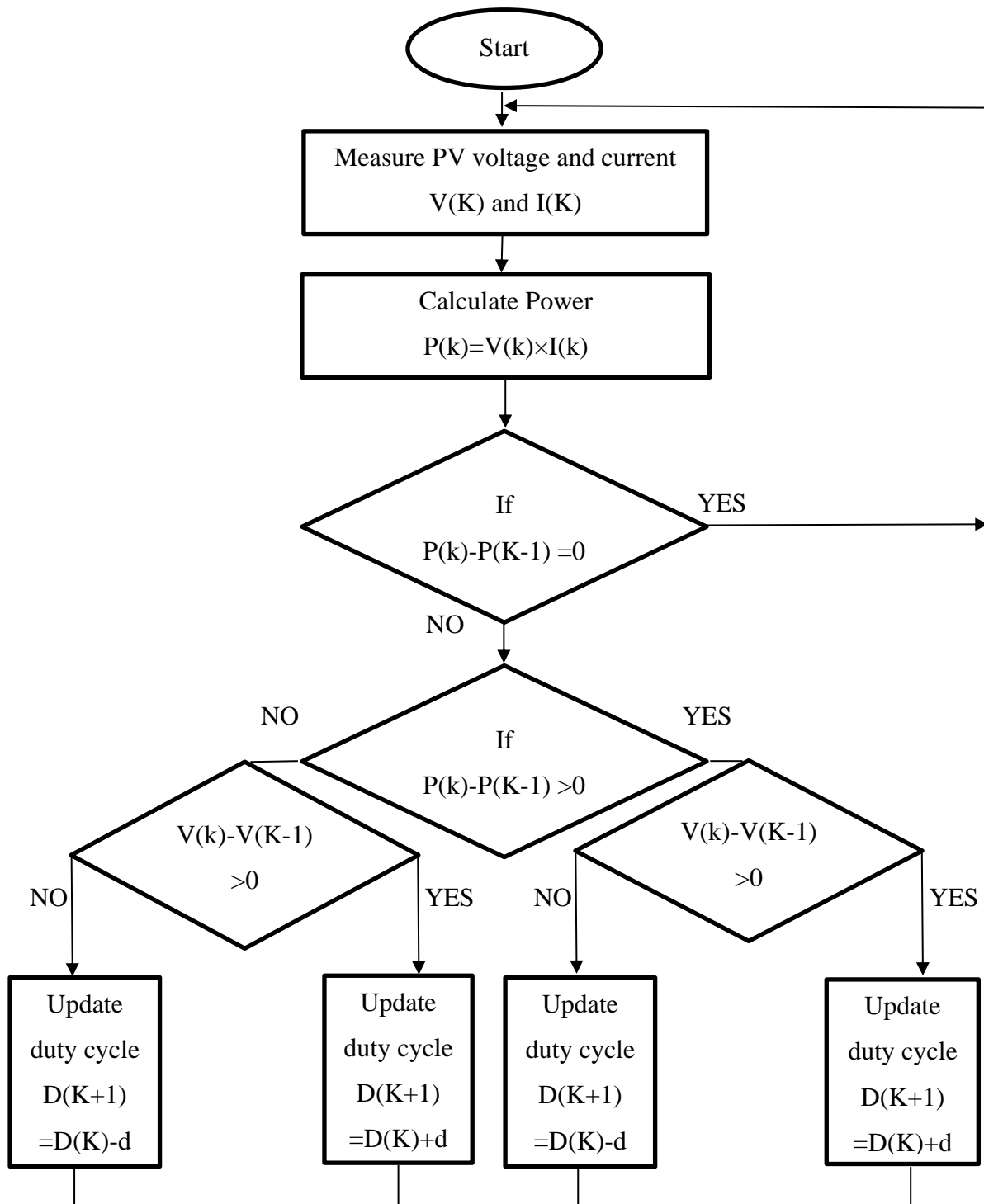
## 3.6 MPPT TECHNIQUES

Maximum power point tracking (MPPT) technique stands an electronic circuit system. MPPT techniques are adapted to control the duty cycle of the DC/DC converters connected across PV array in order to trace the maximum power point of PV array. The maximum power point of PV array is not a constant value but it changes with the alteration in irradiance and temperature of incident sun light. The power at MPP escalate with the increase in irradiance level and decrease with the escalation in temperature level [18]–[22]. The commonly used and basic MPPT technique is perturb and observe maximum power point technique.

### 3.6.1 Perturb and observe

Perturb and observe is a simple and basic MPPT technique. It is used to trail the maximum power point of the solar panels by changing the duty cycle of the chopper. This

tracked duty cycle will help to maintain or change the chopper's output voltage at which the PV array's output power is maximum. The flow chart of perturb and observe is presented in Figure 3.8.



**Figure 3.8: Flow chart of Perturb and Observe algorithm**

But there are some limitations with this method. The tracked maximum power point oscillates around the definite maximum power point of the PV array [24]. This is because the updating step of duty cycle is kept constant and cannot be change when a step less than the

fixed step is required to achieve the actual MPP. This limitation can be eliminated using other techniques such as incremental and conductance MPPT technique.

### 3.6.2 Incremental conductance technique

Incremental Conductance came into picture to overcome the limitation of perturb and observe MPPT technique and by observing P-V characteristics. This set of rules came into picture in 1993. Incremental conductance attempts to produce more energy and improve the tracking time of PV array in continuously changing irradiance and temperature levels [19], [21]. MPP can be evaluated by means of the relation among  $\frac{dI_{PV}}{dV_{PV}}$  and  $-\frac{I_{PV}}{V_{PV}}$ .

Maximum power point is attained as soon as

$$\frac{dP_{PV}}{dV_{PV}} = 0 \quad 3.5$$

Where,  $P_{PV} = V_{PV} \times I_{PV}$

$$\frac{d(V_{PV} \times I_{PV})}{dV_{PV}} = I_{PV} + (V_{PV} \times \frac{dI_{PV}}{dV_{PV}}) \quad 3.6$$

$$I_{PV} + (V_{PV} \times \frac{dI_{PV}}{dV_{PV}}) = 0 \quad 3.7$$

$$\frac{dI_{PV}}{dV_{PV}} = -\frac{I_{PV}}{V_{PV}} \quad 3.8$$

MPP is obtained when  $\frac{dP_{PV}}{dV_{PV}} = 0$  and  $\frac{dI_{PV}}{dV_{PV}} = -\frac{I_{PV}}{V_{PV}}$ ,

$$\text{If } \frac{dP_{PV}}{dV_{PV}} > 0, \text{ then } V_{PV} < V_{MPP} \quad 3.9$$

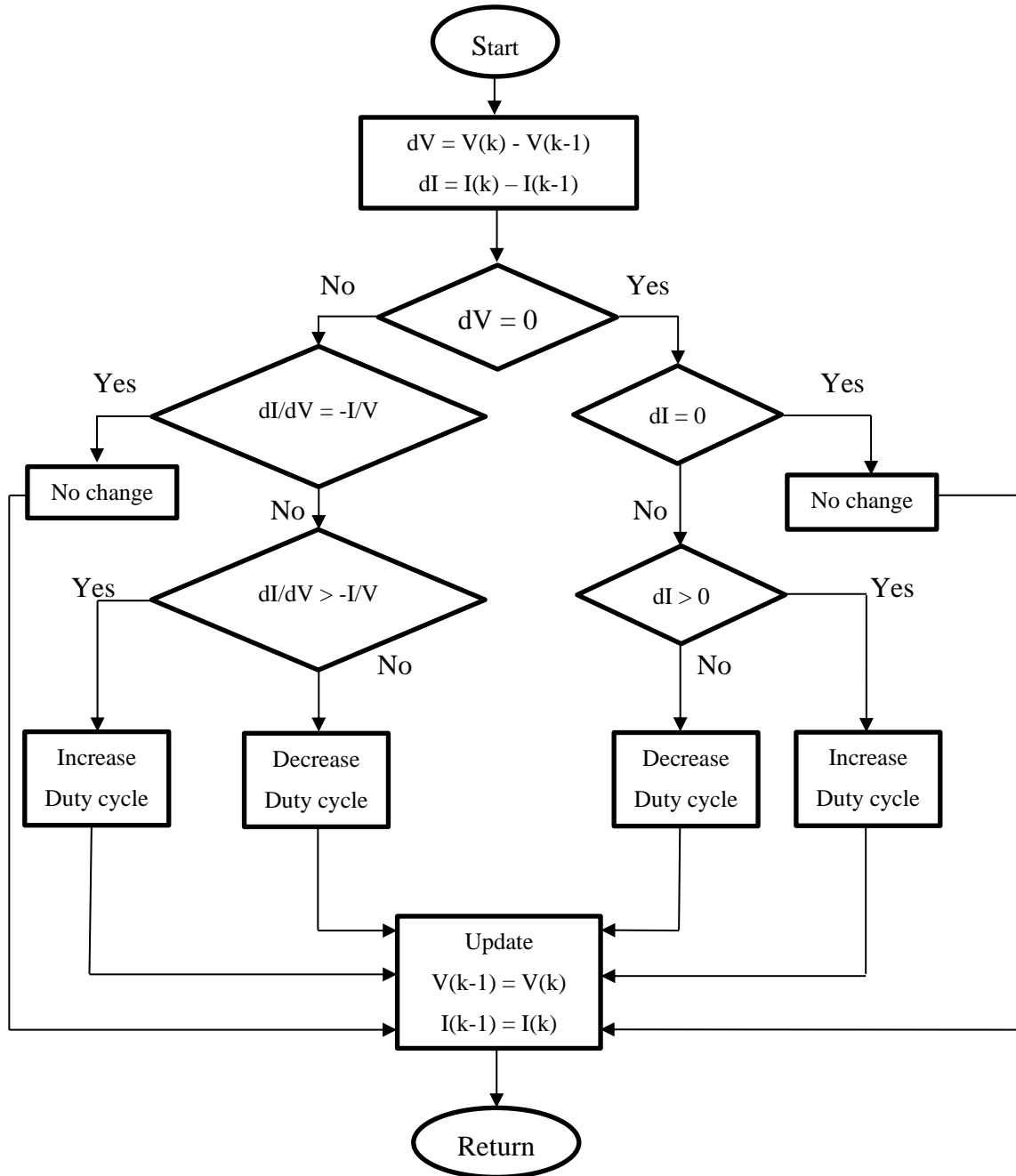
$$\text{If } \frac{dP_{PV}}{dV_{PV}} = 0, \text{ then } V_{PV} = V_{MPP} \quad 3.10$$

$$\text{If } \frac{dP_{PV}}{dV_{PV}} < 0, \text{ then } V_{PV} > V_{MPP} \quad 3.11$$

In this method, the ratio of instantaneous current to instantaneous voltage (conductance) and ratio of rate of change of current to the rate of change of voltage are compared. The duty cycle of chopper is varied depending upon the slope of power against voltage characteristics curve of PV array.

If tracked MPP lies on right side of actual MPP such that  $dI/dV < -I/V$ , at that time the value PV voltage should be decreased and if tracked MPP lies on left side of actual MPP such that  $dI/dV > -I/V$ , at that time the value PV voltage should be increased to grasp actual MPP. The PV voltage can be change by changing the duty cycle of DC/DC convert which is

connected across PV array. If  $dV = 0$  and  $dI = 0$  the duty cycle should remain same as that of previous value. If  $dV = 0$  and  $dI > 0$  then duty cycle should be increased. If  $dV = 0$  and  $dI < 0$  then duty cycle should be decreased. The flow chart explaining incremental conductance is presented in Figure 3.9.



**Figure 3.9: Flow chart explaining incremental conductance MPPT technique**

Incremental conductance method can further be improved by combining it with integral regulator technique.

### 3.7 INTEGRAL REGULATOR

Integral regulator is used to minimize error which is shown in equation 3.12.

$$e = \frac{dI_{PV}}{dV_{PV}} + \frac{I_{PV}}{V_{PV}} \quad 3.12$$

The output signal generated by integral regulator is equal to the correction in duty cycle. The block diagram of incremental conductance with integral regulator is presented in Figure 3.10.

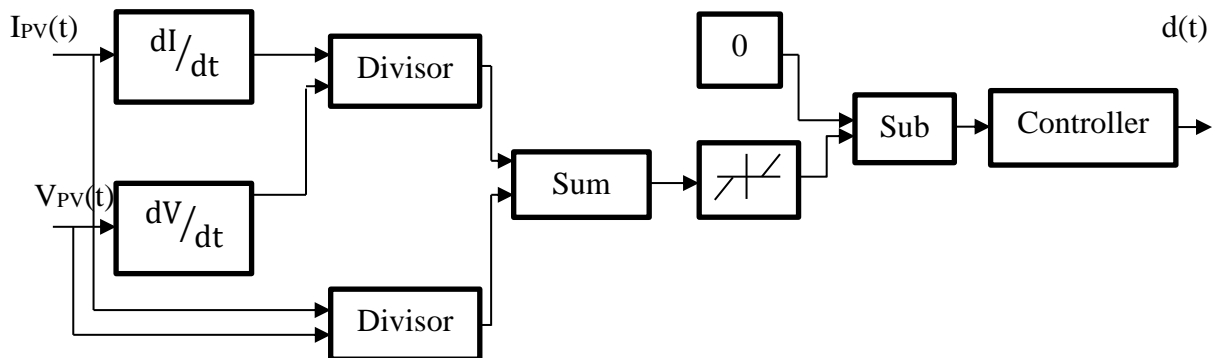


Figure 3.10: Incremental conductance modified with integral regulator

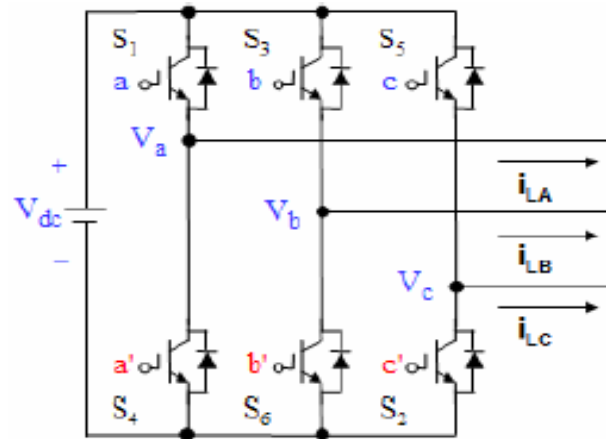
### 3.8 VOLTAGE SOURCE INVERTER

In Power-Electronics inverter stands in category of converters that runs on DC either DC current or DC voltage source and convert it into AC current or AC voltage respectively. It is the opposite of the rectifiers. In voltage source inverter (VSI), the supply of inverter is a voltage source and in current source inverters (CSI) the supply of inverter is current source. In VSI output voltage can be controlled. The voltage waveform of ideal VSI does not depend on load coupled with it. Practically a VSI can be cast-off as both 1-phase and 3-phase configuration.

VSI can function in two behaviors, for instance square wave or stepped wave mode in addition with PWM (pulse width modulation) mode. PWM inverter control scheme offers high output quality whereas, square wave mode offers simplicity.

For a variable input voltage source, the output voltage of the VSI can be maintained constant by shifting the gain of the inverter. And gain can be varied using PWM technique.

The 3-phase VSI comprises of the three single phase inverter legs which are equivalent to three half-bridge inverters. 3-phase output voltage is obtained by the contribution of each inverter leg. The typical circuit diagram of full bridge 3-phase VSI is presented in Figure 3.11.



**Figure 3.11: 3-phase VSI**

Switch  $S_1$  to  $S_6$  stands power switches which can be opened or closed by providing appropriate gate signal. This gate signal should be controlled by using inverter control scheme in a sequential manner. Space vector pulse width modulation (SVPWM) is one of many inverter control schemes. SVPWM utilizes more input DC voltage and cause lesser total harmonic distortions (THD) in the output than that of other PWM technique.

The output of inverter contains harmonic contents and these harmonics has adverse effect on load connected to it. These harmonics can be eliminated using an efficient inverter control scheme and by connecting harmonic filters at the output of inverter.

### 3.9 SPACE VECTOR PWM

The circuit diagram of a typical 3-phase VSI is presented in Figure 3.8.  $S_1$  to  $S_6$  represent six power switches that profiles the output. These switches are controlled by the gate signal given at the terminals  $a'$ ,  $a$ ,  $b'$ ,  $b$ ,  $c'$  and  $c$ . As soon as an upper transistor is switched on, for instance as soon as  $a$ ,  $b$  or  $c$  stands 1, the other transistor on corresponding leg is switched off, for instance  $a'$ ,  $b'$  or  $c'$  stands 0. Consequently, the correlated on, off states of the transistors  $S_1$ ,  $S_3$  and  $S_5$  are the determinants of the output voltage.

The association among the gate signal vector  $[a \ b \ c]'$  and the phase voltage vector  $[V_{an} \ V_{bn} \ V_{cn}]'$  for SVPWM controlled inverter is given in equation 3.13

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (3.13)$$

The eight likely combinations of gate signals generated by SVPWM controller that is given to three upper power switches is given in Table 3.1. The state of upper switches

determines the state of lower switches of the respective leg. Corresponding to the gate signal vectors the line to neutral and line to line voltages are also given in Table 3.1.

**Table 3.1: Gate signal vectors, line to line voltages and phase voltages**

Voltage Vector	Gate signal Vectors			Line to line voltages			Line to neutral voltages		
	a	b	c	$V_{ab}$	$V_{bc}$	$V_{ca}$	$V_{an}$	$V_{bn}$	$V_{cn}$
$V_7$	1	1	1	0	0	0	0	0	0
$V_6$	1	0	1	1	-1	0	1/3	-2/3	1/3
$V_5$	0	0	1	0	-1	1	-1/3	-1/3	2/3
$V_4$	0	1	1	-1	0	1	-2/3	1/3	1/3
$V_3$	0	1	0	-1	1	0	-1/3	2/3	-1/3
$V_2$	1	1	0	0	1	-1	1/3	1/3	-2/3
$V_1$	1	0	0	1	0	-1	2/3	-1/3	-1/3
$V_0$	0	0	0	0	0	0	0	0	0

### 3.10 PROTECTION CIRCUIT

There are some undesired fault conditions during the operation in electrical distribution system. Some of these faulty conditions are listed below-

1. Over voltage in the electricity distribution system of marine ship.
2. Under voltage in the electricity distribution system of marine ship.
3. Over current condition in the electricity distribution system of marine ship.
4. Formation of island, such that when there is power cut due to any fault in electricity distribution system of marine ship.
5. Any of the fault among symmetrical and unsymmetrical line faults.

The protection circuit of PV system should be able to sense these faults and give ON/OFF signal to the circuit breaker connected between PV system and ship's bus. During the faulty conditions, the circuit breaker should be able to isolate PV system and ship's bus to keep it out of the faulty electricity distribution system of the ship.

The electricity distribution of the ship is similar to a micro-power grid. According to the technical standards listed in section 3.12 for take care the synchronization requirement and

the safety requirements of the equipment connected to the ship's bus the protection circuit of PV system should be able to follow the conditions listed below-

1. The tolerable distinct harmonics level intends to be lesser than 3% (individually, current and voltage harmonics) and Total Harmonics Distortion (THD) tolerable for both output current and output voltage intend to be lesser than 5%.
2. If frequency grasps 50.5 Hz or more, and 47.5 Hz or below for at least 0.2 seconds, then the system should be able to provide a tripping signal.
3. At the point of interconnection, the system shall not be the reason for voltage fluctuation superior than  $\pm 5\%$ .
4. If voltage ranges above 110% or below 80% for at least 0.2 seconds, then the system should be able to provide a tripping signal.
5. Inside the window of two seconds after the formation of an island, the protection circuit shall be able to spot the formation of island and terminate the energization of ship's bus.
6. The photovoltaic power systems, for the safety of inbuilt power converters, should have protection degree IP 54 for covered mounting and protection degree IP 65 for open-air mounting

### 3.11 TECHNICAL STANDARDS USED

The following standards have been used in the proposed methodology.

**IEEE 1547:2003**, As per clause 4.4.1, Inside the window of two seconds after the formation of an island, the protection circuit shall be able to spot the formation of island and terminate the energization of ship's bus.

**IEEE 519:2003**, As per clause 5.2, The tolerable distinct harmonics level intends to be lesser than 3% (individually, current and voltage harmonics) and Total Harmonics Distortion (THD) tolerable for both output current and output voltage intend to be lesser than 5%.

**IEC 62109-1, IEC 62109-2**, The photovoltaic power systems, for the safety of inbuilt power converters, should have protection degree IP 54 for covered mounting and protection degree IP 65 for open-air mounting.

**CEA, File No.12/X/STD(CONN)/GM/CEA:2013, Part 3, Section 4**, As per clause 11.6(a), If voltage ranges above 110% or below 80% for at least 0.2 seconds, then the system should be able to provide a tripping signal.

**CEA, File No.12/X/STD(CONN)/GM/CEA:2013, Part 3, Section 4,** As per clause 11.6(b), If frequency grasps 50.5 Hz or more, and 47.5 Hz or below for at least 0.2 seconds, then the system should be able to provide a tripping signal.

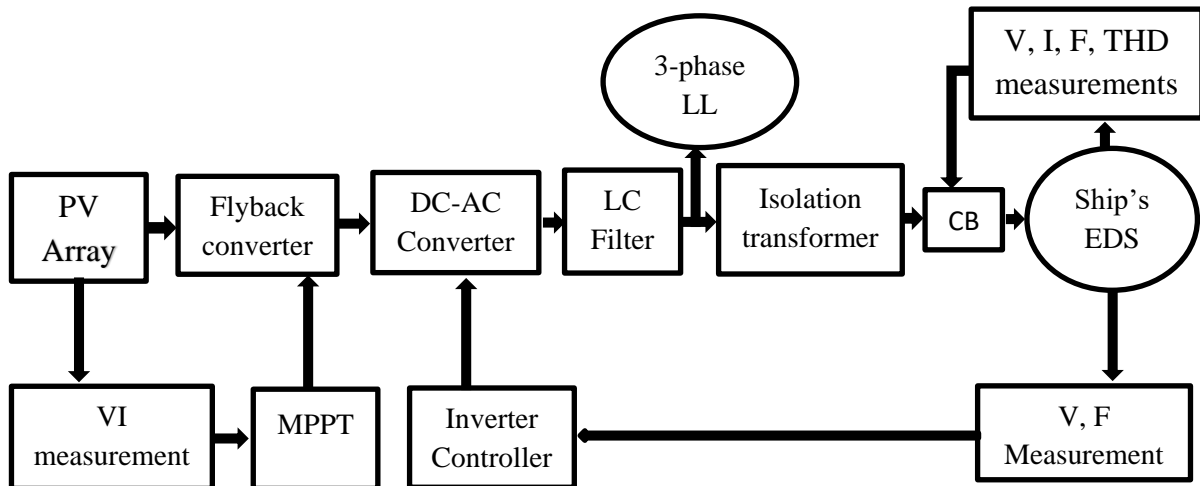
**CEA, File No.12/X/STD(CONN)/GM/CEA :2013, part 3, section 4,** As per clause 11.8, On every occasion when the generating station is synchronized with the electricity distribution system, then at the point of interconnection the system shall not be the reason for voltage fluctuation superior than  $\pm 5\%$ .

## CHAPTER-4

### DESIGN METHODOLOGY

#### 4.1 PROPOSED WORK FLOW/ METHODOLOGY

The proposed model of bus connected PV system for marine ships is an improved system which helps to feed the local-load connected to it and transmit excess solar energy into the electricity distribution system of marine ship. To simulate the model, MATLAB R2017a simulink software is used. The block diagram of the proposed system is presented in Figure 4.1.



**Figure 4.1 Block diagram of bus connected PV system for marine ships**

In the simulation model, variable irradiance and temperature levels with respect to time (as shown in Figure 5.1) are provided to a PV array having 5 parallel strings with 10 series connected modules per string. This PV array is having 700 V peak DC voltage in case of open circuit, 30 A peak current in case of short circuit and is able to produce maximum power of 18 KW.

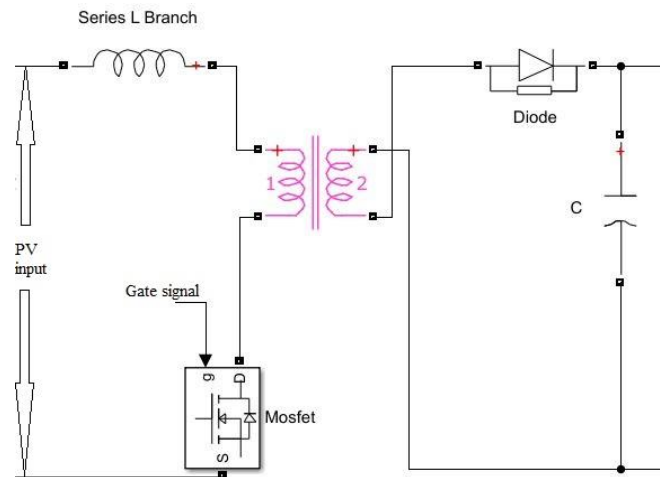
The output current of PV cell is shown in equation 4.1

$$I = I_L - I_o \left( e^{\frac{q(V-IR_S)}{AKT}} - 1 \right) - \frac{V-IR_S}{R_{SH}} \quad 4.1$$

V and I stands for solar cell's output voltage and current respectively,  $I_0$  represents the dark saturation current, q represents the charge of an electron, A stand for diode quality factor, also identified as ideality factor, k symbolizes the Boltzmann constant, T symbolizes the absolute temperature,  $R_{SH}$  and  $R_S$  symbolizes the shunt and series resistances of the solar cell.

For an ideal circumstance  $R_{SH}$  would be infinite and  $R_S$  would be zero.

To trace the MPP of PV array an improved high-power flyback DC to DC converter with silicon carbide (SiC) switch is used, as proposed in literature [42] and the duty cycle of this chopper is controlled by incremental conductance modified with integral regulator MPPT technique. Flyback converter is advantageous to work for different input voltage levels while maintaining desired output voltage by providing appropriate transformer's turn ratio. It provides electrical isolation between PV array and rest of the inverter. It performs both buck and boost operation when required [23]. The simulation model of flyback inverter is presented in Figure 4.2.



**Figure 4.2- Simulation circuit of Flyback converter**

Modified incremental conductance with integral regulator control scheme is helping to follow the trail of MPP of PV array by adjusting the duty cycle of the chopper, which changes chopper's output DC voltage and current values.

The duty cycle of flyback converter is shown in equation 4.2.

$$D = \frac{V_{out}'}{V_{out}' + V_{in}} \quad 4.2$$

$$V_{out}' = V_{out} \times \frac{N_p}{N_s} \quad 4.3$$

Where,

$V_{out}'$  is the output voltage of chopper, but as seen by the primary side.

$N_s$  and  $N_p$  represents the no. of turns in secondary and primary side of the transformer respectively.

Maximum power point is attained when,

$$\frac{dP_{PV}}{dV_{PV}} = 0 \quad 4.4$$

here,  $P_{PV} = V_{PV} \times I_{PV}$

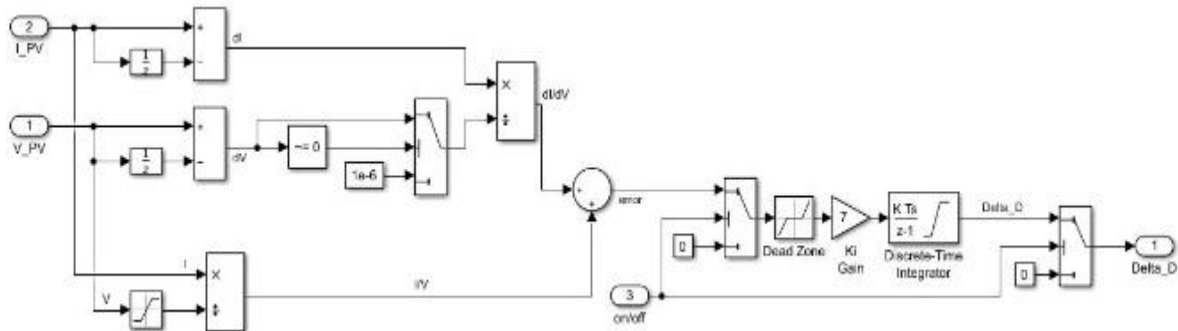
$$\frac{d(V_{PV} \times I_{PV})}{dV_{PV}} = I_{PV} + (V_{PV} \times \frac{dI_{PV}}{dV_{PV}}) \quad 4.5$$

The integral regulator minimizes the error (e)

$$e = \frac{dI_{PV}}{dV_{PV}} + \frac{I_{PV}}{V_{PV}} \quad 4.6$$

Regulator output is equal to the correction in duty cycle.

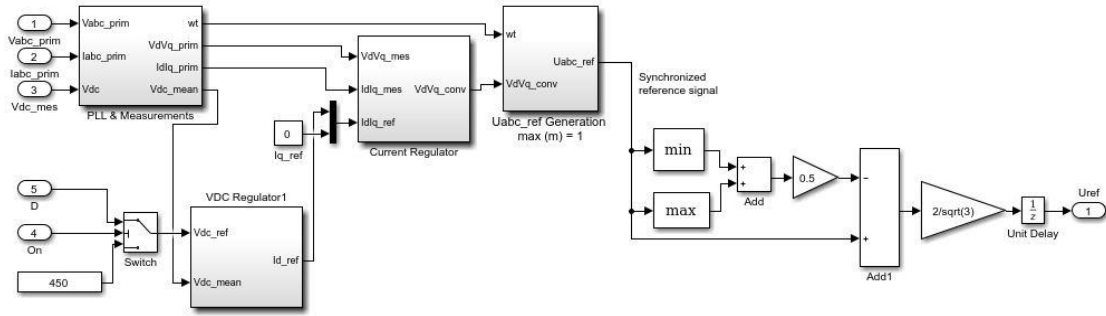
Simulation circuit diagram of incremental conductance modified with integral regulator control technique is presented in Figure 4.3.



**Figure 4.3: Incremental conductance modified with integral regulator MPPT technique**

The tracked maximum power of the PV array is then fed to a 3-phase full-bridge voltage source bridge inverter. This inverter is controlled by a space vector pulse width modulation (SVPWM) control scheme. The control scheme also helps to maintaining the frequency of output AC power of the inverter equals to the frequency of electricity distribution system of ship. With SVPWM control scheme inverter utilizes 15% more input DC power than that of SPWN as compared in literature [33], [43].

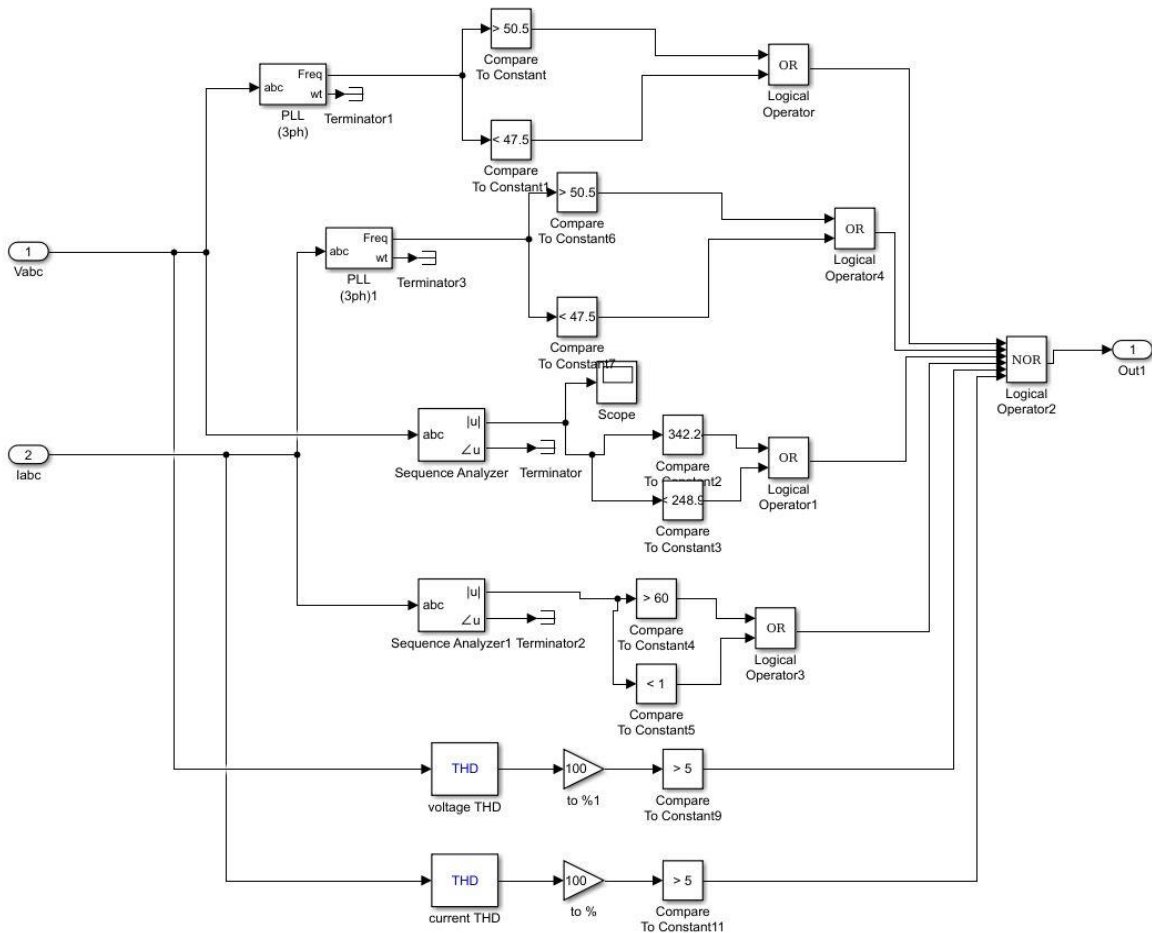
Simulation circuit diagram of SVPWM is made known in Figure 4.4. This control scheme is also helping to maintain constant output voltage, whereas output current may vary depending upon the irradiance and temperature of the incident sun light for that instant of time.



**Figure 4.4: Voltage controlled SVPWM**

To eliminate higher order harmonics in the output a simple LC filter is used in each phase before utilizing 3 phase AC power [34]. This filtered AC power is then feeding 10kW local-load and injecting excess generated electric power into the ship’s power grid. For the protection purposes, an insulation transformer is installed in between inverter and ship’s bus to electrically isolating them.

To protect the PV system and electrical distribution system of ship from some undesired fault conditions (listed in section 3.11) during the operation a protection system is designed as presented in Figure 4.5.



**Figure 4.5: Simulation circuit of protection system**

This protection circuit will detect the fault conditions and give signal to the circuit breaker connected in between PV system and power grid of ship.

## 4.2 ASSUMPTIONS AND CONSTRAINTS

1. Initial value of duty cycle for buck-boost chopper is 0.5.
2. Maximum value of duty cycle values is 0.9.
3. Minimum value of duty cycle is 0.1.
4. Ship's bus is assumed all time energized

## 4.3 SIMULATION MODEL

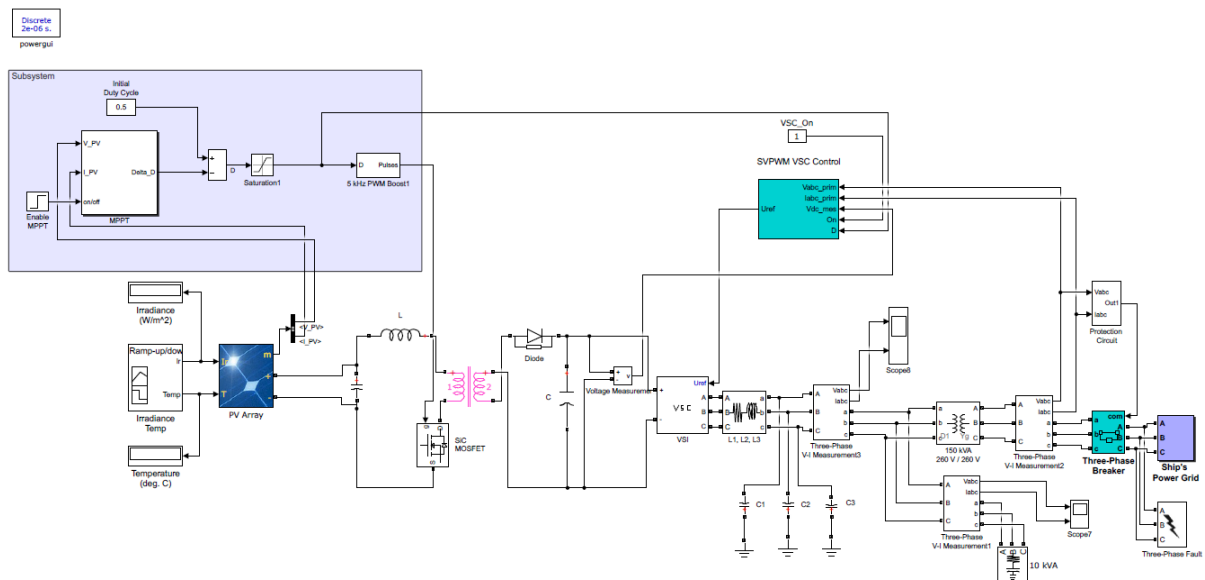


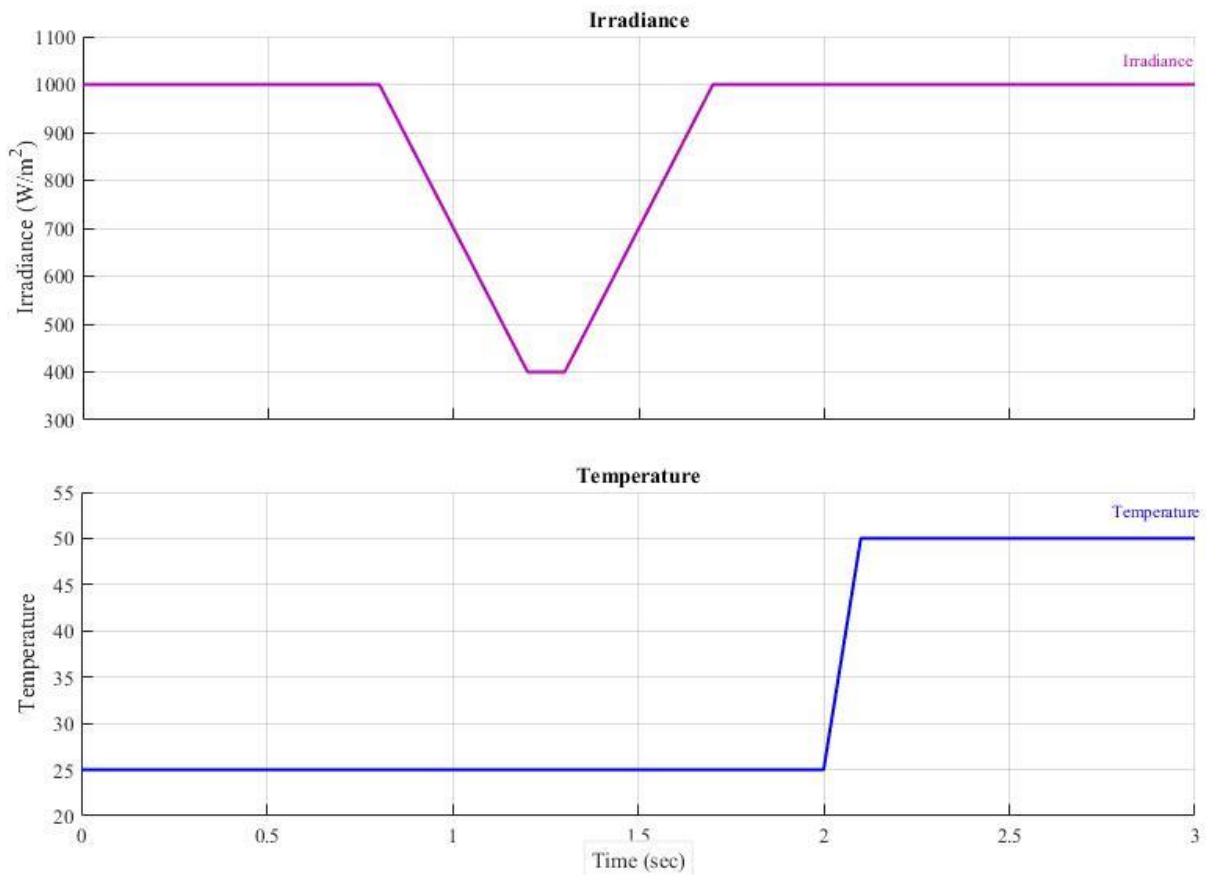
Figure 4.6: Simulation model of bus connected PV system for marine ships

## CHAPTER-5

# RESULTS AND DISCUSSIONS

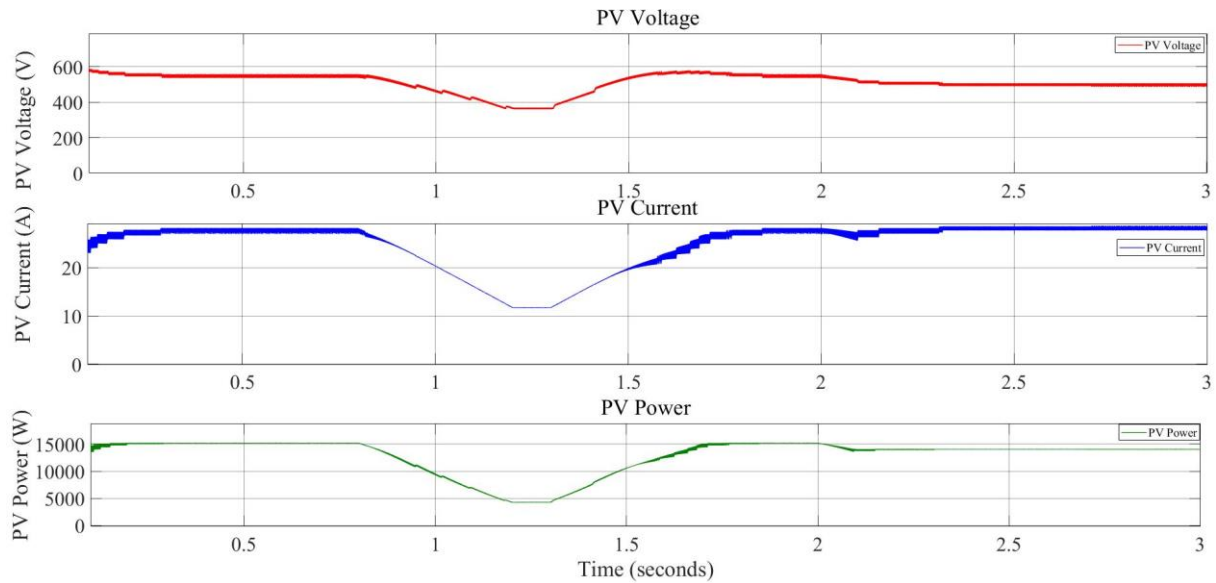
### 5.1 SIMULATION RESULTS

Variable irradiance and temperature input to PV array are shown in Figure 5.1 respectively. Irradiance has been varied from 1000 W/m<sup>2</sup> to 400 W/m<sup>2</sup> and then again to 1000 W/m<sup>2</sup>. Temperature has been varied from 25 °C to 40 °C.



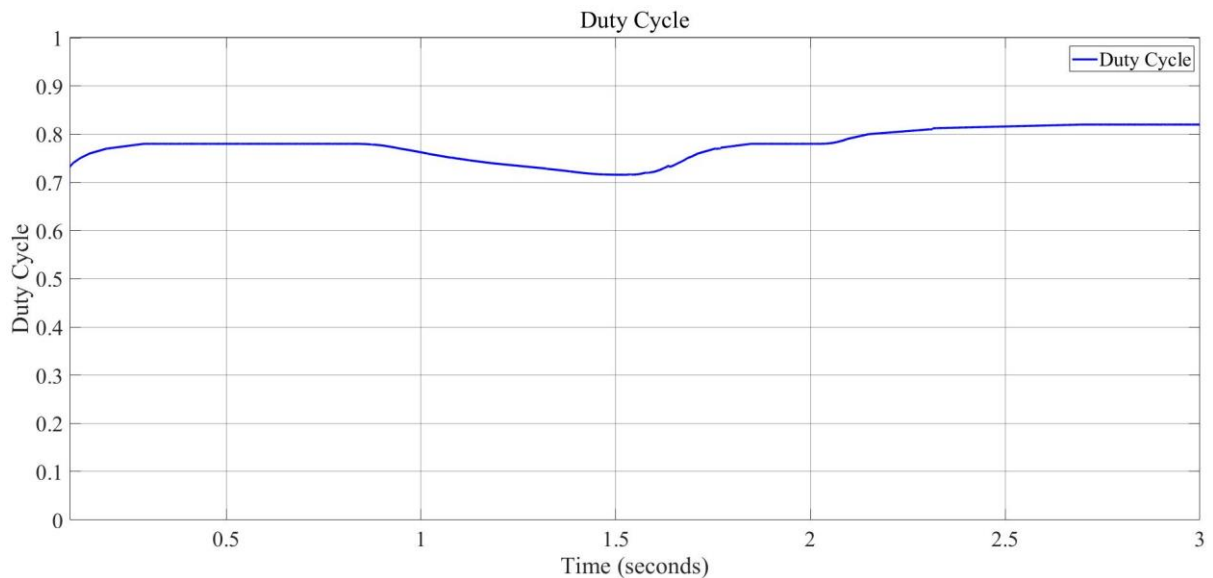
**Figure 5.1: Variable irradiance and temperature inputs to PV array w.r.t time**

PV array's output is dependent on the input irradiance and temperature as explained in section 3.4.2 and 3.4.3. Corresponding to the input irradiance and temperature the output voltage, output current and output power are as presented in Figure 5.2 respectively.

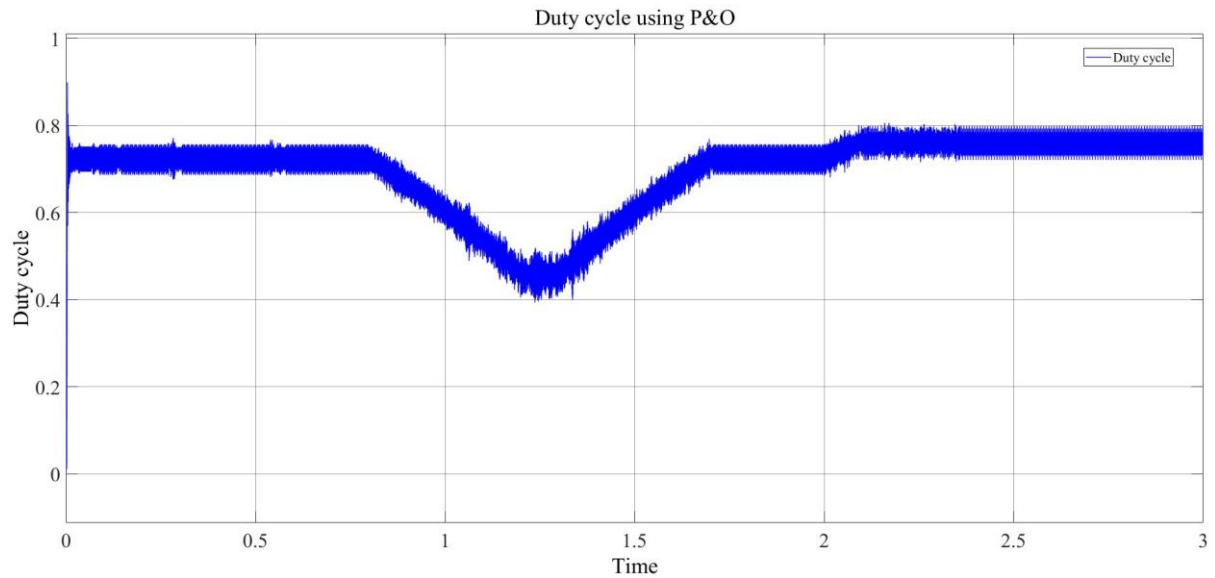


**Figure 5.2: PV array's voltage, current and power outputs**

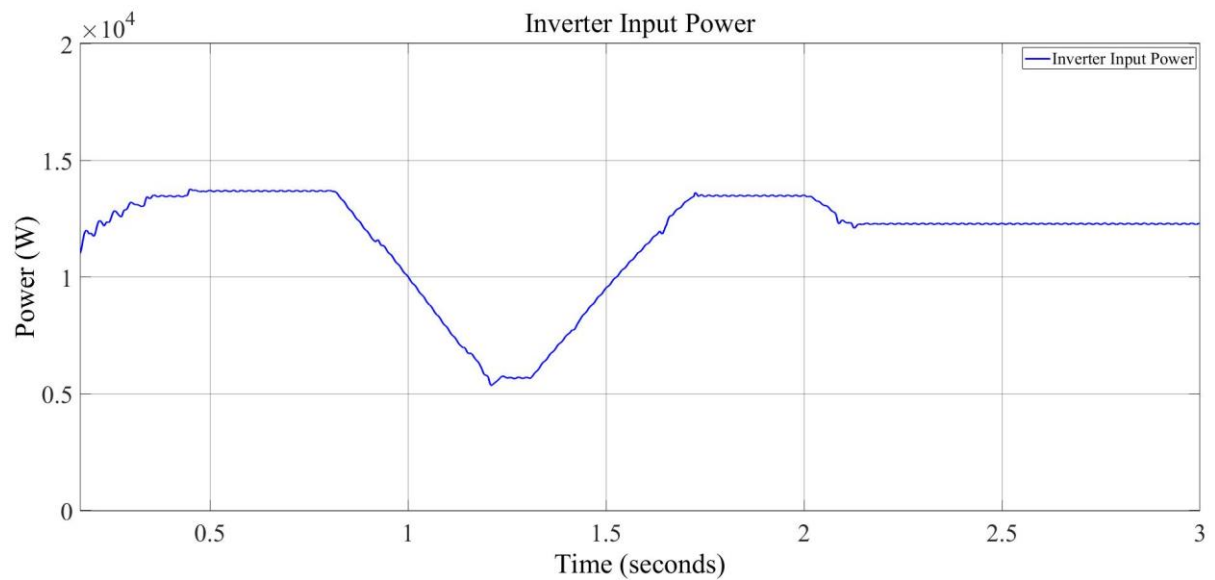
The waveform of duty cycles of flyback converter controlled by incremental conductance with integral regulator and perturb & observe MPPT are presented in Figure 5.3 and Figure 5.4 respectively. As shown in these figures, the proposed system that uses Incremental conductance modified with integral regulator MPPT technique is having very few oscillations around actual MPP then that of perturb & observe MPPT.



**Figure 5.3: Incremental conductance modified with integral regulator controlled chopper's Duty cycle**

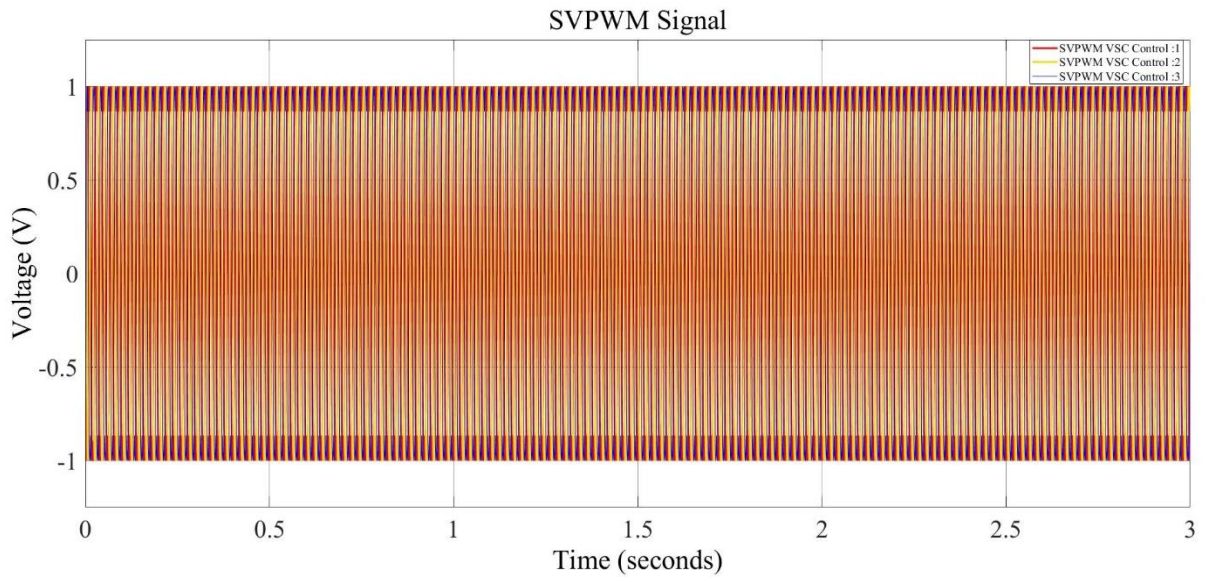


**Figure 5.4: Perturb & Observe controlled chopper's Duty Cycle**

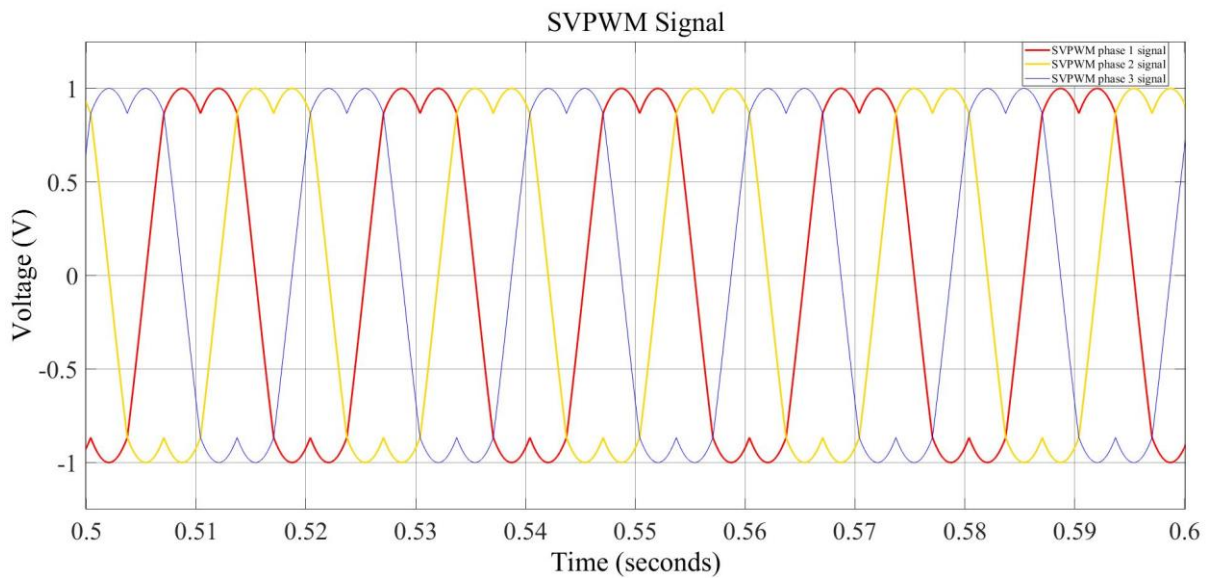


**Figure 5.5: flyback converter's output / inverter's input power**

The output power of high power flyback converter continuously changing with the change in irradiance and temperature and is shown in Figure 5.5.

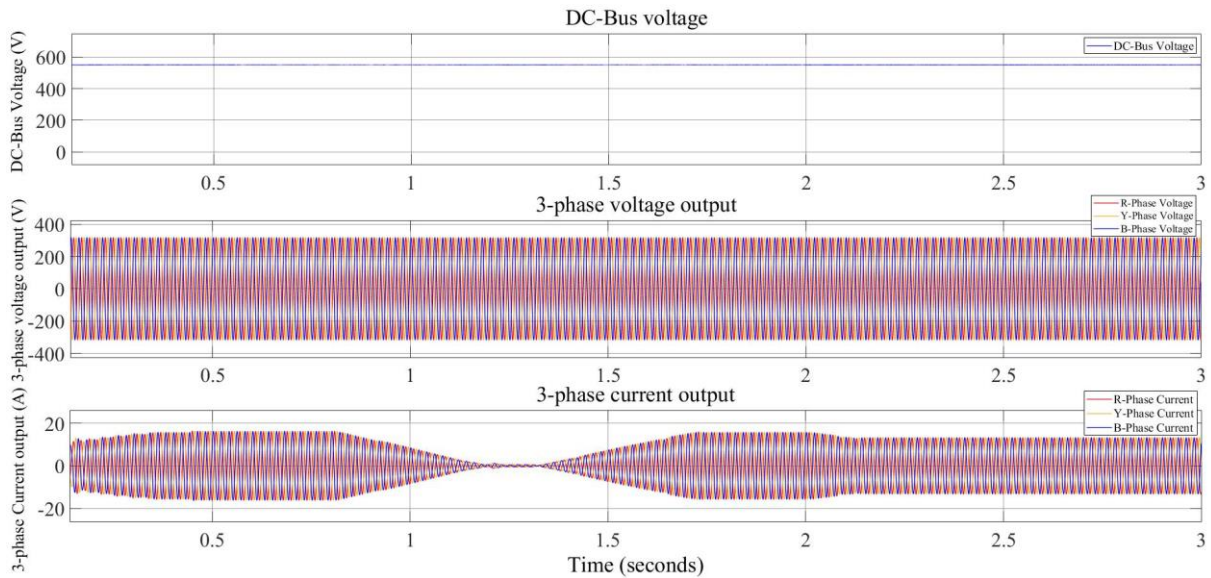


**Figure 5.6: SVPWM output signal**

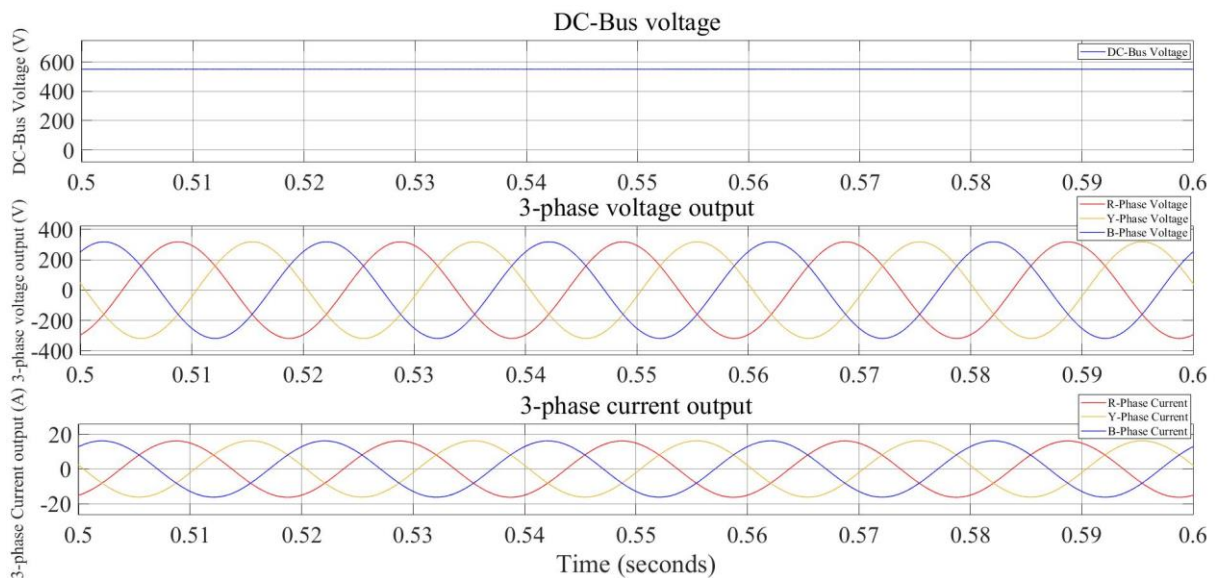


**Figure 5.7: SVPWM instantaneous output signal**

The output signal of SVPWM for 0 to 3 seconds and 0.5 to 0.6 seconds is presented in Figure 5.6 and Figure 5.7 respectively. This signal is such that it helps to control the inverter switches in such a manner so that the inverter and ship's power grid would synchronize. Frequency of this signal is 50 Hz.

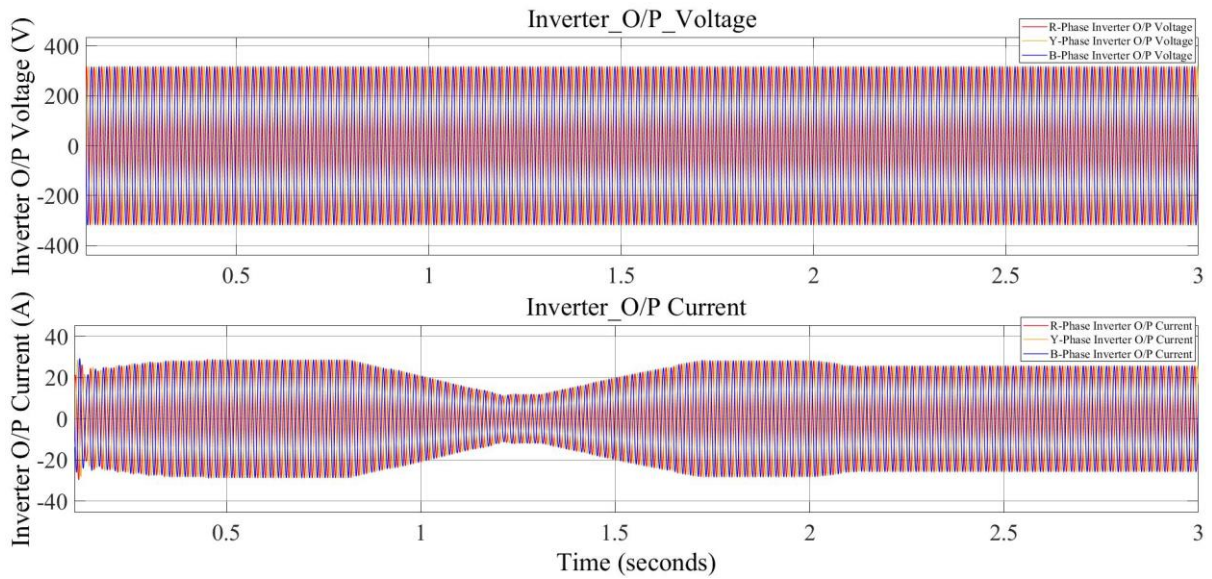


**Figure 5.8: Steady-state chopper output voltage, ship's bus side inverter voltage and current outputs**

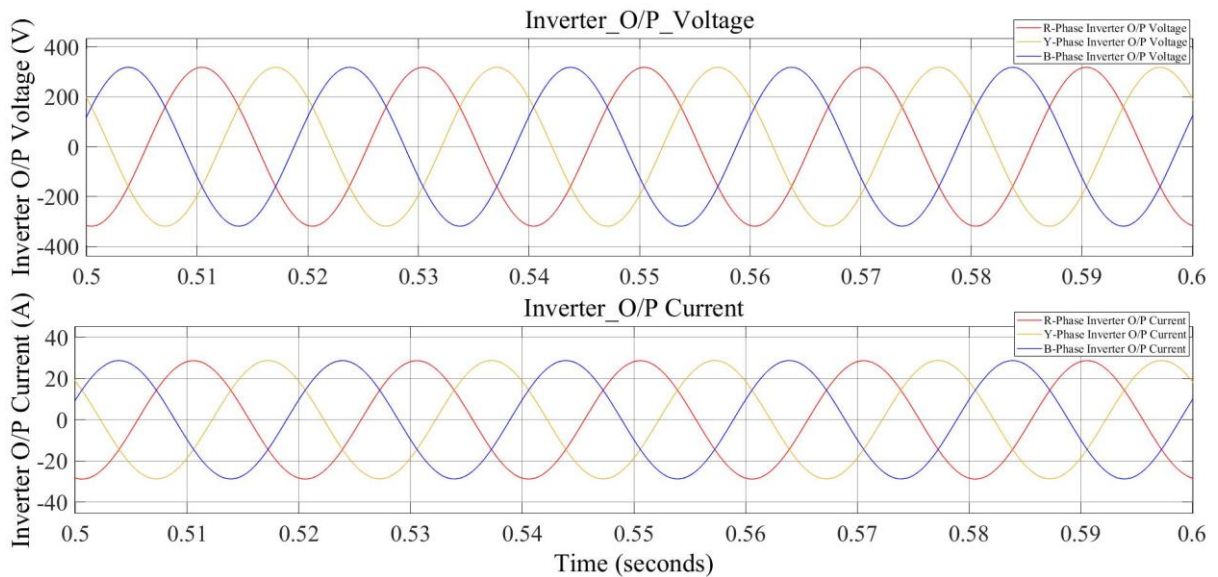


**Figure 5.9: Instantaneous chopper O/P voltage, ship's bus side inverter voltage and current outputs**

Steady-state waveforms of DC bus voltage, output voltage and current feeding ship's bus are given in Figure 5.8. Instantaneous waveform of DC bus voltage, output voltage and current feeding ship's bus for 0.5 to 0.6 second are presented in Figure 5.9. The root mean square value of output voltage is 220 V and frequency is 50 Hz. As shown in these figures, voltage waveform is constant despite of variable input supply whereas current is varying with the change in input. These are the desired conditions.

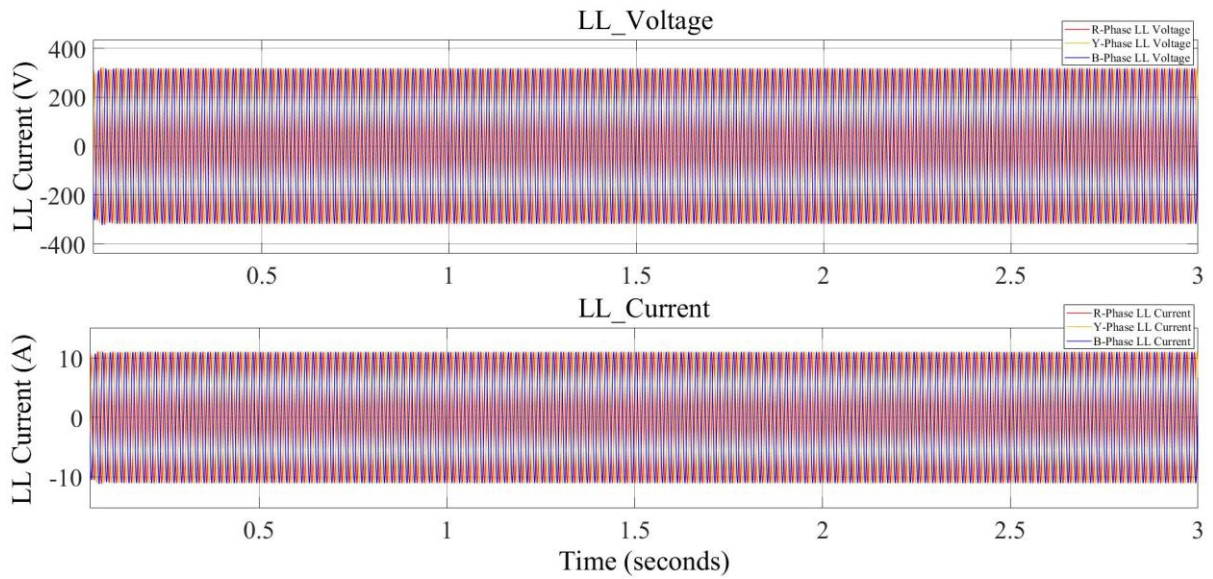


**Figure 5.10: Inverter side steady-state voltage and current outputs of inverter**

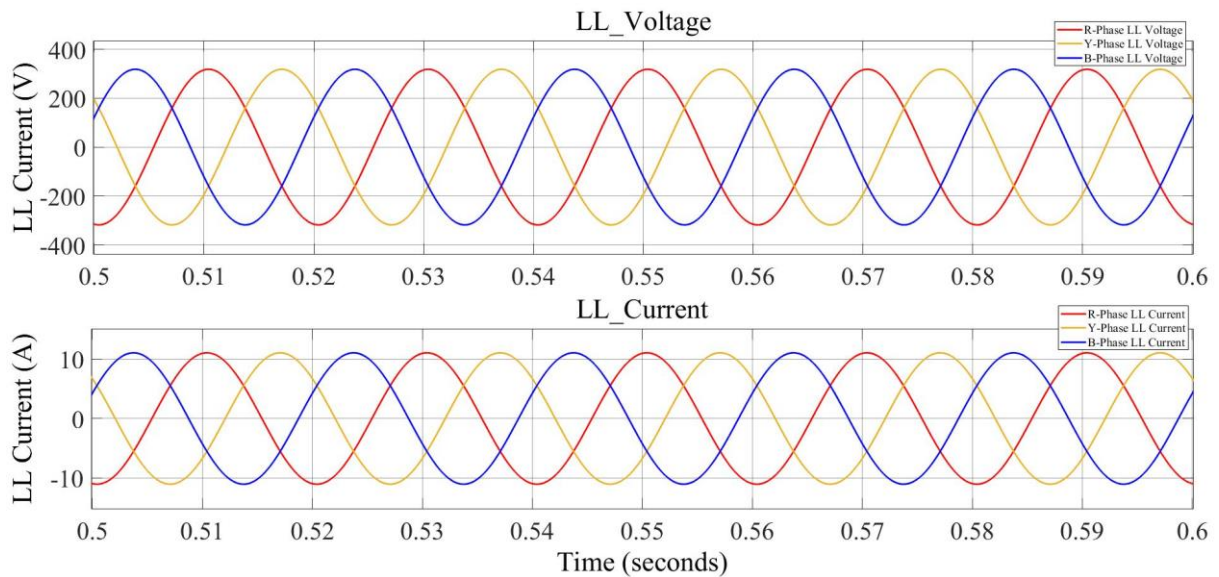


**Figure 5.11: Inverter-side Instantaneous voltage and current output of inverter**

Steady-state waveforms of inverter output voltage and output current are shown in Figure 5.10 respectively and their instantaneous waveform for 0.5 to 0.6 seconds are presented in Figure 5.11. This current will further be distributed to feed the local load and power grid of ship.



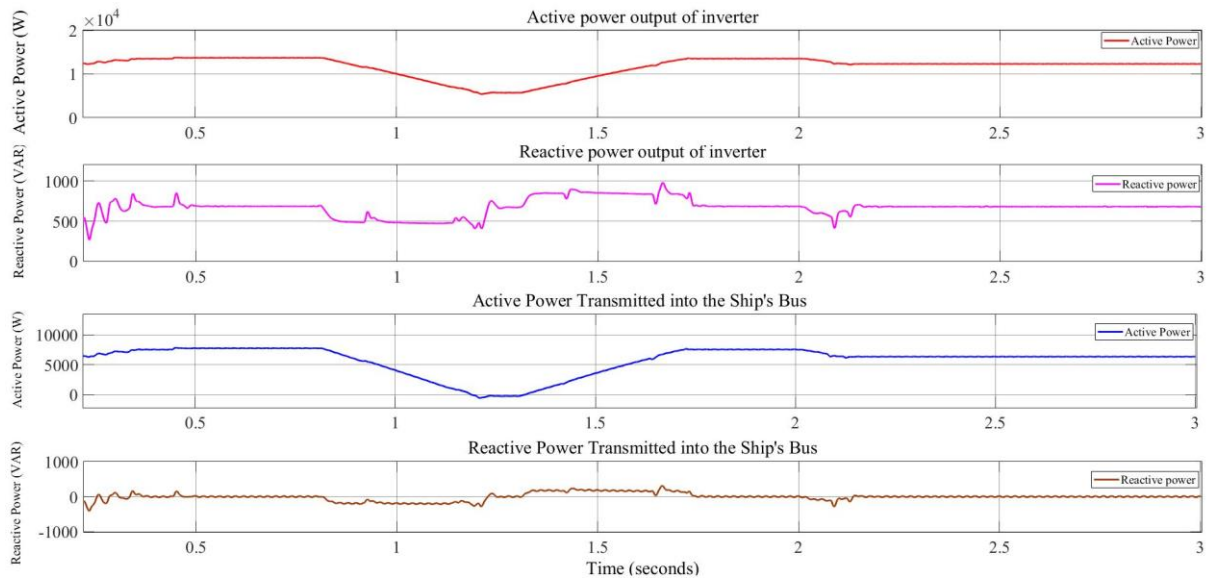
**Figure 5.12: Steady-state voltage and current inputs to the local load**



**Figure 5.13: Instantaneous waveforms of voltage and current inputs to the local load**

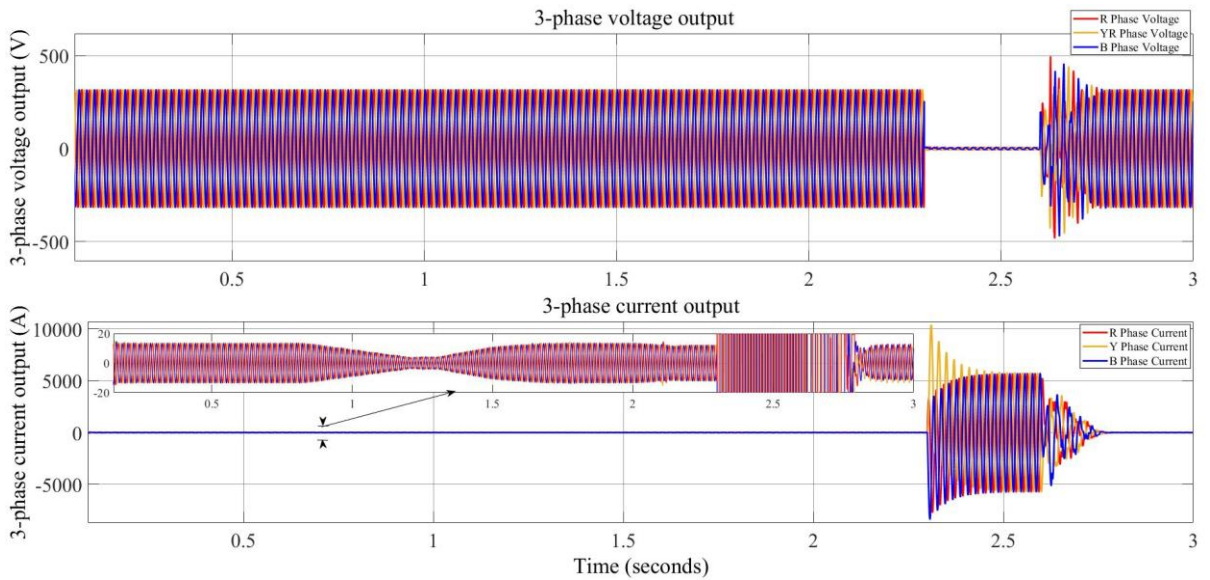
Voltage and current inputs to the local load are shown in Figure 5.12 respectively and their instantaneous waveforms for 0.5 to 0.6 seconds are shown in Figure 5.13 respectively. RMS voltage value is 220 V and frequency is 50 Hz.

Active power, reactive power output of PV inverter, active power, reactive power injected into the grid is shown in figure 5.14 respectively. These waveform shows that the maximum inverter output is contribution toward active power.



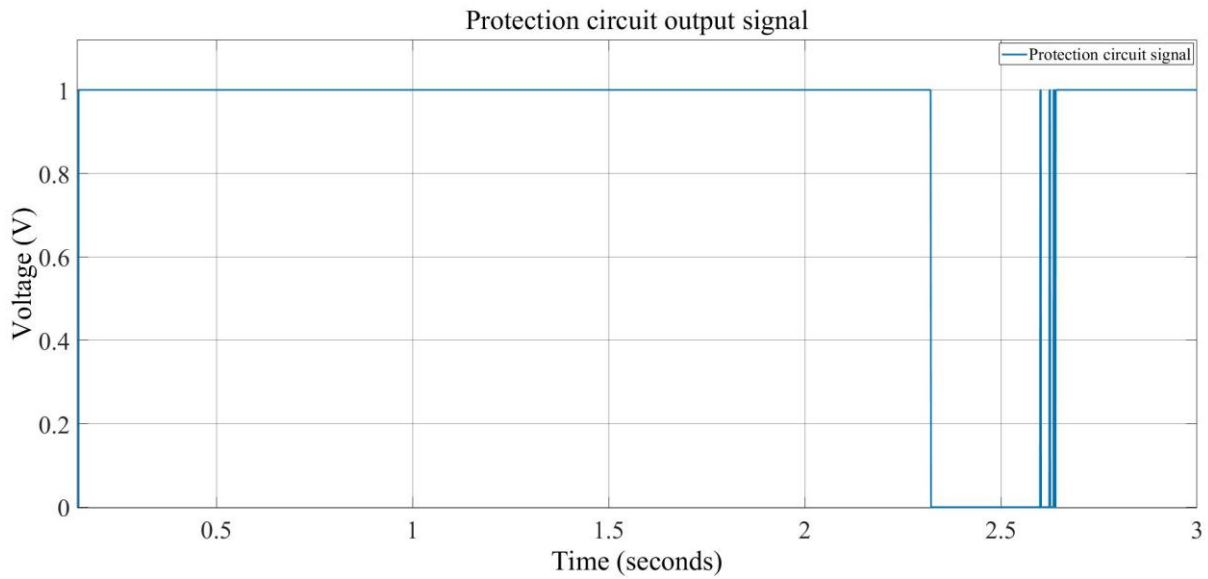
**Figure 5.14: Active and Reactive power output of inverter and of power transmitted into ship's bus**

During a 3-phase symmetrical fault in the power grid from 2.4 to 2.6 seconds of total simulation time, the low voltage and high current waveforms are presented in the Figure 5.15. this high value of current can damage the PV system and connected local load.

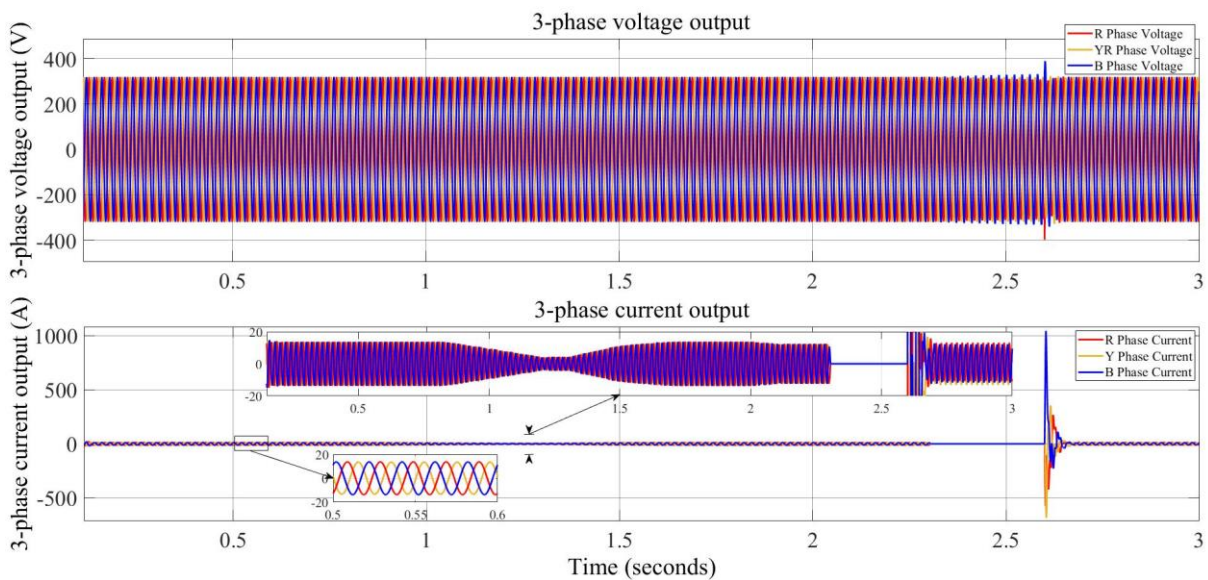


**Figure 5.15: PV inverter's output during fault condition without protection scheme**

The protection circuit is able to sense the fault and give the signal to circuit breaker. The signal generated by the circuit breaker is presented in Figure 5.16.



**Figure 5.16: Protection circuit's output signal**



**Figure 5.17: PV inverter's output during fault condition with protection scheme**

Inverter's output voltage and current at the point of interconnection with the power grid of ship is shown in Figure 5.17 respectively. In this figure, as it can be observed that, during the time of fault the circuit breaker is able to disconnect PV system and ship's power grid within the obligated time period after the happening of fault. There is no any flow of current during fault between PV system and power grid of ship. Also, the terminal voltage and steady-state current values at the interconnection are within the limits.

Despite of desired operation of PV system, due to the switching action of circuit breaker, some transients can be observed in the inverter's output current waveform at the

interconnection terminals. These transients occur for a very few time periods but after a long term use these transients can affect the circuit breaker.

## 5.2 MATHEMATICAL ANALYSIS AND CALCULATIONS

No. of PV modules = 50

Area covered by 1 module = 1.63 m<sup>2</sup>

Area covered by 50 modules = 50×1.63 m<sup>2</sup>  
= 81.5 m<sup>2</sup>

Efficiency of 1 PV module = 30.52%

At STC (Standard Test Conditions),

Irradiance = 1000 W/m<sup>2</sup>

Temperature = 25 °C

Inverter's output for 50 modules at STC,

$V_{\text{Phase}} = 220 \text{ V}$

$I_{\text{Phase}} = 20.8 \text{ A}$

Power ( $P_{\text{Output}}$ ) = 3× $V_{\text{Phase}}$ × $I_{\text{Phase}}$   
=13.5 kVA

Energy trapped in 81.5 m<sup>2</sup> area = 13.5 kVAh

Energy trapped per square meter area = 150.018 VAh/m<sup>2</sup>

Efficiency of power converters =  $\frac{\text{Inverter output}}{\text{PV output}} \times 100$

PV array's output power at STC = 50×305.2 W  
= 15.260 kW

Inverter's output at STC = 13.5 kVA

Therefore, efficiency of power converters = 88.5 %

## 5.3 DISCUSSIONS/ INFERENCES DRAWN

Photovoltaic power generation is acquiring more implications as a source of renewable energy by reason of its numerous benefits. These benefits comprise of eternal green energy production system, effortlessness upkeep and many more. Nevertheless, their high

installations cost is the downside. Furthermore, weather conditions, for instance the temperature, irradiance, sun shading and insolation level influences the PV panel output.

In the proposed system, variable irradiation and temperature levels are provided to the PV array using a signal generator block while simulation.

Perturb and observe MPPT algorithm is a simple method of tracking the maximum power point of PV array. But the tracked power point oscillates around the actual maximum power point because of the limitation of having a fixed step to update the duty cycle of the flyback converter. This limitation can be eliminated by using incremental conductance modified with integral regulator MPPT technique.

High power flyback converter controlled by incremental conductance modified with integral regulator MPPT is helping in efficiently tracking MPP and cause very few oscillations around actual MPP. Also, High power flyback converter is providing electrical isolations b/w PV array & power converters and it helps the PV system to operate for different input voltage levels.

Utilization of DC input power by the Inverter is dependent on type of inverter and inverter control scheme. SVPWM control scheme is able to utilize 15% more DC input power than that of sinusoidal pulse width modulation scheme and cause less THDs in the output voltage and current than that of SPWM. Also, SVPWM is able to synchronize PV inverter and electricity distribution system of marine ship by matching their voltages and frequencies.

Happening of the faulty for instance over voltage, under voltage, over current, under current, THD and frequency deviations can seriously damage the PV system and local load connected to it. In order to protect the system against these faults, the proposed protection circuit is able to sense and provides ON/OFF signal to circuit breaker and prevent the PV system from feeding power grid of ship during any of the above-mentioned faults including islanding. Also, to protect system from transients, electrical noise and flow of DC component into the power grid of ship an isolation transformer has been used to electrically isolate PV inverter and electricity distribution system of ship.

## CHAPTER-6

# CONCLUSIONS AND FUTURE WORK

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### 6.1 CONCLUSIONS

Power demand is growing gradually. To meet the energy demand, conventional energy sources are not sufficient because of environment concern therefore, there is a need to exploit renewable energy sources for meeting the ever-increasing energy demand. It is well known from the literature that the processing of power from renewable energy source is a challenging issue and improvements are needed to make the current technology reliable, optimum and efficient.

The proposed system can be used to transmit solar power into the power grid of ship in a reliable and efficient manner. The system has the ability to efficiently trace the MPP of PV array, input DC voltage utilization by the inverter is 15% more than that of SPWM controlled inverter. The system has electrical isolation between PV array and inverter, also between inverter and ship's power grid. The protection circuit of the proposed PV system can be trusted with the protection against different kinds of faults. This system will definitely prove to be a technology breakthrough for marine ships.

### 6.2 FUTURE WORK

1. Battery backup system can be installed with the proposed PV system to store energy in order to supply load at the time of power outage, shading /cloudy weather and after sun set.
2. Wind turbine can also be installed in alliance with PV system to trap wasted wind energy.
3. Efficiency of flyback converter can be improved by minimizing the switching losses and core losses of flyback transformer.
4. The switching of the circuit led to transients in the output current. These transients can be minimized.
5. The protection circuit can be improved by taking into account the active, reactive power and other constraints.

## LIST OF PUBLICATIONS

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1. A research paper entitled “**Design & Analysis of Improved Bus-Tied Photovoltaic System for Marine Ships**” has been accepted for publication in “Indian Journal of Geo Marine Sciences”.
2. A research paper entitled “**An Improved Protective PV System to Inject Active Power into the Power Grid of Marine Ships**” has been communicated to “Indian Journal of Geo Marine Sciences”.

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