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Solar PV Array Fed Cuk Converter-VSI Controlled BLDC Motor Drive for Water Pumping

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ABSTRACT

The utilization of solar photovoltaic (PV) energy in water pumping is conservative particularly in isolated regions where the transmission of power is either impractical or exorbitant. In this research work, various topologies for solar PV array fed water pumping are developed using a brushless DC (BLDC) motor drive. A high efficiency BLDC motor substantially reduces the size of PV array and hence its installation cost. Moreover, its high power factor results in a reduced capacity of the used voltage source inverter (VSI). Besides these, unlike an induction motor, the speed of a BLDC motor is not limited by power frequency. This leads to a reduced size of the motor. A reduced sensor based simple, efficient and cost-effective BLDC motor drive is investigated with fast control of its speed. The voltage sensor at the DC bus of VSI and the motor phase current sensors are eliminated in the proposed drive. In addition, the speed control loop is not required, as the speed of BLDC motor-pump is adjusted by the DC bus voltage of VSI. The VSI is switched at fundamental frequency, which offers a high conversion efficiency by reducing the switching losses in VSI. The system possesses a maximum power point tracking (MPPT) of PV array by introducing a DC-DC converter between the PV array and a VSI, feeding the motor. The various DC-DC converters are placed for MPPT, and analyzed based on their performance, simplicity, design, cost and efficiency. The work is extended towards an elimination of DC-DC converter and a single stage PV array fed BLDC motor drive is also investigated for water pumping. This system is capable of operating the solar PV array at its optimum power using the same VSI, which is used for motor control. In order to make a PV water pumping further economical and compact, the position sensor-less BLDC motor drives are also developed for both two stageand single stage PV based water pumping. The sensorless control is the only reliable way to operate the BLDC motor for applications in submersible water pumping. A promising case of interruption in the water pumping due to the intermittency of PV power generation is resolved by using a single phase utility grid as an external power backup.A grid interacted PV array and its control are demonstrated to get a reliable and fully utilized water pumping with BLDC motor such that the pumping is not affected by an intermittency of PV generation. The power is drawn from the grid in case the PV array is unable to meet the required power demand. Both unidirectional and bidirectional power flow control are implemented for a grid interfaced PV fed BLDC motor driven water pump. The bidirectional power flow control based topology offers an additional merit of feeding power to the utility grid by the installed PV array, in case the water pumping is not required. This practice leads to a full utilization of installed resources.

Moreover, it emerges as a source of earning by sale of electricity to the utility. The maximum power point (MPP) operation of PV array, and power quality (PQ) standards such as power factor and total harmonic distortion (THD) of grid current as per IEEE-519 standard, are met by this system. All the proposed configurations are modeled and simulated using MATLAB/Simulink platform in order to demonstrate their performance during starting, dynamic and steady stateconditions. Simulated results are verified through test results obtained from hardwareimplementation using a developed prototype in the laboratory. The applicability andcommercial potential of proposed systems are justified by their in depth analysis based on efficiency, cost, simplicity and performance.

Keywords: BLDC motor, SPV, Cuk converter, INC-MPPT, soft starting.

I. INTRODUCTION

Renewable energy generations such as solar photovoltaic (SPV) array and wind energies are receiving wide attention now a days due to the global energy crisis in near future. Despite of low efficiency of SPV generating system and its dependence on variable atmospheric conditions, its several advantages such as everlasting energy source, pollution free generation and no running cost are attracting the researchers towards SPV array installations. Worldwide annual and cumulative SPV array productions have reached 36,241 MW and 128,550 MW respectively in 2012 [1]. Likewise, worldwide cumulative SPV installation has reached 102,156 MW in 2012 [2]. Application of SPV generation in water pumping is appreciable and economical especially in remote areas where the transmission of conventionally generated electricity is either not possible or very costly.

The DC motor and various AC motors have been used to drive the water pumps for household and irrigation purposes in the agriculture. The DC motor can be directly connected to the SPV generator and one conversion stage (VSI-Voltage Source Inverter) can be avoided. The directly coupled SPV-motor pump system necessitates a complete knowledge of the whole system so that the system parameters can be chosen in such a way that the operating curve of the load should match with the PV array MPP (Maximum Power Point) locus [3-4]. Performance improvement of SPV powered permanent magnet DC motor for water pumping application using various maximum power point tracking (MPPT) techniques [5-12] has been studied in [7-8] using an intermediate DC-DC buck converter, in [9] using buck-boost converter and in [10] using Cuk converter. However, a DC motor is not preferred because of the frequent maintenance requirement caused by the commutators and brushes. The water pumping system based on an induction motor is more reliable and maintenance free as compared to the DC motor driven pumping system. Requirement of complex control is the only limitation of induction motors [13] otherwise it is suitable for use even in hazardous and contaminated areas. Current controlled VSI fed cage induction motor [14] and field oriented controlled 3- phase induction motor [15] have been used for solar powered pumping system with a DC-DC boost converter. A high efficiency of permanent magnet synchronous motor (PMSM) as compared to the induction motor and usefulness in submersible installation has turned the attention towards it for high power SPV based water pumping [16]. A DC motor, PMSM and the induction motor are compared and concluded that the PMSM is better choice for global efficiency optimization of SPV fed water pumping system [17].

Because of low inertia and friction, permanent magnet brushless DC (BLDC) motor can run at much higher speed.High efficiency, long life, high reliability, low radio frequency interference and noise and no maintenance are the other important features of this motor. These features attract to use this motor in SPV array fed pumping application. Dynamic performance of BLDC motor for this application has been analyzed in [18] without introducing the MPPT technique, hence requires the complete knowledge of the PV-motorpump system to match the optimum operating point of the SPV characteristics. Nevertheless the MPP can be changed with the variation of weather condition. Fuzzy logic incremental conductance (FL-IC) MPPT is introduced, utilizing the Z-source inverter (ZSI) fed BLDC motor driven SPV based pumping system in [19]. Implementation of FL is difficult and a skilled user is an essential requirement. A boost converter for the same application is used in [20] which cannot ensure the soft starting of the motor. Other DC-DC converters e.g. buck-boost, Cuk, zeta, SEPIC (Single Ended Primary Inductor Converter) converters are also used with BLDC motor but not in SPV array based water pumping applications.

A DC-DC Cuk converter is employed in different SPV array based applications [10-12] for MPPT. Nonetheless, the SPV array based BLDC motor driven water pumping is still unexplored with the use of a Cuk converter. In this paper, a Cuk converter is used as an intermediate DC-DC converter in SPV array based BLDC motor driven water pump. The Cuk converter is operated in both buck and boost modes hence does not have any kind of restrictions on MPPT unlike a simple buck or boost converter where the MPP can be tracked if it lies within a bounded region. This feature is also very important to achieve soft starting of the motor. It has low switching losses and high efficiency. In addition, another important advantage of Cuk converter is a continuous current at its input and output. It is possible to simultaneously eliminate the ripples in input and output currents, hence external filtering is not required. An inductor at the input of the boost converter works as input ripple filter also but using this boost converter cannot provide soft starting of the motor because this always increases the input voltage level at its output. On the other hand, in SPV array based applications, buck and buck-boost converters are always needed a ripple filter to limit the current and voltage ripple at its input. In conclusion, a Cuk type buck-boost converter is a simple DCDC converter which suits for SPV array based applications.

An incremental conductance MPPT algorithm is used to control the SPV array to operate at its optimum operating point. An electronically commutated BLDC motor with inbuilt encoder is used to drive centrifugal pump as a load. Transient, dynamic and steady state performances of the BLDC motor fed by SPV-Cuk converter under varying insolation levels are analyzed based on simulated results using MATLAB/ Simulink.

II. SYSTEM CONFIGURATION

Fig.1 shows the configuration of the proposed SPV-BLDC motor drive based water pumping system. A DC-DC Cuk converter is used between a PV array and a voltage source inverter (VSI). The VSI feeds the BLDC motor which drives a pump load. Switching pulses for VSI are generated through electronic commutation using the Hall Effect position signals. An inbuilt encoder provides the Hall signals according to the rotor position. Switching pulse for the Cuk converter is generated by MPPT algorithm.

The design and working principle of each stage of the configuration are elaborated in the following sections.

III. DESIGN OF PROPOSED SYSTEM

The proposed system consists of a solar PV array, a Cuk converter, a VSI, a BLDC motor and a water pump. These components such as the solar PV array, the Cuk converter and a centrifugal pump are designed as per the requirement of SPV fed pump system. A centrifugal pump of 6 kW and a BLDC motor of 6.14 kW power rating are selected. According to the power rating of the centrifugal pump and a BLDC motor, each stage of the proposed system is designed as follows.

A. Design of Solar PV Array

The maximum power capacity of 6.87 kW of a SPV array is selected and it is designed for a 6 kW pump because SPV generating system should generate somewhat slightly more power than required by motor-pump so that extra generated power can be used to meet converters and motor losses.

First of all, a module consisting of 36 cells connected in series is designed which has an open circuit voltage = 13.32 V and short circuit current = 4.0 A. The maximum power, P_{mpp} generally occurs at 80% of open circuit voltage and short circuit current. Hence, the voltage at MPP is as, V_m =0.8*13.32 = 10.66 V and the current at MPP is as, I_m = 0.8*4 =3.2 A for a module.

The maximum power of the SPV array, P_{mpp} is given

$$P_{mpp} = V_{mpp} * I_{mpp} = 6.87 \text{ kW} \quad (1)$$

As per the requirement of the proposed system, the voltage at M_{PP} is as, V_{mpp} = 286 V which is considered and it gives a current at M_{PP}, $I_{mpp}=P_{mpp}/V_{mpp}=$ 6.87*1000/286 = 24.02 A.

Numbers of modules connected in series are as, N_s = 286/10.66 = 26.83 ≈27.

Numbers of modules connected in parallel are as, N_p = 24.02/3.2 = 7.5 ≈ 8.

Based on these selected parameters, the PV array of appropriate size is used in the proposed system.

B. Design of Cuk Converter

An output voltage polarity of the Cuk converter is opposite to that of the input voltage. The rated DC voltage of the BLDC motor is as, V_{dc} = 310 V and the PV voltage at M_{PP} is as, V_{pv} = V_{mpp} = 286 V. The relationship between the duty ratio, D of the insulated gate bipolar transistor (IGBT) switch, output voltage, V_{dc} and input voltage, V_{pv} of the Cuk converter is given as [21],

$$\frac{V_{dc}}{V_{pv}} = -\frac{D}{1-D} \Rightarrow D = \frac{V_{dc}}{V_{dc}+V_{pv}} = \frac{310}{310+286} = 0.52 \quad (2)$$

A high value of switching frequency, fsw = 20 kHz is selected to keep ripples in the current flowing through the inductors as low as possible even with the lower values of inductors. The current flowing through L_1, equal to the SPV current at M_{PP} is as, I_{pv} = I_{L1} = 24.02 A. Allowing 6% current ripples, an input inductor, L_1 is estimated as [21],

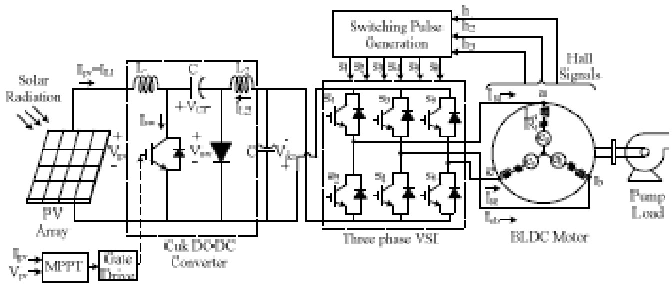

Fig.1 Configuration of the SPV-Cuk converter fed BLDC motor driven water pumping system

$$L_1 = \frac{V_{pv} D}{f_{sw} \Delta I_{L1}} = \frac{286 \times 0.52}{20000 \times 24.02 \times 0.06} = 5.1 \text{ mH} \quad (3)$$

C. Design of DC Link Capacitor of VSI

A new approach to design a low valued DC link capacitor is used. To design a DC link capacitor, C, the lowest and highest frequencies of the VSI output voltage to the motor are taken into account. The highest value of VSI output voltage frequency, ω_h (in rad/sec.) is calculated corresponding to the rated speed of the BLDC motor as,

$$\omega_h = 2\pi f = 2\pi \times \frac{N_{rated} \times P}{120} = 2\pi \times \frac{2300 \times 6}{120} = 722.57 \text{ rad/sec.}$$

where f is the frequency of VSI output voltage in Hz; N_{rated} is rated speed of the BLDC motor; P is the numbers of poles in the BLDC motor. Since 6th harmonic component of the motor voltage appears on the DC link, allowing 8% voltage ripple across C, it is estimated corresponding to ω_h as

$$C = \frac{I_{dc}}{6 \times \omega_h \times \Delta V_{dc}} = \frac{22.16}{6 \times 722.57 \times 310 \times 0.08} = 206.1\ \mu\text{F}$$

where I_{dc} is current flowing through the DC link = P_{pv}/V_{dc} = 6870/310 = 22.16 A; ΔV_{dc} is an amount of ripple voltage allowed across C.

Similarly, the lowest value of VSI output voltage frequency, ω_l (in rad/sec.) is calculated corresponding to the minimum speed of a motor required to pump the water (N = 1100 rpm)as,

$$\omega_l = 2\pi f = 2\pi \times \frac{N \times P}{120} = 2\pi \times \frac{1100 \times 6}{120} = 345.57 \text{ rad/sec.}$$

Allowing 8% voltage ripple across C, it is calculated corresponding to ω_l as,

$$C = \frac{I_{dc}}{6 \times \omega_l \times \Delta V_{dc}} = \frac{22.16}{6 \times 345.57 \times 310 \times 0.08} = 431\ \mu\text{F}$$

D. Design of Centrifugal Pump

A centrifugal pump of 6 kW power rating is selected forproposed system. An output power, P of a centrifugal water pump is given as [22],

IV. REFERENCES

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