BLDC Motor Driven Solar PV Array Fed Water Pumping System Employing Zeta Converter

A. Elizabeth, Bavanirajan, Kannabiran, Surendiran

Abstract*: *This paper proposes a simple, cost effective and efficient brushless DC (BLDC) motor drive for solar photovoltaic (SPV) array fed water pumping system. A zeta converter is utilized in order to extract the maximum available power from the SPV array. The proposed control algorithm eliminates phase current sensors and adapts a fundamental frequency switching of the voltage source inverter (VSI), thus avoiding the power losses due to high frequency switching. No additional control or circuitry is used for speed control of the BLDC motor. The speed is controlled through a variable DC link voltage of VSI. The proposed water pumping system is designed and modeled such that the performance is not affected under dynamic conditions. The suitability of proposed system at practical operating conditions is demonstrated through simulation results using MATLAB/Simulink followed by an experimental validation.

Index Terms*: *BLDC motor, SPV array, Zeta converter, INC-MPPT.

I. INTRODUCTION

The drastic reduction in the cost of power electronic devices and annihilation of fossil fuels in near future invite to use the solar photovoltaic (SPV) generated electrical energy for various applications as far as possible. The water pumping, a standalone application of the SPV array generated electricity is receiving wide attention now a days for irrigation in the fields, household applications and industrial use. Although several researches have been carried out in an area of SPV array fed water pumping, combining various DC-DC converters and motor drives, the zeta converter in association with a permanent magnet brushless DC (BLDC) motor is not explored precisely so far to develop such kind of system. However, the zeta converter has been used in some other SPV based applications. Moreover, a topology of SPV array fed BLDC motor driven water pump with zeta converter has been reported and its significance has been presented more or less. Nonetheless, an experimental validation is missing and the absence of extensive literature review and comparison with the existing topologies, have concealed the technical contribution and originality of the reported work.

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The merits of both BLDC motor and zeta converter can contribute to develop a SPV array fed water pumping system possessing a potential of operating satisfactorily under dynamically changing atmospheric conditions. The BLDC motor has high reliability, high efficiency, high torque/inertia ratio, improved cooling, low radio frequency interference and noise and requires practically no maintenance. On the other hand, a zeta converter exhibits following advantages over the conventional buck, boost, buck-boost converters and buck converter when employed in SPV based applications.

Belonging to a family of buck-boost converters, the zeta converter may be operated either to increase or to decrease the output voltage. This property offers a boundless region for maximum power point tracking MPPT) of a SPV array. The MPPT can be performed with simple buck and boost converter if MPP occurs within prescribed limits.

This property also facilitates the soft starting of BLDC motor unlike a boost converter which habitually steps up the voltage level at its output, not ensuring soft starting. Unlike a classical buck-boost converter, the zeta converter has a continuous output current. The output inductor makes the current continuous and ripples free.

Although consisting of same number of components as a buck converter, the zeta converter operates as non-inverting buck-boost converter unlike an inverting buck-boost and buck converter. This property obviates a requirement of associated circuits for negative voltage sensing hence reduces the complexity and probability of slow down the system response. These merits of the zeta converter are favorable for proposed SPV array fed water pumping system. An incremental conductance (INC) MPPT algorithm is used to operate the zeta converter such that SPV array always operates at its MPP.

II. DC – DC CONVERTERS

A boost converter (step-up converter) is a DC-to-DC power converter steps up voltage (while stepping down current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element, a capacitor, inductor, or the two in combination. To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter).

Dc-dc power converters are employed in a variety of applications, including power supplies for personal computers, office equipment, and spacecraft power systems,

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laptop computers, and telecommunications equipment, as well as dc motor drives. The input to a dc-dc converter is an unregulated dc voltage Vg. The converter produces a regulated output voltage V, having a magnitude (and possibly polarity) that differs from Vg. For example, in a computer off-line power supply, the 120 V or 240 V ac utility voltages is rectified, producing a dc voltage of approximately 170 V or 340 V, respectively. A dc-dc converter then reduces the voltage to the regulated 5 V or 3.3 V required by the processor ICs. High efficiency is invariably required, since cooling of inefficient power converters is difficult and expensive. The ideal dc-dc converter exhibits 100% efficiency; in practice, efficiencies of 70% to 95% are typically obtained. This is achieved using switched-mode, or chopper, circuits whose elements dissipate negligible power.. This approach is also employed in applications involving alternating current, including high-efficiency dc-ac power converters (inverters and power amplifiers), ac-ac power converters, and some ac-dc power converters (low-harmonic rectifiers). A basic dc-dc converter circuit known as the buck converter is illustrated. A single-pole double-throw (SPDT) switch is connected to the dc input voltage Vg as shown. The switch output voltage vs(t) is equal to Vg when the switch is in position 1, and is equal to zero when the switch is in position 2.

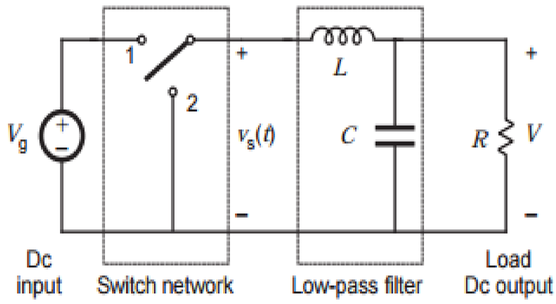

Fig. 1 Schematic Diagram

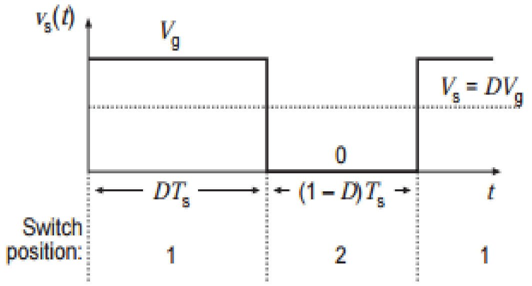

Fig. 2 Switch Voltage Waveform

III. ANALYSIS OF CONVERTER WAVEFORMS

Under steady-state conditions, the voltage and current waveforms of a dc-dc converter can be found by use of two basic circuit analysis principles. The principle of inductor volt-second balance states that the average value, or dc component, of voltage applied across an ideal inductor winding must be zero. This principle also applies to each winding of a transformer or other multiple winding magnetic devices. Its dual, the principle of capacitor amp-second or charge balance, states that the average current that flows through an ideal capacitor must be zero. Hence, to determine the voltages and currents of dc-dc converters operating in periodic steady state, one averages the inductor current and capacitor voltage waveforms over one switching period, and equates the results to zero. The equations are greatly simplified by use of a third artifice, the small ripple approximation. The inductor currents and capacitor voltages contain dc components, plus switching ripple at the switching frequency and its harmonics. In most well designed converters, the switching ripple is small in magnitude compared to the dc components. For inductor currents, a typical value of switching ripple at maximum load is 10% to 20% of the dc component of current. For an output capacitor voltage, the switching ripple is typically required to be much less than 1% of the dc output voltage.

In both cases, the ripple magnitude is small compared with the dc component, and can be ignored. As an example, consider the boost converter of A resistor RL is included in series with the inductor, to model the resistance of the inductor winding. It is desired to determine simple expressions for the output voltage V, inductor current IL, and efficiency. Typical inductor voltage and capacitor current waveforms are sketched in Fig. 5(b). With the switch in position 1, the inductor voltage is equal to vL(t) = Vg – iL(t)RL. By use of the small ripple approximation, we can replace iL(t) with its dc component IL, and hence obtain vL(t) Vg – ILRL. Likewise, the capacitor current is equal to iC(t) = - v(t)/R, which can be approximated as iC(t) - V/R.

IV. TRANSFORMER ISOLATION

In the majority of applications, it is desired to incorporate a transformer into the switching converter, to obtain dc isolation between the converter input and output. For example, in off-line power supply applications, isolation is usually required by regulatory agencies. This isolation could be obtained by simply connecting a 50 Hz or 60 Hz transformer at the power supply ac input terminals. However, since transformer size and weight vary inversely with frequency, incorporation of the transformer into the converter can make significant improvements: the transformer then operates at the converter switching frequency of tens or hundreds of kilohertz. The size of modern ferrite power transformers is minimized at operating frequencies ranging from several hundred kilohertz to roughly one Megahertz. These high frequencies lead to dramatic reductions in transformer size.

When a large step-up or step-down conversion ratio is required, the use of a transformer can allow better converter optimization. By proper choice of the transformer turns ratio, the voltage or current stresses imposed on the transistors and diodes can be minimized, leading to improved efficiency and lower cost. Multiple dc outputs can also be obtained in an inexpensive manner, by adding multiple secondary windings and converter secondary-side circuits. The secondary turns ratios are chosen to obtain the desired output voltages. Usually, only one output voltage can be regulated, via control of the converter duty cycle,

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So wider tolerances must be allowed for the auxiliary output voltages. Cross regulation is a measure of the variation in an auxiliary output voltage, given that the main output voltage is regulated perfectly. The basic operation of transformers in most power converters can be understood by replacing the transformer with the simplified model.

The model neglects losses and imperfect coupling between windings; such phenomena are usually considered to be converter non idealities. The model consists of an ideal transformer plus a shunt inductor known as the magnetizing inductance LM. This inductor models the magnetization of the physical transformer core, and hence it must obey all of the usual rules for inductors. In particular, volt-second balance must be maintained on the magnetizing inductance. Furthermore, since the voltages of all windings of the ideal transformer are proportional, volt-second balance must be maintained for each winding. Failure to achieve volt-second balance leads to transformer saturation and, usually, destruction of the converter. The means by which transformer volt-second balance is achieved is known as the transformer reset mechanism.

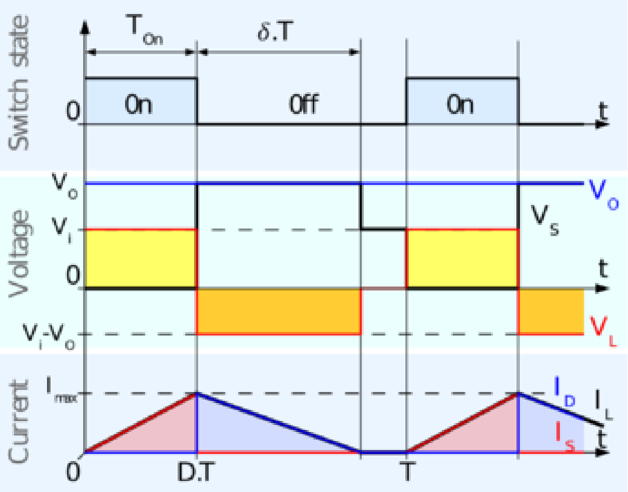

Fig. 3 V –I Characteristics

V. RELATED WORK

For the maximum utilization of solar energy, photovoltaic (PV) power generation systems are operated at the maximum power point (MPP) under varying atmospheric conditions, and MPP tracking (MPPT) is generally achieved using several conventional methods. However, when partial shading occurs in a PV system, the resultant power-voltage (P-V) curve exhibits multiple peaks and traditional methods that need not guarantee convergence to true MPP always. This paper proposes an artificial bee colony (ABC) algorithm for global MPP (GMPP) tracking under conditions of in-homogenous insulation. The formulation of the problem, application of the ABC algorithm, and the results are analyzed in this paper. The numerical simulations carried out on two different PV configurations under different shading patterns strongly suggest that the proposed method is far superior to existing MPPT alternatives. Experimental results are also provided to validate the new dispensation.

This paper describes the optimal operation performance of a brushless dc motor (BLDC), fed by a z-source inverter accompanying with photovoltaic (PV) system, drives a water pumping system. Albeit the conventional PV water pumping systems, including a two stages converter, the proposed system employs a Z-source inverter (ZSI) to extract the Maximum Power of PV array and supply the BLDC motor. Utilizing the Z-source inverter provides some advantages such as high efficiency and low cost. In order to achieve an accurate Maximum Power Point Tracking (MPPT) of the PV array, fuzzy logic controller is applied to accomplish an appropriate variable step size in incremental conductance method. Due to PV power variation, the BLDC motor should be driven with variable reference speed.

Solar Photovoltaic (PV) power keeps changing with solar insolation(S) and ambient temperature (T) because PV cell exhibits non-linear current-voltage characteristic. So the Maximum Power Point (MPP) varies with the changing S and T. However with the advancement of power electronics converter technology, it is now possible to operate the PV power at its MPP in order to improve the overall efficiency.

This paper presents maximum power point tracking (MPPT) based on Perturb & Observe (P&O) and Fuzzy Logic Controller (FLC) for PV with dc-dc buck boost converter for the purpose of performance evaluation and comparison analysis thereof. Both the algorithms were simulated in MATLAB-Simulink with 100W PV module (Solar Alpex Panel 1552P-3613G-166109) connected to buck-boost dc-dc converter. The results of simulation and analysis indicate that the proposed FLC algorithms provide better MPP than that of conventional P&O method. FLC algorithms significantly improve the efficiency of MPPT and provide faster responses particularly during fast changing environmental conditions besides the fact that it is simple and can be implemented with PIC Microcontroller or FPGA. Photovoltaic maximum power point tracker (MPPT) systems are commonly employed to maximize the photovoltaic output power, since it is strongly affected in accordance to the incident solar radiation, surface temperature and load-type changes. Basically, a MPPT system consists on a dc-dc converter (hardware) controlled by a tracking algorithm (software) and the combination of both, hardware and software, defines the tracking efficiency. This paper shows that even when the most accurate algorithm is employed, the maximum power point cannot be found, since its imposition as operation point depends on the dc-dc converter static feature and the load-type connected to the system output. For validating the concept, the main dc-dc converters, i.e., Boost, Buck-Boost, Cuk, SEPIC and Zeta are analyzed considering two load-types: resistive voltage regulated dc bus. Simulation and experimental results are included for validating the theoretical analysis.

This paper presents an evaluation of an optimal DC bus voltage regulation strategy for grid-connected photovoltaic (PV) system with battery energy storage (BES). The BES is connected to the PV system DC bus using a DC/DC buck-boost converter. The converter facilitates the BES power charge/discharge to compensate for the DC bus voltage deviation during severe disturbance conditions. In this way, the regulation of DC bus voltage of the PV/BES system can be enhanced as compared to the conventional regulation that is solely.

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Based on the voltage-sourced converter (VSC). For the grid side VSC (G-VSC), two control methods, namely, the voltage-mode and current-mode controls, are applied. For control parameter optimization, the simplex optimization technique is applied for the G-VSC voltage- and current-mode controls, including the BES DC/DC buck-boost converter controllers. A new set of optimized parameters are obtained for each of the power converters for comparison purposes. The PSCAD/EMTDC-based simulation case studies are presented to evaluate the performance of the proposed optimized control scheme in comparison to the conventional methods.

This paper provides a comprehensive review of the maximum power point tracking (MPPT) techniques applied to photovoltaic (PV) power system available until January, 2012. A good number of publications report on different MPPT techniques for a PV system together with implementation. But, confusion lies while selecting a MPPT as every technique has its own merits and demerits. Hence, a proper review of these techniques is essential. Unfortunately, very few attempts have been made in this regard, excepting two latest reviews on MPPT [Salas, 2006], [Esram and Chapman, 2007]. Since, MPPT is an essential part of a PV system, extensive research has been revealed in recent years in this field and many new techniques have been reported to the list since then.

In this paper, a detailed description and then classification of the MPPT techniques have made based on features, such as number of control variables involved, types of control strategies employed, types of circuitry used suitably for PV system and practical/commercial applications. This paper is intended to serve as a convenient reference for future MPPT users in PV systems.

VI. PROPOSED METHODOLOGY

In proposed work, Zeta converter is used. A zeta converter is utilized in order to extract the maximum power available from a SPV array, soft starting and speed control of BLDC motor coupled to a water pump. Due to a single switch, this converter has very good efficiency and offers boundless region for MPPT. This converter is operated in continuous conduction mode (CCM) resulting in a reduced stress on its power devices and components. Furthermore, the switching loss of VSI is reduced by adopting fundamental frequency switching resulting in an additional power saving and hence an enhanced efficiency. The phase currents as well as the DC link voltage sensors are completely eliminated, offering simple and economical system without scarifying its performance.

The speed of BLDC motor is controlled, without any additional control, through a variable DC link voltage of VSI. Moreover, a soft starting of BLDC motor is achieved by proper initialization of MPPT algorithm of SPV array. These features offer an increased simplicity of proposed system .Advantage are Simple & Cost Effective. Due to the usage of Single switch (power switching device), convertor has a very high efficiency. It operated on continuous conduction mode (CCM) which reduces stress on Power devices. Switching losses are reduced. Soft starting of BLDC Motor us achieved due to INC-MPPT Algorithm.

VII. SYSTEM MODEL

A zeta converter is utilized in order to extract the maximum power available from a SPV array, soft starting and speed control of BLDC motor coupled to a water pump. Due to a single switch, this converter has very good efficiency and offers boundless region for MPPT. This converter is operated in continuous conduction mode (CCM) resulting in a reduced stress on its power devices and components. Furthermore, the switching loss of VSI is reduced by adopting fundamental frequency switching resulting in an additional power saving and hence an enhanced efficiency.

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The advantage and desirable feature of Zeta conductor and BLDC motor drive contribute to develop a simple, efficient and cost-effective and reliable water pumping system based on solar PV energy. Simulation results using MATLAB/Simulink and experimental performances are examined to demonstrate the starting, dynamics and steady state behavior of proposed water pumping system subjected to practical operating conditions. The SPV array and BLDC motor are designed such that proposed system always exhibits good performance regardless of solar irradiance level.

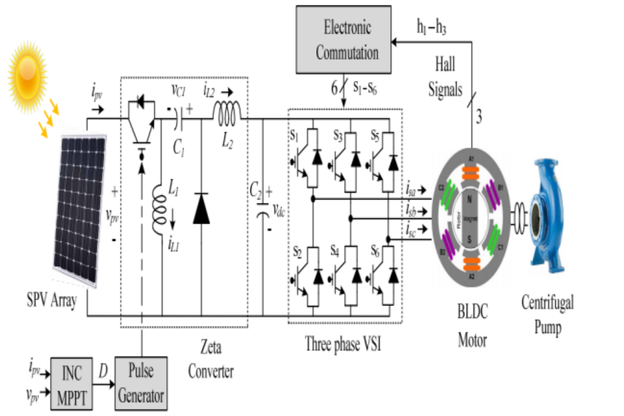

Fig. 4 System Architecture

VIII. WORKING PRINCIPLE

A. Solar PV Array

Solar PV Array acts as an Input DC Voltage source. It converts DC Voltage source to AC Voltage source Using VSI. In addition, the performance of the BLDC motor-pump is influenced by the mechanical and electrical losses associated with them. To compensate these losses, the size of SPV array is selected with slightly more maximum power capacity to ensure the satisfactory operation regardless of the power losses. Therefore the SPV array of maximum power capacity of Pmpp= 3.4 kW under STC (STC: 1000W/m², 25°C, AM 1.5), slightly more than demanded by the motor-pump is selected and its parameters are designed accordingly.

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Sun module® Plus SW 280 mono SPV module made by Solar World is selected to design the SPV array of an appropriate size. Electrical specifications of this module are listed in Table I and the numbers of modules required to connect in series/parallel are estimated by selecting the voltage of the SPV array at MPP under STC as, Vmpp= 187.2 V.

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

I. ELECTRICAL SPECIFICATION SUN MODULE® PLUS SW 280 MONO SPV MODULE

B. BLDC Motor

BLDC Motor connected with Water pump .Speed can be controlled through Variable DC link voltage of VSI No external circuit or control is required for speed control of BLDC Motors. Advantages - High Efficiency, High reliability, High Torque/Inertia ratio, improved cooling, No Maintenance required, Low radio frequency Interference.

C. Zeta Converter

It's a DC-DC Convertor, Made up of 2 capacitors & 2 Inductors; Capable of operating in either Step-up or Step-down Mode. Used to draw maximum power from the Solar PV array with minimum power losses. Pulse Generator is used to operate Zeta convertor. Works on the principle of Incremental conductance-Maximum power point tracking Algorithm. (INC-MPPT), due to this soft starting of BLDC Motor is possible. Output current is continuous & ripple free, Output efficiency is high & Economical. The zeta converter is the next stage to the SPV array. Its design consists of the estimation of the various components such as input inductor, L1, output inductor, L2and intermediate capacitor, C1. These components are so designed that the zeta converter always operated in continuous conduction mode resulting in the reduced stress on them.

D. Voltage Source Inverter

Used to transfer real power from a DC Power source to AC Load (Motor acts as a AC Load) . Avoids power losses due to higher switching frequency. VSI is operated in Fundamental Frequency Switching through an Electronic Commutation of BLDC Motors, which eliminated power losses and improves Efficiency. A new design approach for the estimation of DC link capacitor of the VSI is presented in this sub-section. This approach is based on a fact that 6th harmonic component of the supply (AC) voltage is reflected on the DC side as a dominant harmonic in the three phase supply system. Here, the fundamental frequencies of the output voltage of the VSI are estimated corresponding to the rated speed and the minimum speed of the BLDC motor essentially required to pump the water. These two frequencies are further used to estimate the values of their corresponding capacitors. Out of the two estimated capacitors, larger one is selected to assure the satisfactory operation of the proposed system even under the duration of minimum solar irradiance level.

E. Centrifugal Pump

To estimate the proportionality constant, K for the selected centrifugal water pump, its torque-speed characteristics is used as,

$$T_L = K\omega_r^2 \qquad \rightarrow \quad (1)$$

where T_L is the load torque offered by the centrifugal pump which is equal to the electromagnetic torque developed by the BLDC motor under steady state for stable operation and ωr is the mechanical speed of the rotor in rad/sec. Since the rated torque, T_L and the rated speed, N rated of the selected BLDC motor is 9.2 Nm and 3000 rpm respectively, the proportionality constant, K is estimated using (1) as

$$K = \frac{T_L}{\omega_r^2} = \frac{9.2}{(2\pi * 3000/60)^2} = 9.32 * 10^{-5}$$

The centrifugal pump with this data is selected for the proposed system.

IX. SYSTEM IMPLEMENTATION

A. Operation of the Proposed System

The SPV array generates the electrical power demand by the motor-pump. This electrical power is fed to the motor-pump via a zeta converter and a VSI. The SPV array appears as a power source for the zeta converter as shown in the proposed figure. Ideally, the same amount of power is transferred at the output of zeta converter which appears as an input source for the VSI. In practice, due to the various losses associated with a DC-DC converter, slightly less amount of power is transferred to feed the VSI. The pulse generator generates, through INC-MPPT algorithm, switching pulses for IGBT (Insulated Gate Bipolar Transistor) switch of the zeta converter. The INC-MPPT algorithm uses voltage and current as feedback from SPV array and generates an optimum value of duty cycle. Further, it generates actual switching pulse by comparing the duty cycle with a high frequency carrier wave. In this way, the maximum power extraction and hence the efficiency optimization of SPV array is accomplished The VSI , converting DC output from a zeta converter into AC, feeds the BLDC motor to drive a water pump 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.

B. Control of the Proposed System

The proposed system is controlled in two stages. These two control techniques, viz. MPPT and electronic computation are discussed as follows:

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i. INC-MPPT ALGORITHM:

This technique allows perturbation in either the SPV array voltage or the duty cycle. The former calls for a PI (Proportional-Integral) controller to generate a duty cycle [8] for the zeta converter, which increases the complexity. Hence, the direct duty cycle control is adapted in this work. The INC-MPPT algorithm determines the direction of perturbation.

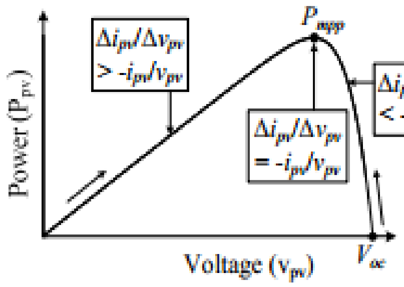

Fig.5 Illustration of INC-MPPT with SPV array Ppv-vpv characteristics

$$\left.\begin{array}{ll} \dfrac{dP_{pv}}{dv_{pv}} = 0; & \text{at MPP} \\ \dfrac{dP_{pv}}{dv_{pv}} > 0; & \text{left of MPP} \\ \dfrac{dP_{pv}}{dv_{pv}} > 0; & \text{right of MPP} \end{array}\right\}$$

$$\left.\begin{array}{ll} \dfrac{\Delta i_{pv}}{\Delta v_{pv}} = -\dfrac{i_{pv}}{v_{pv}}; & \text{at MPP} \\ \dfrac{\Delta i_{pv}}{\Delta v_{pv}} > -\dfrac{i_{pv}}{v_{pv}}; & \text{left of MPP} \\ \dfrac{\Delta i_{pv}}{\Delta v_{pv}} < -\dfrac{i_{pv}}{v_{pv}}; & \text{right of MPP} \end{array}\right\}$$

Thus, based on the relation between incremental conductance and instantaneous conductance decides the direction of perturbation as shown in Fig.3, and increases/decreases the duty cycle accordingly. For instance, on the right of MPP, the duty cycle is increased with a fixed perturbation size until the direction reverses. Ideally, the perturbation stops once the operating point reaches the MPP. Perturbation size (ΔD= 0.001) is selected, which contributes to sequence using a decoder logic. It symmetrically emphasizes phase voltage per the various positions. As the perturbation size reduces, the controller takes more time to track the MPP of SPV array. An intellectual agreement between the tracking time and the perturbation size is held to fulfill the objectives of MPPT and soft starting of BLDC motor. In order to achieve soft starting, the initial value of duty cycle is set as zero. In addition, an optimum value of perturbation soft starting and also minimizes oscillations around the MPP.

X. ELECTRONIC COMMUTATION OF BLDC MOTOR

The BLDC motor is controlled using a VSI operated through an electronic commutation of BLDC motor. An electronic commutation of BLDC motor stands for commutating the currents flowing through its windings in a predefined sequence using decoder logic. These three Hall-effect signals are produced by an inbuilt encoder according the rotor position. A particular combination of Hall-effect signals is produced for each specific range of rotor position at an interval of 60°. It is perceptible that only two switches conduct at a time, resulting in 120° conduction mode of operation of VSI and hence the reduced conduction losses.

XI. RESULTS AND DISCUSSIONS

Performance evaluation of the proposed SPV array fed BLDC motor driven water pumping system employing zeta converter is carried out using simulated results in MATLAB/Simulink. The proposed system is designed, modelled and simulated considering the random and instant variation in solar irradiance level and its suitability is demonstrated by testing the starting, steady state and dynamic behavior.

XII. CONCLUSION

The SPV array-zeta converter fed VSI-BLDC motor-pump has been proposed and its suitability has been demonstrated using simulation results. The proposed system has been designed and modelled approximately to attain desired objective and validated to examine various performances under starting, dynamic and steady state conditions. The performance evaluation has justified the combination of zeta converter and BLDC motor for SPV array based water pumping. The system under study has shown various desired functions such as MPP extraction of the SPV array, soft starting of BLDC motor, fundamental frequency switching of VSI resulting in a reduces witching losses, speed control of BLDC motor additional control and an elimination of phase current and DC voltage sensing, resulting in the reduced cost and complexity. The proposed system has operated successfully even under minimum solar irradiance.

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