Solar PV Array Fed Water Pumping System Using SEpic Converter Based BLDC Motor Drive

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Abstract—This paper deals with the application of a single ended primary inductor converter (SEPIC) in solar photovoltaic (SPV) array fed water pumping system. A permanent magnet brushless DC (BLDC) motor is employed to drive a centrifugal pump coupled to its shaft. Soft starting of the BLDC motor is achieved by controlling the SEpic through the incremental conductance maximum power point tracking (INC-MPPT) algorithm. The SEpic possesses the merits of non-inverting polarity output voltage, simple gate-drive circuit and low input current pulsation. Besides these, the SEpic, operating as a DC-DC buck-boost converter can increase or decrease the input voltage level at its output. This property provides the flexibility of optimizing the operating point of the SPV array at any voltage level. The dynamic and steady state performances of the BLDC motor coupled to a centrifugal water pump fed by the SPV array-SEpic is evaluated and its suitability is verified through simulated results using MATLAB/Simulink environment.

Keywords—SEpic, SPV array, BLDC motor, Centrifugal pump, Soft starting, Buck-Boost converter.

I. INTRODUCTION

Due to its output gain flexibility, single ended primary inductor converter (SEpic) acts as a buck boost DC-DC converter providing non-inverting polarity output voltage, where it changes its output voltage according to its duty cycle [1]. Unlike the DC-DC buck and boost converter, the SEpic has an unbounded maximum power point tracking (MPPT) region [2]. The SEpic has the desirable feature of the switch control terminal being connected to ground; this simplifies the gate-drive circuitry [3]. Because of its non-inverting polarity output voltage, unlike the buck-boost and a Cuk DC-DC converter, the use of either splitting power supply or optocoupler and associated circuit for negative voltage feedback sensing, which added complexity and slowed down the response of the system, is eliminated [4]. The inductor at the input of the SEpic reduces the input current pulsation resulting in a high precision of MPPT [5].

Aforesaid merits of the SEpic, makes its integral characteristics suitable for the solar photovoltaic (SPV) array fed water pumping system. The SEpic has been used for MPPT in various SPV based applications such as PV chargers and standalone PV systems [5-8]. In view of cost and efficiency, the SEpic is not used for high power applications. In this paper, a BLDC motor driven water pump fed by the SPV array-SEpic is proposed. The SEpic is always operated in continuous conduction mode to limit the voltage and current stresses on its power device and components. Switching pulse for the IGBT (Insulated Gate Bipolar Transistor) switch of the SEpic is generated by an incremental conductance (INC) MPPT algorithm [9], used to operate the SPV array at its optimum operating point. Similarly, the switching sequence for the VSI (Voltage Source Inverter) is generated by an electronic commutation of the BLDC motor [10]. A permanent magnet BLDC motor is selected because of its high efficiency, high reliability, low radio frequency interference, no maintenance and low inertia and friction. The starting current of the BLDC motor is controlled within the permissible limit so that the motor has soft starting. The soft starting is achieved by selecting the value of increment size properly in the INC-MPPT algorithm. The SPV array is so designed and the rating of the BLDC motor is selected such that the water can be pumped under all the possible variations in solar insolation level.

The starting, dynamic and steady state behavior of the proposed system under the change in atmospheric conditions are demonstrated through simulated results using Sim-power-system toolboxes of the MATLAB/Simulink environment.

II. CONFIGURATION OF THE PROPOSED SYSTEM

The proposed system under study is shown in Fig. 1. The system consists of the SPV array followed by the SEpic which feeds the VSI, supplying the BLDC motor coupled to a centrifugal type of water pump. MPPT algorithm generates switching pulse for the switch of SEpic whereas the electronic commutation generates the switching sequence for the switches of the VSI. The Hall Effect signals provided by the encoder, mounted on the BLDC motor is logically converted into the 6 pulses for the 6 switches of the VSI. The design and control of each stage of the configuration shown in Fig. 1 are elaborated in the following sections.

III. DESIGN OF THE PROPOSED SYSTEM

The proposed system comprises a solar PV array, a SEpic, a VSI, a BLDC motor and a centrifugal water pump. The solar PV array, the SEpic and the centrifugal pump are designed as per the requirement of the proposed system. Power ratings of the BLDC motor and the centrifugal pump are selected as 2.2
kW and 2 kW respectively. On the basis of these selected ratings, each stage of the configuration shown in Fig. 1 is designed as described in the following section.

A. Design of Solar PV Array

The SPV array is designed for \( P_{app} = 2.73 \) kWeak peak power capacity. First of all, a PV module of 36 cells connected in series is designed to produce an open circuit voltage of 13.32 V and short circuit current of 4 A. It is reported that the peak power generally occurs between 71% and 78% of open circuit voltage and between 78% and 92% of short circuit current [9].

Voltage of the SPV array at MPP is considered as, \( V_{dc} = 130 \) V and the current of a module at MPP, \( I_{dc} = 20.98 \) A. Same current flows through the output inductor, \( i_{L1} \); an output inductor, \( L_2 \); an intermediate capacitor, \( C_1 \) [8] and a DC link capacitor, \( C_2 \) are summarized in Table I, where \( f_s \) is the switching frequency of the switch of SEPIC; \( \Delta i_{L1} \) is an average current flowing through the input inductor; \( \Delta i_{L2} \) is an amount of ripple allowed in the input inductor; \( \Delta V_{cl} \) is the ripple allowed in the voltage across the intermediate capacitor; \( \Delta V_{dc} \) is the ripple allowed in the voltage across the DC link of VSI; \( \omega_h \) and \( \omega_l \) are the highest and lowest values of VSI output voltage frequencies, respectively in rad/sec.; \( f \) is the frequency of VSI output voltage in Hz; \( C_h \) and \( C_l \) are the values of capacitors estimated corresponding to \( \omega_h \) and \( \omega_l \) respectively; \( P \) is the number of poles in the BLDC motor; \( N_{rated} \) is the rated speed of the motor; \( N \) is the minimum speed required to pump the water.

**TABLE I. DESIGN OF SEPIC CONVERTER**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Parameter</th>
<th>Expression</th>
<th>Design data</th>
<th>Value</th>
<th>Selected value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( L_1 )</td>
<td>( \frac{D}{v_{pp}} )</td>
<td>( \frac{L_{dc1}}{V_{mp}} )</td>
<td>0.53</td>
<td>1.27 mH</td>
</tr>
<tr>
<td>2</td>
<td>( L_2 )</td>
<td>( (1-D) \frac{V_{pp}}{I_{dc}} )</td>
<td>( \frac{L_{dc2}}{V_{mp}} )</td>
<td>0.53</td>
<td>1.46 mH</td>
</tr>
<tr>
<td>3</td>
<td>( C_1 )</td>
<td>( \frac{D I_{dc}}{V_{dc} \Delta V_{cl}} )</td>
<td>( \frac{C_{dc}}{V_{dc}} )</td>
<td>0.53</td>
<td>42.77 ( \mu )F</td>
</tr>
<tr>
<td>4</td>
<td>( C_2 )</td>
<td>( \frac{\Delta V_{cl}}{6 * \omega * \Delta V_{cl}} )</td>
<td>( \frac{C_{dc}}{V_{dc}} )</td>
<td>0.53</td>
<td>780 ( \mu )F</td>
</tr>
</tbody>
</table>

\* 6th harmonic component of the motor voltage appears on the DC link of VSI

Hence, the voltage of a module at MPP, \( V_m = 0.78 \times 13.32 = 10.39 \) V and the current of a module at MPP, \( I_m = 0.8 \times 4 = 3.2 \) A.

Voltage of the SPV array at MPP is considered as, \( V_{app} = 114.4 \) V in view of the DC link voltage of the VSI, \( V_{dc} \) which is the output voltage of the SEPIC and the DC voltage rating of the BLDC motor. The current of the SPV array at MPP, \( I_{app} = P_{app} / \frac{V_{app}}{2730/114.4} = 23.86 \) A.

Numbers of modules required to connect in series are as,

\[ N_s = \frac{V_{app}}{V_m} = 114.4 / 10.39 = 11 \] (1)

Numbers of modules required to connect in parallel are as,

\[ N_p = \frac{I_{app}}{I_m} = 23.86 / 3.2 = 7.46 \approx 8 \] (2)

Based on these estimated values of parameters, the solar PV array of required size is designed.

B. Design of SEPIC

When the optimum operating point is reached, the voltage of the solar PV array, \( V_{pp} = V_{app} = 114.4 \) V and the current of the solar PV array, \( I_{pp} = I_{app} = 23.86 \) A. Same current flows through the input inductor of the SEPIC, therefore, the current flowing through the input inductor is as, \( i_{L1} = i_{pp} = 23.86 \) A. Duty cycle, \( D \) of the SEPIC is estimated as [8],

\[ D = \frac{V_{dc}}{V_{dc} + V_{pp}} = \frac{130}{130 + 114.4} = 0.53 \] (3)

where \( V_{dc} \) is the average value of DC link voltage of VSI.

An average current flowing through the DC link, \( I_{dc} \) is estimated as,

\[ I_{dc} = \frac{P_{app}}{V_{dc}} = 2730 / 130 = 20.98 \] A (4)

C. Design of Centrifugal Pump

The characteristic of a centrifugal pump is expressed in terms of speed and torque as [11],

\[ k_w = \frac{T}{\omega^2} \] (5)
where $T_L$ is the rated load torque and $\omega_m$ is the rated mechanical speed of the rotor in rad/sec.
Then the constant $k_\omega$ in Nm/(rad/sec)$^2$ is estimated as,
$$k_\omega = \frac{T_L}{\omega_m^2} = \frac{7}{(2\pi * 3000 / 60)} = 7.1 * 10^{-5} \text{ Nm/(rad/sec)}^2 \quad (6)$$

This designed value of centrifugal water pump is selected for the proposed water pumping system.

IV. CONTROL OF THE PROPOSED SYSTEM

The control at the various stages of the proposed system is classified into two parts as follows.

A. Maximum Power Point Tracking

An INC-MPPT algorithm with direct duty ratio control is used to operate the solar PV array at its optimum operating point. The INC-MPPT technique is preferred because of its precise tracking performance and less confusion under dynamic condition [9]. The increment size determines how fast the MPP is tracked. Fast tracking can be achieved with bigger increments but the system might not operate exactly at the MPP and oscillate about it instead, so there is a tradeoff. Moreover, the bigger increment cannot ensure the soft starting of the motor and hence a smaller value of increment size is selected for satisfactory operation of the system.

B. Electronic Commutation of BLDC Motor

The electronic commutation of the BLDC motor provides the switching sequence for 6 switches of the VSI. This is a process of decoding the Hall Effect signals generated by the inbuilt encoder according to the rotor position and then converting the decoded signals into the switching pulses [10]. Parameters and ratings of the BLDC motor are indicated in Appendix.

V. RESULTS AND DISCUSSION

The configuration of the proposed solar PV array-SEPIC fed BLDC motor driven water pumping system shown in Fig. 1 is simulated using MATLAB/Simulink. The transient, dynamic and steady state behaviors of the proposed system are studied through simulated results. As shown in Figs. 2-3, the proposed system exhibits a very good performance under the various possible working conditions as described.

A. Performance of INC-MPPT algorithm

Figs. 2(a) and 3(a) verify very good tracking performance of the INC-MPPT at the standard solar insolation level of 1000 W/m$^2$ and even under the rapid change in solar insolation level respectively. A small value of the increment size, $\Delta D$ is selected as, $\Delta D = 0.001$ and used in the INC-MPPT algorithm in view of the soft starting of BLDC motor.

B. Performance of SEPIC

Performances of the SEPIC are shown in Figs. 2(b) and 3(b). These results show that the converter always operates in continuous conduction mode. The current flowing through the input inductor, $i_{L1}$ is same as the current of solar PV array which is made almost ripple free by the input inductor and hence, the requirement of additional ripple filter is eliminated. The voltage across the intermediate capacitor, $v_{C1}$ depends on the value of duty ratio, $D$ and is continuous. The current flowing through the output inductor, $i_{L2}$ is equal to the DC link current, $i_{dc}$, neglecting a small amount of current flowing through the DC link capacitor. The output voltage of the SEPIC, $v_{dc}$ is the DC link voltage of the VSI. All of these converter variables vary following the variation in the solar insolation level as shown in Fig. 3(b).

C. Performance of BLDC Motor-Pump at 1000 W/m$^2$

Fig. 2(c) shows the starting and steady state behavior of the BLDC motor-pump fed by the solar PV array-SEPIC at the standard solar insolation level of 1000 W/m$^2$. For the sake of simplicity, the back EMF and the stator current of phase ‘a’
Fig. 2. Performance of SPV array-SEPIC fed BLDC motor-pump system at 1000 W/m², (a) Solar PV array variables, (b) SEPIC variables, (c) BLDC motor variables.

In proportion to the DC link voltage, the back EMF, $e_a$, increases and reaches the rated value at steady state condition. Observing the stator current, $i_{sa}$, it is clear that the motor has a soft starting because the rate of rise of the stator current at the starting is controlled by controlling the SEPIC properly. The speed of the motor, $N$, also increases in proportion to the DC link voltage of VSI and finally reaches rated value. The load torque, $T_L$, increases in proportion to the square of the speed and hence the motor develops the same amount of electromagnetic torque, $T_e$, to stabilize the operation of motor-load system. Small pulsation in the electromagnetic torque, $T_e$, is observed because of the electronic commutation of the BLDC motor. At 1000 W/m² solar insolation level, the motor runs at its full load and develops the rated torque. Satisfactory performance of the
proposed system at 1000 W/m² is verified by the simulated results of Fig. 2(c).

D. Dynamic Performance of BLDC Motor-Pump

Fig. 3(c) shows the dynamic performance of the BLDC motor-pump fed by the solar PV array-SEPIC for water pumping. To demonstrate the dynamic performance, it is considered that the solar insolation levels vary in 3 steps as shown in Table II. This large and rapid variation in the solar insolation level is considered to manifest the suitability of the proposed system under the dynamically changing atmospheric conditions. All the motor variables viz. the back EMF of phase ‘a,’ eα, the stator current of phase ‘a,’ iα, speed, N, the electromagnetic torque, Te and the load torque, TL depend on the solar insolation level, S. Therefore, these variables vary according to the variation in the solar insolation level. The starting stator current is controlled such that the motor has soft starting. The BLDC motor attains the speed more than 1100 rpm, a minimum speed required to pump the water, under each solar insolation level. Simulated results of Fig. 3(c) exhibit the satisfactory performances of the proposed system irrespective of the change in the atmospheric condition.

VI. CONCLUSIONS

The performance of the proposed solar PV array - SEPIC fed water pumping system using BLDC motor drive has been validated. The dynamic and steady state behaviors of the system are the evidence of the suitability of the proposed system for water pumping. The merits of the SEPIC such as non-inverting polarity, easy-to-drive switch and low input current pulsation for a high precision MPPT has contributed to develop a suitable solar PV array fed water pumping system. Maximum power available from the solar PV array has been fully utilized to acquire an efficient operation of the water pumping system. Besides this, properly controlling the SEPIC through MPPT algorithm offers the soft starting of the BLDC motor. Moreover, the VSI is operated in 120° conduction mode, eliminating the high frequency switching losses. The BLDC motor has been proved as a suitable drive for the solar PV array - SEPIC fed water pumping system. The proposed system seems to be very useful for the solar PV array based water pumping applications such as spray irrigation system and drinking water system.

APPENDIX

A. Selected Parameters of SPV Array

Open circuit voltage, Voc = 150 V; Short circuit current, Isc = 26.8 A; Maximum power, Pmpp = 2.73 kW; Voltage at MPP, Vmpp = 114.4 V; Current at MPP, Impp = 23.86 A; Numbers of cells connected in series in a module, Nc = 36; Numbers of modules connected in series, Ns = 11; Numbers of modules connected in parallel, Np = 8.

B. Parameter Selection for Design of SEPIC

Switching frequency, fsw = 20 kHz; Input inductor L1 = 1.3 mH; Output inductor L2 = 1.5 mH; Intermediate capacitor, Ci = 43 μF; Output capacitor, Cs = 780 μF.

C. Parameter Selection for BLDC Motor Pump System

Stator phase/phase resistance, Rs = 0.25 Ω; Stator phase/phase inductance, Ls = 0.8 mH; Torque constant, Ke = 0.32 Nm/Apeak; Voltage constant, Kv = 34 Vpeak-L-L/krpm; Rated current, Irsrated = 21.56 A; Rated torque, Trated = 7 Nm; Rated speed, Nrsrated = 3000 rpm @ 130 V DC; Rated power, Prated = 2.2 kW; No. of poles, P = 6; Moment of inertia, J = 14.1 kg cm²; Constant, kρ = 7.1*10⁻⁵ Nm/(rad/sec)².

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