Abstract—In this paper, modified Sheppard–Taylor DC-DC Converter is utilized for proposed SPV (Solar Photovoltaic) powered water pumping system employing SRM (Switched Reluctance Motor) drive. A unique method of variable DC link operation of SRM drive with a fundamental switching of a mid-point converter is used with the reduction of current sensors at SRM side. Electronic commutation of mid-point converter brings a reduction in IGBT’s (Insulated Gate bipolar transistors) power losses and makes proposed system cost effective and efficient. The DC-DC modified Sheppard–Taylor converter operated in continuous conduction mode (CCM) is used in-between SPV array and SRM drive to provide large operational region for MPPT and also for soft starting of SRM. For enhancing the efficiency of proposed pumping system, an incremental conductance (InC) technique of MPPT (Maximum Power Point Tracking) is used to feed a SRM drive. The dynamic and steady state responses of the SRM drive to support the efficient water pumping is found to be satisfactory that have been analyzed using simulated performance of proposed water pumping system.

Keywords—Continuous conduction mode, MPPT, Sheppard–Taylor converter, SPV Array, soft starting, SRM

I. INTRODUCTION

The pure and hygienic water supply are essential for satisfying human needs, energetic life of human beings, ensuring proper irrigation systems, energy and the restoration of ecosystems, as well as for sustainable development. The conventional energy sources are degrading rapidly with a corresponding rise in cost, considerable attention is being paid to other alternative sources. Solar photovoltaic (SPV) energy which is free and abundant in most parts of the world has proven to be an economical source of energy in many industrial applications.

Solar energy fed water pumping system is one of the most popular and appreciated application of solar energy in standalone system.

The efficiency of solar cell is generally very low so maximum power control of PV panel employing MPPT (Maximum Power Point Tracking) algorithm is necessary to make SPV array as an efficient and stable electrical energy source at all insolation levels and different environmental conditions. The discussions on different MPPT techniques that have been excessively utilize in solar based standalone systems are given in the literature [1] [2] [3]. Generally an induction motor or DC motors are used for water pumping applications. But these motors have suffered from many problems like the need of complex electronic inverter in case of an induction motor and maintaince problem of DC motors due to the presence of brushes and commutator [4]. In order to avoid these problems, brushless dc motors are used in pumping system, but these are also suffered from some serious problems like high converter cost, complex control, moderate over load capacity and irreversible demagnetizing characteristics.

The proposed SPV fed water pumping system consisting a SRM drive with modified Sheppard–Taylor DC-DC converter for maximizing solar energy utilization and ensuring maximum kWh energy use by the pump load. A special mid-point converter is also utilized to feed the power into the SRM drive. The proposed scheme has several benefits and can be utilized in several purposes such as spray irrigation and green-house water supply management. In addition, this paper presents the component sizing of SPV array,
switches and tracking controller to ensure the maximum solar energy utilization.

II. PROPOSED SYSTEM CONFIGURATION

The schematic of proposed 4.3 kW peak power capacity solar PV array using a modified Sheppard–Taylor converter with InC-MPPT control, a mid-point converter, a 4 kW SRM drive and pump load of 3.9 kW using SRM drive is shown in Fig.1. In this system, a 4 kW, 8/6, four-phase SRM selected because torque ripple reduces with increase in number of phases. The characteristics of modified Sheppard–Taylor converter like non-inverting voltage output with reduced ripple in both input and output side make it superior and suitable for water pumping over conventional Sheppard–Taylor, Cuk or other buck-boost converters. The SPV array always supplies maximum available power using MPPT algorithm by regulating duty cycle of modified Sheppard–Taylor DC-DC converter. The complete details including design, control and performance of a proposed water pumping system are given in the following sections. The design data’s used for simulating the proposed water pumping system is also given in Appendix.

III. DESIGN AND OPERATION OF PROPOSED SYSTEM

The design procedure with calculations required for the different parts of proposed SPV fed SRM driven water pumping system are discussed in following sub-sections. An incremental conductance method of MPPT is used in proposed system for achieving maximum power from SPV array at all possible insolation levels. The modified Sheppard–Taylor DC-DC converter used here is operated in CCM (Continuous Conduction Mode) to minimize the losses and reducing the voltage and current stresses on switches and other converter components. The soft starting of SRM drive is also introduced in the proposed system to restrict the high starting current in phases of the motor by mean of adjusting the step size of MPPT controller.

A. Design of SPV Array

The PV(photovoltaic) module chosen is a HB-6102 mono/poly-crystalline silicon solar cell in series to provide 60W of maximum power. Fig. 2 shows the equivalent circuit of the ideal one diode model of photovoltaic cell. The basic equation that describes mathematically the I-V characteristic of the ideal PV cell as follows,

\[
l = I_{pv} - I_d - I_0 \left[ \exp \left( \frac{q(V_{pv} + R_s I)}{N_j k T a} \right) - 1 \right]
\]

(1)

\[
l = I_{pv} - I_0 \left[ \exp \left( \frac{q(V_{pv} + R_s I)}{N_j k T a} \right) - 1 \right] - \frac{V_{pv} + R_s I}{R_p}
\]

(2)

Where, ‘I_d’ diode saturation current, ‘q’ electric charge, ‘R_s’ series resistance of PV cell, ‘k’ Boltzmann’s constant, ‘a’ ideality factor, ‘T’ actual temperature, ‘R_p’ parallel resistance of PV cell. The electrical specification of SPV array used in the proposed system is given in Table I.

B. Design and Operation of Modified Sheppard–Taylor Converter

Figs.3 (a), (b) and (c) show the two modes operation of modified Sheppard–Taylor converter in CCM with charging and discharging states for different indices with proposed water pumping system.
Mode I: When both switches are turned-on, the current in input side inductor \( I_{L1} \) and the output side inductor \( I_{L2} \) increase as shown in Fig. 3a. The intermediate capacitor \( C_m \) discharges in this mode of operation. Moreover, the diode \( D_3 \) remains in off-state and the DC link capacitors \( C_1 \) and \( C_2 \) supply the required energy to the midpoint converter feeding SRM.

Mode II: Switches are turned off in this mode, input and output inductors (\( L_1 \) and \( L_2 \)) start discharging as shown in Fig. 3b. Moreover, the intermediate capacitor \( C_m \) and the DC link capacitors \( C_1 \) and \( C_2 \) start charging.

The duty cycle of modified Sheppard–Taylor converter is given as \([5]\),

\[
D = \frac{V_{DC}}{(V_{mp} + V_{DC})} = \frac{560}{(293+560)} = 0.52 \tag{3}
\]

The \( \Delta i_{L1} \) and \( \Delta i_{L2} \) are the amount of ripple current in both input inductor (\( L_1 \)) and output inductor (\( L_2 \)) respectively; these are considered as 20% of the maximum value of the currents flowing through these inductors.

Let, \( f_{sw} \) is the switching frequency and equal to 20 kHz where, \( V_{DC} \) is the output voltage of the modified Sheppard–Taylor converter taken as 560 V. ‘\( I_m \)’ is the input current of the converter and ‘\( \Delta V_{cm} \)’ is ripple in the voltage across ‘\( C_m \)’ \((10\% \text{ of } V_{cm})\), \( \Delta V_{DC} \) = amount of permitted ripple in the voltage across DC link capacitors \( C_1 \) & \( C_2 \) i.e. 1.5% of \( V_{DC} \). The design values of modified Sheppard–Taylor parameters are given in Table II.

The DC link capacitors (\( C_1 \), \( C_2 \)) of mid-point converter are calculated as \([6]\),

\[
c_1 = c_2 = \frac{I(30^\circ - \alpha)}{2\omega \Delta V_{DC}} \tag{4}
\]

Where, \( \omega \) = rated angular speed of SRM, \( \alpha \) = conduction angle, \( \Delta V_{DC} \) = permitted ripple in the voltage across DC link capacitors \( C_1 \) & \( C_2 \) i.e. 1.5% of \( V_{DC} \). The value of SRM phase current ‘\( I \)’ which is also acting as a DC link current is given as,
Considering $P_{in}$ as 4.3 kW, $V_{dc}$ as 560 V, $f$ as 50 Hz and $\Delta V_{dc}$ as 20% of $V_{DC}$, the obtained value of $I_{dc}$ is 7.67 A and the obtained value of $C_1$ is 3261 µF; hence, $C_1$ and $C_2$ are selected as 3200 µF.

C. Design of Water Pump

The relation between output power and mechanical speed of motor is defined as,

$$P_P = K_p \omega^2$$  \hspace{1cm} (6)

Where, $K_p$ is a constant in Watt/ (rad/sec) and $\omega$ is the mechanical speed of the rotor in rad/sec as,

$$K_p = \frac{T_p}{\omega} = \frac{25}{157.08} = 0.158 \text{ W/ (rad/sec)}$$  \hspace{1cm} (7)

### TABLE-II

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Expressions</th>
<th>Design data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Inductor, $L_1$</td>
<td>$L_1 = \frac{V_{mpp} \times D}{\Delta i_{L1} \times f_{SW}}$</td>
<td>$L_1 = \frac{320 \times 0.63}{(3.04 \times 20 \times 10^3)}$</td>
<td>2.5 mH</td>
</tr>
<tr>
<td>Output Inductor, $L_2$</td>
<td>$L_2 = \frac{(1 - \beta) V_{dc}}{\Delta i_{L2} \times f_{SW}}$</td>
<td>$L_2 = \frac{560 (1 - 0.63)}{2.58 \times 20 \times 10^3}$</td>
<td>5.2 mH</td>
</tr>
<tr>
<td>Energy Transfer Capacitor, $C_m$</td>
<td>$C_m = \frac{i_{in} (1 - \beta)}{(\Delta V_{cm}) \times f_{SW}}$</td>
<td>$C_m = \frac{15.2 (1 - 0.63)}{(92.83 \times 20 \times 10^3)}$</td>
<td>2.14 µF</td>
</tr>
</tbody>
</table>

A. MPPT Control Algorithm

The incremental conductance method determines the maximum power point by comparison of the incremental conductance ($\frac{dI}{dV}$) to array conductance ($\frac{I}{V}$). The governing equations which explain the operating principle of InC method are as,

$$\frac{\Delta I}{\Delta V} = -\frac{I_{PV}}{V_{PV}} \text{ at MPP}$$  \hspace{1cm} (8)

$$\frac{\Delta I}{\Delta V} > -\frac{I_{PV}}{V_{PV}}$$, Left of MPP  \hspace{1cm} (9)

$$\frac{\Delta I}{\Delta V} < -\frac{I_{PV}}{V_{PV}}$$, Right of MPP  \hspace{1cm} (10)

Where, $\Delta I$ & $\Delta V$ = change in PV current and voltage in two consecutive samples.

B. Control of Mid-Point Converter

The voltage - ampere equation for SRM motor can be approximated as [7]-[8],

$$V_{c1} = \frac{\partial \phi}{\partial i} = L_u \frac{di}{dt}$$  \hspace{1cm} (11)

or,

$$V_{c1} = L_u \frac{di}{d\theta} = L_u \frac{d\theta}{dt}$$  \hspace{1cm} (12)

So the advance angle is as,

$$\theta_{adv} = L_u \frac{I}{V_{ci}}$$  \hspace{1cm} (13)

Where $L_u$ is the unaligned inductance, $V_{ci} = \frac{V_{dc}}{2}$.

The angle where inductance starts increasing ($\theta_m$) is given as,

$$\theta_{on} = \theta_m - \theta_{adv}$$  \hspace{1cm} (16)

The commutation signals for the mid-point converter of SRM are generated using these angles.

V. RESULTS AND DISCUSSION

The performance of proposed system is investigated and is shown in Figs.4-11 under different insolation levels and recognized in terms of SPV array voltage, $V_{pv}$, SPV array current, $I_{PV}$, SPV array power, $P$, input inductor current, $i_{L1}$, output inductor current, $i_{L2}$, voltage across energy transfer

IV. CONTROL ALGORITHM OF PROPOSED SYSTEM

The overall performance of proposed system mainly depends upon the MPPT control and midpoint converter control to achieve efficient operation at all possible environmental conditions.
capacitor, \( V_{Cm} \), voltage across DC link capacitors, \( V_{c1} \) and \( V_{c2} \), switch voltage and current \( V_{sw1,2} \) and \( I_{sw1,2} \), phase currents, \( I_1, I_2, I_3, \) \( I_4 \), resultant torque of SRM, \( T_e \), SRM speed, \( N \), and water pump load torque, \( T_p \).

A. Performance of Proposed System Under Fixed Solar Irradiance Level i.e. 1000W/m²

The starting and steady state performances of PV current, voltage and power at 1000W/m² are shown in Figs.4&5. Some time delay is provided to the InC-MPPT algorithm by adjusting step size to provide soft starting of SRM as manifest in Fig.6. The nature of motor currents and torques of each phase in both starting and in steady state conditions is shown in Fig.6 and Fig.7. For view of clarity, the starting and steady state performances are shown in two different figures. As SRM drive is operating at full load, its speed increases and settles at the rated value under steady state condition. The electromagnetic torque, \( T_e \) of SRM is equal to the pump torque, \( T_p \) and to achieve a stable operation in steady state condition which is shown in Fig.7. The voltage across each mid-pont capacitor has similar characteristics and voltage balancing occurs as shown in Figs 4&5.

B. Performance of Proposed System Under Varying Solar Irradiance Level

Figs.9, 10 & 11 show the satisfactory performance of proposed system under varying insolation levels. Figs.9&10 explain the behavior of SPV array and DC-DC converter parameters for two different values of insolation levels i.e. 300W/m² and 1000 W/m² respectively. Fig.11 concludes that the torque and speed of SRM follow the insolation levels and support the efficient variable DC link voltage control of SRM drive. The values of speed and output power with efficiency at different insolation levels are given in Table III and Fig.11 using graph.

VI. CONCLUSION

The mathematical model and simulation of SPV array powered modified Sheppard–Taylor converter fed SRM drive for water pumping application is presented in this paper. SPV array has always been operated at its maximum power point by regulating the duty cycle of DC-DC converter. The variable DC link voltage control of SRM drive with electronic commutation is also used to drive proposed system and it appreciably increases the efficiency of proposed water pumping system.
APPENDICES

A. Switched Reluctance Motor-Pump Specification

4kW, 8/6pole, 1500rpm, R (Phase Resistance) = 0.7 Ω, \( L_u \) (unaligned inductance) = 12mH, \( L_a \) (aligned inductance) = 110mH, \( J = 0.016 \text{kg-m}^2 \), \( B = 0.0065 \text{Nms} \).

B. Design Parameters of Sheppard–Taylor converter

Switching frequency, \( f_{sw} = 20 \text{ kHz} \); Inductors, \( L_1 = 2.5 \text{ mH} \); & \( L_2 = 5.2 \text{ mH} \), Energy Transfer Capacitor, \( C_m = 2.14 \mu\text{F} \), DC link split capacitors, \( C_1 = C_2 = 3200 \mu\text{F} \).

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Fig. 6. Performance of motor current, torque and speed during soft starting condition.

TABLE-III

<table>
<thead>
<tr>
<th>Insolation levels (W/m²)</th>
<th>SPV Array Output, ( P_{in} (W) )</th>
<th>Torque, ( T_e ) (Nm)</th>
<th>Speed, ( \omega ) (rad/sec)</th>
<th>( P_{out} ) (W)</th>
<th>( % \eta ) = ( (P_{out}/P_{in}) \times 100 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>1133</td>
<td>9.68</td>
<td>100.4</td>
<td>971.11</td>
<td>85.75</td>
</tr>
<tr>
<td>500</td>
<td>2008</td>
<td>14.1</td>
<td>120.9</td>
<td>1704.6</td>
<td>84.90</td>
</tr>
<tr>
<td>700</td>
<td>2908</td>
<td>18.2</td>
<td>136.1</td>
<td>2477.9</td>
<td>85.29</td>
</tr>
<tr>
<td>1000</td>
<td>4300</td>
<td>25</td>
<td>157</td>
<td>3925</td>
<td>91.27</td>
</tr>
</tbody>
</table>

Fig. 7. SRM behavior during steady state and at insolation level of 1000W/m²

Fig. 8. Performance of switches of DC-DC converter at fixed insolation levels

Fig. 9. Performance of SPV and DC-DC converter at transient and steady states for different irradiance levels.
Fig. 10 Performance of DC link capacitors and switches of DC-DC converter for two different insolation levels.

Fig. 11. Performance of motor current, torque and speed at transient and steady state conditions for different insolation levels.

Fig. 12 Efficiency and power with different solar insolation levels

REFERENCES


