“DESIGN AND IMPLEMENTATION OF 1.5 kW SOLAR PUMPING SYSTEM”

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the degree of

MASTERS OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(Power Electronics, Machines & Drives)

By

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MAY 2014

Undertaking for Originality of the Work

I **Archan P Parikh**, Roll No. **12MEEP14**, give undertaking that the Major Project entitled **"Design and Implementation of 1.5 kW Solar Pumping System"** submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in **Power Electronics Machines** & **Drives, Electrical Engineering**, under Institute of Technology of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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CERTIFICATE

This is to certify that the Major Project Report entitled **"Design and Implementation of 1.5 kW Solar Pumping System"** submitted by **Mr. Archan Parikh** (**Roll No: 12MEEP14**) towards the partial fulfillment of the requirements for the award of degree in **Master of Technology (Electrical Engineering)** in the field of **Power Electronics, Machines** & **Drives** of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Abstract

Solar Water Pumping System (SWPS) is increasingly popular in remote areas where grid is not available or unreliable. This system is mainly used for irrigation purpose in farming and household purpose. Ministry of New and Renewable Energy(MNRE) gives subsidy on this product, hence product is designed to satisfy the requirement of MNRE. As per MNRE norms either DC motor or AC motor is used. In this topology induction motor along with submersible pump is used. In this project 1.5 kW induction motor is used. On the basis of motor rating solar panel rating is decided to be 1.8 kW considering losses in the system. In this project the main focus is to design boost converter which boosts the voltage obtained from solar panel whose power rating is 1.8 kW. This boost voltage acts as a DC-link voltage for 3-ϕ inverter. 3-ϕ inverter is developed which converts DC voltage to AC voltage. This AC voltage generated is given to induction motor which runs the submersible pump.

Maximum Power Point Tracking (MPPT) algorithm is implemented to obtain maximum power from the solar panel under different solar irradiation and temperature. In this topology incremental conductance method is used to obtain maximum power from solar panel. Modulation index of inverter is controlled by sine-triangle Pulse Width Modulation (PWM) technique. PWM along with V/F method is implemented for the control of inverter which results in the control of speed of induction motor when the output from solar panel changes. Design and simulation verification of the system is performed in PSIM software. After satisfactory results are obtained in simulation, hardware is carried out. Hardware setup is tested on resistive load. Once the required output is obtained on resistive load, hardware setup is tested on motor-pump set. Hence with obtained output necessary corrections are made to enhance the performance of the product. This topology can be synchronized with the AC drive to use the grid supply when solar energy is not available.

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Abbreviations

ADC	Analog to Digital Converter
CV	Constant Voltage
DAC	Digital to Analog Converter
DSP	Digital Signal Processor
GI	Galvanized Iron
HDPE	High Density Polyethylene
HP	Horse Power
IC	Incremental Conductance
IEC	International Electrotechnical Commission
IGBT	Insulated Gate Bipolar Transistor
MNRE	Ministry of New and Renewable Energy
MOSFET	Metal Oxide Field Effect Transistor
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
P&O	Perturb and Observe
PV	Photo Voltaic
PVP	Photovoltaic Pumping
PWM	Pulse Width Modulation
SPV	Solar Photo Voltaic
STC	Standard Test Conditions
SWPS	Solar Water Pumping System
TDH	Total Dynamic Head

Nomenclature

A_r .... Amplitude of reference signal

A_c .... Amplitude of carrier signal

C_{DC} .... Capacitor at DC link

D_{max} .... Maximum Duty Cycle

D_{min} .... Minimum Duty Cycle

f_s .... Switching Frequency

I_l .... Load Current

Δi_l .... Ripple Current

I_{mpp} .... Current at maximum power point

I_{PV} .... PV array Current

P_{DC} .... Power at DC link

P_{max} .... Maximum Power

P_o .... Output Power

V_{DC} .... Voltage at DC link

ΔV_{DC} .... Ripple in voltage at DC link

V_{in} .... Input Voltage

V_{mpp} .... Voltage at maximum power point

V_{out} .... Output Voltage

V_{PV} .... PV array Voltage

V_{ref} .... Reference Voltage

W_p .... Watt peak

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Chapter 1

Introduction

1.1 General

Solar pumping system is gaining momentum in the areas where grid is unreliable or unavailable. This system overcomes the problems faced in other technologies like diesel generator set. The main advantage of this system is that it is pollution free and running or maintenance cost is quite low. In this system DC voltage obtained from solar panel is used to run either DC motor-pump or induction motor-pump set. DC motor-pump set is used to reduce initial cost as inverter is not required but regular maintenance is required as problems occurs in commutator and brushes. By using AC motor initial cost increases but by V/F control energy efficient solutions can be obtained.

Usually in any solar application it is recommended to use battery back-up system, but in pumping system battery back-up is not required as the water obtained from water source is stored in storage tank. If any additional water is available then it can be stored in other tank or capacity of the tank is increased or higher capacity of tank is designed so additional water can be stored.

As the initial capital cost is very high, the buying behavior for solar pumps can be classified into a few categories:
1. High-income individuals setting up a solar pump for personal or commercial use, mostly in off-grid locations
2. Government funded schemes which install solar pumps for both drinking and irrigation requirements in locations with either no-electricity or unreliable supply.
3. Co-operative societies or groups that want to install solar pumps, these can be in both off-grid locations and urban locations with reliable supply [1].

1.2 MNRE Norms and Subsidy for Solar Pumping System

- PV Array
  - PV arry capacity ranges from 200 W to 5 kW
  - It has to be mounted in suitable manner and space for tracking is to be provided.
- Motor-Pump Set (surface or Submersible)
  - DC motor-pump set (with brushes or brush less DC).
  - AC Induction motor with suitable Inverter.
- Electronics
  - Maximum Power Point Tracker (MPPT)
  - controls/protection
- Interconnect cables and ON-OFF Switch

1.2.1 PV Array

Solar panel rating for pumping system is in range of 200 W to 5 kW at standard test condition (STC). To obtain this power rating panels can be connected in series or parallel or combination of both. The output power of individual panel should not be less then 74 W under any solar irradiation condition.

Solar panels must be tested such that it fulfills the below requirement to be used in this system:

1. Solar panel modules supplied for the solar pumping systems should satisfy International Electrotechnical Commission (IEC) 61215 and IEC 61730 specifications or equivalent National or International/ Standards.
2.The efficiency of the solar panel is not less then 15% and fill factor should not exceed above 70%.

1.2.2 Motor-Pump Set

The Solar pumping system can use any of the motor pump sets as listed below:
1.Surface mounted motor-pump set.
2.Submersible motor-pump set.
3.Floating motor-pump set.

The Motor-Pump Set should have a capacity in the range of **0.2 HP to 5 HP**.

1.2.3 Electronics and Protection

- To obtain or track maximum power from solar panel Maximum Power Point Tracking (MPPT) algorithm has to be implemented.

- It is mandatory to use inverter for AC motor.
- Different protections such as short circuit, open circuit, reversing of polarity, under voltage, over voltage etc should be provided for safety purpose.

1.2.4 Performance Specification and Warranty

Solar panels designed have long life i.e. 20 to 25 years. So necessary things needs to be check are, at the end of 10 years power obtained from panel should not decrease below 90%. Output of panel should not go below 80% at the end of 20 years.[2]

1.3 Basic Block Diagram of Solar Pumping System

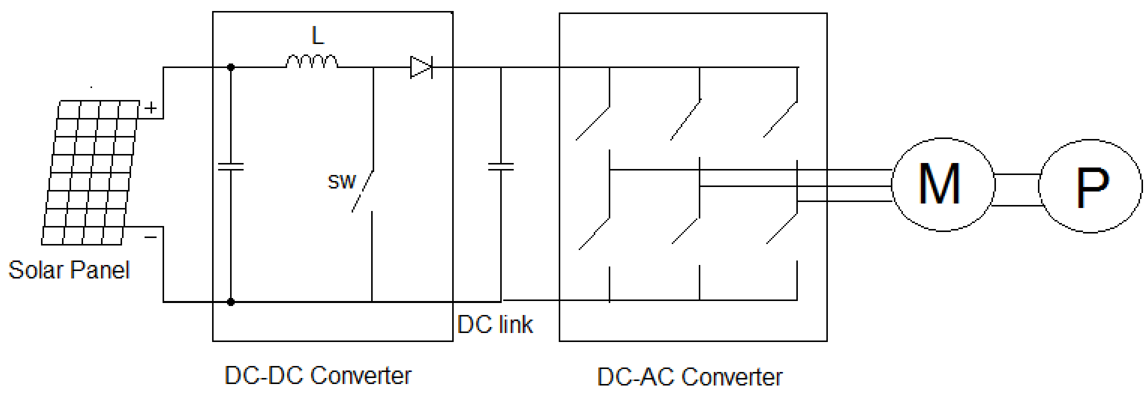

Figure 1.1: Basic Block Diagram of Solar Pumping System

The fig 1.1 shows the simple block diagram of the system. In this topology the output voltage from solar panel is boosted upto 600 V DC with the help of boost converter. In this topology boost converter along with MPPT algorithm is used to extract maximum power from solar panel. This DC voltage acts as a DC-link voltage for 3-ϕ

inverter. V/F is implemented to obtain maximum flow of water when less power is obtained from the solar panel.

1.3.1 Solar Panel

The Solar panels are available in range of 5 W to 290 W. In this system solar panel used is of 210 W. The system designed is for 1.5 kW. Usually the rating of solar panel is taken 1.20 to 1.25 times higher then motor rating i.e. solar panel rating is taken to be 1.8 kW. Hence by connecting 9 panels of 210 W in series gives 1.8 kW power.

The output of Solar Panel depends upon:

- Solar Irradiation
- Temperature

Effect of Solar Irradiation

Solar panels gives output in form of DC when sun rays fall on solar plate. As the radiation changes throughout the day the output keeps on changing. So the irradiation is more during noon time, hence maximum power can be obtained during that time, during morning and evening solar irradiations are less compared to noon, hence output is less. Thus we obtain variable output throughout the day. So to obtain more power or to increase the efficiency different methods are utilized to extract maximum power from panel.

Effect of Temperature

Output of solar panel does not depend too much on temperature as compared to irradiation, but with the increase in temperature at same irradiation condition the output of solar panel gets reduced. Sometimes if panel temperature increases above some permissible limit the solar panel has to be shut down.

In this topology considering above two factors the output voltage available from solar panel varies in the range of 190 V to 290 V.

Below shows the specifications of 210 W panel used in this system

Specification of 210 W Solar Panel:

- Manufacturer: MBPV Max Series.(210 Wp-CAAP)
- Maximum Power, Pmax : 210 Wp
- Voltage at MPP, Vmpp : 29 V
- Current at MPP, Impp : 7.21 A
- Open Circuit Voltage Voc: 36 V
- Short Circuit Current Isc: 7.85 A
- Temperature Coefficient of Pmax: -0.43
- Temperature Coefficient of Voc: -0.344
- Temperature Coefficient of Isc: 0.11
- Number of Cells per Panel: 60

The V-I and P-V characteristics for one panel is as shown in figure below:

Fig 1.2 and 1.3 respectively shows the V-I and P-V characteristics of 210 W solar panel. As shown in fig 1.2 the V-I characteristics open circuit voltage is 36 V and short circuit current is 7.85 A. As shown in fig 1.3 maximum output power obtained by this PV module is 210 W, as shown in P-V characteristics.

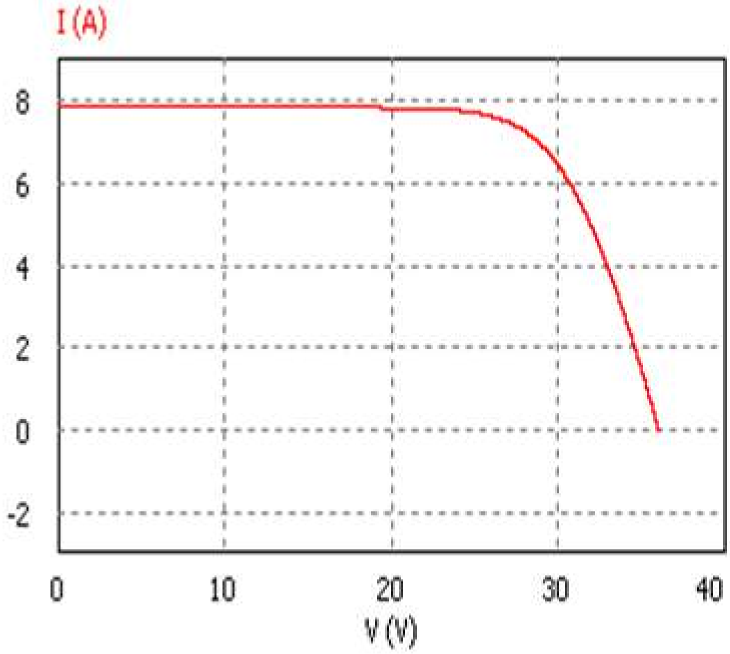

Figure 1.2: V-I Characteristic of Solar Cell

At standard temperature (25^{o}C) and irradiation 1000(W/m^2) the ratings of Power, Voltage and Current are obtained. It is observed that at maximum power, maximum voltage and Current obtained are 29 V and 7.21 A respectively.

1.3.2 DC-DC Converter

The main reason for using DC-DC converter is to obtain DC-link voltage for 3-ϕ inverter. The output voltage from the solar panel is available in range of 190 V to 290 V. To obtain a DC-link voltage of 600 V the output voltage from solar panel is boosted to 600 V with the help of boost converter.

For the higher ratings i.e. above 5 HP, number of solar panels will increase, as a result higher voltage can be obtained. This voltage can be more then 600 V, then

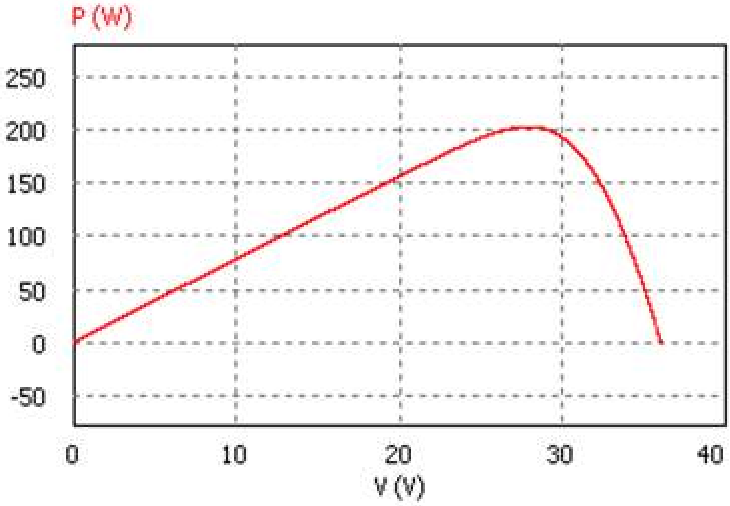

Figure 1.3: P-V Characteristic of Solar Cell

this voltage is to be bucked. Hence for higher system buck converter can be used or in general buck-boost converter can be used.

The control for the boost converter is given with the help of MPPT algorithm. In this system Incremental Conductance (IC) method is used to track maximum power from solar panel.

1.3.3 DC-AC Converter

As the motor is of three phase, 3-ϕ inverter is designed. The voltage obtained from boost converter acts as a input for inverter. The output obtained from inverter is fed to 3-ϕ induction motor which will run the submersible pump.

To control the speed of induction motor V/F method is implemented. In this method with the change in voltage corresponding frequency changes, as a result the speed of the motor changes, hence output discharge rate of the pump changes. So indirectly with the change in output voltage from solar panel the output of the pump also changes.

1.3.4 Motor-Pump Set

Different types of pumps available are as follows:

- Surface Centrifugal pump
- Submersible pump

Surface Centrifugal Pump

Surface centrifugal pump are used for water level which is below 7m at ground level. This pump is best suited to obtain water from lakes, canals, rivers, etc. In case of DC motor solar panels are connected directly to motor.

Submersible Pump

Usually submersible pumps are used to obtain water from ground level i.e. well or deep wells. Submersible pumps usually have long life and are reliable compared to other pumps, but main disadvantage is that these pumps are costlier.

1.4 Scope of Work

- In this project the system is designed for 1.5 kW induction motor. Now on the base of this rating solar panel rating is decided which is 1.8 kW considering the losses.

- The output voltage from solar panel is obtained in range of 190 V to 290 V. The main work carried out in this project is to design boost converter which boosts the voltage to 600 V which acts as a DC-link voltage for inverter. Moreover MPPT algorithm is implemented to obtain maximum power from solar panel. Here Incremental Conductance method is used to obtain maximum power from solar panel.

- 3-ϕ inverter is designed to convert DC voltage to AC voltage. Output of boost converter will act as a DC-link voltage which is converted in AC voltage. Modulation index of the inverter is controlled by PWM technique. V/F method is also implemented to control the speed of induction motor which eventually controls the discharge rate of water from submersible pump.

- On the basis of above data design and rating of each component of topology is carried out and the simulation is done.

- After obtaining desired output in simulation, prototype module is developed for testing and verification.

- This topology is synchronized with AC drive to run motor-pump set when solar energy is not available.

1.5 Literature Survey

Solar Pump Design Guide[3]

In this report titled,"*Solar Water Pumping basics*", discusses the basics related to the working of the solar pump, fixed verses tracking mount structure of solar panel, no requirement of battery for solar pumping system. Instead of using battery additional water can be stored in another storage tank.

Impact of Solar Power in Rural India[4]

In this report titled,"*Case study on solar-powered water pumping project in Samastipur, Bihar, India, 2012*", discusses the Implementation of 2 HP submersible pump using solar energy. The voltage obtained from solar panel are boosted to DC-link voltage which is fed to 1-ϕ induction motor which runs submersible pump.

Rajasthan_Solar_Pump_Presentation[5]

In this report titled,"*Solar water Pumping project 2011-12*", discusses the requirement of water in some villages of rajasthan, availibility of water, suitability of irrigation methods with solar pump,etc. In this region DC motor-pump set is installed.

P.A.Lynn[6]

In this book titled,"*Electricity from Sunlight: An Introduction to Photovoltaics*", discusses the basics of solar cell and photovoltaic arrays. Moreover different methods to track maximum power from solar panel are also discussed which helps to understand the concept of MPPT.

Chetan Singh Solanki[7]

In this book titled,"*Solar Photovoltaic Fundamentals,Technologies and Applications*", discusses the basics of MPPT agorithm and basic steps to develop solar pumping system are given which helps in designing of the system.

Maria Carmela Di Piazza[8]

The paper titled,"*Identification of Photovoltaic Array Model Parameters by Robust Linear Regression Methods*", discusses the PV array parameters identification and effect of change in atmospheric conditions on the output of the PV panel. This paper shows that with change in temperature and irradiation the output power changes.

Guo Heng[9]

In this Paper titled,"*A Novel Maximum Power Point Tracking Strategy for Stand-alone Solar Pumping Systems*", discusses the Perturb and Observe (P&O) method with some modifications, selection of step size and hybrid algorithm using Incremental Conductance Method.

Songbai Zhang[10]
In this paper titled,"*Optimization of MPPT Step Size in Stand-alone Solar Pumping Systems*", discusses different method for MPPT are compared and shows optimum value of step size to used for solar pumping systems.

G.M.S.Azevedo[11]
In this paper titled,"*Evaluation of maximum power point tracking methods for grid connected photovoltaic systems*", discusses the technique for the MPPT algorithm and flow chart for incremental conductance method is given which results in good efficency to track maximum power from the panel.

S.G. Malla[12]
In this paper titled,"*Photovoltaic based Water Pumping System*", discusses Control strategies to regulate the flow of water supply of a PV based water pumping system through induction motor. By maintaining DC-link voltage (V_{DC}) at its reference value (V_{mpp}) and control the speed of induction motor based on vector control with respective of power availability from PV is presented.

M.S.Taha[13]
In this paper titled,"*Maximum Power Point Tracking Inverter For Photovoltaic Source Pumping Applications*", discusses the loading of photovoltaic panel, without having maximum power point tracking (MPPT) always gave an output much below the capability of the system. When inverter with MPPT was used along with the motor-pump unit, it is observed that the maximum available power from the solar panel is utilised.

Hence it is observed that by using inverter with the MPPT the solar energy can be utilised more efficiently than the conventional methods.

Nafisa Binte Yousuf[14]

In this Paper titled,"*Development of a Three Phase Induction Motor Controller for Solar Powered Water Pump*", discusses the advantages of using Induction Motor by replacing it with the DC motor. Control technique used for inverter is sine-triangle comparison.

N.Hamrouni[15]

In this paper titled,"*Measurements and Simulation of a PV Pumping Systems Parameters Using MPPT and PWM Control Strategies*", discusses MPPT with DC-DC converter and control of asynchronous motor with V/F implementation.

S.R.Bhat[16]

In this paper titled,"*Performance Optimization of Induction Motor-Pump System Using Photovoltaic Energy Source*", discusses that there exists an optimum V-F relationship for a given system head, which minimizes the motor power input, while the microprocessor technique has certain advantages, there are limitations like the resolution of the pulse width, frequency, cost, etc.

Chapter 2

Design of Solar Pumping System

The basic steps to determine the size and rating of solar pumping system are as shown below:

2.1 Water Requirement

First step to design solar pumping system is to determine the water requirement. Water requirement is obtained from the type of application i.e. domestic use or for irrigation purpose.

2.2 Water Source

For the providing water for domestic and irrigation system the water is available from water source such as lakes, ponds, rivers, well etc. Depending on the water source the motor-pump rating and its specifications are decided. For getting water from rivers, lakes, pond surface pumps are used while for wells, submersible pumps are used.

2.3 Water Storage

Usually in any application such as irrigation and domestic purpose storage of water is done in a tank. The main advantage of this system is that battery is not used as extra or additional water is stored in additional tank or capacity of tank is increased. Hence the cost as well as size of the system is reduced.

2.4 Solar radiation and PV Panel Location

To obtain maximum power from the solar panel it is important to fix the direction of solar panel. The radiation from the sun should fall directly on the solar panel to obtain higher efficiency. For the exact location of the panel one needs to know the direction of the sun throughout the day. Moreover panels should be located in such a way that tree is not coming in picture otherwise shading may reduce the output voltage from panel. Moreover one needs to study the pattern of solar radiation throughout the day.

2.5 Design flow rate for the Pump

Design of the solar pump is carried out on the basis of flow rate i.e on the requirement of water for any particular application. Lets assume an example:

suppose water require per day is 37000 liters, and solar radiation are available for 6.5 hours a day, then flow is as as shown in eqn 2.1. As shown in calculation it can be converted into minutes also.

$$Flow = \frac{37000 liter/day}{6.5 hr/day} \tag{2.1}$$

$$= 5692 \text{ liter/hr}$$
$$= 95 \text{ liter/min}$$

2.6 Total Dynamic Head (TDH) for the Pump

The Total Dynamic Head for the pump can be given as by summation of vertical life, pressure head and friction loss.

TDH = V.L + P.H + F.L

TDH is an important factor in selecting the rating and specification of pump. As

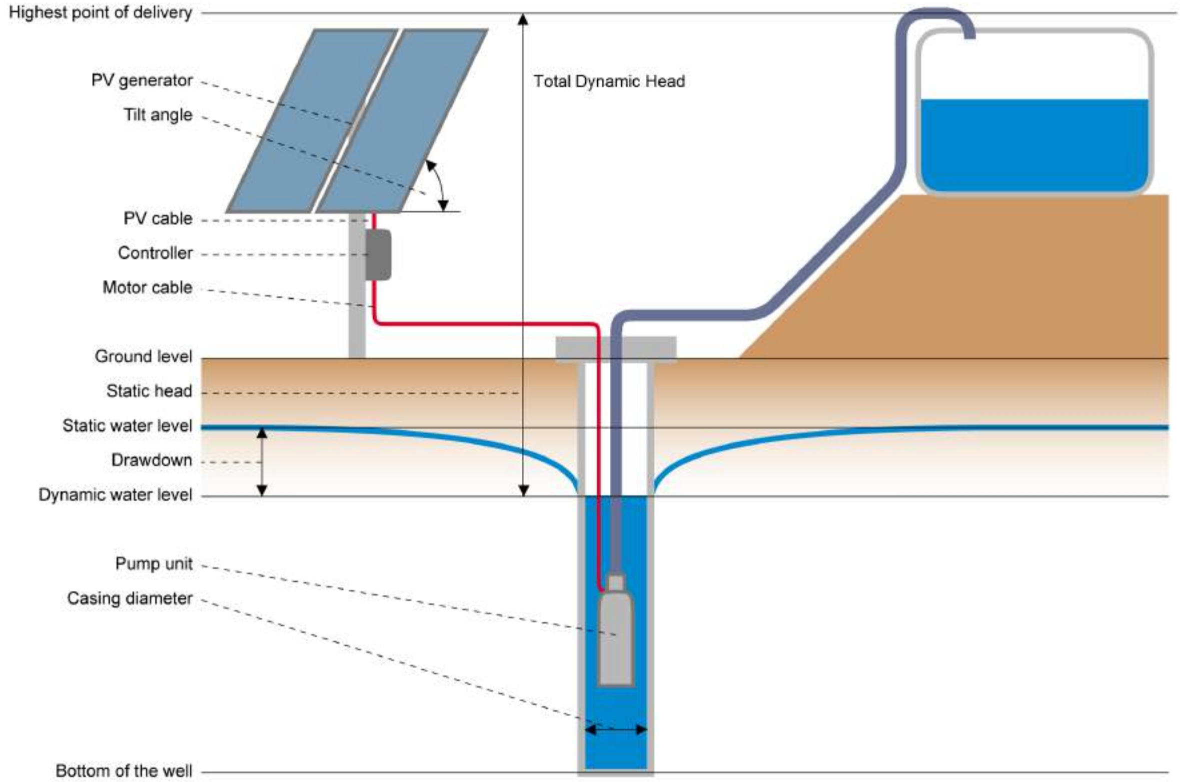

Figure 2.1: Generalized Solar Pumping System

the TDH increases the output of the pump or discharge rate of water decreases and vice-versa. In calculation of TDH friction loss occuring in the pipes which carries water reduces the discharge rate of water from pump.

2.7 Pump Selection and Associated Power Requirement

On the basis of total dynamic head and discharge rate of water selection of pump is made. Moreover each manufacturer of the pump gives pump performance curve. This curve shows the output discharge rate of water versus total dynamic head.

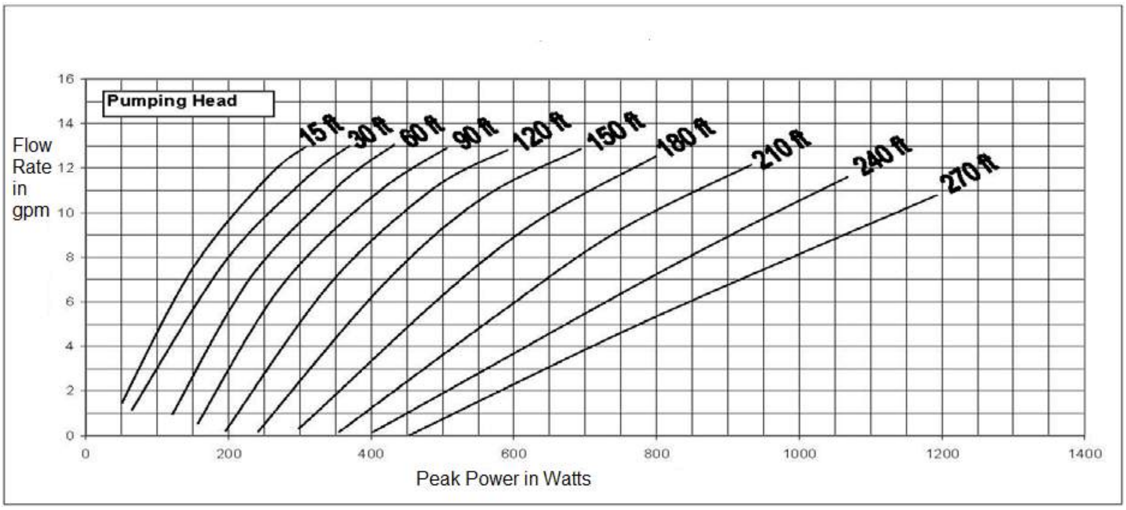

Figure 2.2: Pump Performance Curve

By studying this pump performance curve power requirement can be found. The figure shows an example of pump performance curve.

2.8 PV Panel Selection

Once the rating of the pump is selected rating of solar panels is decided. Usually 1.20 to 1.25 times higher is the rating of solar panel to compensate the losses in the system. To increase the voltage rating panels are connected in series and to increase the current panels are connected in parallel. In series or parallel combination power increases. Hence selction of panel is depended mostly on selection of pump.

2.9 Design of DC-DC Converter

Depending on the output voltage from solar panel buck or boost or buck-boost topology needs to be selected. Usually DC-DC converter is required for low rating pumps. If DC-DC converter is not to be used then PV panels need to be increased which can supply DC link voltage to run inverter.

If the pump is DC than the PV panel should give the output voltage equal to the rated voltage of motor-pump. If output of PV Panel is less then DC-link voltage boost converter is required, buck converter is used if voltage is higher then input voltage and if panel voltage is same no DC-DC converter is required.

2.10 Design of DC-AC Converter

For AC pumps DC-AC converter is used to convert DC voltage into AC voltage. PWM technique is used to control the output of an inverter. V/F method is implemented to control the output of the inverter.

Chapter 3

DC-DC Converter

3.1 Specification of the Boost Converter

- Output Power,P_o : 1.5(kW)
- Output Voltage,V_{out} : 600(V)
- Load Current,I_l : 5.15(A)
- Input Voltage,V_{in} : $190 - 290$(V)
- Switching Frequency,f_{sw} : 16(kHz)

3.2 Design of Boost Inductor

The duty cycle for the range of input voltage (190 to 290)V is as shown below:

$$V_{out} = \frac{1}{1-D} * V_{in} \tag{3.1}$$

$$600 = \frac{1}{1-D_{max}} * 190 \tag{3.2}$$

$$D_{max} = 0.68 \tag{3.3}$$

$$600 = \frac{1}{1 - D_{min}} * 290 \tag{3.4}$$

$$D_{min} = 0.53 \tag{3.5}$$

$$L = \frac{Vi_{max} * D_{min}}{\Delta i_l * f_s} \tag{3.6}$$

$$L = \frac{282 * 0.53}{2.06 * 16000} \tag{3.7}$$

$$L = 4.5mH \tag{3.8}$$

3.3 Design of DC-Link Capacitor

$$C_{DC} = \frac{P_{DC}}{2 * \omega * V_{DC} * \Delta V_{DC}} \tag{3.9}$$

$$C_{DC} = \frac{1500}{2 * 314 * 600 * 60} \tag{3.10}$$

$$C_{DC} = 1.88mF \tag{3.11}$$

3.4 Simulation of Boost Converter

The circuit diagram for the boost converter is as shown below:-

The simulation results for the above circuit are as shown below:

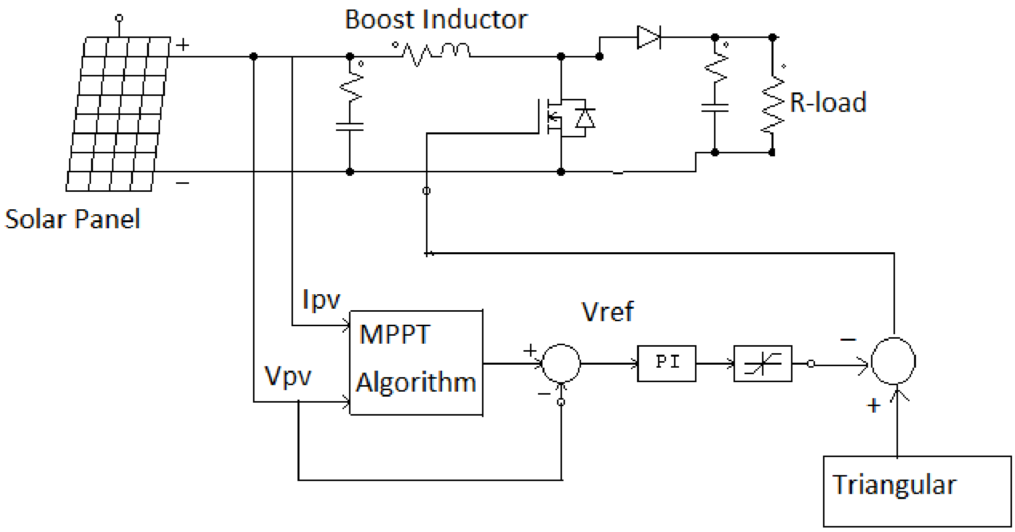

Figure 3.1: Closed Loop of Boost Converter

In the below fig 3.3 red colour shows the output voltage and blue colour shows the input voltage. Thus the output voltage is 600 V when the input voltage is 250 V.

As shown in fig 3.5 the current flowing through inductor is shown.The maximum value of current during charging is 8 A and minimum value of current during discharging is 6.2 A. The ripple content for this current is 25 %. The ripple in inductor current is due to charing and discharging of current when the switch is ON or OFF.

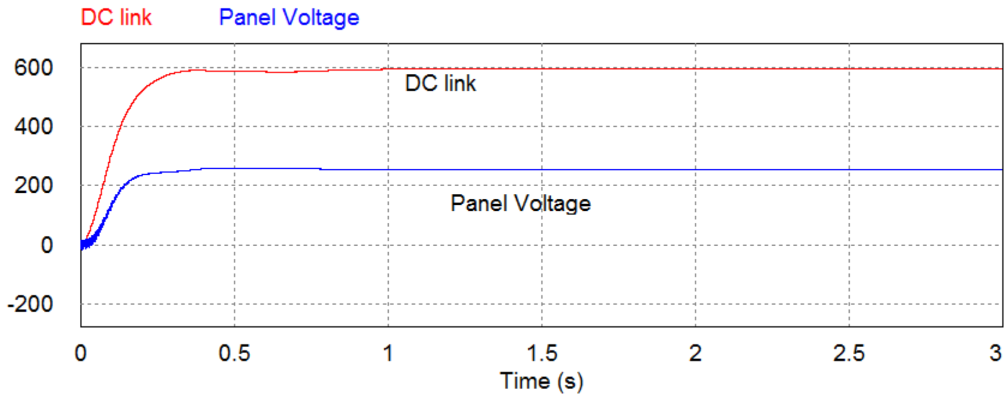

Figure 3.2: DC-Link Voltage and Panel Voltage

Scale: DC link Voltage (red): X-axis:1 div=0.5 sec, Y-axis:1 div=200 V.
Panel Voltage (blue):X-axis: 1 div=0.5 sec, Y-axis: 1 div=200 V.

3.5 Prototype of Boost Converter

The rating for each component of the circuit is as shown below:-

- Filter Capacitance :- 4700 μF, 400 V
- Boost Inductor :- 4.5 mH
- IGBT as Switch :- 1200 V, 40 A
- DC link Capacitance :- 470 μF , 900 V
- Resistive Load :- 284 Ω , 1500 Watt

The basic block diagram of boost converter for the hardware setup is as shown in fig 3.6:
DC voltage is generated with the help of diode bridge. To obtain variable voltage 3-ϕ variac is connected before 3-ϕ supply which gives variable voltage from 0 V to 440 V AC. So with the help of this dimmer DC voltage in range of 190 V to 290 V are

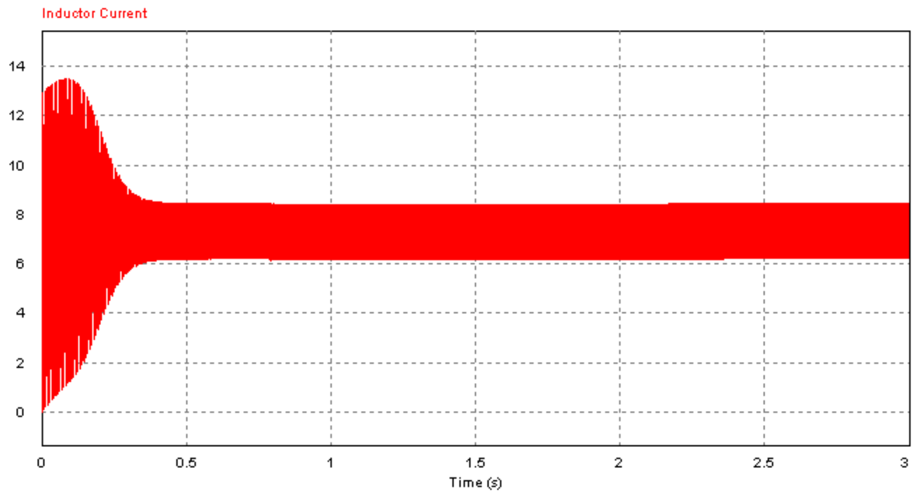

Figure 3.3: Inductor Current

Scale: Output Voltage (red): X-axis:1 div=0.5 sec, Y-axis:1 div=2 A.

obtained which acts as solar panel voltage.

This input voltage obtained from dimmer is boosted to 600 V DC. This output voltage will be obtained across resistance of 284 ohm,1500 Watt.

As shown in the fig 3.7 Channel A shows the input Voltage which is 233 V. Channel B shows the output voltage which is boosted to 586 V. Hence the desired operation of boost converter is obtained.

As shown in fig 3.8 pulses going to IGBT are shown. The switching frequency is 16 kHz.

From the above results it is clear that circuit is able to boost the voltage to 600 V when input is varied. Now the circuit is to be tested with connecting solar panels.

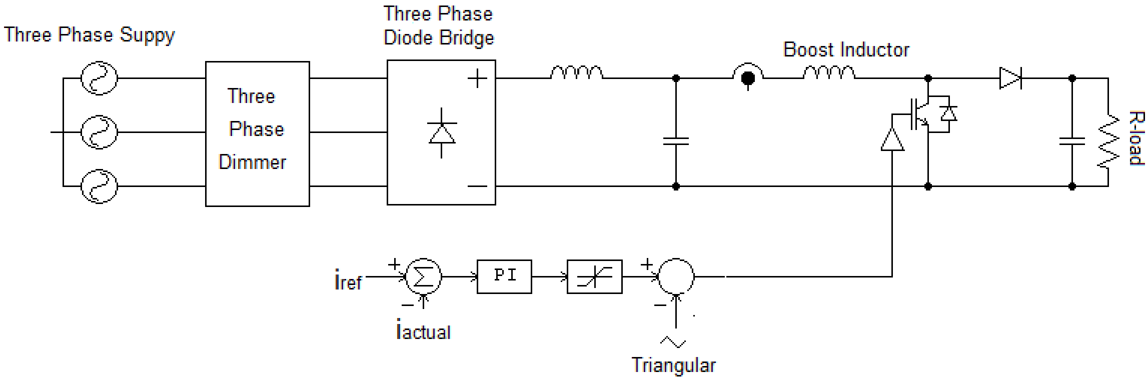

Figure 3.4: Close loop Circuit of Boost Converter

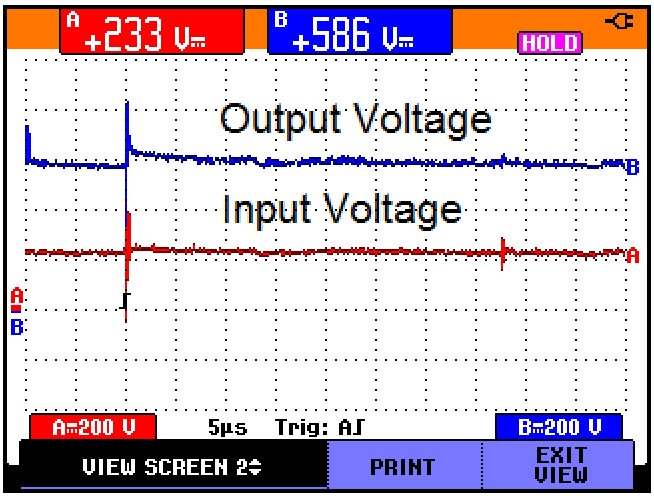

Figure 3.5: Input and Output Voltage of Boost Converter

Scale:Input Voltage (red): X-axis:1 div= 5 μs,Y-axis:1 div=200 V
Output Voltage(blue):X-axis: 1 div=5 μs,Y-axis:1 div=200 V

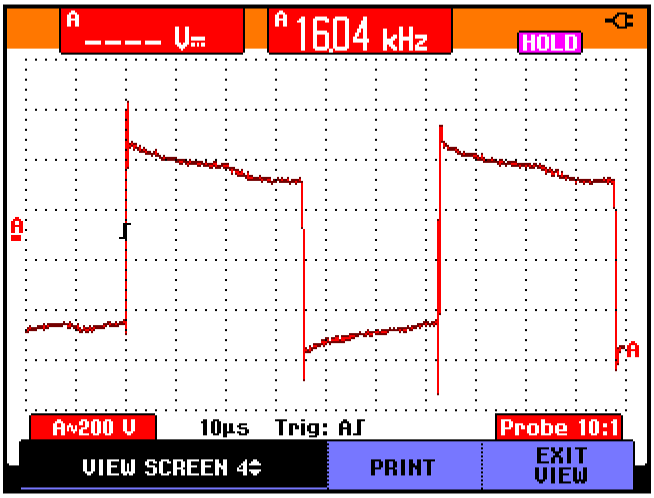

Figure 3.6: Gate Pulses to IGBT

Scale:Pulses to IGBT (red): X-axis:1 div= 10 μs,Y-axis:1 div=5 V

The basic block diagram for the close loop control of boost converter is as shown in fig 3.9:-

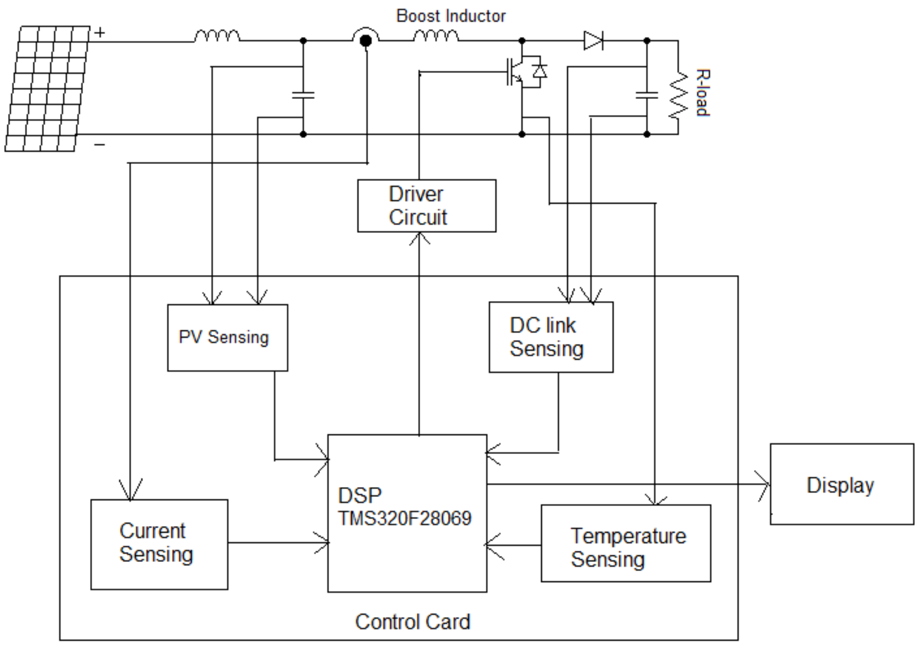

Figure 3.7: Basic Block Diagram of Closed Loop of Boost Converter

Driver Card

The PCB 929 driver from SHARP is used to drive the IGBT. It is designed to convert logic level control signals into optimal IGBT gate drive. Input signals are isolated from IGBT. It also provides Short circuit protection by monitoring the collector-emitter voltage of IGBT. A collector feedback is taken for this purpose.

The driver initiates a controlled slow turn-off and generates a fault signal when short is detected. The slow turn-off helps to control dangerous transient voltages that can occur when high short circuit currents are interrupted.

In order to achieve efficent and reliable operation of high current, high voltage IGBT module a gate drive with high current capability and low output impedance is required.

Short Circuit protection is provided by measuring collector-emitter voltage with a monitoring circuit. In case of a fault both the IGBTs are turned off immediately and an error signal is provided to the control circuit. The switching signals are transmitted by optocoupler and are interfaced with driver card through 10 pin FRC connector. As shown in the figure input panel voltage sensing is done.

Control Card

For control purpose TMS 320F28069 digital signal processor (DSP) is selected. All the sensing and close loop computations are done through this controller. For voltage it is given to Analog to Digital Converter (ADC) of the controller through DC voltage sensing and leveling circuit.

The maximum DC voltage is converted into 3.3 Volt and other voltage levels are in linear relation to this. Over voltage protection is also provided through this segment only.

For current sensing hall effect sensor are used which gives output of 4 V with respect to the peak value of current. After getting this 4 V output is again converted into 3.3 V format and the processed signal is provided to the ADC for further close loop computations. With this sensing and leveling circuit analog over current protection is also provided to avoid damage to the power device.

Here DC-link voltage is also sensed. If the DC-link voltage is more then 650 V then again DSP pin will go low and display will display output over voltage fault.

In PV panel voltage and DC-link voltage sensing, the actual voltage is converted into 3.3 V with the help of resistances in series. A reference value of voltage is kept. When the actual value exceeds reference value DSP pin goes low resulting in trip.

Here current sensing is done with the help of Hall Effect Sensor. When there is no turn it gives output in form of 4 V when current is 50 A. when there are two turns then sensor gives output of 4 V at 12.5 A. In this system two turns are taken as current of the system would not exceed more then 10 A. Trip signal set for the over current is 7.5 A.

Thermistor of 20 kΩ is taken to sense the temperature of IGBT. Thermistor is mounted on heat sink. In control card the maximum allowable temperature is set to be 87^0 C. So if the temperature increases more than 87^0 C temperature fault will be displayed on the display.

After setting all this values in control card and having selected the rating of each component the setup for boost converter is carried out. Hardware Setup of Boost converter is as shown in fig 3.10:-

Figure 3.8: Hardware Setup of Boost Converter

When the circuit is given supply the output waveforms are as shown below:-
As shown in fig 3.11 the output voltage obtained from solar panel at that time is 285 V. Hence the boosted voltage obtained is 592 V. The ripple content in input Voltage is 6% while in output voltage it is 11%. Hence the ripple content in voltage is nearer to theoretically calculated value.

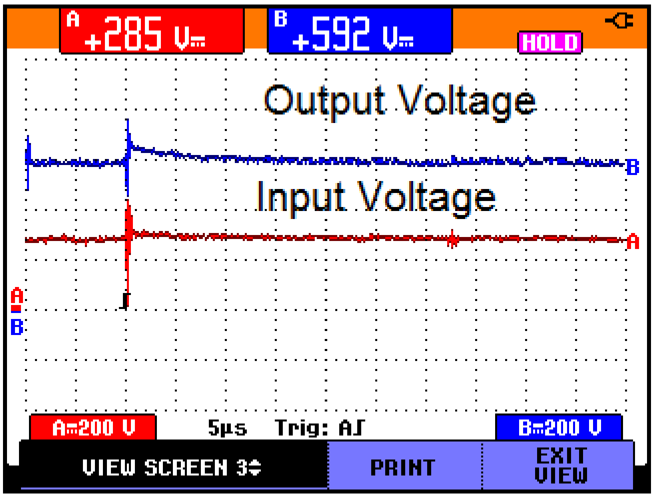

Figure 3.9: Input and Output Voltage of Boost Converter

Scale:Input Voltage (red): X-axis:1 div= 5 μs,Y-axis:1 div=200 V
Output Voltage(blue):X-axis: 1 div=5 μs,Y-axis:1 div=200 V

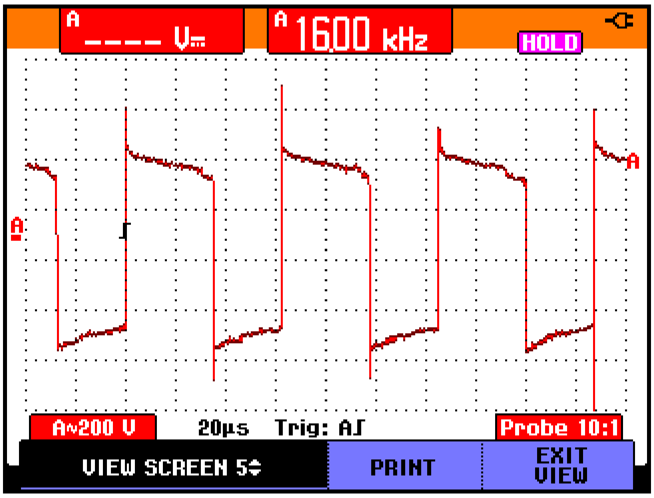

Figure 3.10: Gate Pulses to IGBT

Scale:Pulses to IGBT (red): X-axis:1 div= 20 μs,Y-axis:1 div=5 V

The above waveform shown in fig 3.12 the pulses given to IGBT. Pulses obtained are at 16 kHz frequency. The duty cycle is 0.51.

Once the boost converter was working properly Heat and Run test is performed on it to see the temperature rise and at what temperature it gets stable.

The Table-I shows the temperature rise at 4.40 A current and DC link voltage of 425 V. IGBT is allowed to get natural cooling i.e. no fan is kept.

Table I: Heat and Run Test at 425 V DC and 4.40 A

Time (PM)	Current (A)	Display Temp (^{0} C)	Measured Temp (^{0} C)	Ambient Temp (^{0} C)	DC link(V)	Panel Voltage DC (V)
12:30	4.40	31	30.7	29.0	425.2	149.9
12:45	4.41	33	32.5	29.1	425.9	150.3
01:00	4.40	44	43.6	29.4	425.3	149.9
01:15	4.40	46	46.8	29.6	425.2	150.8
01:30	4.41	46	46.8	30.3	425.1	149.9
01:45	4.41	48	48.1	30.6	425.2	149.9
02:00	4.40	48	48.2	31.0	425.2	151.5
02:30	4.40	48	48.2	31.2	425.9	149.9
03:00	4.41	49	48.9	31.5	424.2	148.7
03:30	4.40	49	48.9	31.3	425.2	149.9
04:00	4.40	49	48.9	31.8	425.9	150.0
04:30	4.40	49	48.9	32.0	425.7	149.9

Heat and Run test is performed for four hours. The temperature rise in at 425 V DC and 4.40 A current is almost 19^0 C . So if the ambient temperature is even 50^0 C then temperature rise will be 69^0 C which is less then permissible limit of IGBT. This test was carried out without fan i.e. in natural cooling condition.

Table II: Heat and Run Test at 600 V DC and 7.10 A

Time (AM)	Current (A)	Display Temp (^{0} C)	Measured Temp (^{0} C)	Ambient Temp (^{0} C)	DC link(V)	Panel Voltage DC (V)
10:00	7.70	33	32.5	30.0	599.8	199.0
10:15	7.70	50	49.7	30.1	600.2	199.3
10:30	7.71	60	59.8	30.4	600.3	200.0
10:45	7.70	62	61.5	30.6	600.1	201.2
11:00	7.70	62	61.5	30.3	600.2	199.5
11:15	7.71	62	61.5	30.6	600.2	199.2
11:30	7.70	62	61.5	31.0	600.2	200.6
12:00	7.70	62	61.5	31.2	600.1	202.4
12:30	7.70	62	61.5	31.5	600.1	200.2
1:00	7.71	62	61.5	31.3	600.3	199.1
1:30	7.70	62	61.5	31.8	600.2	200.3
2:00	7.71	62	61.8	32.0	600.1	200.6

Table-II shows the Heat and Run test performed at 600 V DC and 7.11 A current. The rise in temeperature was 30^0 C. Now if ambient temperature is 50^0 C then rise in temperature will be maximum upto 80^0 C which is still under permissible limit.

In natural cooling condition temperature of IGBT went upto 87^0 C within 10 minutes, hence external cooling is needed. So fan was kept for cooling of IGBT and temeprature became stable at 62^0 C.

Chapter 4

DC-AC Converter And V/F Control of Motor

DC-AC converter (Inverter) is used to convert DC voltage into AC voltage. 600 V DC obtained from boost converter acts as a DC-link voltage. This DC is converted into AC.

In inverter PWM technique (sine-triangle) is used to give pulses to IGBTs of the inverter. PWM pulses are generated with the help of sine-triangle comparision. Here triangle will be carrier frequency and sine will be reference frequency. Output of inverter changes or controlled by changing modulation index.
Modulation index is defined as the ratio of amplitude of reference to amplitude of carrier. Mathematically it is represented as shown below:

$$m = \frac{A_r}{A_c} \tag{4.1}$$

where A_r= amplitude of reference (sine)
A_c= amplitude of carrier (triangle)

Advantages of sine PWM

- Output voltage of inverter is controlled by change in modulation index.
- Lower order harmonics are reduced which results in less THD.

Disadvantages of sine PWM

- Due to high switching, switching losses increases
- Higher order harmonics produces EMI problems

V/F Control of Induction Motor

Usually V/F method is implemented to obtain the variable speed of induction motor. In V/F control V/F ration is maintained constant i.e. flux is constant hence the speed can be controlled by controlling voltage and frequency in the same ratio. In recent times almost every application related to induction motor uses this technology.

The main advantage of using induction motor with V/F control is that, induction motor does not draws the high current at starting. In general either by changing stator voltage or frequency V/F control of induction motor is achieved.

Below shows the rating and specification of induction motor :

Rating of Induction Motor

- Voltage rating : 415 V
- Current rating : 3.4 A
- Power rating : 1.5 kW

- Speed : 3000 rpm
- Number of poles: 2

Parameters of Induction Motor of above rating

- Stator Resistance R_s : 4.552 Ω
- Rotor Resistance R_r : 0.01868 H
- Stator Inductance L_s: 1.707 Ω
- Rotor Inductance L_r :0.01868 H
- Magnetizing Inductance L_m : 0.3344 H

4.1 Simulation of Inverter with Resistive Load

The circuit above shows the 3-ϕ inverter with induction motor. V/F technique is implemented for the control of motor. PWM technique is used for obtaining pulses for IGBTs of inverter. By changing the modulation index and frequency speed of the motor can be varied. The simulation results for the same are as shown above:

The fig 4.2 shows the comparision between sine and triangle. The pulses generated are given to IGBT1 and IGBT4.

when $A_r > A_c$ IGBT 1 will get the pulse.
when $A_r < A_c$ IGBT 4 will get the pulse.

The fig 4.3 shows the simulation waveforms of output voltage and output current. The peak value of voltage is 600 V and rms value is 415 V. The rms value of current is 0.89 A. As the simulation is carried out on resistive load voltage and current are in

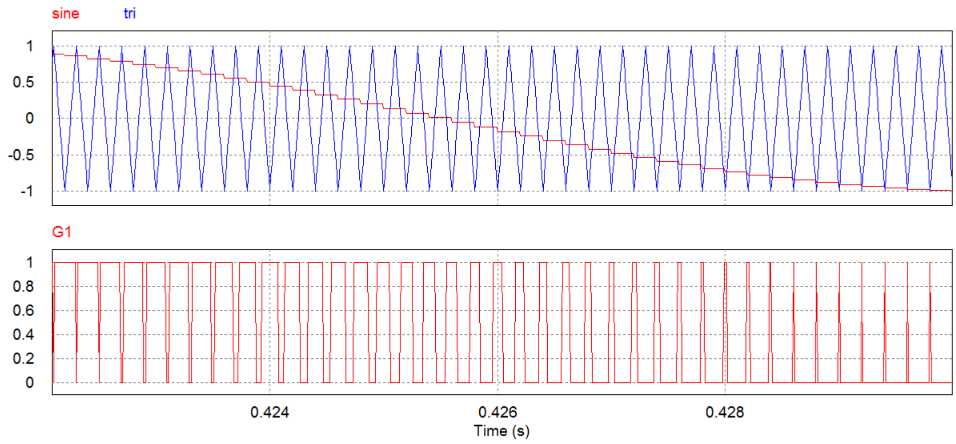

Figure 4.1: Sine-Triangle comparison and Gating Signals G1

Scale:Sine(red): X-axis: 1 div = 2 ms,Y-axis:1 div = 0.5.
triangle(blue): X-axis: 1 div = 2 ms, Y-axis:1 div = 0.5.
Gating signal G1(red) :X-axis: 1 div = 2 ms, Y-axis:1 div = 0.2.

phase with each other, hence power factor is unity.

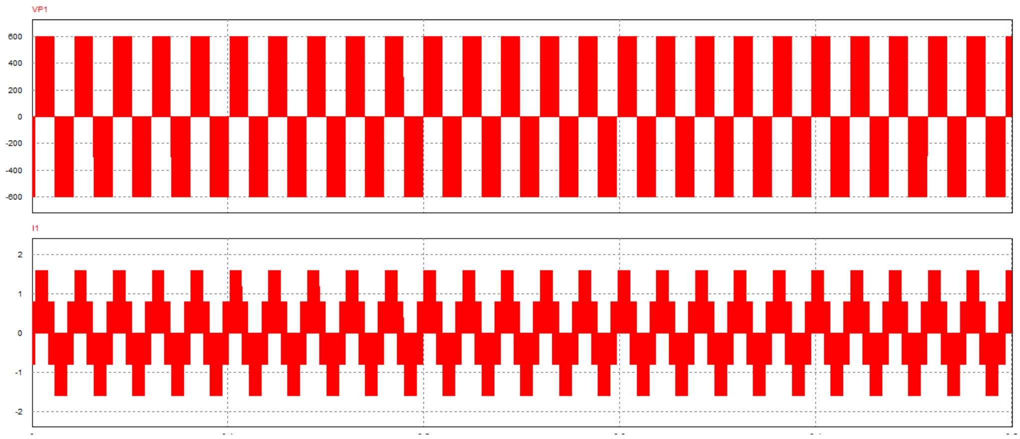

Figure 4.2: Output Voltage and Output Current of Inverter

Scale: X-axis: 1 div = 0.2 s,Y-axis: 1 div = 200 V

4.2 Hardware Results of Inverter

The IGBTs used in this 3-ϕ inverter is of make IKW40. The ratings of IGBTs is 1200 V, 40 A. Value of DC-link capacitance is 1.88 mF.

The Input DC Voltage given to 3-ϕ inverter is 519 V. This DC-link voltage will be converted into 285 V AC with the help of inverter. By controlling the modulation index output voltage of inverter is controlled. The output current flowing through the resistive load is 0.74 A. The hardware results of inverter are as shown below:-

Testing of inverter is carried out on 250 ohm , 1000 Watt resistive load.

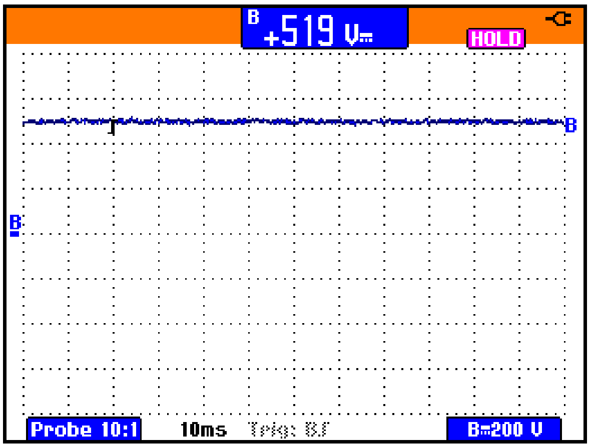

Figure 4.3: Input Voltage of Inverter

Scale:Input Voltage (red): X-axis: 1 div = 10 ms, Y-axis: 1 div = 200 V.

The fig 4.4 shows the DC-link voltage which will act as an input to inverter. The voltage given as an input is 519 V.

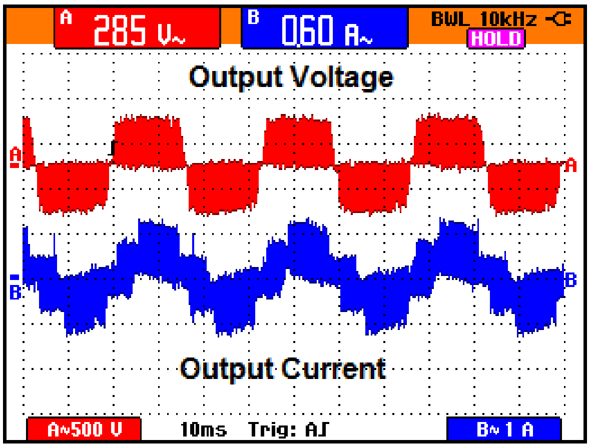

Figure 4.4: Output Voltage and Output Current of Inverter

Scale:Output Voltage(red) : X-axis: 1 div = 10 ms, Y-axis: 1 div = 500 V
Output Current(blue): X-axis: 1 div = 10 ms, Y-axis: 1 div = 1 A

The fig 4.5 shows the output voltage and output current obtained from Inverter. The rms value of voltage obtained is 285 V. The rms value of output current is 0.60 A. The output voltage and output current are obtained at 50 Hz frequency.

The fig 4.6 shows the gate pulses given to R bottom switch of inverter. The frequency is of 2.5 kHz.

The fig 4.7 shows the ringing during turn off time. The maximum value of peak goes to 560 V and minimum value goes to 472 V when IGBT is blocking 520 V.

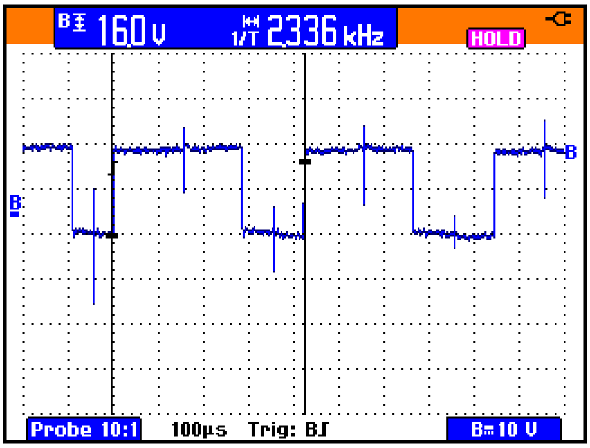

Figure 4.5: Pulses given to R Bottom Switch of Inverter

Scale: Gate pulse: X-axis:1 div = 100 μs, Y-axis:1 div = 10 V.

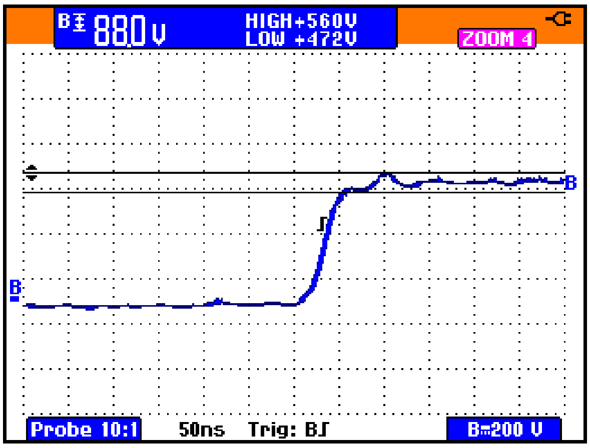

Figure 4.6: Ringing during OFF Time

Scale: Voltage: X-axis:1 div = 50 ns, Y-axis:1 div = 200 V.

Chapter 5

Maximum Power Point Tracking Algorithm

Basically there are two problems with output of solar panel:- 1. The output of solar panel is very less, i.e. the efficiency of solar panel is 10% to 15%. 2. The output of solar panel changes with the change in weather conditions i.e. output is less during cloudy conditions and output keeps changing throughout the day. In morning and evening time it is less compared to noon time when maximum output from panel is available.[9]

It is also seen that I-V and P-V characteristics solar cell is not linear, hence there is one point on the graphs where maximum power from the solar panel can be tracked. There are different methods used to track the maximum power point. Different methods of MPPT are as shown below: [9]

5.1 MPPT Algorithm

Some of the general MPPT algorithms are as follows:

- Constant Voltage (CV)

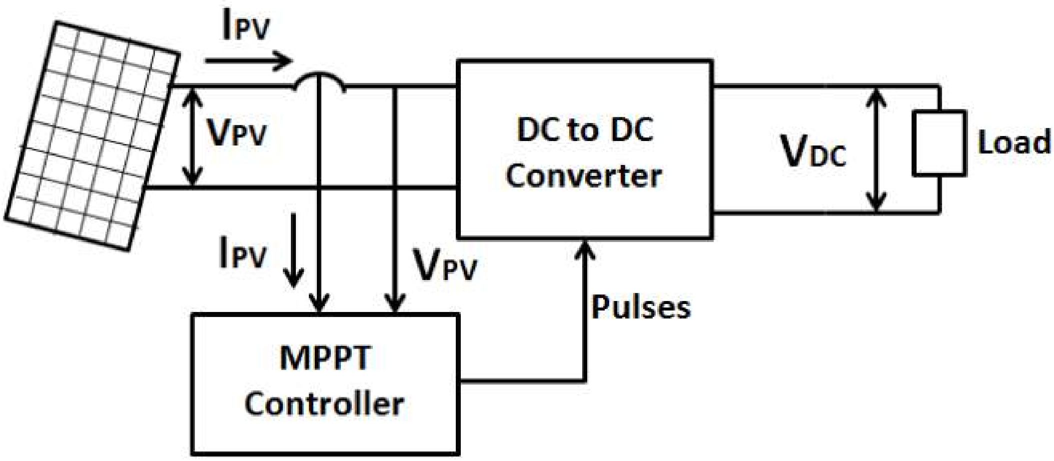

Figure 5.1: MPPT basic building block

- Fuzzy Logic Control
- Perturb and Observe (P&O)
- Neutral Networks
- Fractional open circuit voltage
- Incremental Conductance (IC)
- Fractional short circuit current

above described method works in different ways to obtain maximum power from solar panel. All methods vary in their speed, step size, logic etc. Each method has its merits and demerits. P&O method and Incremental conductance method are almost similar to each other. Most commonly used technique to track maximum power from solar panel are P&O and IC method. Demerits of perturb and observe method are overcome by IC method.

5.2 Incremental Conductance (IC)

The demerits of the P&O method is that it cannot track the maximum power from solar panel under varying condition. This disadvantage is overcome by incremental conductance method.

The incremental conductance is based on the equation as shown below:-

$$(\frac{dI_{PV}}{dV_{PV}}) + (\frac{I_{pv}}{V_{PV}}) = 0 \tag{5.1}$$

where I_{PV} is solar panel current and V_{PV} is solar panel voltage.

Basically this algorithm works as shown in fig 5.2. As shown in fig there is one point or unique point where the maximum power can be obtained. Now to obtain that power with the help of incremental conductance method derivative of the power is calculated. This algorithm compares the conductance (I/V) with derivative of conductance (dI/dV) and on the basis of this reference voltage is obtained, which brings the actual voltage near to the maximum power point. This reference value generated is zero if the point obtained is MPP, it is on left if reference value is positive and it is on right if reference value is negative.[10]

$$(\frac{dP_{PV}}{dV_{PV}}) = (\frac{dV_{PV} * dI_{PV}}{dV_{PV}}) = V_{PV} * (\frac{dI_{PV}}{dV_{PV}}) + I_{PV} \tag{5.2}$$

which imply:

$$(\frac{dP_{PV}}{dV_{PV}}) > 0 \Longrightarrow (\frac{I_{PV}}{V_{PV}}) > -(\frac{dI_{PV}}{dV_{PV}}) \tag{5.3}$$

Point is at the left of the MPP.

$$(\frac{dP_{PV}}{dV_{PV}}) = 0 \Longrightarrow (\frac{I_{PV}}{V_{PV}}) = -(\frac{dI_{PV}}{dV_{PV}}) \tag{5.4}$$

Point is at the MPP.

$$(\frac{dP_{PV}}{dV_{PV}}) < 0 \Longrightarrow (\frac{I_{PV}}{V_{PV}}) < -(\frac{dI_{PV}}{dV_{PV}}) \tag{5.5}$$

Point is on the right of MPP.

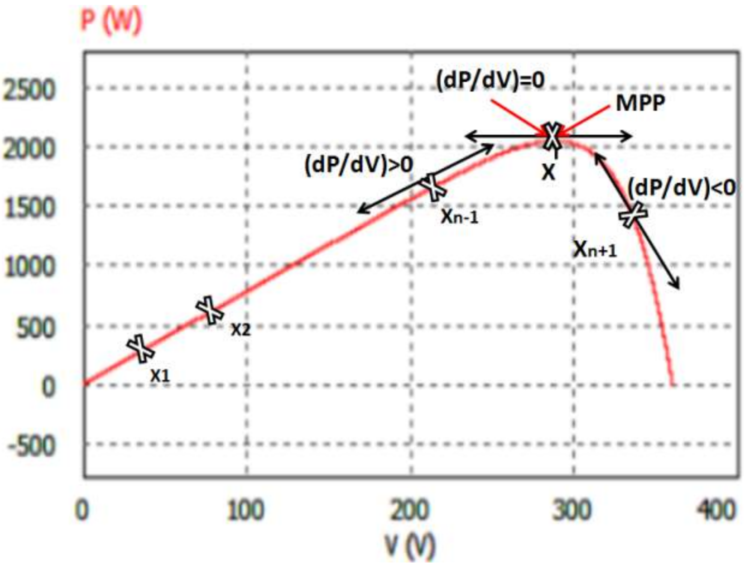

Figure 5.2: Incremental Conductance Tracking of MPP

The flow chart for this method is as shown in fig 5.3. Voltage and current from the panel are sensed and given to algorithm. Power is calculated on the basis of voltage and current. After some interval again the values of voltage and current are taken. The difference of the two values of voltage and current are taken. On the basis of this power is calculated and difference in power is also obtained. Now the condition for change in current is checked. On the basis of this condition and as shown in flow chart reference voltage is incremented or decremented. The computation with this method is easy as compared to other methods.

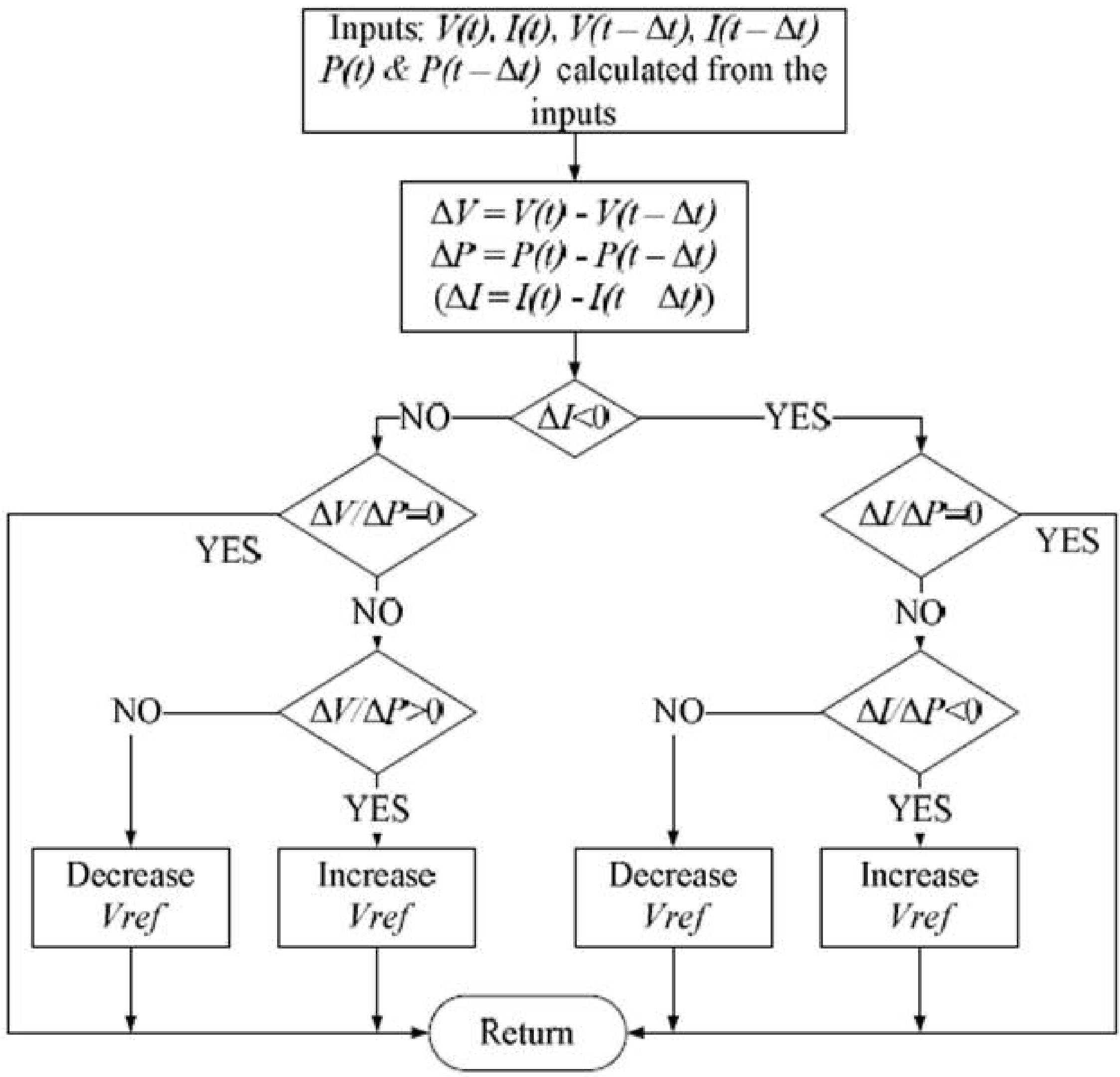

Figure 5.3: Flow chart for the modified Incremental Conductance Method

Chapter 6

Implementation of Topology

6.1 Simulation Results of Topology

The figure below shows the basic block diagram of the selected topology for solar pumping system.

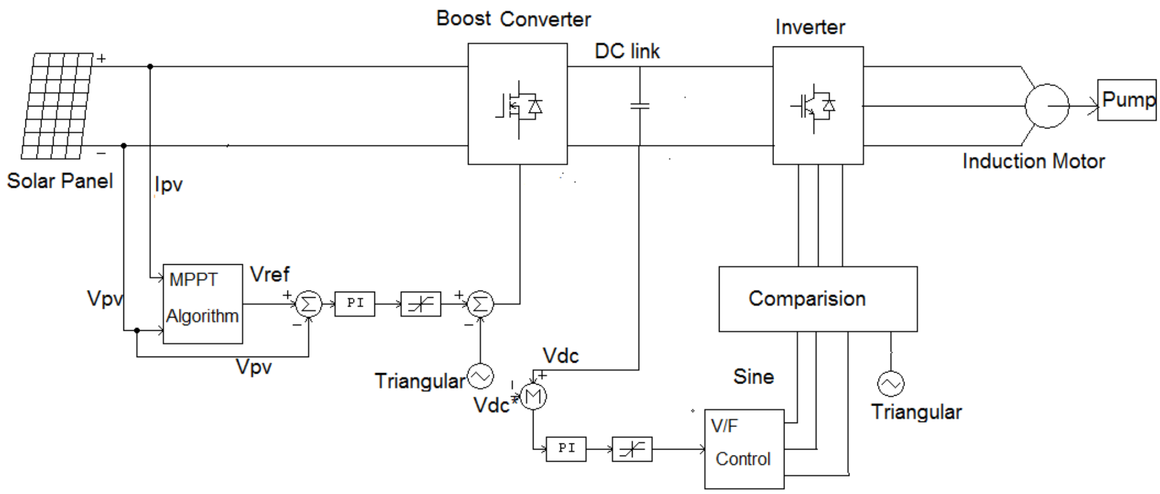

Figure 6.1: Simulation Diagram of Topology

As shown in fig 6.1 the output voltage from the solar panel are boosted to achieve

DC-link voltage for inverter. MPPT algorithm is implemented to abstract maximum power from the solar panel. The voltage and current are sensed from the panel and is given to MPPT algorithm. Reference Voltage (Vref) is generated which is compared with panel voltage and error generated is compared to triangular wave which controls the duty cycle of IGBT and hence DC-link is maintained constant.

Now to control inverter and to implement V/F control DC-link voltage is compared to reference DC-link voltage and it is given to V/F algorithm. Now with respect to voltage, frequency is change by V/F and three sine references are generated which are 120^0 phase shifted. These sine are compared with triangle wave, hence pulses are generated and given to IGBTs of inverter which runs motor-pump set.

Now the V/F method is implemented in such a way that when the DC-link voltage reaches 600 V or above frequency increases and tries to maintain DC-link upto 600 V. Now as the frequency increases speed will also increase which results in to more discharge of water. Usually this system delivers maximum power at 40 Hz frequency i.e. 2400 rpm speed.

Simulation Results obtained with this Topology is as shown below:

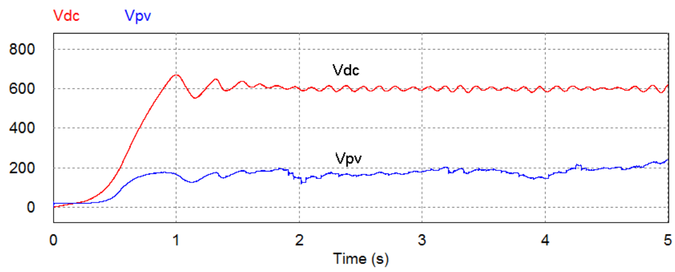

Figure 6.2: Panel Voltage and DC-link Voltage

Scale: Panel Voltage(red): X-axis: 1 div = 1 s, Y-axis: 1 div = 200 V.
DC link Voltage(blue): X-axis: 1 div =1 s, Y-axis: 1 div = 200 V.

The fig 6.2 shows the waveforms of input voltage from panel and DC-link voltage. DC-link voltage is around 600 V while panel voltage varies in range of 150 to 200 V. The ripple content in DC-link voltage is of 15%.

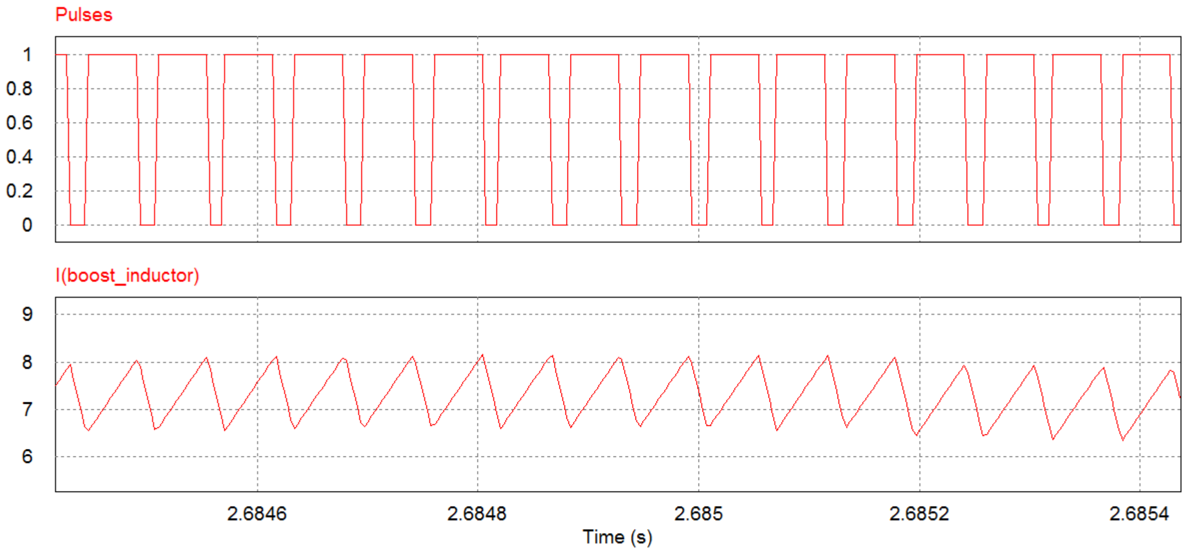

Figure 6.3: Pulses and Inductor Current

Scale: Pulses : X-axis:1 div=0.2 ms, Y-axis:1 div=0.2 V.
Inductor Current : X-axis: 1 div=0.2 ms, Y-axis: 1 div=1 A.

Waveforms in fig 6.3 shows the charging and discharging of boost inductor with respect to ON-OFF time of IGBT. When IGBT is ON boost inductor current increases and when IGBT is OFF current decreases. Due to this charging and discharging the voltage at output side gets boosted.

The maximum value of current during charging state is 8 A and minimum value of current during discharging state is 6.5 A. More over the ripple in inductor current comes out to be almost 25 %. The value of inductor selected here is 4.5 mH which has been derived in chapter 3.

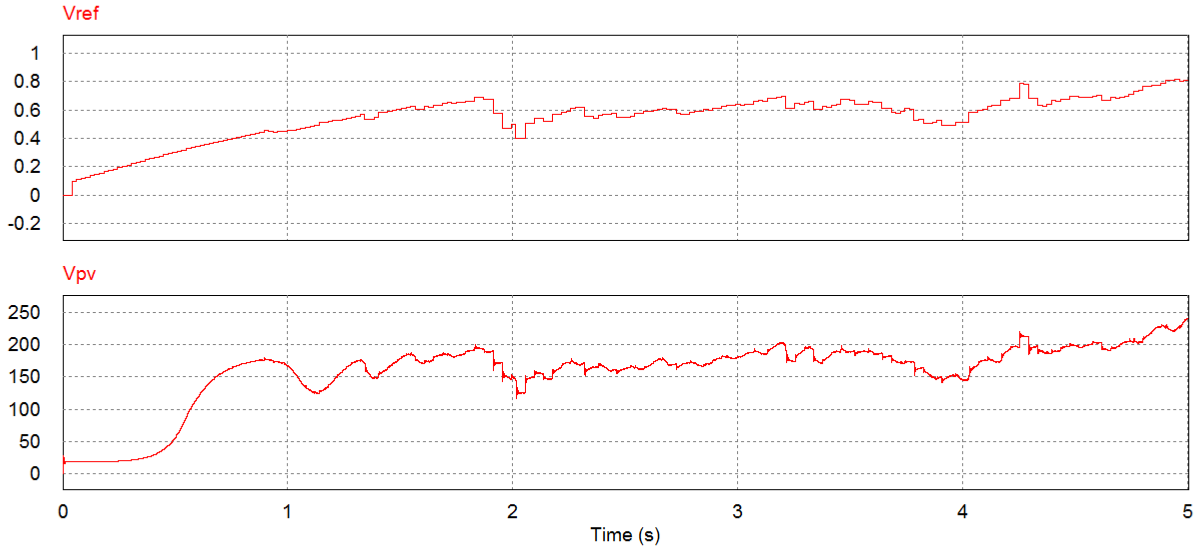

Figure 6.4: MPP ref Voltage and Panel Voltage

Scale: MPP ref Voltage : X-axis:1 div=1 s, Y-axis:1 div=0.2 V.
Panel Voltage: X-axis: 1 div=1 s, Y-axis: 1 div=50 V.

The fig 6.4 shows the generated reference voltage from the MPPT algorithm. It is clear from the waveform that panel voltage is trying to follow the path of reference voltage to obtain maximum power from panel. Hence MPPT algorithm is sucessfully implemented. Here the step size is 0.1.

Waveforms in fig 6.5 shows the output voltage and current. The rms value of voltage is 380 V and rms value of current is 3.36 A. Thus voltage and current attained matches the rating of motor. The output voltage obtained are due to sine-triangle PWM technique. Fig 6.6 shows the two cycles of output voltage and output current. It is clear from waveforms that frequency of output voltage and output current is 40 Hz. Moreover the power factor is 0.85.

As the input power from panel decreases DC-link voltage decreases as a result rms

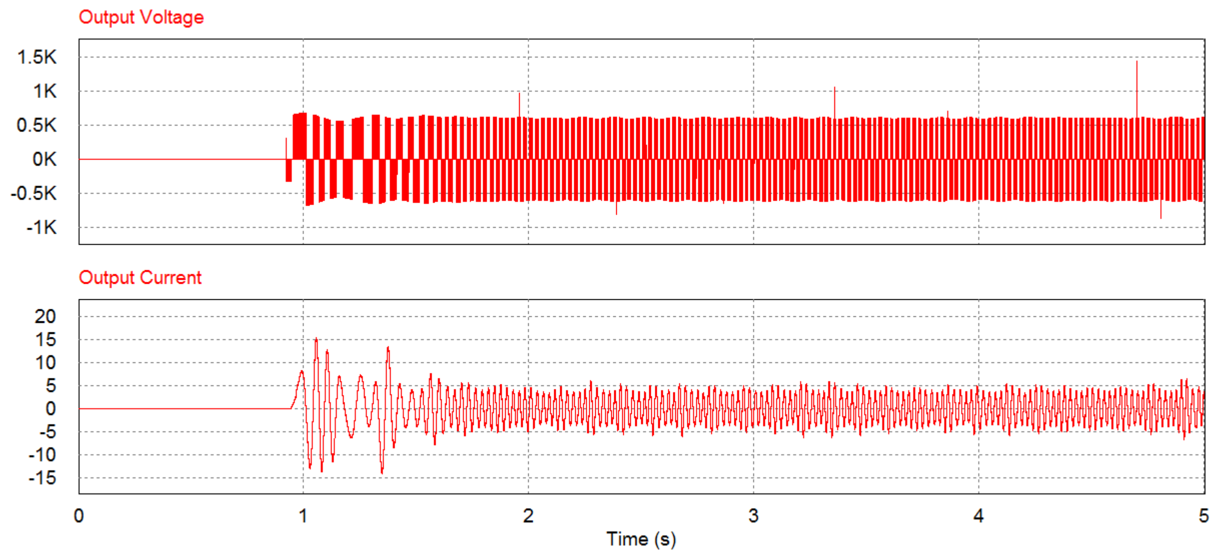

Figure 6.5: Output Voltage and Output Current of Inverter

Scale: Output Voltage : X-axis:1 div=1 s, Y-axis:1 div=500 V.
Output Current: X-axis: 1 div=1 s, Y-axis: 1 div=5 A.

output voltage also decrease which results in decrease in frequency and motor speed.

Waveforms in fig 6.7 shows that frequency is increased upto 40 Hz. Usually the output of MPPT is 80% i.e maximum power can be trasferred when motor runs at 80 percent speed i.e at 40 Hz. Since speed changes with frequency speed increases upto 2400 rpm.

V/F control is implemented in such a manner that once the voltage is reached upto 600 V and above, frequency starts to generate reference. Moreover motor draws more current as a result DC-link voltage decreases for same power, as a result the reference for frequency decreases.

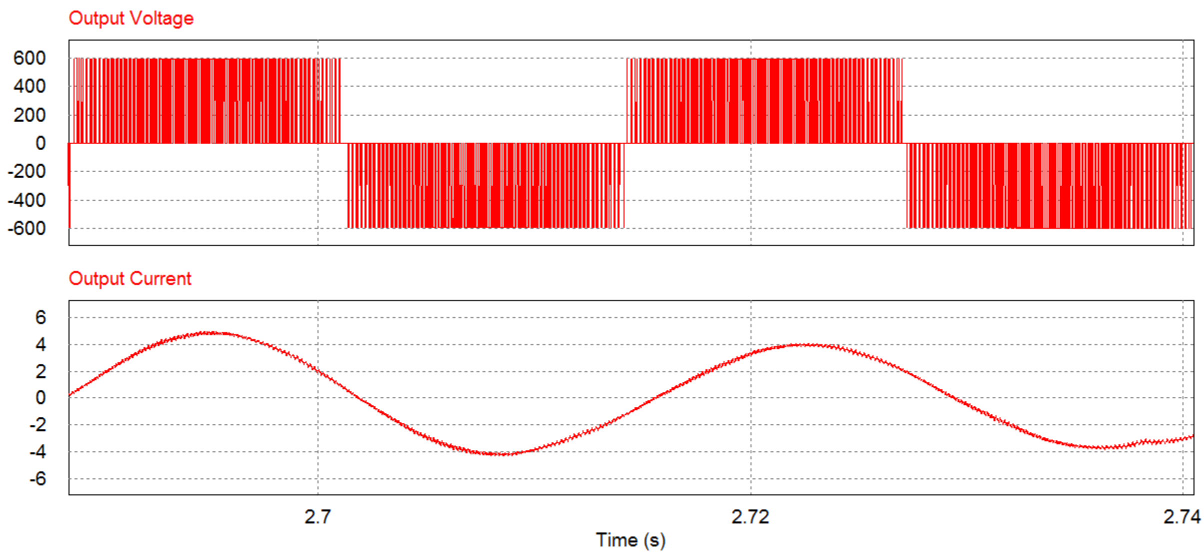

Figure 6.6: Output Voltage and Output Current of Inverter

Scale: Output Voltage : X-axis:1 div=0.02 s, Y-axis:1 div=200 V.
Output Current: X-axis: 1 div=0.02 s, Y-axis: 1 div=2 A.

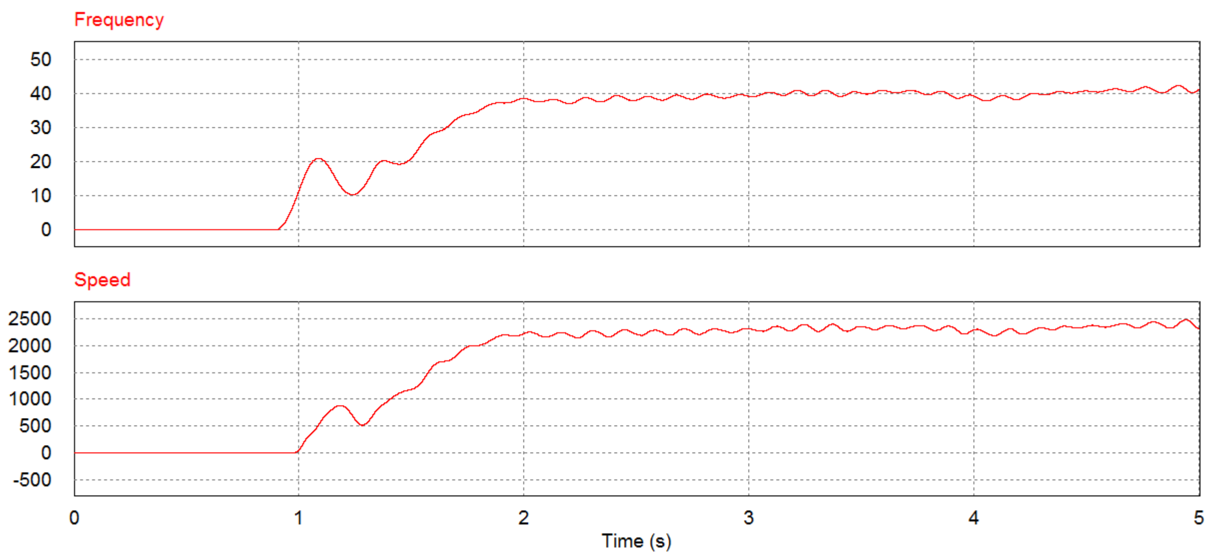

Figure 6.7: Frequency and Speed of Motor

Scale: Frequency: X-axis:1 div=1 s, Y-axis:1 div=0.2 V.
Speed: X-axis: 1 div=1 s, Y-axis: 1 div=50 V.

6.2 Hardware Results of Topology

The hardware results obtained when whole topology i.e. Boost Converter and Inverter are run together are as shown below:-

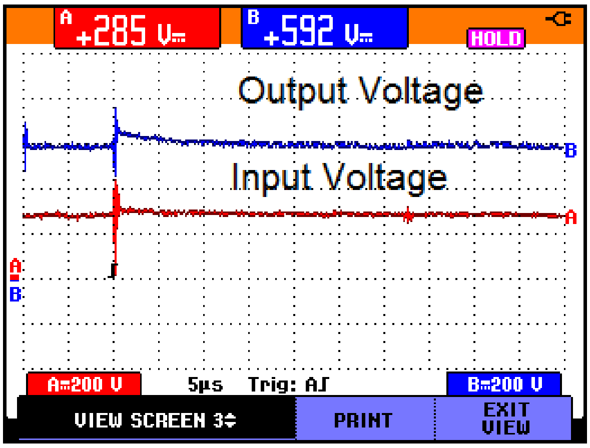

Figure 6.8: Input and Output Voltage of Boost Converter

Scale: Input Voltage (red): X-axis:1 div=5 μs, Y-axis:1 div=200 V.
Output Voltage (blue): X-axis: 1 div=5 μs, Y-axis: 1 div=200 V.

Input voltage obtained from the Solar panel is 285 V. The output voltage obtained from boost converter is 592 V. This voltage will act as a DC-link voltage for 3-ϕ inverter.

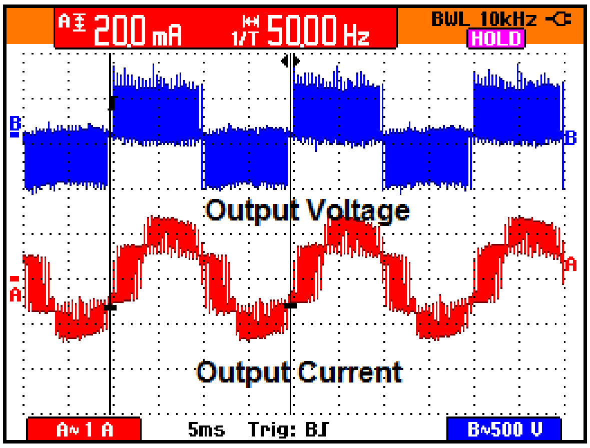

Figure 6.9: Output Voltage and Output Current of Inverter at 50 Hz

Scale:Output Voltage (blue): X-axis:1 div=5 ms, Y-axis:1 div=500 V.
Output Current (red): X-axis: 1 div=5 ms, Y-axis: 1 div=1 A.

The fig 6.9 shows the output voltage and output current of an inverter. The supply frequency is 50 Hz. The rms value of voltage and current are 415 V and 0.8 A respectively.

Testing of this topology is carried out on resistive load. As a result the voltage and current are in phase with each other i.e. power factor is unity. As the DC-link voltage is around 590 V the frequency of the system is 50 Hz.

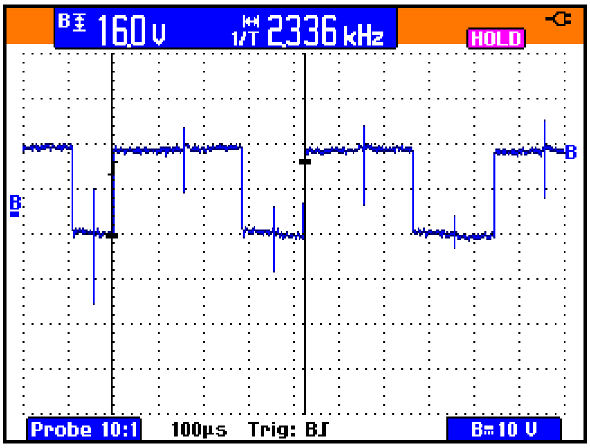

Figure 6.10: Pulses to R Bottom Switch of Inverter

Scale: Gate pulse: X-axis:1 div=100 μs, Y-axis:1 div=10 V.

The fig 6.10 shows the pulses given to bottom switch of R-phase. Here IGBT is given 16 V to get triggered. This pulses are generated with PWM technique. The switching frequency is of 2.336 kHz.

The fig 6.11 shows the ringing during turn off. The maximum voltage is 704 V and minimum voltage is 592 V when IGBT is blocking 600 V.

The fig 6.12 shows the output voltage and output current of inverter at 30 Hz frequency. Here voltage and current are in phase with each other as it is tested on resistive load.

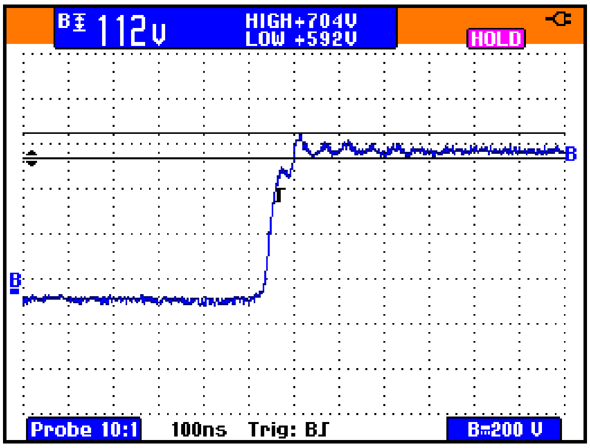

Figure 6.11: Ringing during Turn OFF

Scale: Voltage: X-axis:1 div=100 ns, Y-axis:1 div=200 V.

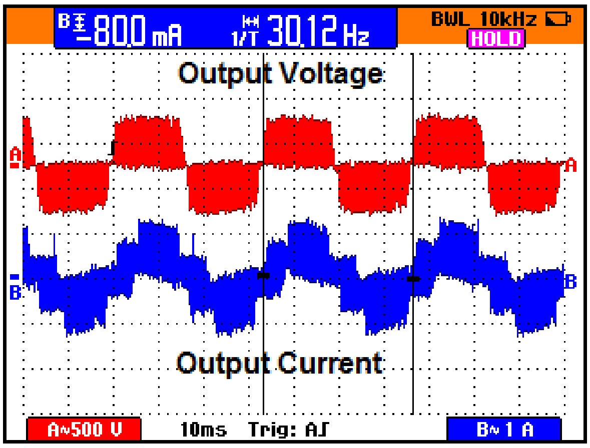

Figure 6.12: Output Voltage and Output Current at 30 Hz

Scale: Voltage (red): X-axis:1 div=10 ms, Y-axis:1 div=500 V.
Current (blue): X-axis: 1 div=10 ms, Y-axis: 1 div=1 A.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

From the above results it is concluded that when the boost converter is developed and MPPT algorithm is implemented, the hardware results are obtained as per requirement and are similar to simulation results. Moreover 3-ϕ inverter along with V/F control works properly giving desired output. The speed of motor changes with the change in output from solar panel.

Once individually boost converter and inverter works properly the whole system is tested. This topology is tested on resistive load, waveforms obtained from the hardware are as per requirement and waveforms are similar to the results obtained in simulation.

7.2 Future Work

In future this topology is to be tested with induction motor and submersible pump. Once the topology works properly it can be synchronized with AC drive so that grid voltage can be used when solar energy is not available.

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