DESIGN AND CONTROL OF STANDALONE SOLAR PHOTOVOLTAIC POWERED AIR COOLING SYSTEM

Shobha Rani Depuru
Department of Electrical and Electronics Engineering, Institute of Aeronautical Engineering, Hyderabad, India

Muralidhar Mahankali
Department of Electrical and Electronics Engineering, S V University College of Engineering, Tirupati, India

Navya Sree S
Department of Mechanical Engineering, MLR Institute of Technology, Hyderabad

ABSTRACT

Solar photovoltaic (SPV) power systems can be employed as electrical power sources to meet the daily residential energy needs of rural areas that have no access to grid systems. In view of this, a standalone SPV powered air cooling system is proposed in this paper, which constitutes a DC-DC buck-boost converter, two voltage source inverters (VSI) connected to two brushless dc (BLDC) motors which are coupled to a centrifugal water pump and a fan blower. To maximize the power output of the SPV system, Perturb & Observe (P&O) based maximum power point tracking (MPPT) algorithm is used. While the VSI executes the electronic commutation of the BLDC motor, the variable DC link voltage controls the speed of BLDC motor to attain the required speed for the fan blower. The air cooling system is developed and simulated using the MATLAB/Simulink environment considering the dynamic and steady state variation in the solar irradiance.

Index Terms: Solar Photovoltaic, Maximum Power Point Tracking, Buck-Boost Converter, Brushless DC Motor, Voltage Source Inverter, Perturb & Observe, Solar Irradiance.

http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=8&IType=7
1. INTRODUCTION

Renewable energy sources have become a decisive part of world energy consumption during the recent years as the precise energy requirements can be met via these resources. Currently, solar energy is gaining much significance as it is the most viable source of energy profusely available. Ample research has been done in the SPV technology to exploit it for industrial applications. Later, the advancement in technology led to reduction in the price of SPV components and began to be used for several household applications. In the present research, SPV technology is incorporated for a PV based home appliance, an air cooler that can be particularly utilized in the rural realms of the developing countries. The proposed SPV fed air cooler utilizes two brushless dc (BLDC) motors fed by a buck-boost converter and two voltage source inverters (VSI) connected to the two BLDC motors. The two BLDC motors are coupled to two loads of the air cooler: centrifugal water pump and fan blower. [1].

A BLDC motor accomplishes commutation electronically using rotor position feedback to determine when to switch the current. BLDC motors use electric switches to realize current commutation, and thus continuously rotate the motor. The advantages of BLDC motors over brushed DC motors, includes better speed versus torque characteristics, high efficiency and reliability, noiseless operation, longer lifetime, elimination of ionizing sparks from the commutator, and overall reduction of electromagnetic interference (EMI). Because of the above advantages, BLDC motor has been chosen to develop SPV fed air cooler.

P &O is the most commonly used MPPT method due to its ease of implementation. This method may result in top-level efficiency, provided that a proper predictive and adaptive hill climbing strategy is adopted. This method will control the DC-DC converter such that the solar PV system always operates at its maximum power point.

The proposed system efficiently operates under all the variations in the environment. The rest of the paper is organized as follows. Section II illustrates the overall system configuration. Section III briefly summarizes the design of SPV array modeling and Section IV depicts the design parameters of DC-DC buck-boost converter. Section V describes the BLDC motor drive system and various significant parameters for speed control of the motor. Section VI elaborates the various control techniques and Section VII presents simulation work carried through MATLAB/simulink and the final section elucidates the conclusion.

2. SYSTEM CONFIGURATION

The paper aims to show that a standalone SPV powered air cooling system can be accomplished by employing a DC-DC buck-boost converter with a BLDC drive system. The functional block diagram pertaining to the overall system is presented in Fig. 1 which consists of a SPV array, a buck-boost converter, two VSI’s connected to two BLDC motors which are coupled to a centrifugal water pump and a fan blower respectively. The design and the control of the proposed system are elaborated in the following sections:
3. DESIGN OF SPV ARRAY
A solar cell is usually quite small, producing about 1 or 2 W of power, yet forming a basic building block of any SPV system. The PV cells have to be connected together in the form of large units called modules to boost the power output. The modules, in turn can be connected to form larger units called arrays, which can be interconnected to produce more power. The peak power capacity of a SPV array is chosen as 900 W, which is slightly more than the rating of the two motors, to reduce the losses incurred due to converter and the BLDC motors. The parameters of the SPV array are approximated at the standard solar irradiance of 1000 W/m².

4. DESIGN OF BUCK-BOOST CONVERTER
DC-DC converters are employed in SPV systems to regulate and control the varying output of the solar panel [2]. A DC-DC buck-boost converter is used in this paper where the input voltage is the SPV array voltage at MPP, \( V_i = V_{pv} = 113 \) V and the output voltage is the DC link voltage of VSI, \( V_0 = V_{dc} = 182 \) V. The converter design consists of the estimation of the various components such as input inductor, \( L \), intermediate capacitor, \( C_{pv} \) and the dc link capacitor, \( C \).

The duty ratio (D) of buck-boost converter is evaluated using the Eq. (1):

\[
D = \frac{V_d}{V_{dc} + V_{pv}} = 0.616
\]  

On the other hand, neglecting the buck-boost converter losses, an average current flowing through the DC link, \( I_{dc} \) is approximated by using the Eq. (2):
Design and Control of Standalone Solar Photovoltaic Powered Air Cooling System

\[ I_{dc} = \frac{P_{mpp}}{V_{dc}} = 4.94 \ A \quad (2) \]

The design parameters inductor, \( L \) and DC link capacitor, \( C \) of the buck-boost converter are depicted in Appendix A2. [3].

5. DESIGN OF BLDC MOTOR DRIVE SYSTEM

A. Design of BLDC motor

BLDC motors are considered to have various advantages and hence are used to develop a SPV fed air cooler, which can operate satisfactorily for longer time as compared to the brushed motors under the dynamically changing atmospheric conditions [4]–[6]. The practical converters are associated with the various power losses and the performance of the BLDC motors is influenced by the mechanical and electrical losses associated with them. To compensate these losses, the parameters of the BLDC-motors [7] as shown in Appendix A3, are chosen.

B. Design of BLDC motor driven centrifugal water pump and fan blower:

The two BLDC motors are coupled to two loads of the air cooler, the water pump and fan blower. These two loads are driven by giving a load-torque signal depending on the torque-speed characteristic equation of a pump and blower. The ratings of the pump and blower are taken as 0.4 kW and the estimation of proportionality constants, \( K_p \) and \( K_b \) for the selected water pump and blower respectively are given by Eqs. (3) and (4):

\[ K_p = \frac{\tau_p}{\omega_p^2} = \frac{P_p}{\omega_p^3} \quad (3) \]

Where \( \omega_p \) is the mechanical speed of the rotor in rad/sec, \( \tau_p \) is the electromagnetic torque developed and \( P_p \) is the rated power developed by the BLDC motor connected to the water pump under steady state for stable operation.

\[ K_b = \frac{\tau_b}{\omega_b^2} = \frac{P_b}{\omega_b^3} \quad (4) \]

Where, \( \tau_b \) is the load torque offered by the blower which is equal to the electromagnetic torque developed by the BLDC motor under steady state for stable operation, \( \omega_b \) is the mechanical speed of the rotor in rad/sec and \( P_b \) is the rated power developed by the BLDC motor connected to the blower under steady state condition.

6. PROPOSED SYSTEM CONTROL TECHNIQUES

In the proposed air cooling system, the SPV array, the VSI and the speed of the fan blower are modulated through the P&O MPPT, the electronic commutation and the DC-link voltage controller respectively. The three control techniques are elaborated as follows:

A. P&O-MPPT algorithm

Since P&O method has a simple structure and needs less parameters, it is the most prevalent algorithm to track the maximum power [8]–[10]. Via this method, the MPPT of PV modules is yielded by repetitively perturbing, observing and comparing the power generated by the SPV modules. The direction of change for maximizing the power can be found by perturbing...
the operating point of the SPV system. Maximum power control is gained by bringing the derivative of the power equal to zero under power feedback control [11]–[13]. In this algorithm, the operating voltage is sampled and the algorithm changes the operating voltage by changing the duty ratio in the required direction depending on the sign of difference between the samples of power and voltage as shown in Fig. 2.

B. Electronic commutation
Switching sequence for the VSI is contributed by the electronics commutation of BLDC motor. Electronic commutation decodes three Hall effect signals which are produced by an inbuilt encoder of the motor depending on the angular position of the rotor. A particular combination of Hall effect signals are produced for each specific range of rotor position at an interval of 60° [4], [14]. The switching states for electronic commutation of BLDC motor are shown in Table I. It is perceptible that only two switches conduct at a time, resulting in 1200 conduction mode of operation of VSI and hence the reduced conduction losses. The 6 switching pulses received as a result of logical conversion from the Hall effect signals are utilized to operate the 6 IGBT switches of VSI [15], [16].

Figure 2 Flow chart of P&O MPPT.
Table I Switching states for electronic commutation of BLDC Motor

<table>
<thead>
<tr>
<th>0°</th>
<th>Hall Signals</th>
<th>Switching States</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H1</td>
<td>H2</td>
</tr>
<tr>
<td>NA</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0-60</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>60-120</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>120-180</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>180-240</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>240-300</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>300-360</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>NA</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

For the fan blower, a fixed speed is obtained by using hysteresis control method. It compares the reference speed with the original speed of the BLDC motor and generates a torque reference, which when divided by the constant $K_B$ obtained from Eq. (4) gives the current reference magnitude. This current reference magnitude is multiplied with the Hall signals generated current pattern to get current reference. Three such current references are generated which are then compared with the actual current flowing in the stator and the error signal is then made to pass via the proportional integral (PI) controller which then generates two pulses each. Hence, the 6 pulses produced are muxed and fed to the gates of the VSI switches resulting in the required speed of the BLDC motor.

For the pump-load, the speed of the BLDC motor is modulated via dc link voltage and no external controlling circuit is utilized to control the speed. In this way, it is ensured that the dc link voltage remains within the limits.

C. DC-Link voltage controller

If only the fan blower is to be operated, then the DC-link voltage increases gradually, in the absence of controller. The general torque and power expressions are given in Eqs. (5) and (6) and the power balance equation is given in Eq. (7): and to maintain the balance,

$$\text{Torque (T)} = K \omega^2 \quad (5)$$

$$\text{Power (P)} = T \times \omega \quad (6)$$

Generated power = Power Consumed + losses \quad (7)

However the exact estimation of the losses is not easy. The DC-link voltage is regulated through the DC-link voltage controller; nevertheless, if the voltage reference to the DC-link voltage controller is other than $V_{mpp}$, then the PV operation falls below MPP. Hence, less power is extracted, but this is not a problem as the mechanical load required to be driven now is also reduced.

7. SIMULATION RESULTS

The dynamic and steady state performances of the proposed air cooling system are simulated through the MAT LAB / Simulink environment as shown in Figs. 3 - 15. These results successfully validate the satisfactory performance of the proposed system even under varying weather conditions.
A. Dynamic performance of proposed system

The various performance indices at various stages of the air cooler such as the SPV array, buck-boost converter, BLDC motor water pump and fan blower are depicted on an individual basis subjected to the rapid variation in solar irradiance, illustrated in Figs. 3 - 7, and elaborated in the following sub- sections. To demonstrate the dynamic behaviour, the solar irradiance is varied dynamically from 1000 W/m$^2$ to 400 W/m$^2$ as depicted in Fig. 3.

![Figure 3 Variation of irradiance with time.](image)

1) Performance of SPV array: Fig. 4 shows SPV array indices $P_{\text{power}}$ ($p_{\text{pv}}$) $P_{\text{voltage}}$ ($v_{\text{pv}}$) and $P_{\text{current}}$ ($i_{\text{pv}}$), subjected to the rapid variation in solar irradiance. Proper selection of the perturbation size avoids the oscillation around the peak power point. The figure shows that the peak power point is tracked instantaneously even with the variation of the solar irradiance. The presented results manifest that the maximum power available from the SPV array is extracted regardless of the variation in the irradiance level.

2) Performance of buck-boost converter: Fig. 5 shows the dynamic behaviour of buck-boost converter where the DC link voltage ($V_{\text{dc}}$) is presented. The $V_{\text{dc}}$ equal to 182 V is obtained at the maximum irradiance and voltage equal to 124 V at the minimum irradiance. It is shown from the figure that the DC link voltage vary relative to the solar irradiance. It is also observed from the waveforms that the converter always operates in CCM irrespective of the variation in solar irradiance.

3) Performance of BLDC motor-pump and motor-fan: Figs. 6 and 7 exhibits the dynamic behaviour of the BLDC motor-pump and motor-fan respectively, under the dynamically varying conditions of irradiance. All the motor pump and fan indices such as the stator current, electromagnetic torque, speed and power follow the variation in solar irradiance and reach their steady state values as MPP is tracked. Further, a minimum speed of 750rpm is always maintained regardless of the variation in the solar irradiance. The electromagnetic torque produced by the BLDC motor is always equal to the torque required to drive the pump and blow the fan irrespective of the variations in the level of solar irradiance, which clearly indicates the stable operation of the proposed system under dynamically varying atmospheric conditions.
B. Starting and steady state performances of the proposed system at solar irradiance of 1000 W/m² and 500 W/m²

The various performance indices of SPV array, buck-boost converter, BLDC motor-pump and motor-fan under starting and steady state condition of the solar irradiance of 1000 W/m² and 500 W/m² are illustrated in Figs. 8 - 15 and elaborated in the following sub-sections.

1) Performance of SPV array: Figs. 8 and 10 shows the SPV array indices \( v_{pv} \), \( i_{pv} \) and \( p_{pv} \) for the solar irradiance of 1000 W/m² and 500 W/m² respectively. All the three PV array indices reach their steady state values at standard value of solar irradiance of 1000 W/m² and above the minimum values at minimum solar irradiance level of 500 W/m². The three indices obtained correlate to the SPV array working at MPP as the PV output power reaches 900 W at 1000 W/m² and 450 W at 500 W/m². The oscillation around the MPP can be averted by the suitable choice of the perturbation range.

2) Performance of buck-boost converter: Figs. 9 and 11 present the behaviour of buck-boost converter at solar irradiance levels of 1000 W/m² and 500 W/m² respectively. The DC link voltage \( V_{dc} \) at the two irradiance levels are presented and it is observed from the waveforms that the converter operates in CCM at both the irradiance levels. It is also observed from the Figs. 9 and 11 that at the steady state irradiance of 1000 W/m², the rated DC voltage of 182V is obtained at the output terminals of the converter and at the minimum irradiance of 500 W/m², a DC voltage equal to 130V sufficient for the BLDC motor to pump the water as well as to drive the fan blower is attained.
**Figure 6** BLDC-motor-fan parameters with variable irradiance (a) current (b) torque (c) speed (d) power.

**Figure 7** BLDC-motor-pump parameters with variable irradiance (a) current (b) torque (c) speed (d) power.
Design and Control of Standalone Solar Photovoltaic Powered Air Cooling System

Figure 8 Output parameters of the PV at constant irradiance of 1000 W/m² (a) $P_{V\text{power}}$ (b) $P_{V\text{oltage}}$ (c) $P_{V\text{current}}$ ($i_{pv}$)

Figure 9 DC-link voltage at constant irradiance of 1000 W/m²

Figure 10 Output parameters of the PV at constant irradiance of 500 W/m² (a) $P_{V\text{power}}$ (b) $P_{V\text{oltage}}$ (c) $P_{V\text{current}}$ ($i_{pv}$)
3) Performance of BLDC motor-pump and motor-fan: The starting and steady state behaviors of the BLDC motor-pump and motor-fan at 1000 W/m$^2$ and 500 W/m$^2$ are shown from Figs. 13 to 15. All the motor indices such as the the stator current, the electromagnetic torque, the speed and the power offered by pump and fan reach their rated values under steady state condition. Further, it is also inferred that the motor attains a speed required to pump the water and run the fan load even at the minimum irradiance of 500 W/m$^2$. From the simulated results, it is seen that there is always torque balance between the BLDC motor and the loads irrespective of the solar irradiance as the electromagnetic torque developed by BLDC motor is same as torque required by the loads. This torque balance between the BLDC motor and the loads irrespective of the solar irradiance variation verifies the stable operation of the proposed system. However, a minute and admissible pulsation in the electromagnetic torque is seen due to the electronic commutation in the DC link current of VSI. At the starting, the rate of rise of stator current of the BLDC motor is decreased as an evidence of appropriate choice of the perturbation size. Moreover, the soft starting and stable solar irradiance shows the satisfactory working of the proposed system.

Figure 11 DC-link voltage at constant irradiance of 500 W/m$^2$

Figure 12 BLDC motor-fan parameters at constant irradiance of 1000 W/m$^2$ (a) current (b) torque (c) speed (d) power.
Figure 13 BLDC motor-pump parameters at constant irradiance of 1000 W/m² (a) current (b) torque (c) speed (d) power.

Figure 14 BLDC motor-fan parameters at constant irradiance of 500 W/m² (a) current (b) torque (c) speed (d) power.

Figure 15 BLDC motor-pump parameters at constant irradiance of 500 W/m² (a) current (b) torque (c) speed (d) power.
C. Efficiency evaluation of proposed system

Table II shows the efficiency evaluation of the proposed system and its graphical representation is shown in Fig. 16 which is subjected to the variation in irradiance, where $S$ is the irradiance in W/m$^2$, $P_{pv}$ is the PV output power in Watt, $P_m$ is the output power of the proposed BLDC drive in Watt and $\eta$ is efficiency of the overall system. This efficiency assessment excludes SPV array efficiency and includes the efficiency of MPPT algorithm, buck-boost converter, VSI and BLDC motor-pump & motor-fan. It is observed from the efficiency values attained, that an efficiency of 83.7% is obtained at the minimum solar irradiance of 400 W/m$^2$ and as the irradiance increases beyond 600 W/m$^2$, the efficiency of the system improves over 85%, hence showing a very good efficiency even at 40% of the standard solar irradiance.

<table>
<thead>
<tr>
<th>$S$ (W/m$^2$)</th>
<th>$P_{pv}$ (Watt)</th>
<th>$P_m$ (Watt)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>370</td>
<td>310</td>
<td>83.7</td>
</tr>
<tr>
<td>500</td>
<td>450</td>
<td>380</td>
<td>84.4</td>
</tr>
<tr>
<td>600</td>
<td>580</td>
<td>495</td>
<td>85.3</td>
</tr>
<tr>
<td>800</td>
<td>740</td>
<td>650</td>
<td>87.8</td>
</tr>
<tr>
<td>1000</td>
<td>900</td>
<td>810</td>
<td>90</td>
</tr>
</tbody>
</table>

1 Irradiance, 2 PV output power 3 BLDC drive output power, 4 Efficiency of proposed system

Figure 16 Efficiency evaluation of proposed system.

CONCLUSION

The dynamic and steady state behaviors of the proposed BLDC driven SPV powered system have been validated for air cooling. A DC-DC buck-boost converter provides the flexibility of increasing and decreasing the voltage level and hence does not possess a limited region of MPPT. The integration of buck-boost converter and BLDC motor into the SPV array for air cooling has been emerged as a feasible solution in context of simplicity, economy, compactness, efficiency, reliability and availability. Using the simulated results, a buck-boost converter with the BLDC motor is proved as an efficient combination for SPV based air cooling. Compatibility of the proposed system regardless of the weather condition has been demonstrated using the MATLAB/simulink based simulation results. Besides these, successful operation even at 40% of solar irradiance has revealed that the proposed system is undoubtedly acceptable for air cooling and is the efficient air cooling system.
APPENDICES
A1 Parameters of Solar PV Array: \(V_{oc} = 44.5V; \; I_{sc} = 8.83A; \; P_{mpp} = 900W; \; V_{mp} = 113V; \; I_{mpp} = 8.83A; \; N_{SS} = 72; \; N_s = 3; \; N_p = 1.\)
A2 Parameters of Buck-boost Converter: \(L_1 = 1.5 \; mH; \; C_1 = 3000 \; \mu F.\)
A3 Parameters for BLDC Motor: Stator phase/phase resistance, \(R_s = 0.2 \; \Omega; \) stator phase/phase inductance, \(L_s = 8.5 \; mH; \) torque constant, \(K_t = 1.4 \; Nm/A; \) voltage constant, \(K_e = 146.6077 \; V/Krpm; \) rated speed, \(N_{rated} = 1000 \; rpm; \) pole pairs, \(P = 4.\)

REFERENCES


