BLDC Motor-Driven Grid Interfaced Solar PV Based Water Pumping Using Zeta Converter

A dissertation

Submitted in partial fulfillment of the requirements

For the award of the degree of

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In

Power Electronics & Drives

Submitted by

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CERTIFICATE

This is to certify that the project work entitled **"BLDC Motor-Driven Grid Interfaced Solar PV Based Water Pumping Using Zeta Converter"** that is being submitted by **K VIJAYA DATTU (19NK1D5207)** in partial fulfillment of the requirement of **MASTER OF TECHNOLOGY IN POWER ELECTRONICS&DRIVES** to the **VELAGA NAGESWARA RAO COLLEGE OF ENGINEERING** during the year 2018-2020 is carried out by him under my guidance and supervision.

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The accompanying thesis entitled **"BLDC Motor-Driven Grid Interfaced Solar PV Based Water Pumping Using Zeta Converter"** is submitted for **Master of Technology (Power Electronics and Drives)** at the **Velaga Nageswara Rao college of engineering, Ponnur.** I declare this is my original work supervision of Mr**. Sri. A. ARUN KUMAR**. All the work ideas recorded are original where acknowledged in the text or reference. The work presented here has not previously been submitted for a degree or diploma at this or any other, University or Examining body.

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Abstract: In this project zeta converter-fed brushless direct current (BLDC) motor drive as a cost-effective solution for low-power applications is presented. The VSI, converting dc output from a zeta converter into ac, feeds the BLDC motor to drive a water pump coupled to its shaft. The VSI is operated in fundamental frequency switching through an electronic commutation of BLDC motor assisted by its built-in encoder. The high frequency switching losses are thereby eliminated, contributing in an increased efficiency of proposed water pumping system. By adjusting the dc link voltage of the voltage source inverter (VSI) feeding a BLDC motor, the speed of the BLDC motor is controlled. This paper deals with the implementation of pulse width modulated Zeta converter, lower total harmonic distortion factor and better efficiency. The proposed zeta converter based BLDC Motor drive is implemented to improve the efficiency of water pumping system and to obtain a wide range of speed control.

Index Terms—Brushless dc (BLDC) motor, incremental conductance maximum power point tracking (INC-MPPT), solar photovoltaic (SPV) array, voltage-source inverter (VSI), water pump, zeta converter

CHAPTER 1
INTRODUCTION

1.1 BLDC MOTOR

A BLDC motor is a permanent magnet synchronous that uses position detectors and an inverter to control the armature currents. The BLDC motor is sometimes referred to as an inside out dc motor because its armature is in the stator and the magnets are on the rotor and its operating characteristics resemble those of a dc motor. Instead of using a mechanical commutator as in the conventional dc motor, the BLDC motor employs electronic commutation which makes it a virtually maintenance free motor.

There are two main types of BLDC motors: trapezoidal type and sinusoidal type. In the trapezoidal motor the back-Emf induced in the stator windings has a trapezoidal shape and its phases must be supplied with quasi-square currents for ripple free operation. The sinusoidal motor on the other hand has a sinusoidally shaped back – emf and requires sinusoidal phase currents for ripple free torque operation. The shape of the back – emf is determined by the shape of rotor magnets and the stator winding distribution.

The sinusoidal motor needs high resolution position sensors because the rotor position must be known at every time instant for optimal operation. It also requires more complex software and hardware. The trapezoidal motor is a more attractive alternative for most applications due to simplicity, lower price and higher efficiency.

BLDC motors exist in many different configurations but the three phase motor is most common type due to efficiency and low torque ripple. This type of motor also offers a good compromise between precise control and number of power electronic devices needed to control stator currents. Fig. 2.1 shows a transverse section of a BLDC motor. Position detection is usually implemented using three Hall - an effect sensor that detects the presence of small magnets that are attached to the motor shaft.

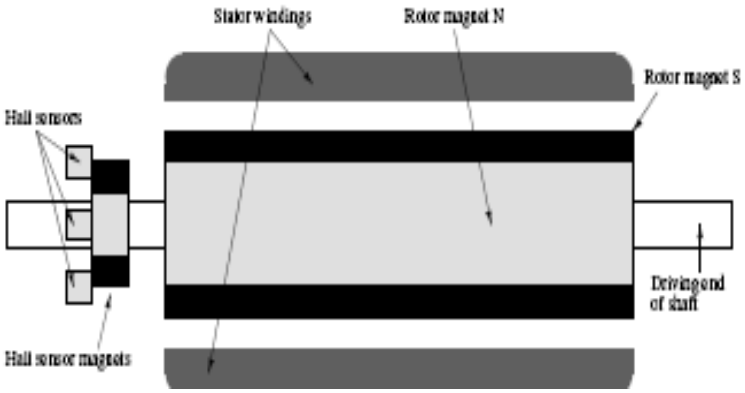


Fig.1.1 BLDC motor transverse section.

1.2 OPERATION

Typically,aBrushlessdcmotorisdrivenbyathree-phaseinverterwith,whatis called,six-stepcommutation.Theconductingintervalforeachphaseis120^{o}by electrical angle. The commutation phase sequence is like AB-AC-BC-BA-CA-CB. Each conductingstageiscalledonestep.Therefore,only twophasesconductcurrentatany time,leaving thethird phasefloating.Inordertoproducemaximumtorque,theinverter shouldbecommutatedevery60^{o} sothatcurrentisinphasewiththebackEMF.The commutationtiming isdeterminedby therotorposition,whichcanbedetectedby Hall sensorsas shown in the figure 1.2 (H1, H2, H3). The figure also shows ideal currents and back emf waveforms.

Figure 1.2 shows a cross section of a three phase star connected motor along with its phase energizing sequence. Each interval starts with the rotor and stator field lines 120^{0} apart and ends when they are 60^{0} apart. Maximum torque is reached when the field lines are perpendicular. Current commutation is done by inverter as shown in a simplified from in figure. The switches are shown as bipolar junction transistors but MOSFET switches are more common. Table 1.1 shows the switching sequence, the current direction and the position sensor signals.

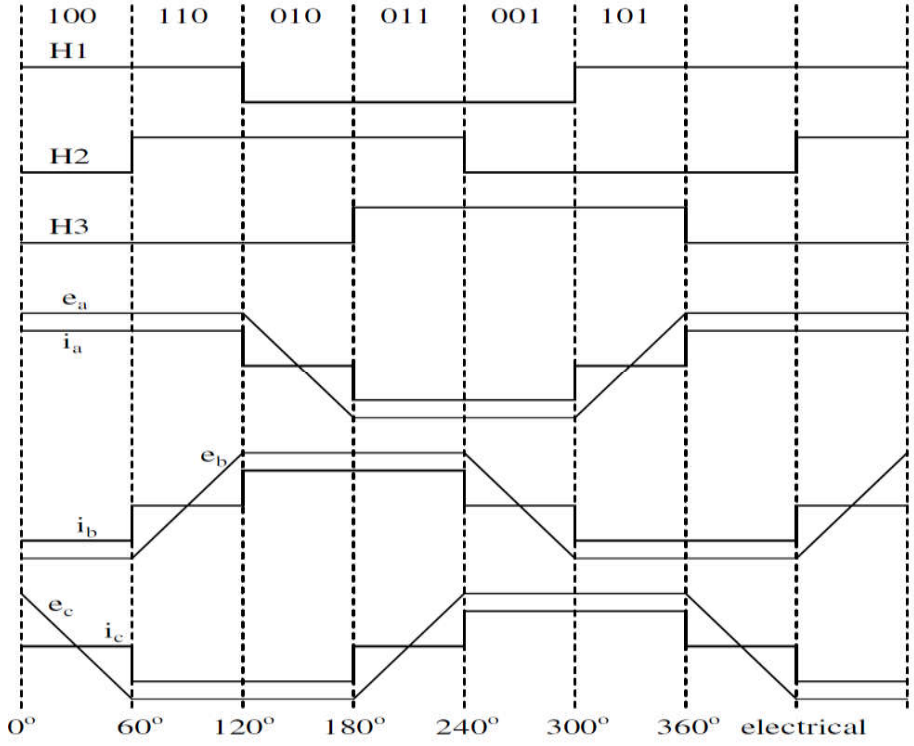


Fig.1.2 Ideal back-emf's, phase currents, and position sensor signals.

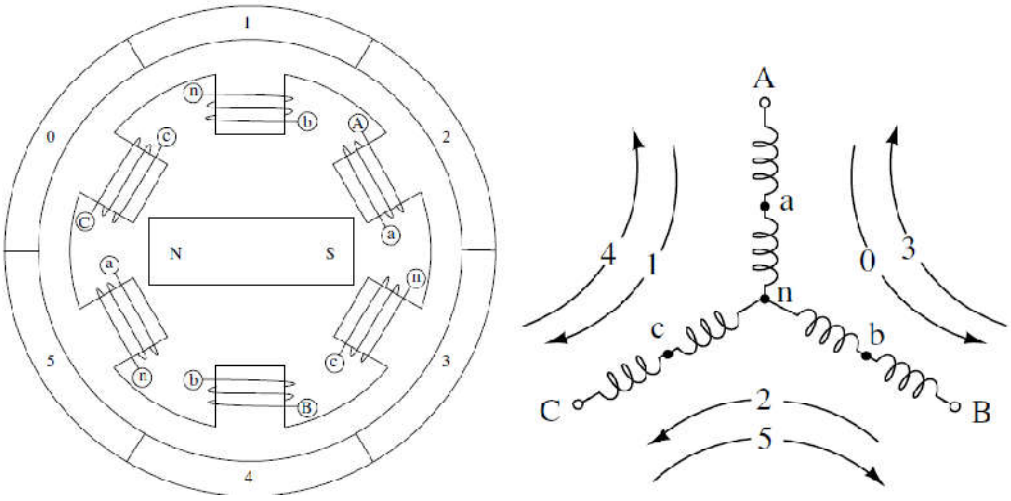


Fig.1.3: BLDC motor cross section and phase energizing sequence

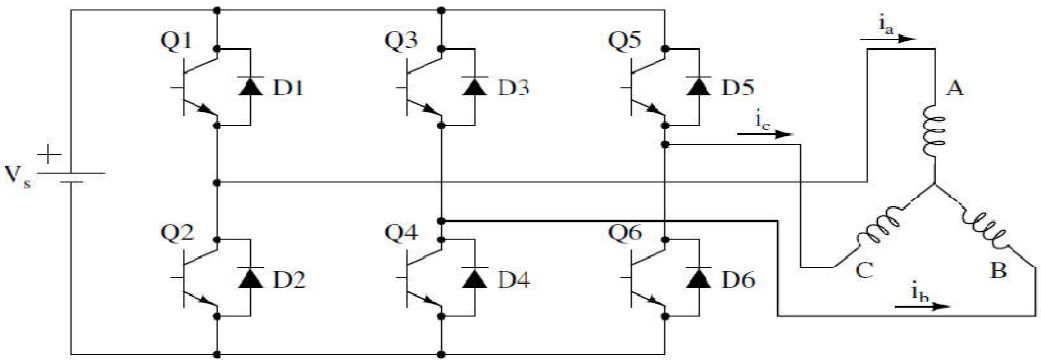


Fig.1.4: Simplified BLDC drive scheme

Table1.1: Switching Sequence.

Switching interval	Seq. number	Pos. sensors			Switch closed		Phase Current		
		H1	H2	H3			A	B	C
0° – 60°	0	1	0	0	Q1	Q4	+	-	off
60° – 120°	1	1	1	0	Q1	Q6	+	off	-
120° – 180°	2	0	1	0	Q3	Q6	off	+	-
180° – 240°	3	0	1	1	Q3	Q2	-	+	off
240° – 300°	4	0	0	1	Q5	Q2	-	off	+
300° – 360°	5	1	0	1	Q5	Q4	off	-	+

1.3PHOTOVOLTAIC TECHNOLOGY

A PV array consists of a number of PV modules, mounted in the same plane and electrically connected to give the required electrical output for the application. The PV array can be of any size from a few hundred watts to hundreds of kilowatts, although the larger systems are often divided into several electrically independent sub arrays each feeding into their own power conditioning system.

Photovoltaic's is the field of technology and research related to the devices which directly convert sunlight into electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic effect involves the creation of voltage in a material upon exposure to electromagnetic radiation.

The photovoltaic effect was first noted by a French physicist, Edmund Becquerel, in 1839, who found that certain materials would produce small amounts of electric current when exposed to light. In 1905, Albert Einstein described the nature of light and the photoelectric effect on which photovoltaic technology is based, for which he later

won a Nobel prize in physics. The first photovoltaic module was built by Bell Laboratories in 1954. It was billed as a solar battery and was mostly just a curiosity as it was too expensive to gain widespread use. In the 1960s, the space industry began to make the first serious use of the technology to provide power aboard spacecraft. Through the space programs, the technology advanced, its reliability was established, and the cost began to decline. During the energy crisis in the 1970s, photovoltaic technology gained recognition as a source of power for non-space applications.

The solar cell is the elementary building block of the photovoltaic technology. Solar cells are made of semiconductor materials, such as silicon. One of the properties of semiconductors that makes them most useful is that their conductivity may easily be modified by introducing impurities into their crystal lattice. For instance, in the fabrication of a photovoltaic solar cell, silicon, which has four valence electrons, is treated to increase its conductivity. On one side of the cell, the impurities, which are phosphorus atoms with five valence electrons (n-donor), donate weakly bound valence electrons to the silicon material, creating excess negative charge carriers.

On the other side, atoms of boron with three valence electrons (p-donor) create a greater affinity than silicon to attract electrons. Because the p-type silicon is in intimate contact with the n-type silicon a p-n junction is established and a diffusion of electrons occurs from the region of high electron concentration (the n-type side) into the region of low electron concentration (p-type side). When the electrons diffuse across the p-n junction, they recombine with holes on the p-type side.

However, the diffusion of carriers does not occur indefinitely, because the imbalance of charge immediately on either sides of the junction originates an electric field. This electric field forms a diode that promotes current to flow in only one direction.

Ohmic metal-semiconductor contacts are made to both the n-type and p-type sides of the solar cell, and the electrodes are ready to be connected to an external load. When photons of light fall on the cell, they transfer their energy to the charge carriers. The electric field across the junction separates photo-generated positive charge carriers (holes) from their negative counterpart (electrons). In this way an electrical current is extracted once the circuit is closed on an external load.

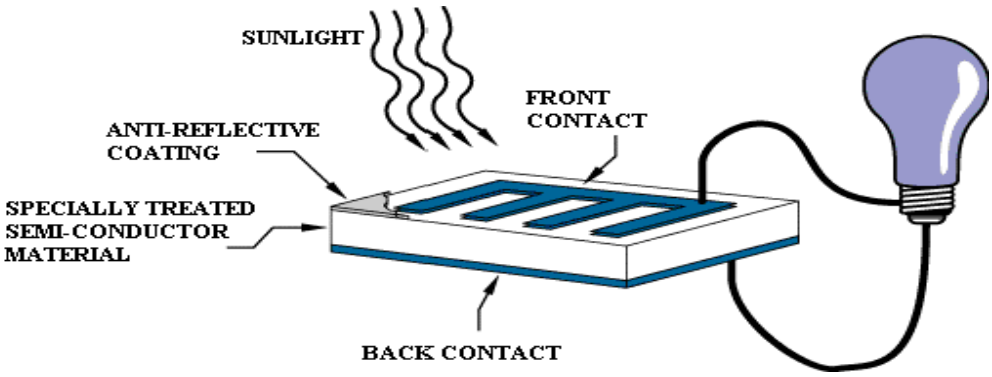


Fig:1.5Photovoltaic system

1.4CLASSIFICATION OF PV SYSTEM

Figure 1.6. The two main general classifications as depicted in the figure are the stand-alone and the grid-connected systems. The main distinguishing fact tor between these two systems is that in stand-alone systems the solar energy output is matched with the load demand. To cater for different load patterns, storage elements are generally used and most systems currently use batteries for storage. If the PV system is used in conjunction with another power source like a wind or diesel generator then it falls under the class of hybrid systems. The balances of system (BOS) components are a major contribution to the life cycle costs of a photovoltaic system. They include all the power conditioning units, storage elements and mechanical structures that are needed. They especially have a huge impact on the operating costs of the PV system.

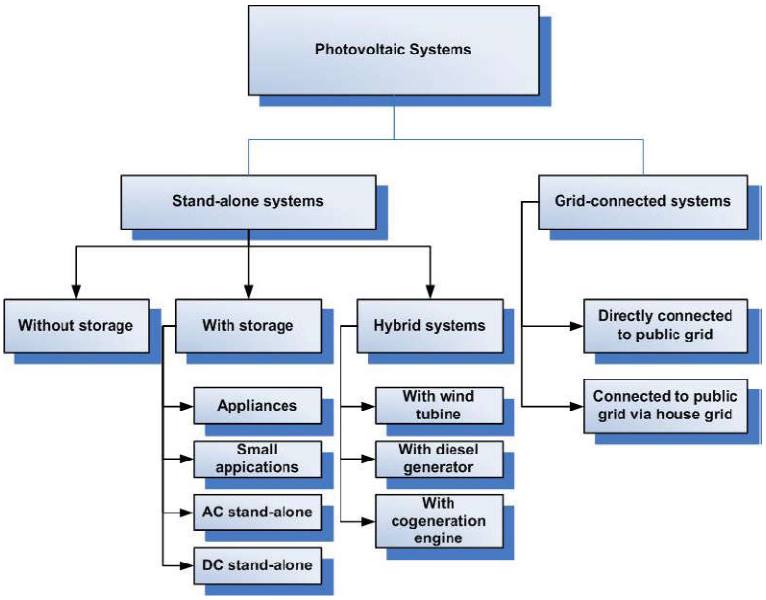


Fig.1.6: Classification of PV systems

1.4.1 PV cell

PVs generate electric power when illuminated by sunlight or artificial light. To illustrate the operation of a PV cell the p-n homo junction cell is used. PV cells contain a junction between two different materials across which there is a built in electric field. The absorption of photons of energy greater than the band gap energy of the semiconductor promotes electrons from the valence band to the conduction band, creating hole-electron pairs throughout the illuminated part of the semiconductor.These electron and hole pairs will flow in opposite directions across the junction thereby creating DC power.

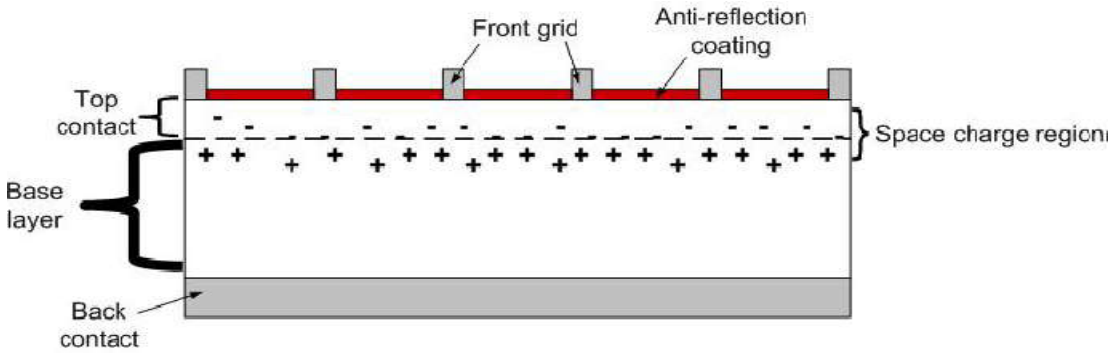


Fig.1.7: Structure of a PV cell

The cross-section of a PV cell is shown in Figure 1.7. The most common material used in PV cell manufacture is mono-crystalline or poly-crystalline silicon. Each cell is typically made of square or rectangular wafers of dimensions measuring about 10cm x10cm x0:3mm. In the dark the PV cell's behavior is similar to that of a diode and the well known Shockley-Read equation can be used to model its behavior i.e.

$$\mathrm{i} = I_S\left(e^{\frac{qV}{\beta kT}} - 1\right)$$

1.4.2 PV Module

For the majority of applications multiple solar cells need to be connected in series or in parallel to produce enough voltage and power. Individual cells are usually connected into a series string of cells (typically 36 or 72) to achieve the desired output voltage. The complete assembly is usually referred to as a module and manufacturers basically sell modules to customers. The modules serves another function of protecting

individual cells from water, dust etc. as the solar cells are placed into an encapsulation of single or double at glasses.

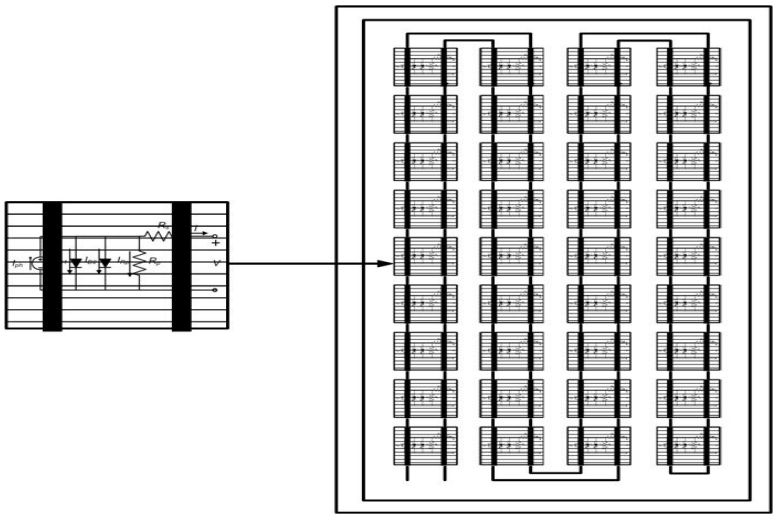


Fig.1.8: Structure of a PV module with 36 cells connected in series

Within a module the different cells are connected electrically in series or in parallel although most modules have a series connection. Figure 1.8 shows a typical connection of how 36 cells are connected in series. In a series connection the same current flows through all the cells and the voltage at the module terminals is the sum of the individual voltages of each cell. It is therefore, very critical for the cells to be well matched in the series string so that all cells operate at the maximum power points. When modules are connected in parallel the current will be the sum of the individual cell currents and the output voltage will equal that of a single cell.

1.4.3 Array

An array is a structure that consists of a number of PV modules, mounted on the same plane with electrical connections to provide enough electrical power for a given application. Arrays range in power capacity from a few hundred watts to hundreds of kilowatts. The connection of modules in an array is similar to the connection of cells in a single module. To increase the voltage, modules are connected in series and to increase the current they are connected in parallel. Matching is again very important for the overall performance of the array. The structure of an array is shown in figure 1.9, which has 4 parallel connections of 4 module strings connected in series.

The voltages for n modules in series are given as:

$$V_{series} = \sum_{j=1}^{n} V_j = V_1 + V_2 + \ldots\ldots\ldots + V_n \quad \text{for I} > 0 \tag{1.1}$$

$$V_{seriesoc} = \sum_{j=1}^{n} V_j = V_{oc1} + V_{oc2} + \ldots\ldots\ldots + V_{ocn} \quad \text{for I} = 0 \tag{1.2}$$

The current and voltage for m modules in parallel is given

$$I_{parallel} = \sum_{j=1}^{n} I_j = I_1 + I_2 + \ldots\ldots\ldots + I_n$$

$$V_{parallel} = V_1 = V_2 = \ldots\ldots\ldots = V_n \tag{1.3}$$

For an array to perform well all the modules must not be shaded otherwise it will act as a load resulting in heat that may cause damage. Bypass diodes are usually used to avoid damage although they result in further increase in cost. Integration of bypass diodes in some large modules during manufacturing is not uncommon and reduces the extra wiring required. It must be pointed out though that it becomes very difficult to replace the diode if it fails.

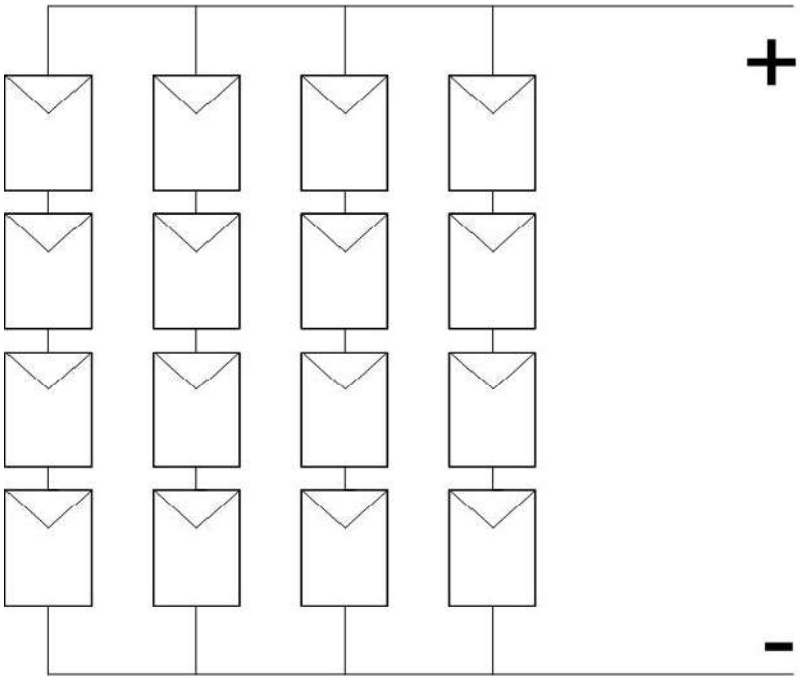


Fig.1.9: Structure of a PV array

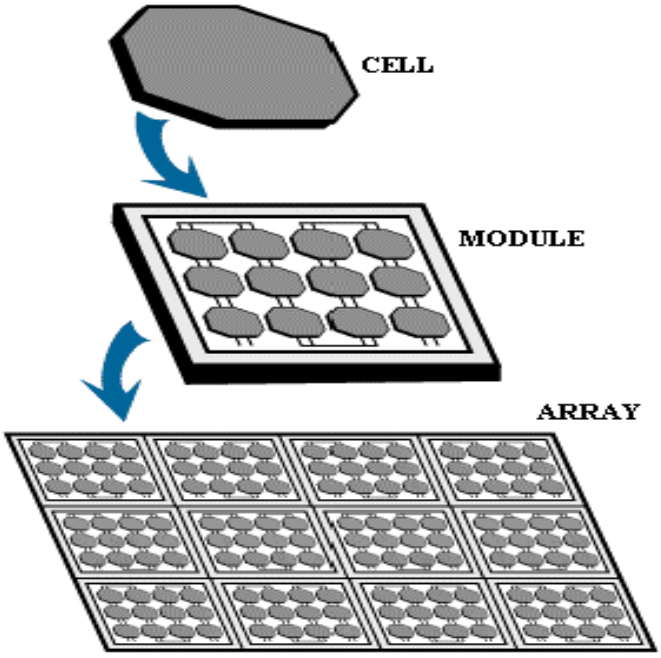


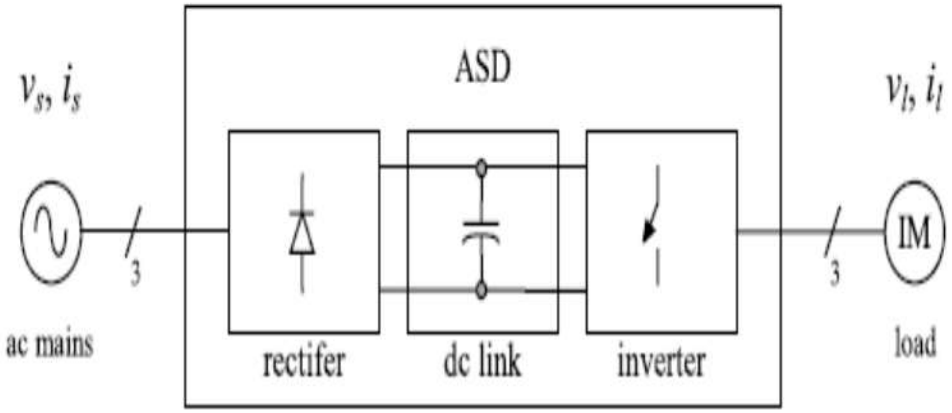
Fig: 1.10Model of PV cell

1.5VOLTAGE SOURCE INVERTERS

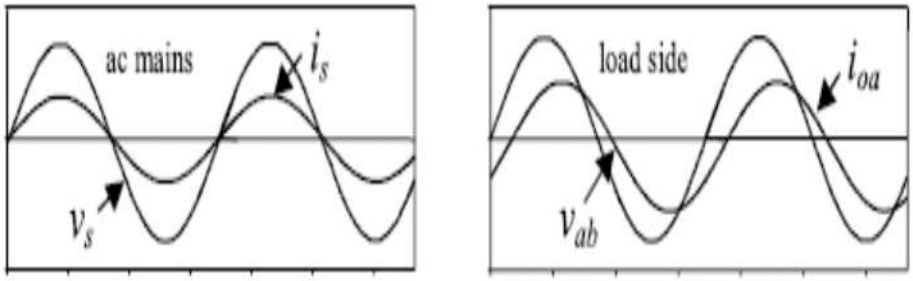
The main objective of static power converters is to produce an ac output waveform from a dc power supply. These are the types of waveforms required in adjustable speed drives (ASDs), uninterruptible power supplies (UPS), static var compensators, active filters, flexible ac transmission systems (FACTS), and voltage compensators, which are only a few applications. For sinusoidal ac outputs, the magnitude, frequency, and phase should be controllable. According to the type of ac output waveform, these topologies can be considered as voltage source inverters (VSIs), where the independently controlled ac output is a voltage waveform. These structures are the most widely used because they naturally behave as voltage sources as required by many industrial applications, such as adjustable speed drives (ASDs), which are the most popular application of inverters. Similarly, these topologies can be found as current source inverters (CSIs), where the independently controlled ac output is a current waveform. These structures are still widely used in medium-voltage industrial applications, where high-quality voltage waveforms are required. Static power converters, specifically inverters, are constructed from power switches and the ac output waveforms are therefore made up of discrete values. This leads to the generation of waveforms that feature fast transitions rather than smooth ones. For instance, the ac

output voltage produced by the VSI of a standard ASD is a three-level waveform (Fig.1.11c). Although this waveform is not sinusoidal as expected (Fig.1.11b), its fundamental component behaves as such. This behavior should be ensured by a modulating technique that controls the amount of time and the sequence used to switch the power valves on and off. The modulating techniques most used are the carrier-based technique (e.g., sinusoidal pulse width modulation, SPWM), the space-vector (SV) technique, and the selective-harmonic elimination (SHE) technique.

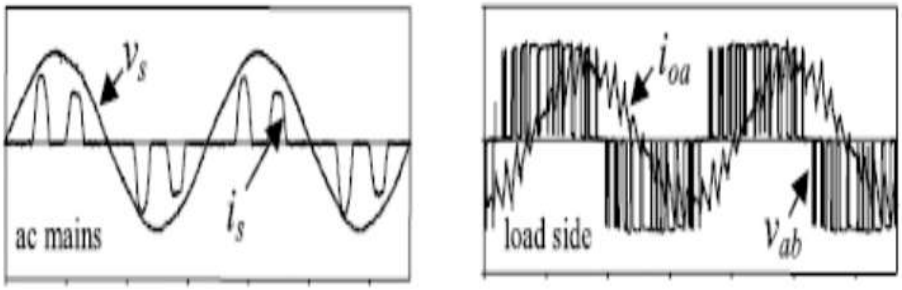
VSI-based controller is to introduce a semiconductor controlled device which is capable of emulating the characteristics of the excitation capacitors and injecting adequate reactive power into the induction generator and the load. The secondary objective is the regulation of the real power. The proposed controller employes a DC side resistor such that the unwanted real power will be consumed in this resistor. As a consequence, the induction generator will always observe a constant real power demand. This VSI-based controller can replace the earlier reported impedance controller and eliminates the need for excitation capacitor. Due to the nature of the VSI-based controller, a wider control range that cm accommodate various control operations of the overall system is achievable. The controller is capable of delivering or receiving real and reactive power. This control should be performed in such a way that the real and reactive power components cm be controlled independently. Moreover, the VSI-based controller should be able to respond rapidly to the control commands, and drive the operating point of the system to the desired one.



1.11(a) The electrical power conversion topology



1.11 (b) The ideal input (ac mains) and output (load) waveforms



1.11 (c) The actual input (ac mains) and output (load) waveforms

Fig.1.11: The ac output voltage produced by the VSI of a standard ASD

1.6SINGLE-PHASE VOLTAGE SOURCE INVERTERS

Single-phase voltage source inverters (VSIs) can be found as half-bridge and full-bridge topologies. Although the power range they cover is the low one, they are widely used in power supplies, single-phase UPSs, and currently to form elaborate high-power static power topologies, such as for instance, the multicell configurations.

1.7HALF-BRIDGE VSI

Fig.1.12 shows the power topology of a half-bridge VSI, where two large capacitors are required to provide a neutral point N, such that each capacitor maintains a constant voltage (Vi)/2. Because the current harmonics injected by the operation of the inverter are low-order harmonics, a set of large capacitors (C+ and C-) is required. It is clear that both switches S+ and S- cannot be ON simultaneously because a short circuit across the dc link voltage source Vi would be produced. There are two defined (states 1 and 2) and one undefined (state 3) switch state as shown in Table 1.2. In order to avoid the short circuit across the dc bus and the undefined ac output voltage condition, the modulating technique should always ensure that at any instant either the top or the bottom switch of the inverter leg is on.

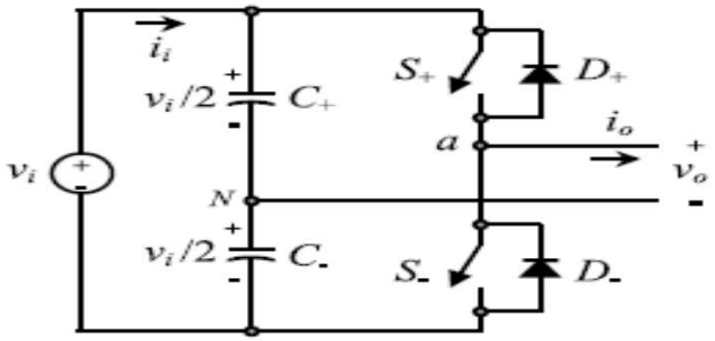


Fig.1.12: Single-phase half-bridge VSI.

State	State	v	Components Conducting
$_+$ is on and $_-$ is off	1	$v/2$	$_+$ if > 0
			$_+$ if < 0
$_-$ is on and $_+$ is off	2	$-v/2$	$_-$ if > 0
			$_-$ if < 0
$_+$ and $_-$ are all off	3	$-v/2$	$_-$ if > 0
		$v/2$	$_+$ if < 0

Table 1.2: Switch states for a half-bridge single-phase VSI

1.8 FULL-BRIDGE VSI

Fig.1.13 shows the power topology of a full-bridge VSI. This inverter is similar to the half-bridge inverter; however, a second leg provides the neutral point to the load. As expected, both switches S1+ and S1- (or S2+ and S2-) cannot be on simultaneously because a short circuit across the dc link voltage source Vi would be produced. There are four defined (states 1, 2, 3, and 4) and one undefined (state 5) switch states as shown in Table 1.3. The undefined condition should be avoided so as to be always capable of defining the ac output voltage. It can be observed that the ac output voltage can take values up to the dc link value Vi, which is twice that obtained with half-bridge VSI topologies. Several modulating techniques have been developed that are applicable to full bridge VSIs. Among them are the PWM (bipolar and unipolar) techniques.

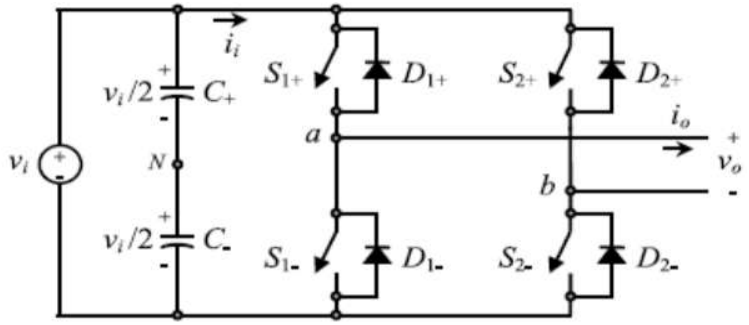


Fig.1.13: Single-phase full-bridge VSI.

State	State	v_a	v_b	v	Components Conducting	
$_{1+}$ and $_{2-}$ are on and $_{1-}$ and $_{2+}$ are off	1	$v/2$	$-v/2$	v	$_{1+}$ and $_{2-}$	if >0
					$_{1+}$ and $_{2-}$	if <0
$_{1-}$ and $_{2+}$ are on and $_{1+}$ and $_{2-}$ are off	2	$-v/2$	$v/2$	$-v$	$_{1-}$ and $_{2+}$	if >0
					$_{1-}$ and $_{2+}$	if <0
$_{1+}$ and $_{2+}$ are on and $_{1-}$ and $_{2-}$ are off	3	$v/2$	$v/2$	0	$_{1+}$ and $_{2+}$	if >0
					$_{1+}$ and $_{2+}$	if <0
$_{1-}$ and $_{2-}$ are on and $_{1+}$ and $_{2+}$ are off	4	$-v/2$	$-v/2$	0	$_{1-}$ and $_{2-}$	if >0
					$_{1-}$ and $_{2-}$	if <0
$_{1-}$, $_{2-}$, $_{1+}$, and $_{2+}$ are all off	5	$-v/2$	$v/2$	$-v$	$_{1-}$ and $_{2+}$	if >0
		$v/2$	$-v/2$	v	$_{1+}$ and $_{2-}$	if <0

Table 1.3: Switch states for a full-bridge single-phase VSI

1.9 THREE PHASE VOLTAGE SOURCE INVERTERS

Single-phase VSIs cover low-range power applications and three-phase VSIs cover the mediumto high-power applications. The main purpose of these topologies is to provide a three-phase voltage source, where the amplitude, phase, and frequency of the voltages should always be controllable. Although most of the applications require sinusoidal voltage waveforms (e.g., ASDs, UPSs, FACTS, VAR compensators), arbitrary voltages are also required in some emerging applications (e.g., active filters, voltage compensators). The standard three-phase VSI topology is shown in Fig.1.14 and the eight valid switch states are given in Table 1.4. As in single-phase VSIs, the switches of any leg of the inverter (S1 and S4, S3 and S6, or S5 and S2) cannot be switched on simultaneously because this would result in a short circuit across the dc link voltage supply. Similarly, in order to avoid undefined states in the VSI, and thus undefined ac output line voltages, the switches of any leg of the inverter cannot be switched off simultaneously as this will result in voltages that will depend upon the respective line

current polarity. Of the eight valid states, two of them (7 and 8 in Table 1.4) produce zero ac line voltages. In this case, the ac line currents freewheel through either the upper or lower components. The remaining states (1 to 6 in Table 1.4) produce non-zero ac output voltages. In order to generate a given voltage waveform, the inverter moves from one state to another. Thus the resulting ac output line voltages consist of discrete values of voltages that are Vi , 0, and -Vi for the topology shown in Fig.1.14. The selection of the states in order to generate the given waveform is done by the modulating technique that should ensure the use of only the valid states

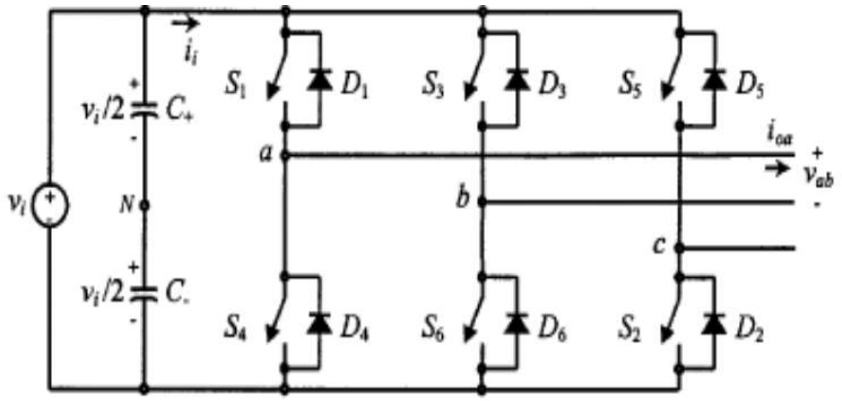


Fig.1.14: Three-phase VSI topology.

State	State	v_{ab}	v_b	v_a	Space Vector
1, 2, and 6 are on and 4, 5, and 3 are off	1	v	0	$-v$	$V_1 = 1 + j0.5$
2, 3, and 1 are on and 5, 6, and 4 are off	2	0	v	$-v$	$V_2 = j1.155$
3, 4, and 2 are on and 6, 1, and 5 are off	3	$-v$	v	0	$V_3 = -1 + j0.5$
4, 5, and 3 are on and 1, 2, and 6 are off	4	$-v$	0	v	$V_4 = -1 - j0.5$
5, 6, and 4 are on and 2, 3, and 1 are off	5	0	$-v$	v	$V_5 = -j1.155$
6, 1, and 5 are on and 3, 4, and 2 are off	6	v	$-v$	0	$V_6 = 1 - j0.5$
1, 3, and 5 are on and 4, 6, and 2 are off	7	0	0	0	$V_7 = 0$
4, 6, and 2 are on and 1, 3, and 5 are off	8	0	0	0	$V_8 = 0$

Table 1.4: Valid switch states for a three-phase VSI

1.10 MAXIMUM POWER POINT TRACKING

Maximum power point tracking (MPPT) is a technique used with wind turbines and photovoltaic (PV) solar systems to maximize power output.

This concerns itself primarily with solar photovoltaics, but the basic theory applies to other uses of power photovoltaics such as optical power transmission and thermophotovoltaics. The efficiency of other types of power generation systems (such as wind turbines) can be optimized with similar load optimization concepts, though the form of the I-V curve may differ. It is of greatest interest when the power available to the system is variable, which is commonly the case in solar photovoltaics.

PV solar systems exist in many different configurations with regard to their relationship to inverter systems, external grids, battery banks, or other electrical loads. Regardless of the ultimate destination of the solar power though, the central problem addressed by MPPT is that the efficiency of power transfer from the solar cell depends on both the amount of sunlight falling on the solar panels and the electrical characteristics of the load. As the amount of sunlight varies, the load characteristic that gives the highest power transfer efficiency changes, so that the efficiency of the system is optimized when the load characteristic changes to keep the power transfer at highest efficiency. This load characteristic is called the maximum power point and MPPT is the process of finding this point and keeping the load characteristic there. Electrical circuits can be designed to present arbitrary loads to the photovoltaic cells and then convert the voltage, current, or frequency to suit other devices or systems, and MPPT solves the problem of choosing the best load to be presented to the cells in order to get the most usable power out.

Solar cells have a complex relationship between temperature and total resistance that produces a non-linear output efficiency which can be analyzed based on the I-V curve. It is the purpose of the MPPT system to sample the output of the PV cells and apply the proper resistance (load) to obtain maximum power for any given environmental conditions. MPPT devices are typically integrated into an electric power converter system that provides voltage or current conversion, filtering, and regulation for driving various loads, including power grids, batteries, or motors.

- Solar inverters convert the DC power to AC power and may incorporate MPPT: such inverters sample the output power (I-V curve) from the solar modules and apply the proper resistance (load) so as to obtain maximum power.
- The power at the MPP (P_{mpp}) is the product of the MPP voltage (V_{mpp}) and MPP current (I_{mpp}).

1.10.1 I-V curve

Photovoltaic cells have a complex relationship between their operating environment and the maximum power they can produce. The fill factor, abbreviated FF, is a parameter which characterizes the non-linear electrical behavior of the solar cell. Fill factor is defined as the ratio of the maximum power from the solar cell to the product of Open Circuit Voltage Voc and Short-Circuit Current Isc. In tabulated data it is often used to estimate the maximum power that a cell can provide with an optimal load under given conditions, P=FF*Voc*Isc. For most purposes, FF, Voc, and Isc are enough information to give a useful approximate model of the electrical behavior of a photovoltaic cell under typical conditions.

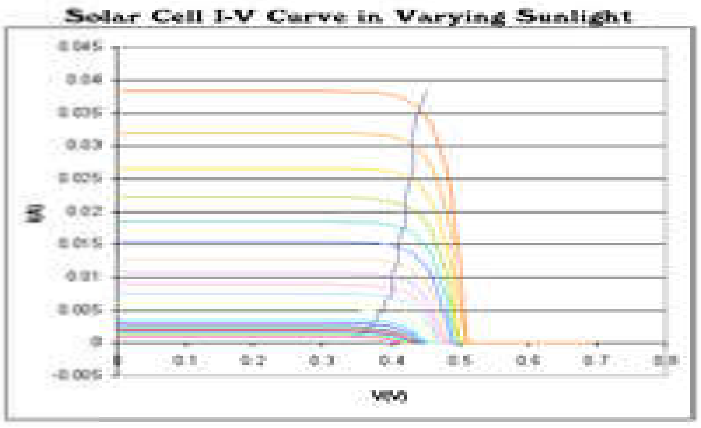


Fig.1.15 Photovoltaic solar cell I-V curves where a line intersects the knee of the curves where the maximum power transfer point is located.

For any given set of operational conditions, cells have a single operating point where the values of the current (I) and Voltage (V) of the cell result in a maximum power output. These values correspond to a particular load resistance, which is equal to V / I as specified by Ohm's Law. The power P is given by P=V*I. A photovoltaic cell, for the majority of its useful curve, acts as a constant current source. However, at a photovoltaic cell's MPP region, its curve has an approximately inverse exponential relationship between current and voltage. From basic circuit theory, the power delivered from or to a device is optimized where the derivative (graphically, the slope) dI/dV of the I-V curve is equal and opposite the I/V ratio (where dP/dV=0). This is known as the maximum power point (MPP) and corresponds to the "knee" of the curve.

A load with resistance R=V/I equal to the reciprocal of this value draws the maximum power from the device. This is sometimes called the 'characteristic resistance' of the cell. This is a dynamic quantity which changes depending on the level of illumination, as well as other factors such as temperature and the age of the cell. If the resistance is lower or higher than this value, the power drawn will be less than the maximum available, and thus the cell will not be used as efficiently as it could be. Maximum power point trackers utilize different types of control circuit or logic to search for this point and thus to allow the converter circuit to extract the maximum power available from a cell.

1.11 CLASSIFICATION

Controllers can follow several strategies to optimize the power output of an array. Maximum power point trackers may implement different algorithms and switch between them based on the operating conditions of the array.

1.11.1 Perturb and observe

In this method the controller adjusts the voltage by a small amount from the array and measures power; if the power increases, further adjustments in that direction are tried until power no longer increases. This is called the perturb and observe method and is most common, although this method can result in oscillations of power output. It is referred to as a hill climbing method, because it depends on the rise of the curve of power against voltage below the maximum power point, and the fall above that point. Perturb and observe is the most commonly used MPPT method due to its ease of implementation. Perturb and observe method may result in top-level efficiency, provided that a proper predictive and adaptive hill climbing strategy is adopted.

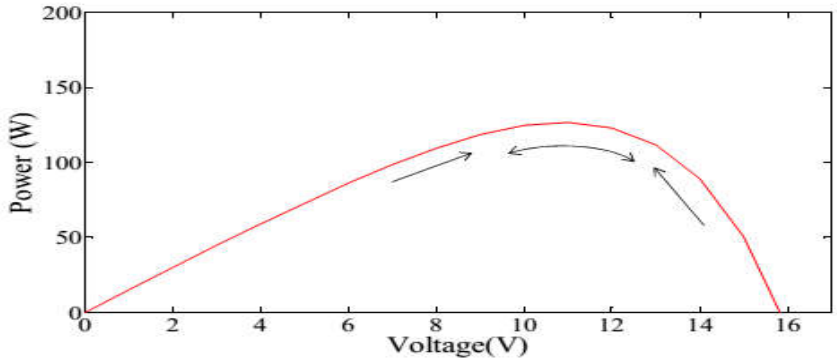


Fig.1.16. Perturb and observe algorithm

The algorithm observes output power of the array and perturbs the power based on increment of the array voltage. The algorithm continuously increments or decrements the reference voltage based on the value of the previous power sample.

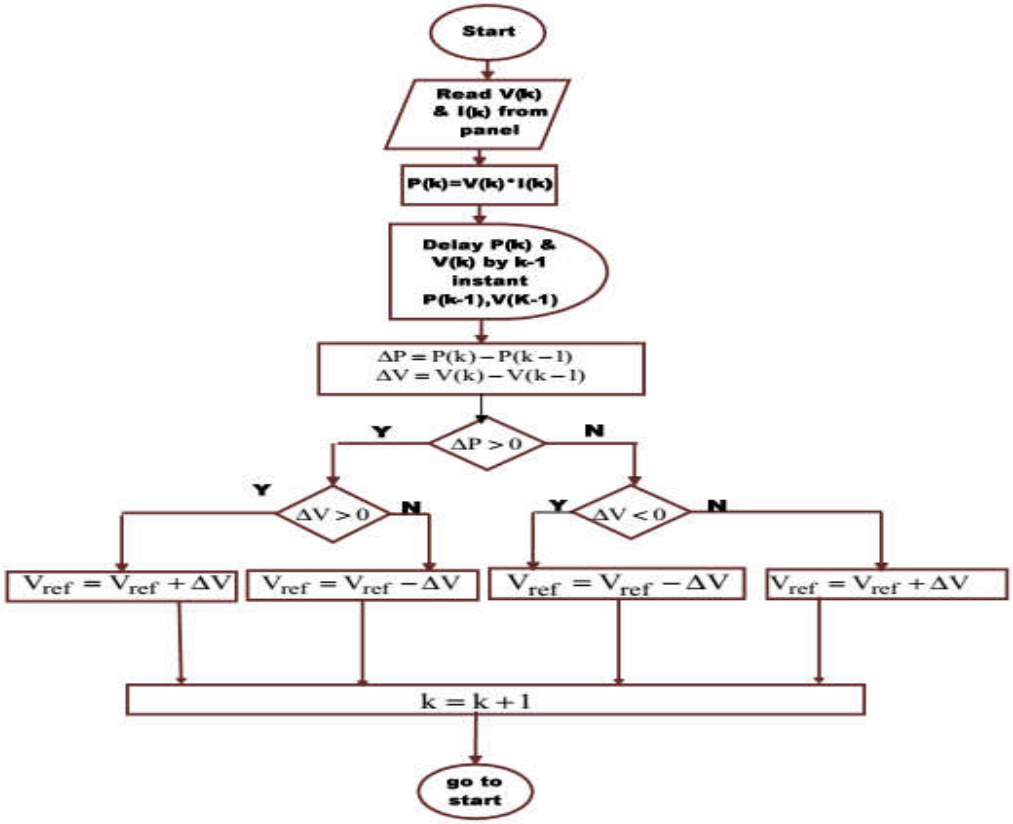


Fig.1.17. Flowchart Perturb and observe algorithm

1.11.2 Incremental conductance

In the incremental conductance method, the controller measures incremental changes in PV array current and voltage to predict the effect of a voltage change. This method requires more computation in the controller, but can track changing conditions more rapidly than the perturb and observe method (P&O). Like the P&O algorithm, it can produce oscillations in power output. This method utilizes the incremental conductance (dI/dV) of the photovoltaic array to compute the sign of the change in power with respect to voltage (dP/dV).

The incremental conductance method computes the maximum power point by comparison of the incremental conductance (I_Δ / V_Δ) to the array conductance (I / V).

When these two are the same ($I / V = I_\Delta / V_\Delta$), the output voltage is the MPP voltage. The controller maintains this voltage until the irradiation changes and the process is repeated.

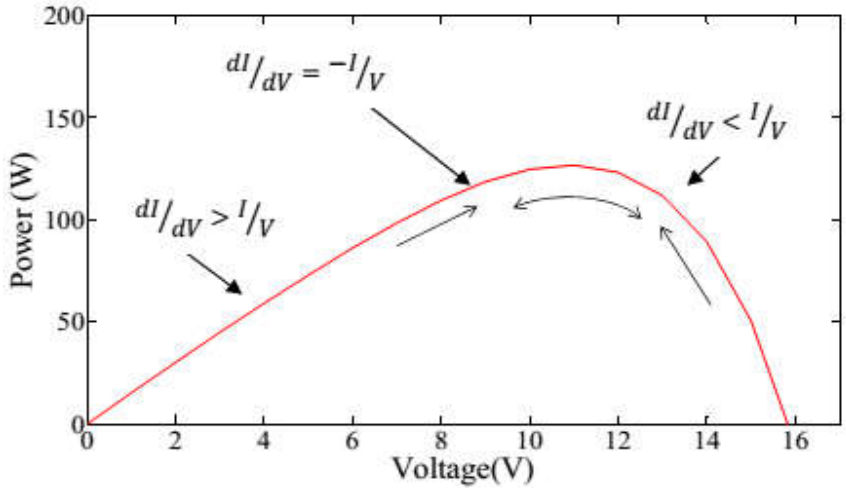


Fig.1.18. Incremental conductance algorithm

1.11.3 Current sweep

The current sweep method uses a sweep waveform for the PV array current such that the I-V characteristic of the PV array is obtained and updated at fixed time intervals. The maximum power point voltage can then be computed from the characteristic curve at the same intervals.

1.11.4 Constant voltage

The term "constant voltage" in MPP tracking is used to describe different techniques by different authors, one in which the output voltage is regulated to a constant value under all conditions and one in which the output voltage is regulated based on a constant ratio to the measured open circuit voltage (VOC). The latter technique is referred to in contrast as the "open voltage" method by some authors. If the output voltage is held constant, there is no attempt to track the maximum power point, so it is not a maximum power point tracking technique in a strict sense, though it does have some advantages in cases when the MPP tracking tends to fail, and thus it is sometimes used to supplement an MPPT method in those cases.

In the "constant voltage" MPPT method (also known as the "open voltage method"), the power delivered to the load is momentarily interrupted and the open-circuit voltage with zero current is measured. The controller then resumes operation with the voltage controlled at a fixed ratio, such as 0.76, of the open-circuit voltage VOC. This is

usually a value which has been determined to be the maximum power point, either empirically or based on modelling, for expected operating conditions. The operating point of the PV array is thus kept near the MPP by regulating the array voltage and matching it to the fixed reference voltage $V_{ref}=kV_{OC}$. The value of V_{ref} may be also chosen to give optimal performance relative to other factors as well as the MPP, but the central idea in this technique is that Vref is determined as a ratio to VOC.

One of the inherent approximations to the "constant voltage" ratio method is that the ratio of the MPP voltage to VOC is only approximately constant, so it leaves room for further possible optimization.

1.11.5 Comparison of methods

Both perturb and observe, and incremental conductance, are examples of "hill climbing" methods that can find the local maximum of the power curve for the operating condition of the PV array, and so provide a true maximum power point.

The perturb and observe method requires oscillating power output around the maximum power point even under steady state irradiance.

The incremental conductance method has the advantage over the perturb and observe (P&O) method that it can determine the maximum power point without oscillating around this value. It can perform maximum power point tracking under rapidly varying irradiation conditions with higher accuracy than the perturb and observe method. However, the incremental conductance method can produce oscillations (unintentionally) and can perform erratically under rapidly changing atmospheric conditions. The sampling frequency is decreased due to the higher complexity of the algorithm compared to the P&O method.

In the constant voltage ratio (or "open voltage") method, the current from the photovoltaic array must be set to zero momentarily to measure the open circuit voltage and then afterwards set to a predetermined percentage of the measured voltage, usually around 76%. Energy may be wasted during the time the current is set to zero. The approximation of 76% as the MPP/VOC ratio is not necessarily accurate though. Although simple and low-cost to implement, the interruptions reduce array efficiency and do not ensure finding the actual maximum power point. However, efficiencies of some systems may reach above 95%.

1.11.6 MPPT placement

Traditional solar inverters perform MPPT for the entire PV array (module association) as a whole. In such systems the same current, dictated by the inverter, flows through all modules in the string (series). Because different modules have different I-V curves and different MPPs (due to manufacturing tolerance, partial shading, etc.) this architecture means some modules will be performing below their MPP, resulting in lower efficiency.

Some companies (see power optimizer) are now placing maximum power point tracker into individual modules, allowing each to operate at peak efficiency despite uneven shading, soiling or electrical mismatch.

Data suggests having one inverter with one MPPT for a project that has east and west-facing modules presents no disadvantages when compared to having two inverters or one inverter with more than one MPPT.

1.11.7 Operation with batteries

At night, an off-grid PV system may use batteries to supply loads. Although the fully charged battery pack voltage may be close to the PV panel's maximum power point voltage, this is unlikely to be true at sunrise when the battery has been partially discharged. Charging may begin at a voltage considerably below the PV panel maximum power point voltage, and an MPPT can resolve this mismatch.

When the batteries in an off-grid system are fully charged and PV production exceeds local loads, an MPPT can no longer operate the panel at its maximum power point as the excess power has no load to absorb it. The MPPT must then shift the PV panel operating point away from the peak power point until production exactly matches demand. (An alternative approach commonly used in spacecraft is to divert surplus PV power into a resistive load, allowing the panel tooperate continuously at its peak power point.)

In a grid connected photovoltaic system, all delivered power from solar modules will be sent to the grid. Therefore, the MPPT in a grid connected PV system will always attempt to operate the PV modules at its maximum power point.

1.12Water Pumps

The two broad categories of pumps are generally used for PV powered pumpingsystems: centrifugal and volumetric (displacement) pumps.

1.12.1 Centrifugal Pumps

Centrifugal pumps have a rotating impeller that throws the water radiallyagainst a casing so shaped that the momentum of the water is converted intouseful pressure for lifting. They are normally used for low head / low pressureapplications, particularly if direct connection to the solar panels is required.They are well suited to high pumping rates and due to their compactness;wherever small diameter bores or well exists. Centrifugal pumps arecharacterized by the torque being proportional to the square of the speed(angular velocity of the impeller).

These pumps have relatively high efficiencies, but rapidly loose pumpingperformances as their speed reduces and in fact do not pump at all unless quitesubstantial spin speeds are achieved. This is a problem for a PV poweredsystem when light intensity is reduced. Maximum speeds performance isachieved at high spin speeds, making them easy to match to motors, whichtend to develop maximum torque (maximum efficiency) at similar speeds.

For conventional centrifugal pump designs, high efficiencies are only obtainedfor low pumping pressures and hence relatively small pumping heads of lessthan 25 meters. To overcome this limitation, either multistage or regenerativecentrifugal pumps can be used.

Other advantages of centrifugal pumps include their simplicity (with aminimum of moving parts) and corresponding reliability, low cost, robustness,tolerance to pumping particulates and low starting torque. On the other hand,another potential limitation of centrifugal pumps is their inability to be selfpriming.Consequently, they are frequently used as submersible pumps,preferably in conjunction with a submersible motor. Alternatively, self-primingcentrifugal pumps where a chamber containing water at the side of the pumpkeeps the pump effectively submerged and hence primed is also used.

The major trade-off involved with the design and use of centrifugal pumps isthe requirement for high efficiency versus the need for an impeller with longlife and good tolerance of aggressive impurities in the water. High efficiencycan be obtained with small clearances and narrow passages, but this isundesirable for pump reliability and the ability to pump liquids contaminatedwith particles. In addition, high efficiency can be obtained

with a high speedimpeller which again acts to shorten the life of the pump. In summary, pumpsneed to be designed and selected for specific application and environments.

1.12.2 Volumetric Pumps

Volumetric or positive displacement pumps are the other class of pumps oftenused for water pumping applications, particularly for lower pump rates fromdeep wells or bores. Examples of volumetric or positive displacement pumpsare poster pumps, diaphragm pumps, rotary-screw type pumps and progressivecavity pumps.

1.13 ZETA CONVERTER

A zeta converter is a fourth order non linearsystem being that, with regard to energy input, it canseen as buck-boost-buck converter and with regard tothe output, it can be seen as boost-buck-boostconverter.

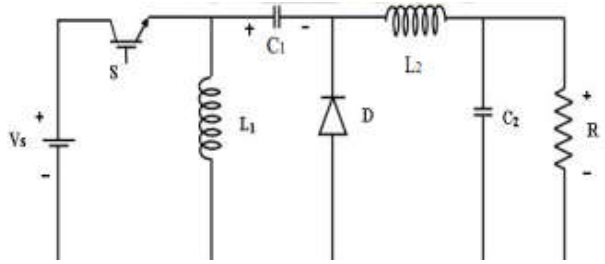


Fig.1.19 Basic Zeta converter circuit

The ideal switch based realization of zetaconverter is depicted. A non-isolated zeta converter circuit is shown in the fig.1.14 above.Although several operating modes are possible forthis converter depending on inductance value, loadresistance and operating frequency, here only continuous inductor current, i_{L1}‟ analyzed using thewell known state-space averaging method.

The analysis uses the following assumptions.

1. Semiconductors switching devices are consideredto be ideal.
2. Converter operating in continuous inductorcurrent mode.
3. Line frequency ripple in the dc voltage isneglected.

1.13.1 Modes of Operation

Zeta converter exhibits two different modesas follows:

Mode1: The first mode is obtained when the switch isON (closed) and instantaneously, the diode D is OFF.An equivalent circuit shown in Fig.1.20. During thisperiod, the

current through the inductor L1 and L2 aredrawn from the voltage source V_s. This mode is the**charging** mode

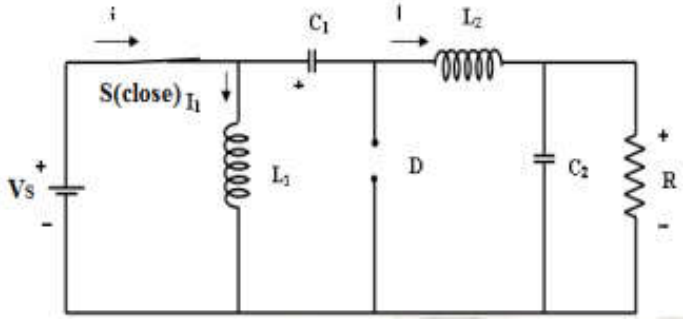


Fig.1.20 Equivalent circuit of converter (switch ON)

Mode2: The second mode of operation startswhen the switch is OFF and the diode D is ONposition, the equivalent circuit shown in Fig.1.21. Thisstage or mode of operation is known as thedischargingmode since all the energy stored in $\mathbf{L_2}$ isnow transferred to the load R.

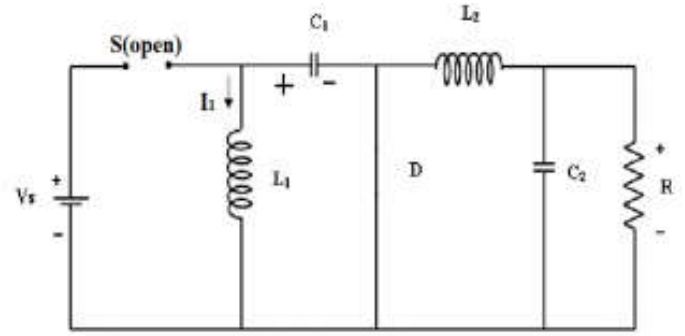


Fig.1.21 Equivalent circuit of converter (switch OFF)

CHAPTER 2

LITERATURE SURVEY

2.1 DC-to-DC Converter with Low Input CurrentRipple for Maximum PhotovoltaicPower Extraction [11]

Owing to the need for maximum utilization of solarcells, fuel cells, wind turbines, and batteries, dc-to-dcconverters with continuous input energy flow are widely usedfor renewable energy applications. To save energy,rather than converting to another energy form, the photovoltaic(PV) source output current and voltage should be continuous(and nonzero) for maximum renewable energy extraction. Also,the dc-to-dc converters must assure continuous input and outputcurrent to provide maximum energy flow from the sourceto the load. Therefore, an LCfilter, a large capacitor, or acontinuous current converter can be adopted for continuous PVoutput energy. Adding either anLCor aCfilter can createelectrical resonance issues, costs money, increases weight andvolume, plus decreases reliability, particularly in the case ofelectrolytic capacitors. In avoiding these issues, the PV mustdraw continuous current to provide better maximum powerpoint tracking (MPPT) with minimal energy ripple.

Power supplies employ electrolytic capacitors for energystorage and to reduce input current and output voltage ripple.Although electrolytic capacitance can be large, such capacitorshave a short lifetime owing to the liquid electrolyte, thusrestricting performance enhancement of a long lifetime system. The lifetime of the electrolytic capacitor is limited to afew thousand hours at rated operating conditions, which areshorter than the lifetime of other components like light-emittingdiodes (LEDs), lead–acid batteries, and PV panels. Hence, theelectrolytic capacitor is an obstacle to the overall reliability ofPV systems and thus is significantly derated. The lifetime mayonly be 1000 h at rated conditions, as every 10^{o}C decrease inoperating temperature doubles the lifetime. The LED lifetime isgenerally higher than 80 000 h, while the lead–acid batterylifetime reaches ten years and additionally is recyclable.

The current ripple creates a problem in power electronicsystems, which affects the voltage and, thus, the power. Theextent of the loss problem due to PV current ripple is a featurerealized for the first time in this paper. The exponential curveof the PV cells

causes nonlinear mapping in the current axiswhich, in turn, leads to the high loss of output power dueto the input current ripple. With current ripple, the controller,which will have a bandwidth less than the converter switchingfrequency, does not operate around the dc MPP. Rather, theaverage point is changed when extracting maximum power. Asthe PV current ripple decreases, the average operating pointconverges to the PV dc operating MPP. The assessment ofconverter interfacing for PV sources has underlying decoupling capacitance requirements to operate at maximum powerwith minimal ripple, with large capacitance filteringneeded for converters with discontinuous input current.

The actual power losses are considerably larger than thatexpected from modest small-signal approaches. The higherdrop in power is clarified andexperimentally established in theauthors establish that the 8% ripple rms amplitude of the MPPvoltage results in a 5% drop in the PV power output whichis 5% of the PV efficiency. Under nonuniform irradiance, thispercentage loss can be significantly higher, and such results areconfirmed in this paper.The authors consideredsensitivity to ripple in voltage and current at the terminals ofthe PV module. Their simulations verify a power loss of 1%when the amplitude of the ripple voltage is equal to 6% ofthe MPP voltage, and a loss of 2% for an 8.5% voltage ripple.Such effects have not been studied extensively in the literature,particularly the effects of the current ripple on the PV module,in terms of MPPT design or ripple from the dc-to-dc converter.The losses reach 5%, while in the losses reach 2%of the PV efficiency at around 8% ripple of the MPP voltage.This is because many factors affect the percentage loss, such asirradiance level, fill factor of the PV module, and nonuniformweather conditions. In this paper, as established in previousstudies, the higher the irradiance level, the lower the effect ofthe current ripple, or the lower the irradiance level, the greaterthe effect of the current ripple and hence the lower the PVefficiency.

2.1.1 Effect ofInputCurrentRipple

Current ripple refers to the variations of the dc componentmet in switching mode power supplies (SMPSs). Input currentripple from SMPS encloses harmonics, requiring appropriatedesign to decrease or eliminate the ripple. Some concepts concerning the effect of the current ripple are discussed. Filtering is usually used to accomplish low current ripple, whichcommonly employs bulky reactive components to guaranteethe

significant harmonic suppression of low-order components.Utilizing bulky filters, nevertheless, is not an economic solutionfor SMPS.

The notion of zero input current ripple of SMPS is not new. Itis utilized to maximize the power density of the converter andconsequently is of significant concern in SMPS. Two motivesmake it essential to eliminate the input current ripple. First, itdecreases the capacitor stress, resulting in either small losses ora stress-free filter. Second, it reduces the noise accompanied tothe load, where the pulsating current affects most converters' output and input.

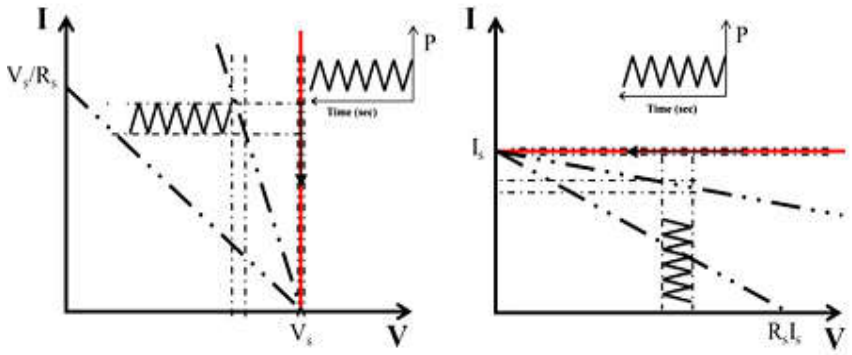


Fig.2.1. Effect of the input current ripple on the dc power supply.

Moreover, current ripple has a notable impact when connected to a solar panel. In Fig.2.1, both ideal current and voltagesources do not produce any ripple. Usually, voltage and currentpower supplies are not ideal, and the input resistance reflectsinsignificant ripple on the voltage and current curves. The solarpanel works as a current or voltage source and can also becounted as both a voltage and a current source. Fig.2.2 clarifiesthe impact of the current ripple on the power curve, whenceconsiderable PV power is dropped off because of the curveknee. Unluckily, the characteristics of the solar panel varyaccording to the temperature and radiation, which maximize thelosses. As current ripple increases, the operating point movesto the constant voltage region of the solar panel characteristic,which causes a severe drop in the average power. Therefore,the algorithms based on maximum average power are notMPP trackers. By increasing the average power, the operatingpoint's mean moves to the MPP as the current ripple decreasesto zero.

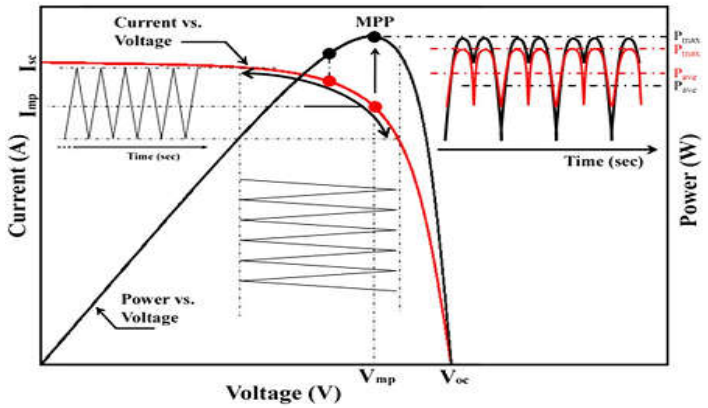


Fig.2.2. Effect of input current ripple on the PV power curve

If current ripple exists, the MPP algorithm cannot achieve themaximum power. For zero input current ripple, the maximumpower can be accomplished since the MPP can be tracked.

2.2 A Comparative Study on Maximum Power Point Tracking Techniques for Photovoltaic Power Systems [16]

Due to the growing demand on electricity, the limitedstock and rising prices of conventional sources (such ascoal and petroleum, etc.), photovoltaic (PV) energy becomesa promising alternative as it is omnipresent, freely available,environment friendly, and has less operational and maintenancecosts. Therefore, the demand of PV generation systemsseems to be increased for both standalone and grid-connectedmodes of PV systems. Therefore, an efficient maximum powerpoint tracking (MPPT) technique is necessary that is expectedto track the MPP at all environmental conditions and thenforce the PV system to operate at that MPP point. MPPT is anessential component of PV systems. Several MPPT techniquestogether with their implementation are reported in the literature. Users always feel confused while selecting an MPPTtechnique for a particular application. Unfortunately, only a fewpapers are available in thisfield that includes discussions on MPPT techniques until 2007. But many new MPPTtechniques such as distributed MPPT, the Gauss-Newton technique, adaptive perturbation and observation, estimated perturband perturb, adaptive fuzzy and particle swarm optimization (PSO)-based MPPT, etc., have been reported since then. Hence,it is necessary to prepare a review that includes all the efficientand effective MPPT techniques proposed before 2007 and afterthat until 2012. In this review, an attempt has also been made tocompare

the MPPT techniques on the basis of their advantages,disadvantages, control variables involved, types of circuitry,complexity of algorithm, complexity level on hardware implementation, and types of scientific and commercial application.This paper attempts to provide a comparative review on mostof the reported MPPT techniques excluding any unintentionallyomitted papers because of space limitations.

2.2.1 Review on MPPT Techniques

The following techniques are some of the widely used MPPTtechniques applied on various PV applications such as spacesatellite, solar vehicles, and solar water pumping, etc.

- **Curve-Fitting Technique**

MPP is the extreme value of the P–V characteristic of a PVpanel, hence atfirst the P–V characteristic of a PV panel is predicted in this technique. To predict, this P–V characteristic, PVpanel can be modeled offline based on mathematical equationsor numerical approximations.

- **Fractional Short-Circuit Current (FSCI) Technique**

There exists a single operating point P (V_{mpp}, I_{mpp}) calledMPP at which the power of the panel is maximum (P_{mpp}) at agivenenvironmental condition (Fig.2.3). If by some means, anyone of I_{mpp}or $V_{mpp}$are tracked then the corresponding P_{mpp}can be tracked. In the FSCI technique, the nonlinear – characteristics of PV system are modeled using mathematical equations or numerical approximations taking account of a widerange of environmental conditions and degradation level of PVpanel.

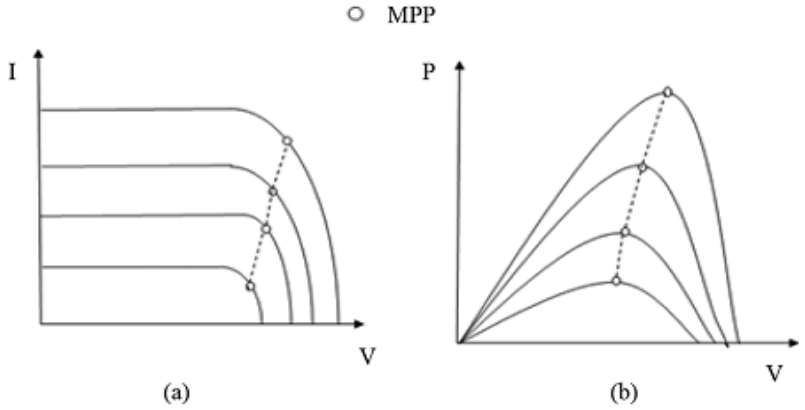


Fig.2.3 (a) I–V and (b) P–V characteristics of PV panel at different environmental conditions.

- **Look-up Table Technique**

In this technique, MPP of a PV system is calculated beforehand for each probableenvironmental condition and stored inthe memory device of MPPT's control system. During the operation, the corresponding MPP for a particular condition is selected from that memory and implemented

- **One-Cycle Control (OCC) Technique**

OCC is a nonlinear MPPT control technique. It involves theuse of a single-stage inverter where the output current (I_{out}) ofthe inverter can be adjusted according to the voltage of the PVarray (V) so as to extract the maximum power from it.There is only one power conversion stage that realizes on bothMPPT control and dc/ac inversion. The OCC system is shown in Fig.2.4. The parameters (L,C) involved in this system shouldbe properly tuned as their values greatly affect the accuracy ofOCC technique.

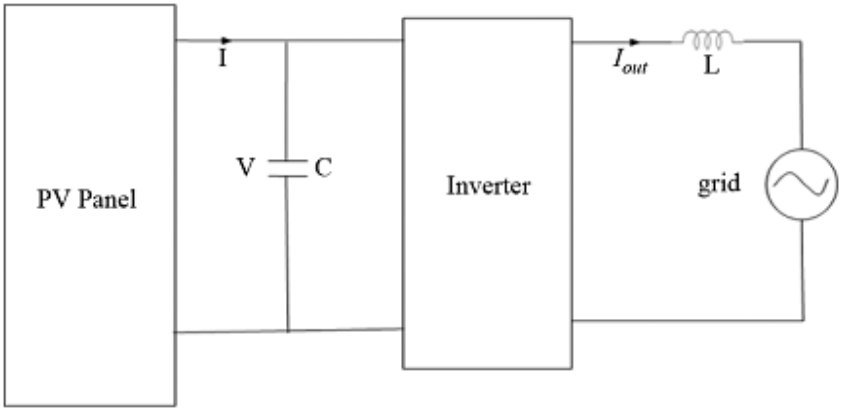


Fig.2.4. Block diagram of OCC technique.

2.3 Evaluation of the Main MPPT Techniques for Photovoltaic Applications [17]

The growing energy demand coupled with the possibilityof reduced supply of conventional fuels, evidenced bypetroleum crisis, along with growing concerns about environmental conservation, has driven research and development ofalternative energy sources that are cleaner, are renewable, andproduce little environmental impact. Among the alternativesources, the electrical energy from photovoltaic (PV) cells iscurrently regarded as a natural energy source that is moreuseful, since it is free, abundant, clean, and distributed overthe Earth and participates as a primary factor of all otherprocesses of energy production on Earth. Moreover, in spiteof the phenomena of reflection and absorption of sunlight bythe atmosphere, it is estimated that solar energy incident on

theEarth’s surface is on the order of ten thousand times greaterthan the world energy consumption. A great advantage of PVcells is the reduction of carbon dioxide emissions. By the year2030, the annual reduction rate of CO2due to the usage of PVcells may be around 1 Gton/year, which is equivalent to India’stotal emissions in 2004 or the emission of 300 coal plants.According to experts, the energy obtained from PV cells willbecome the most important alternative renewable energy source until 2040. In this context, the concept of distributed energygeneration became a real and present technical possibility,promoting various research works and standardizations in theworld. Despite all the advantages presented by the generationof energy through PV cells, the efficiency of energy conversionis currently low, and the initial cost for its implementation is stillconsidered high; thus, it becomes necessary to use techniquesto extract the maximum power from these panels, in order toachieve maximum efficiency in operation. Under uniform solarirradiation conditions, PV panels exhibits a unique operatingpoint where PV power is maximized. The PV power characteristic is nonlinear, as shown in Fig.2.5 — considering a singlePV cell, which varies with the level of solar irradiation andtemperature, which make the extraction of maximum powera complex task, considering load variations. Thus, in order toovercome this problem, several methods for extracting the maximum power have been proposed in the literature, and acareful comparison of these methods can result in important information for the design of these systems. Therefore, this paperaims to assess the main maximum power point (MPP) tracking(MPPT) techniques through models in MatLab/Simulink andexperimental results, doing depth comparisons among themwith regard to the voltage ripple, start-up of the method, tracking factor (TF), and usage of sensors. It should be informedthat other papers related to comparisons of MPPT algorithmscan be found in the literature. However, this paperpresents additional comparisons about the MPPT algorithms,their flowcharts, more interesting experimental results, and theimproved modified MPPT proportional–integral (PI)-based ICand perturb and observe (P&O) methods, which presentedoutstanding performances because of their inherent adaptativecapabilities. Finally, experimental results with typical dailypower profile are not found in the literature for so many MPPTmethods.

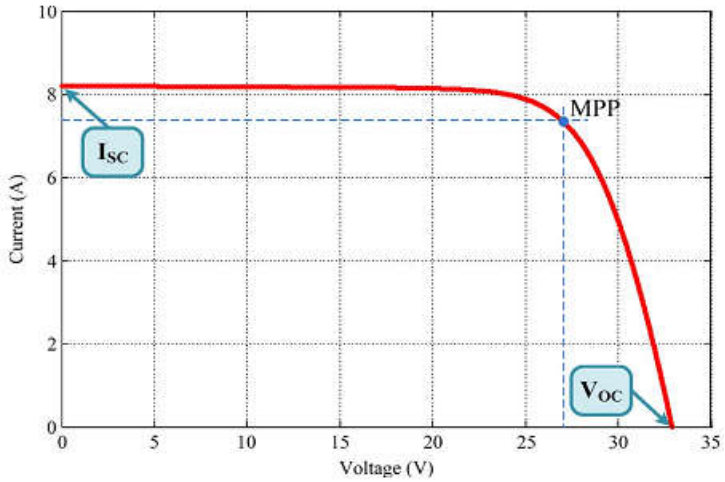


Fig.2.5. PV current-versus-voltage characteristic.

- **P&O and P&O Based on PI**

The P&O method operates by periodically incrementing ordecrementing the output terminal voltage of the PV cell andcomparing the power obtained in the current cycle with thepower of the previous one (performsdP/dV). If the voltagevaries and the power increases, the control system changesthe operating point in that direction; otherwise, it changes theoperating point in the opposite direction. Once the directionfor the change of voltage is known, the voltage is variedat a constant rate. This rate is a parameter that should beadjusted to allow the balance between faster response and lessfluctuation in steady state. A modifiedversion is obtained when the steps are changed according to thedistance of the MPP, resulting in higher efficiency. This is anexcellent method to reach the MPP, and it is independent fromthe PV panel/manufacturer; however, this method may sufferfrom fast changes in environmental conditions.

- **MPP Locus Characterization**

The basic idea of this method is to find a linear relationshipbetween voltage and current at the MPP (MPP locus). Thisrelationship is the tangent line to the MPP locus curve forthe PV current in which the minimum irradiation conditionsatisfies the sensitivity of the method. The equation that guides this method is given. It should be informed that themathematical derivation is found. As one can observe,it is hard to obtain all the necessary parameters, and a linearapproximation is made offline with the PV panel, translatingit as an estimation method. As the MPP locus varies withtemperature, the model needs to be updated. This is done bymeasuring the open-circuit voltage

periodically, which meansthat the interface converter must open the PV circuit, resultingin loss of power in these instants. This MPPT method worksbetter for high solar irradiations.

- **CV Method**

The constant voltage (CV) method uses empirical results,indicating that the voltage at MPP(VMPP)is around 70%–80%of the PV open-circuit voltage(VOC), for the standard atmospheric condition. Among the points of MPP (varying atmospheric conditions), the voltage at the terminals of the modulevaries very little even when the intensity of solar radiationchanges, but it varies when the temperature changes. So, thismethod must be used in regions where the temperature variesvery little. A positive point is that only the PV voltage isnecessary to be measured, and a simple control loop can reach the MPP.

CHAPTER 3
PROPOSED CONCEPT

3.1 INTRODUCTION

The drastic reduction in the cost of power electronicdevices and annihilation of fossil fuels in near futureinvite to use the solar photovoltaic (SPV) generated electricalenergy for various applications as far as possible. The waterpumping, a standalone application of the SPV array-generatedelectricity, is receiving wide attention nowadays for irrigation inthe fields, household applications, and industrial use. Althoughseveral researches have been carried out in an area of SPVarray-fed water pumping, combining various dc–dc converters and motor drives, the zeta converter in association with apermanent-magnet brushless dc (BLDC) motor is not explored precisely so far to develop such kind of system. However, thezeta converter has been used in some other SPV-based applications [1]–[3]. Moreover, a topology of SPV array-fed BLDCmotor-driven water pump with zeta converter has been reportedand its significance has been presented more or less in [4].

Nonetheless, an experimental validation is missing and theabsence of extensive literature review and comparison with theexisting topologies has concealed the technical contributionand originality of the reported work.

The merits of both BLDC motor and zeta converter can contribute to develop an SPV array-fed water pumping systempossessing a potential of operating satisfactorily under dynamically changing atmospheric conditions. The BLDC motorhas high reliability, high efficiency, high torque/inertia ratio,improved cooling, low radio frequency interference, and noiseand requires practically no maintenance [5], [6]. On the otherhand, a zeta converter exhibits the following advantages overthe conventional buck, boost, buck–boost converters, and Cukconverter when employed in SPV-based applications.

1) Belonging to a family of buck–boost converters, thezeta converter may be operated either to increase or todecrease the output voltage. This property offers a boundless region for maximum power-point tracking (MPPT) ofan SPV array [7]. The MPPT can

be performed with simple buck [8] and boost [9] converter if MPP occurs withinprescribed limits.

2) This property also facilitates the soft starting of BLDCmotor unlike a boost converter which habitually steps upthe voltage level at its output, not ensuring soft starting.

3) Unlike a classical buck–boost converter [10], the zetaconverter has a continuous output current. The outputinductor makes the current continuous and ripples free.

4) Although consisting of same number of components asa Cuk converter [11], the zeta converter operates as non-inverting buck–boost converter unlike an inverting buck–boost and Cuk converter. This property obviates a requirement of associated circuits for negative voltage sensing,and hence reduces the complexity and probability of slowdown the system response [12].

These merits of the zeta converter are favorable for proposedSPV array-fed water pumping system. An incremental conductance maximum power point tracking (INC-MPPT) algorithm[8], [13]–[18] is used to operate the zeta converter such thatSPV array always operates at its MPP.

The existing literature exploring SPV array-based BLDCmotor-driven water pump [19]–[22] is based on a configurationshown in Fig.3.1. A dc–dc converter is used for MPPT of an SPVarray as usual. Two phase currents are sensed along with Hallsignals feedback for control of BLDC motor, resulting in anincreased cost. The additional control scheme causes increasedcost and complexity, which is required to control the speedof BLDC motor. Moreover, usually a voltage-source inverter(VSI) is operated with high-frequency PWM pulses, resultingin an increased switching loss and hence the reduced efficiency.

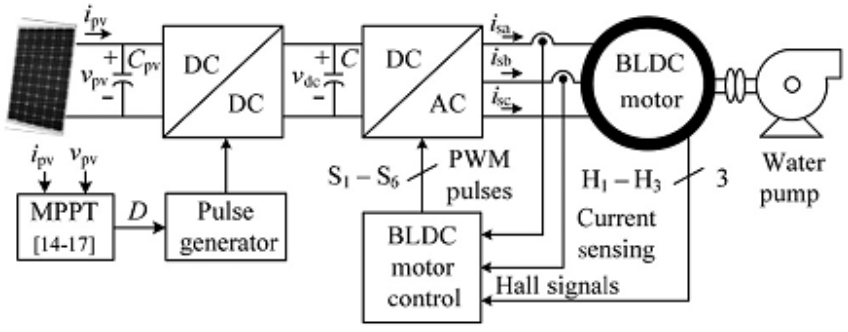


Fig.3.1. Conventional SPV-fed BLDC motor-driven water pumping system

Although a Z-source inverter (ZSI) replaces dc–dc converter in[22], other schematic of Fig.3.1 remains unchanged, promisinghigh efficiency and low cost. Contrary to it, ZSI also necessitates phase current and dc link voltage sensing resulting in thecomplex control and increased cost.

To overcome these problems and drawbacks, a simple, costeffective, and efficient water pumping system based on SPVarray-fed BLDC motor is proposed, by modifying the existing topology (Fig. 1) as shown in Fig.3.2. A zeta converteris utilized to extract the maximum power available from anSPV array, soft starting, and speed control of BLDC motorcoupled to a water pump. Due to a single switch, this converter has very good efficiency and offers boundless regionfor MPPT. This converter is operated in continuous conduction mode (CCM) resulting in a reduced stress on its powerdevices and components. Furthermore, the switching loss ofVSI is reduced by adopting fundamental frequency switchingresulting in an additional power saving and hence an enhancedefficiency. The phase currents as well as the dc link voltage sensors are completely eliminated, offering simple and economicalsystem without scarifying its performance. The speed of BLDCmotor is controlled, without any additional control, through a variable dc link voltage of VSI. Moreover, a soft starting ofBLDC motor is achieved by proper initialization of MPPT algorithm of SPV array. These features offer an increased simplicityof proposed system.

The advantages and desirable features of both zeta converterand BLDC motor drive contribute to develop a simple, efficient,cost-effective, and reliable water pumping system based onsolar PV energy. Simulation results using MATLAB/Simulinkand experimental performances are examined to demonstratethe starting, dynamics, and steady-state behavior of proposedwater pumping system subjected to practical operating conditions. The SPV array and BLDC motor are designed such thatproposed system always exhibits good performance regardlessof solar irradiance level.

3.2 CONFIGURATION OFPROPOSEDSYSTEM

The structure of proposed SPV array-fed BLDC motordriven water pumping system employing a zeta converter is shown in Fig.3.2. The proposed system consists of (left toright) an SPV array, a zeta converter, a VSI, a BLDC motor,and a water pump. The BLDC motor has an inbuilt encoder.The pulse generator is used to operate the zeta

converter. Astep-by-step operation of proposed system is elaborated inSection 3.3 in detail.

3.3 OPERATION OF PROPOSEDSYSTEM

The SPV array generates the electrical power demanded bythe motor-pump. This electrical power is fed to the motorpump via a zeta converter and a VSI. The SPV array appearsas a power source for the zeta converter as shown in Fig.3.2.Ideally, the same amount of power is transferred at the output of zeta converter which appears as an input source for theVSI. In practice, due to the various losses associated with a dc–dc converter [23], slightly less amount of power is transferredto feed the VSI. The pulse generator generates, through INCMPPT algorithm, switching pulses for insulated gate bipolartransistor (IGBT) switch of the zeta converter. The INC-MPPTalgorithm uses voltage and current as feedback from SPV arrayand generates an optimum value of duty cycle. Further, it generates actual switching pulse by comparing the duty cycle with ahigh-frequency carrier wave. In this way, the maximum powerextraction and hence the efficiency optimization of the SPVarray is accomplished.

The VSI, converting dc output from a zeta converter into ac,feeds the BLDC motor to drive awater pump coupled to itsshaft. The VSI is operated in fundamental frequency switchingthrough an electronic commutation of BLDC motor assisted byits built-in encoder. The high frequency switching losses arethereby eliminated, contributing in an increased efficiency ofproposed water pumping system.

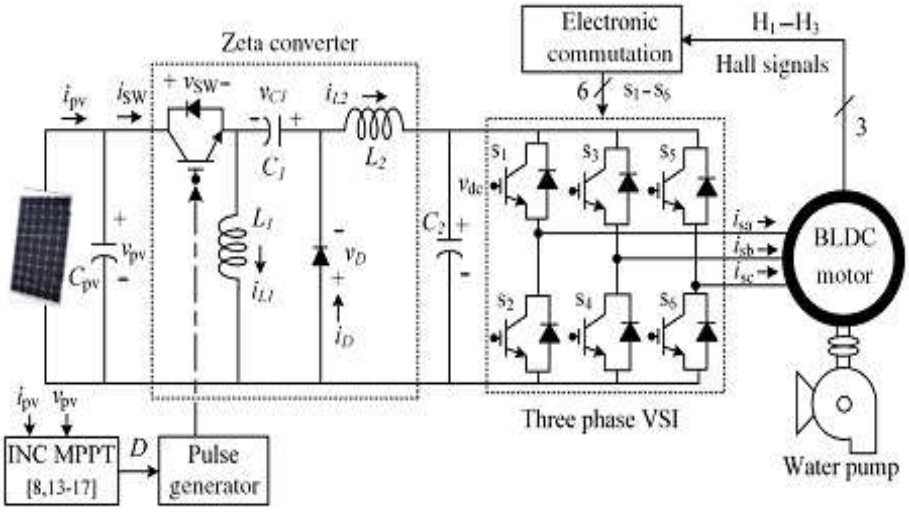


Fig.3.2. Proposed SPV-zeta converter-fed BLDC motor drive for water pump

3.4 DESIGN OF PROPOSEDSYSTEM

Various operating stages shown in Fig.3.2 are properlydesigned to develop an effective water pumping system, capable of operating under uncertain conditions. A BLDC motor of2.89-kW power rating and an SPV array of 3.4-kW peak powercapacity under standard test conditions (STC) are selected todesign the proposed system. The detailed designs of variousstages such as SPV array, zeta converter, and water pump aredescribed as follows.

3.4.1 Design of SPV Array

As per above discussion, the practical converters are associated with various power losses. In addition, the performanceof BLDC motor-pump is influenced by associated mechanicaland electrical losses. To compensate these losses, the size ofSPV array is selected with slightly more peak power capacity to ensure the satisfactory operation regardless of powerlosses. Therefore, the SPV array of peak power capacity ofP_{mpp}=3.4 kW under STC (STC: 1000 W/m^2, 25^{o}C,AM 1.5), slightly more than demanded by the motor-pumpis selected and its parameters are designed accordingly.SolarWorld make Sunmodule Plus SW 280 mono [24] SPVmodule is selected to design the SPV array of an appropriatesize. Electrical specifications of this module are listed in Table 3.1 and numbers of modules required to connect in series/parallelare estimated by selecting the voltage of SPV array at MPPunder STC asV_{mpp}= 187.2V.

TABLE 3.1

Specifications ofSunmoduleplusSW 280monoSPV Module

Peak power, P_m (W)	280
Open circuit voltage, V_o (V)	39.5
Voltage at MPP, V_m (V)	31.2
Short circuit current, I_s (A)	9.71
Current at MPP, I_m (A)	9.07
Number of cells connected in series, N_{ss}	60

The current of SPV array at MPP$I_{mpp}$is estimated as

$$I_{\mathrm{mpp}} = P_{\mathrm{mpp}}/V_{\mathrm{mpp}} = 3400/187.2 = 18.16 \text{ A} \tag{3.1}$$

The numbers of modules required to connect in series are asfollows:

$$N_s = V_{\text{mpp}}/V_m = 187.2/31.2 = 6. \tag{3.2}$$

The numbers of modules required to connect in parallel areas follows:

$$N_p = I_{\text{mpp}}/I_m = 18.16/9.07 = 2. \tag{3.3}$$

Connecting six modules in series, having two strings in parallel, an SPV array of required size is designed for the proposedsystem.

3.4.2 Design of Zeta Converter

The zeta converter is the next stage to the SPV array. Itsdesign consists of an estimation of various components such asinput inductorL_1, output inductor L_2, and intermediate capacitor C_1. These components are designed such that the zetaconverter always operates in CCM resulting in reduced stresson its components and devices. An estimation of the duty cycleDinitiates the design of zeta converter which is estimated as [6]

$$D = \frac{V_{\text{dc}}}{V_{\text{dc}} + V_{\text{mpp}}} = \frac{200}{200 + 187.2} = 0.52 \tag{3.4}$$

Where$V_{dc}$is an average value of output voltage of the zeta converter (dc link voltage of VSI) equal to the dc voltage rating ofthe BLDC motor.

An average current flowing through the dc link of the VSI$I_{dc}$is estimated as

$$I_{\text{dc}} = P_{\text{mpp}}/V_{\text{dc}} = 3400/200 = 17 \text{ A}. \tag{3.5}$$

Then,L_1,L_2, andC_1 are estimated as

$$L_1 = \frac{DV_{\text{mpp}}}{f_{\text{sw}}\Delta I_{L1}} = \frac{0.52 \times 187.2}{20\,000 \times 18.16 \times 0.06} = 4.5 \times 10^{-3} \approx 5 \text{ mH} \tag{3.6}$$

$$L_2 = \frac{(1-D)V_{\text{dc}}}{f_{\text{sw}}\Delta I_{L2}} = \frac{(1-0.52) \times 200}{20\,000 \times 17 \times 0.06} = 4.7 \times 10^{-3} \approx 5 \text{ mH} \tag{3.7}$$

$$C_1 = \frac{DI_{\text{dc}}}{f_{\text{sw}}\Delta V_{C1}} = \frac{0.52 \times 17}{20\,000 \times 200 \times 0.1} = 22\ \mu\text{F} \tag{3.8}$$

Wheref_{sw} is the switching frequency of IGBT switch of thezeta converter;$\Delta I_{L1}$is the amount of permitted ripple in thecurrent flowing throughL_1,sameasI_{L1}=I_{mpp}; $\Delta I_{L2}$is

theamount of permitted ripple in the current flowing throughL_2,same as IL2=Idc; ΔVC1 is permitted ripple in the voltageacrossC_1,sameas$V_{C1}=V_{dc}$.

3.4.3 Estimation of DC-Link Capacitor of VSI

A new design approach for estimation of dc-link capacitor ofthe VSI is presented here. This approach is based on a fact thatsixth harmonic component of the supply (ac) voltage is reflectedon the dc side as a dominant harmonic in the three-phase supplysystem [25]. Here, the fundamental frequencies of output voltage of the VSI are estimated corresponding to the rated speedand the minimum speed of BLDC motor essentially required pumping the water. These two frequencies are further used to estimate the values of their corresponding capacitors. Out of thesetwo estimated capacitors, larger one is selected to assure a satisfactory operation of proposed system even under the minimumsolar irradiance level.

The fundamental output frequency of VSI corresponding tothe rated speed of BLDC motor$\omega_{rated}$is estimated as

$$\omega_{\text{rated}} = 2\pi f_{\text{rated}} = 2\pi \frac{N_{\text{rated}} P}{120} = 2\pi \times \frac{3000 \times 6}{120} = 942 \text{ rad/s.} \tag{3.9}$$

The fundamental output frequency of the VSI correspondingto the minimum speed of the BLDC motor essentially requiredto pump the water(N= 1100r/min)$\omega_{min}$is estimated as

$$\omega_{\text{min}} = 2\pi f_{\text{min}} = 2\pi \frac{NP}{120} = 2\pi \times \frac{1100 \times 6}{120} = 345.57 \text{ rad/s} \tag{3.10}$$

Wheref_{rated} and$f_{min}$are fundamental frequencies of outputvoltage of VSI corresponding to a rated speed and a minimumspeed of BLDC motor essentially required to pump the water,respectively, in Hz;$N_{rated}$is rated speed of the BLDC motor;Pis a number of poles in the BLDC motor.

The value of dc link capacitor of VSI at$\omega_{rated}$is as follows:

$$\begin{aligned} C_{2,\text{rated}} &= \frac{I_{\text{dc}}}{6 \times \omega_{\text{rated}} \times \Delta V_{\text{dc}}} = \frac{17}{6 \times 942 \times 200 \times 0.1} \\ &= 150.4 \ \mu\text{F.} \end{aligned} \tag{3.11}$$

Similarly, a value of dc link capacitor of VSI at$\omega_{min}$is asfollows:

$$C_{2,\min} = \frac{I_{\rm dc}}{6 \times \omega_{\min} \times \Delta V_{\rm dc}} = \frac{17}{6 \times 345.57 \times 200 \times 0.1} = 410\ \mu\text{F} \quad (3.12)$$

Where$\Delta V_{dc}$is an amount of permitted ripple in voltage acrossdc-link capacitorC_2.Finally, C_2= 410μF is selected to design the dc-linkcapacitor.

3.4.4 Design of Water Pump

To estimate the proportionality constantKfor the selectedwater pump, its power–speed characteristics [26], [27] isused as

$$K = \frac{P}{\omega_r^3} = \frac{2.89 \times 10^3}{(2\pi \times 3000/60)^3} = 9.32 \times 10^{-5} \quad (3.13)$$

WhereP=2.89 kWis rated power developed by the BLDCmotor andω_r is rated mechanical speed of the rotor (3000r/min) in rad/s.

A water pump with these data is selected for proposedsystem.

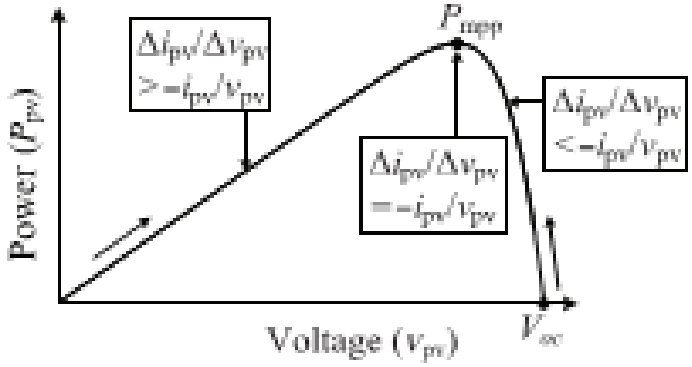


Fig.3.3. Illustration of INC-MPPT with SPV arrayP_{pv}–v_{pv}characteristics.

TABLE 3.2

SwitchingStates forElectronicCommutation ofBLDC Motor

Rotor position θ (°)	Hall signals			Switching states					
	H_3	H_2	H_1	S_1	S_2	S_3	S_4	S_5	S_6
NA	0	0	0	0	0	0	0	0	0
0–60	1	0	1	1	0	0	1	0	0
60–120	0	0	1	1	0	0	0	0	1
120–180	0	1	1	0	0	1	0	0	1
180–240	0	1	0	0	1	1	0	0	0
240–300	1	1	0	0	1	0	0	1	0
300–360	1	0	0	0	0	0	1	1	0
NA	1	1	1	0	0	0	0	0	0

3.5 CONTROL OFPROPOSEDSYSTEM

The proposed system is controlled in two stages. These twocontrol techniques, viz., MPPT and electronic commutation, arediscussed as follows.

3.5.1 INC-MPPT Algorithm

An efficient and commonly used INC-MPPT technique [8],[13] in various SPV array based applications is utilized in orderto optimize the power available from a SPV array and to facilitate a soft starting of BLDC motor. This technique allowsperturbation in either the SPV array voltage or the duty cycle.The former calls for a proportional-integral (PI) controller togenerate a duty cycle [8] for the zeta converter, which increasesthe complexity. Hence, the direct duty cycle control is adaptedin this work. The INC-MPPT algorithm determines the direction of perturbation based on the slope of Ppv−vpv curve, shown in Fig.3.3. As shown in Fig.3.3, the slope is zero at MPP,positive on the left, and negative on the right of MPP, i.e.,

$$\left.\begin{aligned} \frac{dP_{\text{pv}}}{dv_{\text{pv}}} &= 0; \quad \text{at mpp} \\ \frac{dP_{\text{pv}}}{dv_{\text{pv}}} &> 0; \quad \text{left of mpp} \\ \frac{dP_{\text{pv}}}{dv_{\text{pv}}} &> 0; \quad \text{right of mpp} \end{aligned}\right\} \tag{3.14}$$

Since

$$\frac{dP_{\text{pv}}}{dv_{\text{pv}}} = \frac{d(v_{\text{pv}} * i_{\text{pv}})}{dv_{\text{pv}}} = i_{\text{pv}} + v_{\text{pv}} * \frac{di_{\text{pv}}}{dv_{\text{pv}}} \cong i_{\text{pv}} + v_{\text{pv}} * \frac{\Delta i_{\text{pv}}}{\Delta v_{\text{pv}}} \tag{3.15}$$

Therefore, (3.14) is rewritten as

$$\left.\begin{aligned} \frac{\Delta i_{\text{pv}}}{\Delta v_{\text{pv}}} &= -\frac{i_{\text{pv}}}{v_{\text{pv}}}; \quad \text{at mpp} \\ \frac{\Delta i_{\text{pv}}}{\Delta v_{\text{pv}}} &> -\frac{i_{\text{pv}}}{v_{\text{pv}}}; \quad \text{left of mpp} \\ \frac{\Delta i_{\text{pv}}}{\Delta v_{\text{pv}}} &< -\frac{i_{\text{pv}}}{v_{\text{pv}}}; \quad \text{right of mpp} \end{aligned}\right\} \tag{3.16}$$

Thus, based on the relation between INC and instantaneousconductance, the controller decides the direction of perturbation as shown in Fig. 3, and increases/decreases the dutycycle accordingly. For instance, on the right of MPP, the dutycycle is increased with a fixedperturbation size until the direction reverses. Ideally, the perturbation stops once the operatingpoint reaches the MPP. However, in practice, operating pointoscillates around the MPP.

As the perturbation size reduces, the controller takes moretime to track the MPP of SPV array. An intellectual agreementbetween the tracking time and the perturbation size is held tofulfill the objectives of MPPT and soft starting of BLDC motor.In order to achieve soft starting, the initial value of duty cycle isset as zero. In addition, an optimum value of perturbation size($\Delta D=0.001$)is selected, which contributes to soft startingand also minimizes oscillations around the MPP.

3.5.2 Electronic Commutation of BLDC Motor

The BLDC motor is controlled using a VSI operated throughan electronic commutation of BLDC motor. An electronic commutation of BLDC motor stands for commutating the currentsflowing through its windings in a predefined sequence using decoder logic. It symmetrically places the dc input current atthe center of each phase voltage for 120^{o}. Six switching pulsesare generated as per the various possible combinations of threeHall-effect signals. These three Hall-effect signals are producedby an inbuilt encoder according to the rotor position.

A particular combination of Hall-effect signals is producedfor each specific range of rotor position at an interval of60^{o}[5], [6]. The generation of six switching states with theestimation of rotor position is tabularized in Table II. It is perceptible that only two switches conduct at a time, resultingin 120^{o}conduction mode of operation of VSI and hence thereduced conduction losses. Besides this, the electronic commutation provides fundamental frequency switching of the VSI;hence, losses associated with high-frequency PWM switching are eliminated. A motor power company makes BLDC motor[28] with inbuilt encoder is selected for proposed system andits detailed specifications are given in the Appendixes.

CHAPTER 4

MATLAB AND SIMULINK MODEL

4.1 Introduction to MATLAB

- ***MATLAB***

Initially developed by a lecturer in 1970's to help students learn linear algebra.It waslater marketed and further developed under Math Works Inc. (founded in 1984) www.mathworks.com. MATLAB is a software package which can be used to perform analysis and solve mathematical and engineering problems.It has excellent programming features and graphics capability – easy to learn and flexible. Available in many operating systems – Windows, Macintosh, UNIX, DOSIt has several tool boxes to solve specific problems.

MATLAB (matrix laboratory) is a multi-paradigm numerical computing environment and fourth-generation programming language. A proprietary programming language developed by Math Works, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, Fortran and Python.

Although MATLAB is intended primarily for numerical computing, an optional toolbox uses the MuPAD symbolic engine, allowing access to symbolic computing abilities. An additional package, Simulink, adds graphical multi-domain simulation and model-based design for dynamic and embedded systems.

- ***SIMULINK***

Simulink, developed by Math Works, is a graphical programming environment for modeling, simulating and analyzing multi-domain dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in automatic control and digital signal processing for multi-domain simulation and Model-Based Design.

Used to model, analyze and simulate dynamic systems using block diagrams. Fully integrated with MATLAB, easy and fast to learn and flexible.It has comprehensive

block library which can be used to simulate linear, non–linear or discrete systems – excellent research tools.C codes can be generated from Simulink models for embedded applications and rapid prototyping of control systems.

- ***Simulink and its Relation to MATLAB***

The MATLAB and Simulink environments are integrated into one entity, and thus we cananalyze, simulate, and revise our models in either environment at any point. We invoke Simulinkfrom within MATLAB.

MATLAB is an interactive programming language that can be used in many ways, including data analysis and visualization, simulation and engineering problem solving. It may be used as an interactive tool or as a high level programming language. It provides an effective environment for both the beginner and for the professional engineer and scientist. SIMULINKTM is an extension to MATLAB that provides an iconographic programming environment for the solution of differential equations and other dynamic systems.

The package is widely used in academia and industry. It is particularly well known in thefollowing industries: aerospace and defence; automotive; biotech, pharmaceutical; medical;and communications. Specialist toolboxes are available for a diverse range of otherapplications, including statistical analysis, financial modelling, and image processing and so on.Furthermore, real time toolboxes allow for on-line interaction with engineering systems, idealfor data logging and control.

Building on MATLAB (the language of technical computing), Simulink provides a platform for engineers to plan, model, design, simulate, test and implement complex electromechanical, dynamic control, signal processing and communication systems. Simulink-Matlab combination is very useful for developing algorithms, GUI assisted creation of block diagrams and realization of interactive simulation based designs. The eleven chapters of the book demonstrate the power and capabilities of Simulink to solve engineering problems with varied degree of complexity in the virtual environment.

4.2 Proposed work:

4.2.1 Importance of Fuzzy Logic

Fuzzy logic is all about the relative importance of precision: use as Fuzzy Logic Toolbox software with MATLAB technical computing software as a tool for solving problems with fuzzy logic. Fuzzy logic is a fascinating area of research because it does a good job of trading off between significance and precision something that humans have been managing for a very long time.

In this sense, fuzzy logic is both old and new because, although the modern and methodical science of fuzzy logic is still young, the concept of fuzzy logic relies on age-old skills of human reasoning.

4.2.2 Usage of Fuzzy Logic

Fuzzy logic is a convenient way to map an input space to an output space. Mapping input to output is the starting point for everything. Consider the following examples:

- With information about how good your service was at a restaurant, a fuzzy logic system can tell you what the tip should be.
- With your specification of how hot you want the water, a fuzzy logic system can adjust the faucet valve to the right setting.
- With information about how far away the subject of your photograph is, a fuzzy logic system can focus the lens for you.
- With information about how fast the car is going and how hard the motor is working, a fuzzy logic system can shift gears for you.

To determine the appropriate amount of tip requires mapping inputs to the appropriate outputs. Between the input and the output, the preceding figure shows a black box that can contain any number of things: fuzzy systems, linear systems, expert systems, neural networks, differential equations, interpolated multidimensional lookup tables, or even a spiritual advisor, just to name a few of the possible options. Clearly the list could go on and on.

Of the dozens of ways to make the black box work, it turns out that fuzzy is often the very best way. As LotfiZadeh, who is considered to be the father of fuzzy logic, once remarked: "In almost every case you can build the same product without fuzzy logic, but fuzzy is faster and cheaper".

4.2.3 Convenience of Fuzzy Logic

Fuzzy logic is not a cure-all. When should you not use fuzzy logic? The safest statement is the first one made in this introduction: fuzzy logic is a convenient way to map an input space to an output space. Fuzzy logic is the codification of common sense — use common sense when you implement it and which will probably make the right decision. Many controllers, for example, do a fine job without using fuzzy logic. However, it take the time to become familiar with fuzzy logic, it can be a very powerful tool for dealing quickly and efficiently with imprecision and nonlinearity.

4.2.4 The Fuzzy Logic Concept

Fuzzy logic arose from a desire to incorporate logical reasoning and the intuitive decision making of an expert operator into an automated system. The aim is to make decisions based on a number of learned or predefined rules, rather than numerical calculations. Fuzzy logic incorporates a rule-base structure in attempting to make decisions. However, before the rule-base can be used, the input data should be represented in such a way as to retain meaning, while still allowing for manipulation. Fuzzy logic is an aggregation of rules, based on the input state variables condition with a corresponding desired output. A mechanism must exist to decide on which output, or combination of different outputs, will be used since each rule could conceivably result in a different output action.

Fuzzy logic can be viewed as an alternative form of input=output mapping. Consider the input premise, x, and a particular qualification of the input x represented by Ai. Additionally, the corresponding output, y, can be qualified by expression Ci . Thus, a fuzzy logic representation of the relationship between the input x and the output y could be described by the following:

R1: IF x is A1 THEN y is C1

R2: IF x is A2 THEN y is C2

. . . . . .

. . . . . .

. . . . . .

Rn: IF x is An THEN y is Cn

where x is the input (state variable), y is the output of the system, Ai are the different fuzzy variables used to classify the input x and Ci are the different fuzzy variables used to classifythe output y. The fuzzy rule representation is linguistically based.

Thus, the input x is a linguistic variable that corresponds to the state variable under consideration. Furthermore, the elements Ai are fuzzy variables that describe the input x. Correspondingly, the elements Ci are the fuzzy variables used to describe the output y. In fuzzy logic control, the term ‘‘linguistic variable’’ refers to whatever state variables the system designer is interested in . Linguistic variables that are often used in control applications include Speed, Speed Error, Position, and Derivative of Position Error. The fuzzy variable is perhaps better described as a fuzzy linguistic qualifier. Thus the fuzzy qualifier performs classification(qualification) of the linguistic variables. The fuzzy variables frequently employed include Negative Large, Positive Small and Zero. Several papers in the literature use the term ‘‘fuzzy set’’ instead of ‘‘fuzzy variable’’, however; the concept remains the same. Table 4.1 illustrates the difference between fuzzy variables and linguistic variables. Once the linguistic and fuzzy variables have been specified, the complete inference system can be defined. The fuzzy linguistic universe, U, is defined as the collection of all the fuzzy variables used to describe the linguistic variables .

i.e. the set U for a particular system could be comprised of Negative Small (NS), Zero (ZE) and Positive Small (PS). Thus, in this case the set U is equal to the set of [NS, ZE, PS]. For the system described by , the linguistic universe for the input x would be the set Ux . .A1A2 . . . An.. Similarly,

TABLE 4.1 Fuzzy and linguistic variables

Linguistic Variables		Fuzzy Variables (Linguistic Qualifiers)	
Speed error	(SE)	Negative large	(NL)
Position error	(PE)	Zero	(ZE)
Acceleration	(AC)	Positive medium	(PM)
Derivative of position error	(DPE)	Positive very small	(PVS)
Speed	(SP)	Negative medium small	(NMS)

The linguistic universe for the output y would be the set Uy ..CaC2 . . . Cn.

The Fuzzy Inference System (FIS) The basic fuzzy inference system (FIS) can be classified as: Type 1 Fuzzy Input Fuzzy Output (FIFO)

Type 2 Fuzzy Input Crisp Output (FICO)

Type 2 differs from the first in that the crisp output values are predefined and, thus, built into the inference engine of the FIS. In contrast, type 1 produces linguistic outputs. Type 1 is more general than type 2 as it allows redefinition of the response without having to redesign the entire inference engine. One drawback is the additional step required, converting the fuzzy output of the FIS to a crisp output. Developing a FIS and applying it to a control problem involves several steps:

1. Fuzzification
2. Fuzzy rule evaluation (fuzzy inference engine)
3. Defuzzification.

The total fuzzy inference system is a mechanism that relates the inputs to a specific output or set of outputs. First, the inputs are categorized linguistically (fuzzification), then the linguistic inputs are related to outputs (fuzzy inference) and, finally, all the different outputs are combined to produce a single output (defuzzification). Figure 4.1 shows a block diagram of the fuzzy inference system.

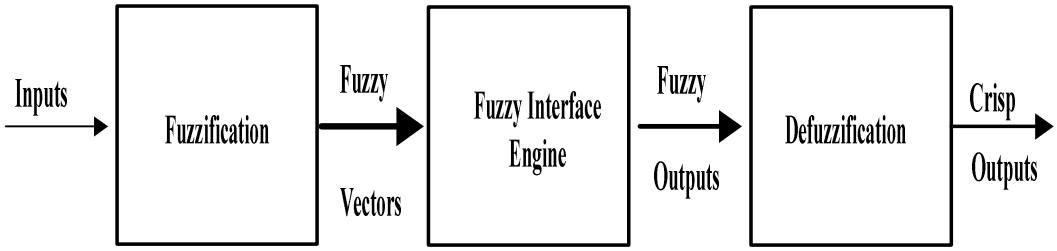


Fig .4.1 Fuzzy inference system

4.2.5 Fuzzification:

Fuzzy logic uses linguistic variables instead of numerical variables. In a control system, error between reference signal and output signal can be assigned as Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive small (PS), Positive Medium (PM), Positive Big (PB). The triangular membership function is used for fuzzifications. The process of fuzzification convert numerical variable (real number) to a linguistic variable (fuzzy number).

4.2.6.Defuzzification:

The rules of fuzzy logic controller generate required output in a linguistic variable (Fuzzy Number), according to real world requirements; linguistic variables have to be transformed to crisp output (Real number). This selection of strategy is a compromise between accuracy and computational intensity.

4.2.7 Fuzzy Logic Controller

Fuzzy logic is a method of rule-based decision making used for expert systems and process control that emulates the rule-of-thumb thought process used by human beings. The basis of fuzzy logic is fuzzy set theory which was developed by LotfiZadeh in the 1960s. Fuzzy set theory differs from traditional Boolean (or two-valued) set theory in that partial membership in a set is allowed. Traditional Boolean set theory is two-valued in the sense that a member belongs to a set or does not and is represented by 1 or 0, respectively. Fuzzy set theory allows for partial membership, or a degree of membership, which might be any value along the continuum of 0 to 1. A linguistic term can be defined quantitatively by a type of fuzzy set known as a membership function. The

membership function specifically defines degrees of membership based on a property such as temperature or pressure. With membership functions defined for controller or expert system inputs and outputs, the formulation of a rule base of IF-THEN type conditional rules is done. Such a rule base and the corresponding membership functions are employed to analyze controller inputs and determine controller outputs by the process of fuzzy logic inference. By defining such a fuzzy controller, process control can be implemented quickly and easily. Many such systems are difficult or impossible to model mathematically, which is required for the design of most traditional control algorithms. In addition, many processes that might or might not be modeled mathematically are too complex or nonlinear to be controlled with traditional strategies. However, if a control strategy can be described qualitatively by an expert, fuzzy logic can be used to define a controller that emulates the heuristic rule-of-thumb strategies of the expert. Therefore, fuzzy logic can be used to control a process that a human can control manually with expertise gained from experience. The linguistic control rules that a human expert can describe in an intuitive and general manner can be directly translated to a rule base for a fuzzy logic controller.

4.3MATLAB/SIMULATION RESULTS

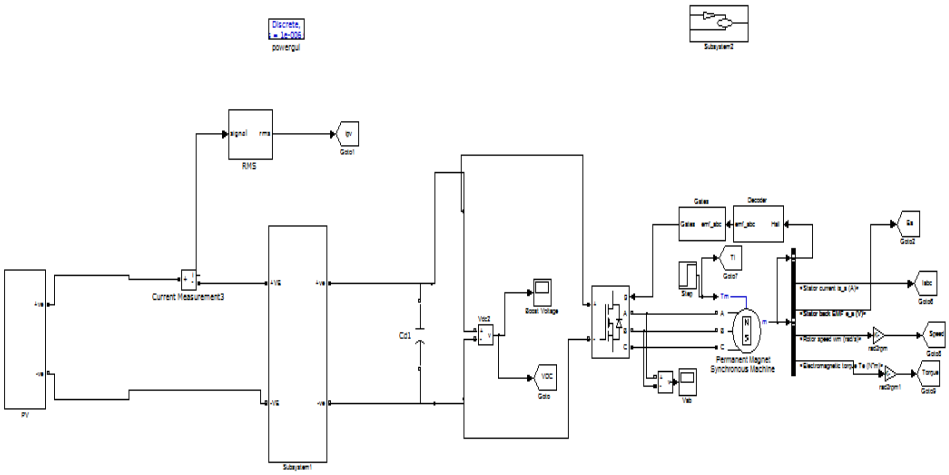
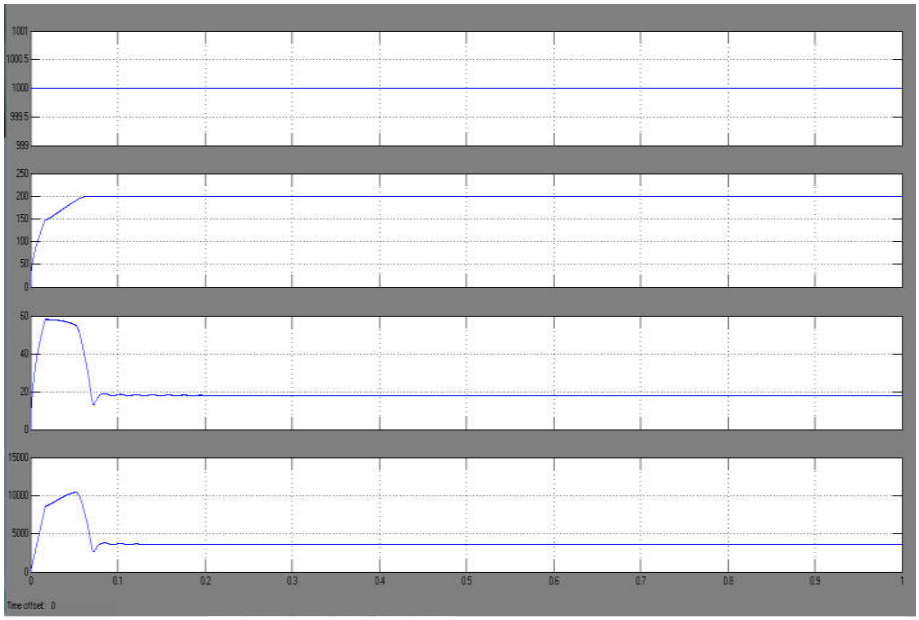
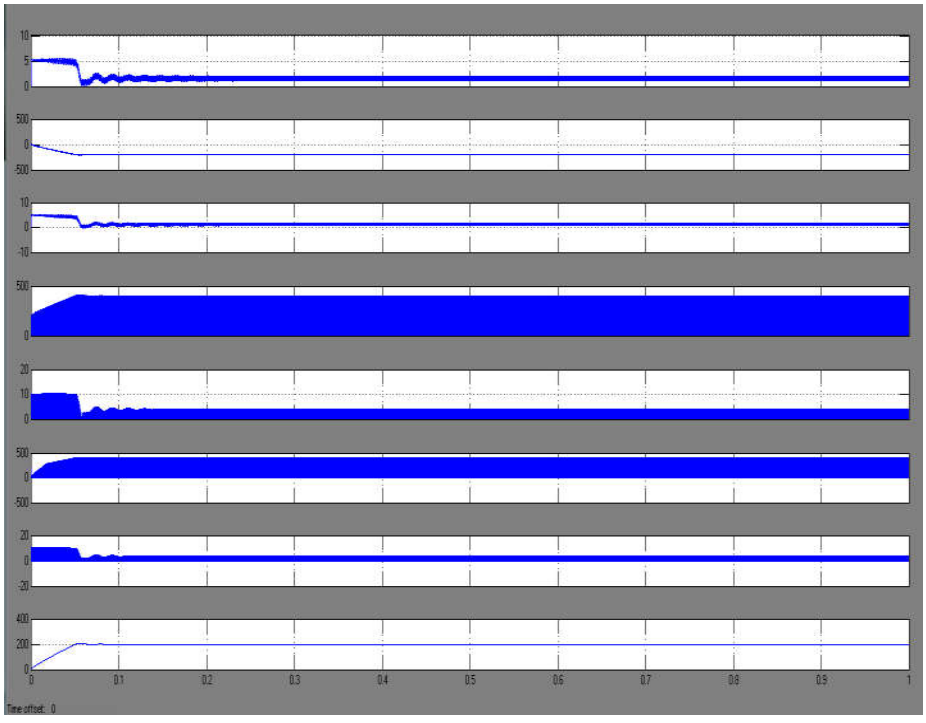


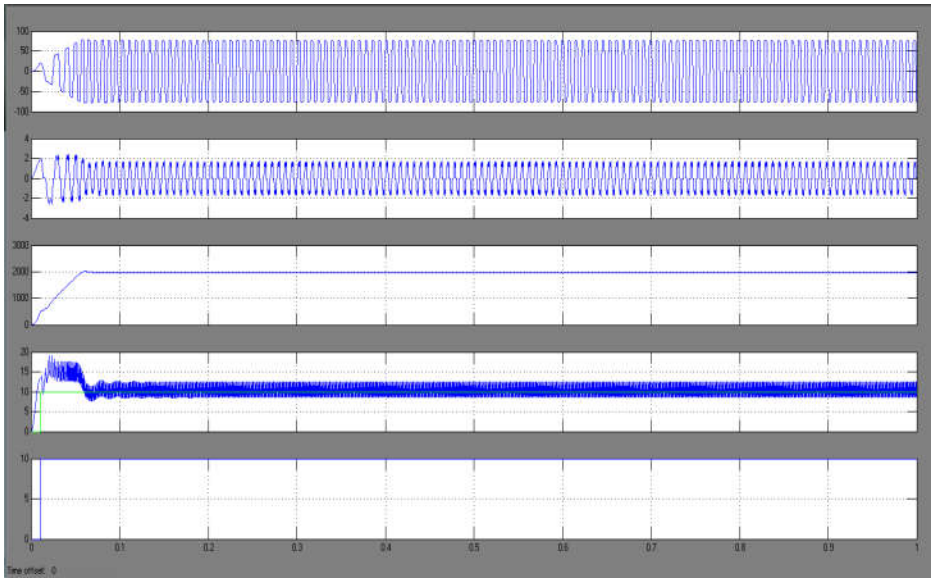
Fig 4.2 Matlab/Simulink circuit of Starting and steady-state performances of the proposed SPV arraybased zeta converter-fed BLDC motor drive for water pump



(a)



(b)



(c)

Fig.4.3 Starting and steady-state performances of the proposed SPV arraybased zeta converter-fed BLDC motor drive for water pump. (a) SPV arrayvariables. (b) Zeta converter variables. (c) BLDC motor-pump variables.

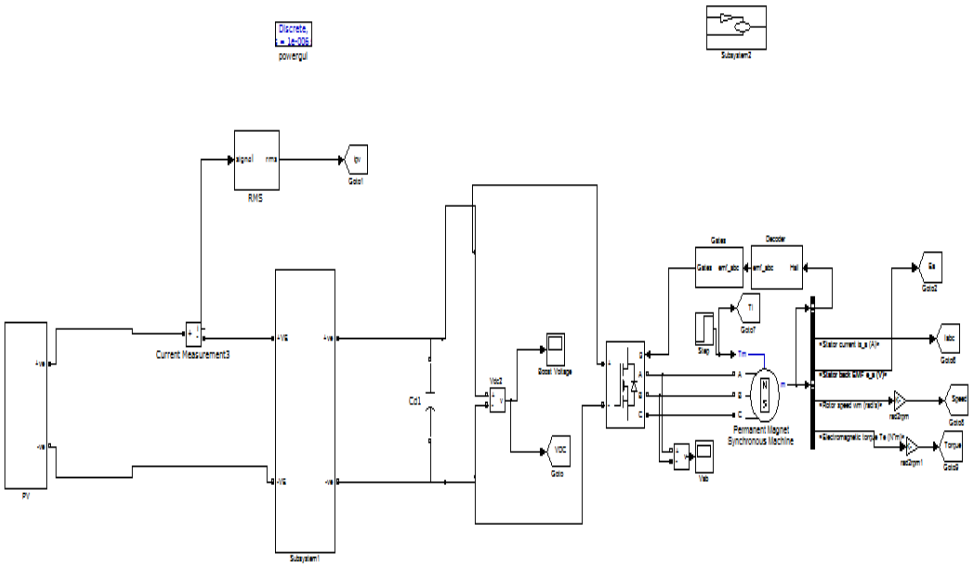
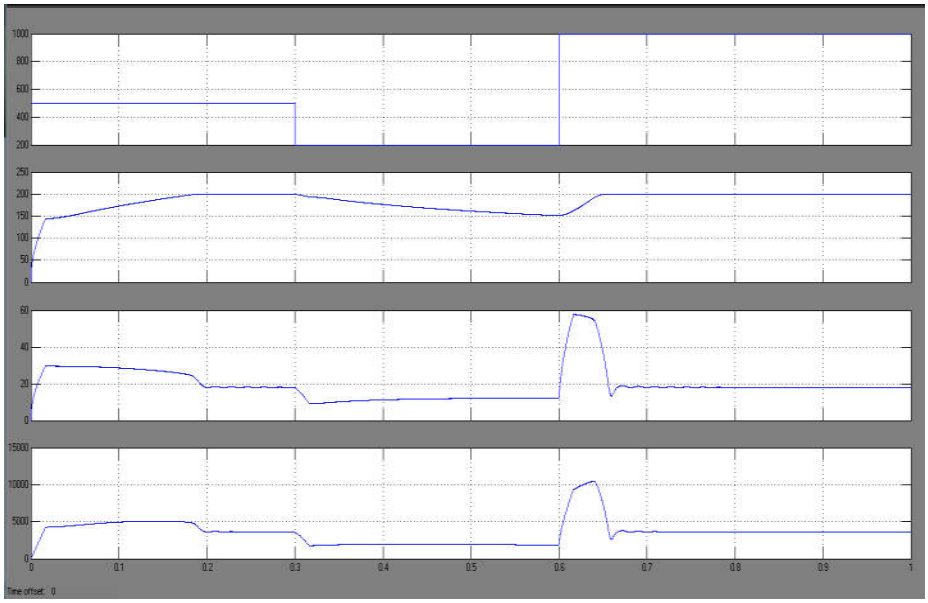
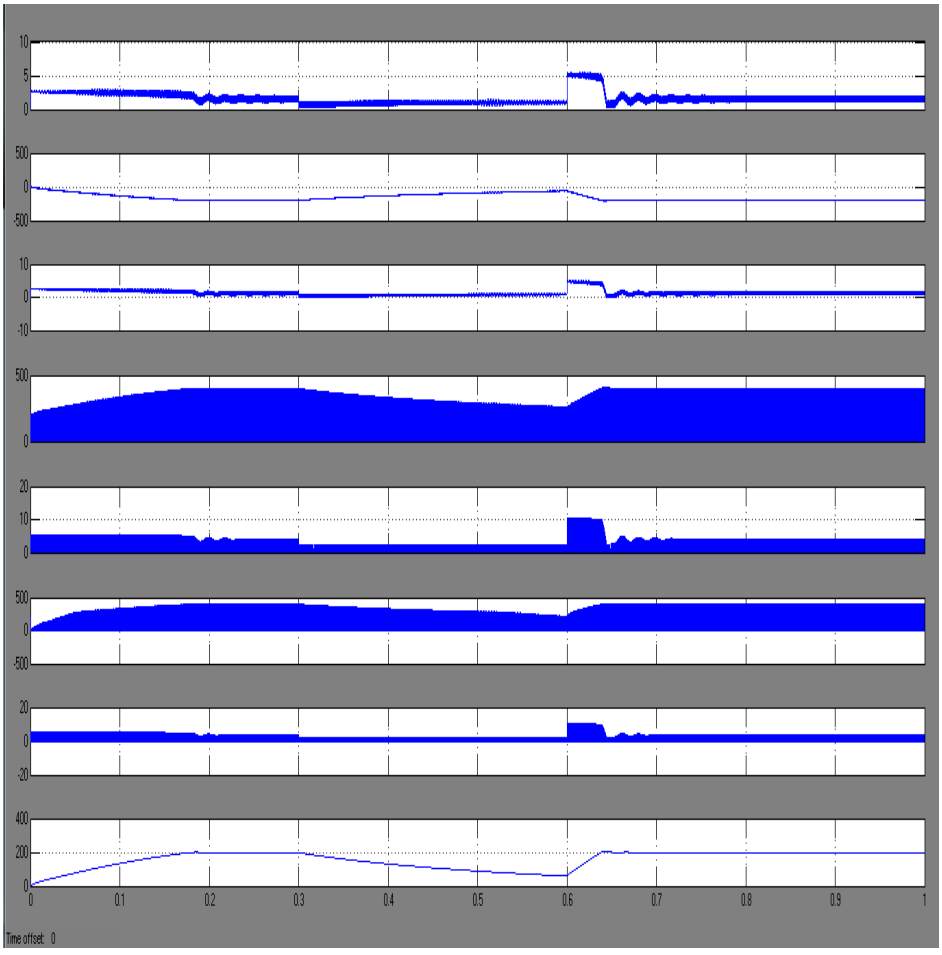


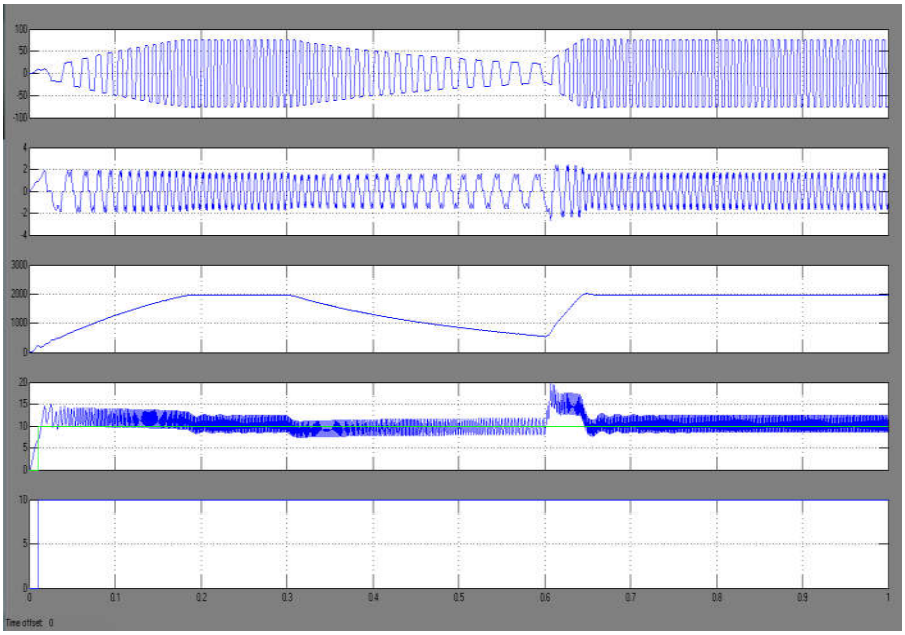
Fig 4.4Matlab/Simulink circuit for Dynamic performance of SPV array-based zetaconverter-fed BLDC motor drive for water pump


1000
800
600
400
200
250
200
150
100
50
0
60
40
20
0
15000
10000
5000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time offset: 0

(a)


10
5
0
500
0
-500
10
0
-10
500
0
20
10
0
500
0
-500
20
0
-20
400
200
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time offset: 0

(b)



(c)

Fig.4.5. Dynamic performances of the proposed SPV array-based zeta converter-fed BLDC motor drive for water pump. (a) SPV array variables. (b) Zeta converter variables. (c) BLDC motor-pump variables.

CHAPTER 5
CONCLUSION

The SPV array-zeta converter-fed VSI–BLDC motor-pumphas been proposed and its suitability has been demonstratedthrough simulated results and experimental validation. Theproposed system has been designed and modeled appropriatelyto accomplish the desired objectives and validated to examinevarious performances under starting, dynamic, and steady-stateconditions. The performance evaluation has justified thecombination of zeta converter and BLDC motor for SPVarray-based water pumping. The system under study has shownvarious desired functions such as maximum power extractionof the SPV array, soft starting of BLDC motor, fundamentalfrequency switching of VSI resulting in a reduced switchinglosses, speed control of BLDC motor without any additionalcontrol, and an elimination of phase current and dc-linkvoltage sensing, resulting in the reduced cost and complexity.The proposed system has operated successfully even underminimum solar irradiance.

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