Solar Powered Water Pumping System Employing Switched Reluctance Motor Drive

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***Abstract*— This paper deals with the simple design method and performance investigation of a solar photovoltaic (SPV) array fed water pumping system employing a switched reluctance motor (SRM) drive coupled to a centrifugal water pump. SRM possessing a number of advantages over the dc and ac motors such as high torque density, low inertia, quick response, low losses because of the absence of permanent magnet or winding on the rotor, wide speed range capability, and simple control, suits for the SPV powered water pumping system. A DC-DC Cuk converter which facilitates the continuous and smooth input/output current and boundless region for maximum power point tracking (MPPT) operation is used as an intermediate DC-DC converter between the SPV array and the mid-point converter, in order to operate the SPV array at its optimum power point. The proposed system, subjected to the dynamically changing atmospheric condition is designed; modeled and simulated using MATLAB/Simulink and the simulation results of SRM are represented to demonstrate its suitability and performance.**

Keywords— SPV array, SRM, centrifugal water pump, MPPT.

I. INTRODUCTION

Providing and ensuring clean and safe water in sufficient quantities, protecting health and ensuring sustainable development are the major concern for farmers and ranchers. Abundant water supply in remote locations is required to ensure the grazing evenly. Solar photovoltaic (SPV) array based water pumping is most accepted and admired application of solar energy in developing countries such as India.

Various dc and ac motors have been used so far in SPV array based water pumping system. The problems associated with dc motors are the frequent maintenance requirement because of commutator and brushes. On the other side, the problems with ac motors are inability to operate at low speeds, poor positing control and low reliability. In comparison with special machines, the switched reluctance motor (SRM) has the simplest construction among all. The rotor contains no conductors or permanent magnets [1]. Because of its high torque density, low inertia, quick response, low losses, wide speed range capability, simple control and low overall cost, SRM could be a viable candidate for water pumping powered by SPV array [2].Moreover, the stator windings of SRM are electrically separated; hence, the choice of converter topology and control strategy has more flexibility than any other drive system. Both the SRM and the permanent magnet (PM) machines are free of rotor copper loss, but the SRM phases are independently controlled by the converter which makes the short circuit current decay quickly [3], while in the PM machine the short circuit current persists as long as the machine continues to to rotate due to back-emf generation. The robust brushless construction and good thermal features make the SRM drive attractive for SPV powered water pumping system [4].

Although the DC-DC boost and buck converters have less number of components, these are not suitable because of possessing the limited region of maximum power point tracking (MPPT). The DC-DC Cuk converter not only provides the boundless region for MPPT [5] but it also gives the ripple free input and output current with the proper control via the MPPT algorithm execution; it facilitates the soft starting of SRM. In this paper, a P& O (Perturbation and Observe) MPPT method with varying step size is used in order to avoid the oscillations around the MPP. The proposed water pumping system is designed and modeled using MATLAB/Simulink and performance analysis is carried out to demonstrate its suitability under the fixed and varying solar isolation levels.

II. PROPOSED SYSTEM CONFIGURATION

The topology of the proposed SPV array fed water pumping system using SRM driveis shown in Fig.1. It consists of theSPVarray, the Cuk converter, the mid-point converter feedingthe SRM coupled to a centrifugal water pump. The SPV array output power is optimized by P & O MPPT technique. The design and control of the proposed system are elaborated in the following.

III. CONTROL OF THE PROPOSED SYSTEM

In the proposed system, maximum power of the SPV array is tracked using P & O MPPT technique and the mid-point converter feeding the SRM is operated through the electronic commutation. These two controls at the various stages are discussed in brief in the following sub-sections.

A. MPPT Technique

The location of MPP in the I-V characteristics of SPV array is not predicted in advance and always varies dynamically with irradiance and temperature. There are observable voltage shifts where the MPP occurs. Therefore, the MPP needs to be located by tracking algorithms. The P&O method of MPPT tracking,

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which is also known as 'hill climbing' method is very advantageous and commonly used because of its simplicity and the ease of implementation [5-7].It is also called three step operations method.The duty ratio of Cuk converter is routinely regulated through this MPPT controller. Thus MPPT produces PWM pulses for the switch of Cuk converter. This method

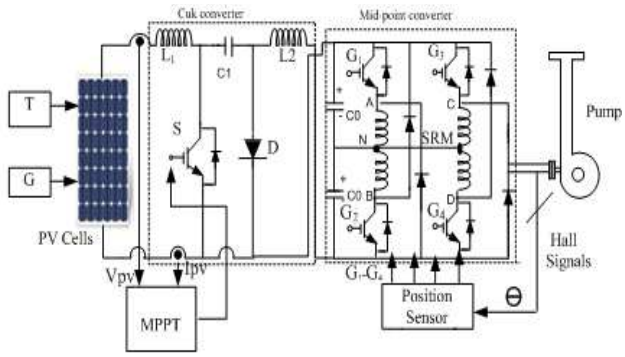

Fig.1. Schematic diagram of standalone solar PV based SRM drive for water pumping system

Includes other advantages such as low implementation complexity and no periodic tunings [8].

B. Conduction Angle Control of SRM

An absolute way to obtained smooth, continuous torque and high efficiency is by using Rotor position information to control phase energization of SRM drive. The conduction angle for phase currents of stator is controlled and synchronized with the rotor position usually by means of shaft position sensor [9]. The SRM is integrated with a closed loop control circuit, which is essential to run the machine. The main function of the control circuit is to optimize the switching angles of the applied phase voltage to make the current pulse coincide with the active interval of the motoring inductance profile [10]. The whole switching of converter is control by three parameters; the advance angle (turn- on angle), θ_α, turn-off angle, θ_β, and the value of the effective supply voltage. The switching angles are defined for each phase based on the rotor position information provided by a position sensor located on the shaft [11]. The value of θ_α is chosen to permit the current to grow to an adequate level while the inductance is at its minimum value. To avoid the generation of a reverse or braking torque in the motoring mode that results in reduction of total average torque, the current pulse duration must be confined to half of the rotor pole pitch. The mechanical stroke-angle, ε is given as [12].

$$\varepsilon = 2\pi / (N_{ph} N_r) \tag{1}$$

Where N_{ph} is the number of phases and N_r is the number of rotor teeth.

C. Control of Mid-point Converter

The order of excitation pattern and ON-OFF switching of SRM phase winding are carried out using a combination of semiconductor switches connected in a predefined configuration. The mid-point converter is selected for SRM whose phases are in even number. Unlike the other converters it requires less number of switches equal to the number of phases. The mid-point converter contains two DC-link capacitors Because of less number of switches and absence of PWM switching, operation of this converter results in a lower switching losses compared to other converters [13].

IV. Design Of the Proposed System

The design of SPV array fed water pumping system employing SRM drive consist of SPV array, DC-DC Cuk converter, a mid-point converter and the SRM coupled with a centrifugal water pump. The designs procedure of the components at the various stages of the proposed system is discussed in the following sub-sections.

A. Design of SPV Array

The proposed system is designed for the peak power capacity of 4.8 kW. A solar PV module has short circuit module current (I_{sc}) of 8.21 A and open circuit module voltage (V_{ocn}) of 32.9 V. The maximum power for SPV array is given as,

$$P_{mp} = (n_s*V_{mp})*(n_p*I_{mp}) = 4.8 \text{ kW} \tag{2}$$

Where n_s and n_p represent series and parallel strings of PV module, V_{mp} is the voltage of a module at MPPT, I_{mp} is the current of a module at MPPT and P_{mp} is the nominal power of a module at MPPT. The P_{mp} is generally achieved under the condition given as,

$$P_{mp} = (n_s*85\% \text{ of } V_{ocn} * n_p*85 \% \text{ of } I_{sc}) = 4.8 \text{ kW} \tag{3}$$

Thus, I_{mp} is 7.61A and V_{mp} is 26.3 V of each module. Considering, PV array open circuit voltage (V_{OCT}) =315.6 V. The PV modules connected in series string are estimated as,

$$V_{OCT} = n_s * V_{ocn} \tag{4}$$

thus n_s = 315.6/26.3 = 12 Modules
Maximum current of the PV array is given as,

$$I_{mp} = P_{mp} / (0.85 * V_{OCT}) = 15.22 \text{ A} \tag{5}$$

The PV modules connected in parallel string are estimated as,

$$I_{mp} = n_p*I_{sc}, \quad \text{thus } n_p \approx 2 \text{ Modules} \tag{6}$$

Thus the array of 4.8 kW peak power capacity is designed with 2 modules in parallel and 12 modules in series with an PV array of 2*12 modules [14-15].

B. Design of Cuk Converter

The Cuk converter transfers the active power from PV array to the DC link capacitor of mid- point converter feeding SRM-

pump system. The Cuk converter is so designed that it always operates in continuous conduction mode (CCM) regardless of the atmospheric conditions. Considering, $\Delta i1 \& \Delta i_2$=20% of the currents flowing through $L_1$and L_2respectively, f_{sw} =25 kHz and V_0=605V, the design parameters of the Cuk converter are estimated as [16],

The value of duty cycle, D is estimated as,

$$D = V_0/ (V_{mpp} + V_0) =605/ (315.6+605)= 0.66 \quad (7)$$

The value of input inductor, L_1 is given as,

$$L_1 = V_{mpp}\, D/ (\Delta\, i_1\, f_{sw}) = 315.6*0.66/(3.04*25*10^3)= 2.69\text{mH} \quad (8)$$

The value of output inductor, L_2 is given as,

$$L_2 = V_0\, (1\text{-}D) /(\Delta\, i_2\, f_{sw}) = 605(1\text{-}0.66)/(1.58*25*10^3) = 5.25\text{mH} \quad (9)$$

The value of energy transfer capacitor, C_1 is given as:

$$C_1=I_1\, (1\text{-}D) / (\Delta\, Vc1 f_{sw}) =15.2(1\text{-}0.66)/(92.83*25*10^3) =2.23\mu\text{F} \quad (10)$$

where D is the duty cycle, f_{sw} is the switching frequency, I_1 is the input current of the Cuk converter, Δi_1 is permitted ripple in the current flowing through L_1, Δi_2 is permitted ripple in the current flowing through L2, ΔV_{c1} is permitted ripple in the voltage across C_1 (10% of V_{c1}), V_0 is the output voltage of the Cuk converter.

C. Design of Centrifugal Water Pump

In general, pumps are classified as centrifugal pumps (or rotor-dynamic pumps) and positive displacement pumps. In displacement pumps, the water output is directly proportional to the pump speed, but independent of head. The centrifugal pumps produce a head and a flow by increasing the velocity of the liquid through the machine with the help of a rotating vane impeller and its water output is directly proportional to the square of pump speed [17]. It is generally used where water pump is directly interfaced with the SPV array. The characteristics of the centrifugal water pump are well matched with the characteristics of SPV array.

The Centrifugal water pump is designed using its torque-speed relationship as,

$$T_p=K\omega^2 \quad (11)$$

Where K is the proportionality constant and it estimated

$$K = T_p/\omega^2 = 25/157.08^2 = 0.001 \quad (12)$$

IV. Results And Discussion

The proposed system is designed, modeled and simulated using MATLAB/ Simulinkand its performances are demonstrated under various operating conditions using the obtained simulation results. The performances of the proposed SPV array fed SRM drive for water pumping system are figured out under different operating conditions and recognized in terms of SPV array voltage,V_{PV}**,** SPV array currents, I_{PV}**,**SPV array power**,** P_{pv}**,** input inductor current, I_{L1}, output inductor current, I_{L2}, voltage across energy transfer capacitor, V_{C1}, voltage across DC link capacitors, V_{c1} and V_{c2} and the resultant DC link voltage, V_c, phase currents, I_1, I_2, I_3, $I_4$and Resultant Torque of SRM, T_e, SRM speed, N**,** water pump load torque, T_p and DC link voltage, V_{dc} of Mid-point.

A. Performance of Proposed System Under Fixed Solar Irradiance Level

Figs. 2-3 shows the behavior of current, voltage and power of the SPV array, voltage and current of the elements of Cuk converter in both transient and steady state conditions. The DC link voltage across each capacitor of mid-point converter is equal throughout the operation of the proposed system. Under steady state condition, all the indices such as voltage, current and power output of SPV array, inductor currents, voltage

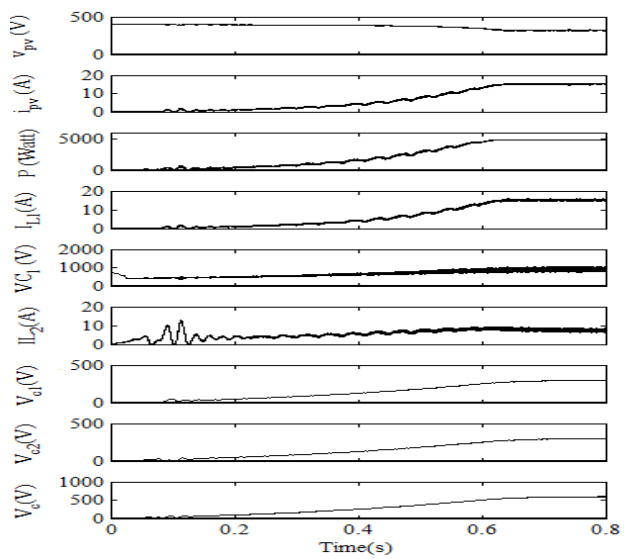

Fig.2. PV and converter indices during starting

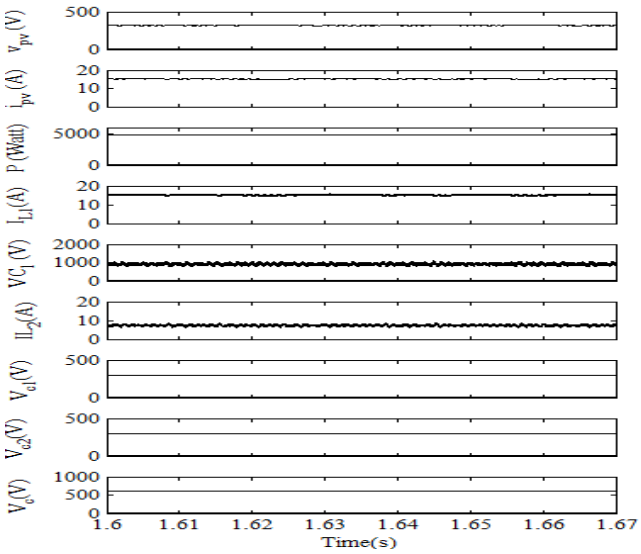

Fig.3. PV and converter indices during steady state

across energy transfer capacitor of Cuk converter and dc link voltage of mid-point converter exhibit constant and regulated response. Each capacitor of mid-point converter is charging with equal voltages. Fig. 4 shows that the starting current is higher than the rated current in some phases of SRM; therefore, the SRM produces high starting torque as compared to its rated value. Under steady state condition, load torque of water pump reaches the rated torque of the motor and SRM attains rated speed which is shown in Fig. 5.

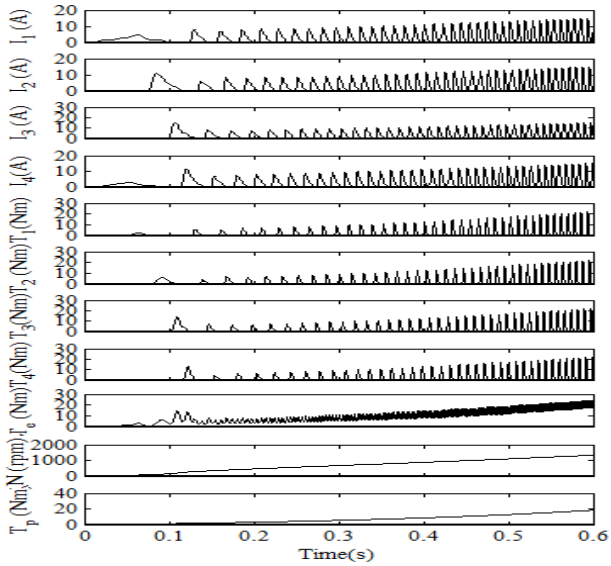

Fig.4. Performance of SRM drive during starting at fixed irradiances

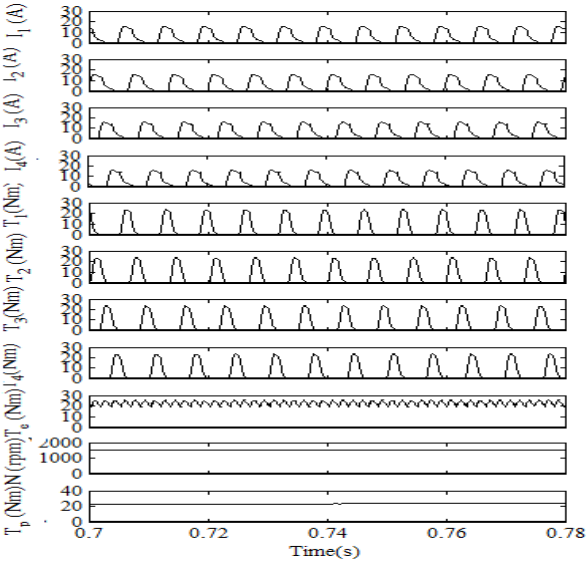

Fig.5. Performance of SRM drive during steady state at fixed irradiances

B. *Performance of the Proposed System Under Varying Solar Irradiance Level*

Fig. 6 shows that the SRM indices vary with solar irradiance level and reach their rated value under steady states on the other side Fig. 7 exhibit that the DC link capacitors of mid-point converter are charging with varying voltage depending upon the solar irradiance level.

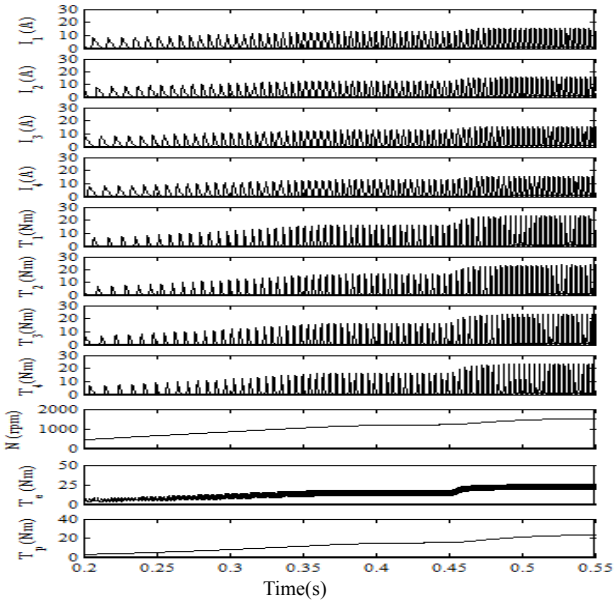

Fig.6 PV and converter indices for transient and steady state at different solar irradiance.

CONCLUSIONS

The SPV array fed SRM driven water pumping system has been design, modeled, simulated using MATLAB/Simulink and its various starting, dynamic and steady state performances are demonstrated using the simulated results. Following merits of the proposed system have been observed:

- SPV array is forced to operate at its MPP resulting in the efficiency optimization of the proposed system regardless of the operating conditions.
- The mid- point converter losses are reduced due to its operation with electronics commutation which results in an overall efficiency improvement of the proposed water pumping system.
- The proposed system is reliable, simple and requires less maintenance.

It has been revealed that the proposed water pumping system exhibits satisfactory performance under the change in solar irradiation which verifies its suitability for SPV array fed water pumping. The proposed system is reliable, simple and requires less maintenance.

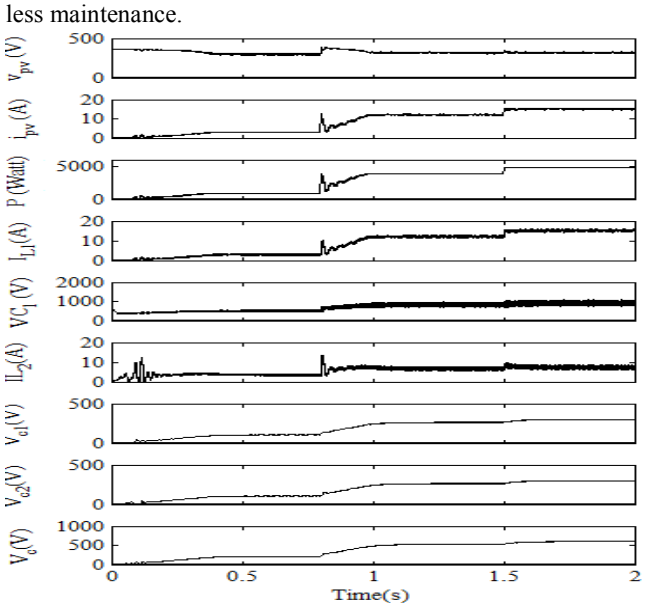

Fig.7. Performance of PV and converter at transient and steady State for Different solar irradiance

APPENDIX

Specification of SRM	4 kW, 9A, 8/6 pole, 1500 rpm, 0.7 Ω, L_u=10mH, L_a = 110mH, L_{sat} =6.39mH, J=0.016kg-m^2, B=0.0065Nms.
Specification of Cuk converter	L_{in}=2.69mH, L_{out}=5.25mH,C_{middle}=2.23 µf, P=4.8kW

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