PV-Battery Powered Direct Torque Controlled Switched Reluctance Motor Drive

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Abstract— **Categorized as one of the renewable energies, Photo-Voltaic system has a great potential compared to its counterparts of renewable energies. This paper deals with the design of a Photovoltaic (PV)-Battery fed Switched Reluctance Motor(SRM). The system mainly composed of a PV module, boost converter, rechargeable battery, bidirectional converter, asymmetric bridge converter, SRM and system controllers. The main problems of SRM are high torque ripple, acoustic noise and vibration problems. In order to reduce these problems, a new direct torque control of 3.5 kW 8/6 SRM is proposed, which is simple and can be implemented with low cost processor. It can be seen from the simulation results that this scheme has well regulated the torque output of the motor with in hysteresis band. The proposed system assures its suitability for solar applications like solar vehicles, solar water pumping system and floor mills in hilly and isolated areas.**

Keywords-PV module, switched reluctance motor, direct torque control, battery energy storage system.

I. INTRODUCTION

The technological development of the solar power is well known [1], as also its importance and scope in meeting the energy requirements. Its environmental friendly nature, low operating cost and everlasting supply has made solar energy as one of the most promising source of energy [2].

The output of PV source is DC source. Solar power fed permanent magnet brush-less DC(PMBLDC) motor are being used for water pumping and solar vehicles. But the high cost and difficulties in availability of permanent magnets are still major hurdle in the application. Use of a cage induction motor for water pumping application has been reported[4]. A PV-fed Induction motor uses VSI with neutral-point connection needs at least a dc-link voltage of 600V. The reason why the neutral point should be connected to the dc-link is to minimize common-mode voltages at the PV module. Much attention is given to back-end because every kW of loss saved in the process drive, 6kW of fuel gets saved on the front end. Switched reluctance motor (SRM), with simple and rugged construction, is an alternative. The other advantages are no possibility of shoot through fault, high reliability due to the electric and magnetic independence of the machine phases and less cooling requirement. The main problems with SRM drives are acoustic noise and high torque ripple. These problems can be avoided by improving the machine design and proper control technique to reduce torque ripples. Fig.1 shows the difference in topology in conventional one and proposed one.

In this paper, 3.5 kW 8/6 four-phase SRM is chosen because torque ripple reduces with increase in number of phases. Even though it has some torque ripples which can eliminated by direct torque control which has advantages of less complexity and high performance. The present paper describes the details of a PV array fed 3.5kW 8/6 SRM drive system. Control strategy is explained and model equations are systematically developed. Salient features of SRM drive with PV array have been highlighted, which assures its suitability for solar energy applications in solar vehicles, water pumping, floor mills etc.

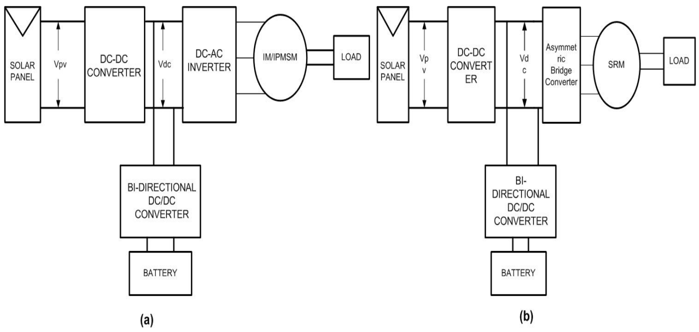

Figure 1. (a)PV-Battery fed Induction Motor drive (b) PV-Battery Switched Reluctance Motor drive

II. SYSTEM DESCRIPTION

The complete solar powered SRM drive system is as shown in fig 1(b). It includes a PV panel, a Boost converter, a Bidirectional converter, SRM and its controller. Each block is modelled separately and integrated together.

A. PV cell model

A solar PV cell consists of the semiconductor material which converts solar radiation into the dc current using the photovoltaic effect. By connecting solar cell in series a solar PV module is formed. Solarex MSX 64 PV module is considered .Here the module has 36 cells in series. Fig 2 shows

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the single diode model of PV cell. The characteristic of the solar cell output current I_{pv} can be given as

$$I_{pv} = I_{ph} - I_D \quad (1)$$

$$I_{pv} = I_{ph} - I_s e^{(\frac{-q(V_{pv}+I_{pv}Rs)}{nkT})} \quad (2)$$

$$I_{phT1} = \frac{I_{scT1}G}{1000} \quad (3)$$

$$I_{pv} = I_{ph}T1 + K_o(T - T1) \quad (4)$$

$$I_s = I_{so}(\frac{T}{T1})^3 e^{(\frac{qV_q}{nk(\frac{1}{T}-\frac{1}{T1})})} \quad (5)$$

$$V_q = \frac{nkT}{q} \quad (6)$$

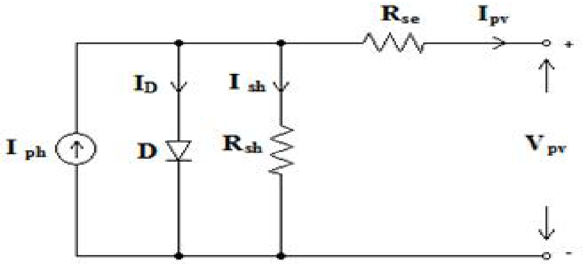

Figure 2. Simple equivalent circuit of solar cell

Where I_{pv}, V_{pv} Solar cell current and voltage; I_D – Diode current; I_{ph}- Light generated current; G - Irradiance; T-p-n junction cell temperature; T_1 - p-n junction temperature at reference Condition; K_o - First order temperature coefficient for I_{ph}; n - Diode ideality factor; k - Boltzmann's constant; q- Electron charge; Is - Reverse saturation current; I_{so} – diode saturation current at reference condition; R_{sh}, Rs- Shunt and series resistance.

When PV cells are arranged together in series and parallel to form arrays, these cells are usually considered to have the same characteristics.

$$I_{pv} = N_p I_{ph} - N_p I_s (e^{\frac{q}{AkT}(\frac{V_{pv}}{N_s}+\frac{IR_s}{N_p})} - 1) - \frac{N_p}{R_{sh}}(\frac{V_{pv}}{R_s} + \frac{IR_s}{N_p}) \quad (7)$$

where N_s& N_p are cell numbers of series and parallel cells respectively. Both I-V and P-V output characteristics of PV

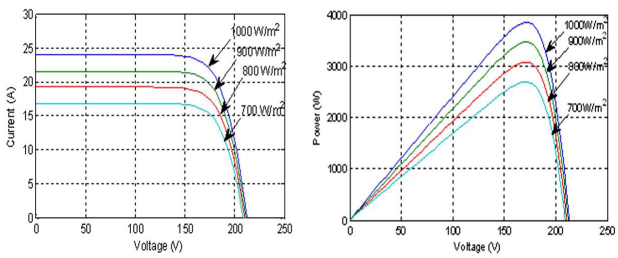

Figure 3. I-V and P-V output characteristics with different solar irradiation levels at 25°C

module at various isolation and temperatures are carried out and the results are shown in Fig 3-4. The DC-DC boost converter is used to extract maximum power output from the array. Perturb & Observe method is used for maximum power point tracking [9].

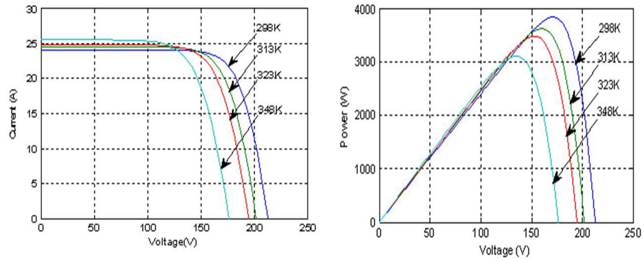

Figure 4. I-V and P-V output characteristics with different temperatures at 1000 W/m^2.

TABLE I. CHARACTERSTICS OF SINGLE PV MODULE

Parameter	value
Maximum power (P_{max})	64W
Voltage@P_{max}(V_{mp})	17.5V
current@P_{max}(I_{mp})	3.66A
Short circuit current(I_{sc})	4A
Open Circuit voltage(V_{oc})	21.6V

B. *Battery Energy Storage System(BESS)*

BESS is composed of a battery bank, a bi-directional DC/DC converter and its controller. The system should be able to operating in modes: the battery can be charged to store the extra energy and also can discharge the energy to loads. The primary objective of this converter is to maintain the common dc link voltage constant. When charging, switch S_1 is activated. and the converter works as a boost circuit, otherwise, when discharging, switch S_2 is activated and the

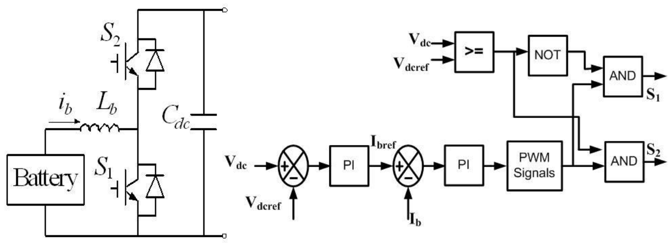

Figure 5. Bidirectional converter and its controller

converter works as a buck circuit. Fig 5 presents the bi-directional converter and its controller. When the voltage at dc link is lower than the voltage reference, switch S_2 is activated; when the voltage at dc link is higher than the voltage reference, switch S_1 is activated.

III. DTC SCHEME

The control scheme directly controls the amplitude of the flux and torque with in hysteresis bands. The voltage equation of each phase of can be written as

$$v = Ri + \frac{d\psi(i,\theta)}{d\theta} \quad (8)$$

The non-linear flux linkage term can be expanded into partial fractions such that

$$v = Ri + \frac{\partial \psi(i,\theta)}{\partial i}\frac{di}{dt} + \frac{\partial \psi(i,\theta)}{\partial \theta}\frac{d\theta}{dt} \tag{9}$$

The expression for instantaneous torque production of a SR motor is

$$T = i\frac{\partial \psi(i,\theta)}{\partial \theta} - \frac{\partial W_f'}{\partial \theta} \tag{10}$$

It was shown by Byrne that due to saturation in the SR motor, the influence of the second term in (3) is small. Therefore, by using this approximation, the following equation for torque production may be derived:

$$T \cong i\frac{\partial \psi(i,\theta)}{\partial \theta} \tag{11}$$

where θ is the rotor position angle, i is the phase current. It is note that in the SRM unipolar drives are normally used and thus the current in a motor phase is always positive. Hence from (11), the sign of the torque is directly related to the sign of $\frac{\partial \psi(i,\theta)}{\partial \theta}$.

The proposed control scheme of SRM is based on the results as follows:

- The stator flux linkage vector of the motor is kept at a constant (within amplitude hysteresis bands)
- The torque can be controlled during accelerating or decelerating the stator flux vector

The stator current can be found to have a first order delay relative to the change in stator flux $\frac{\partial \psi(i,\theta)}{\partial \theta}$ as

$$\frac{di}{dt} = \frac{(v - Ri) - \frac{\partial \psi}{\partial \theta}\frac{d\theta}{dt}}{\frac{\partial \psi}{\partial i}} \tag{12}$$

This allows the control method to control torque based only on the change in the value of the flux acceleration and deceleration only, without consideration of the current change. Similarly to conventional ac machines, equivalent space voltage vectors may be defined for a SRM. Due to the salient pole structure of the SR motor, the voltage space vector for each phase is defined as lying on the center axis of the stator pole. According to the circuit topology configuration of the SRM in Fig. 6, each motor phase can have three possible voltage states.

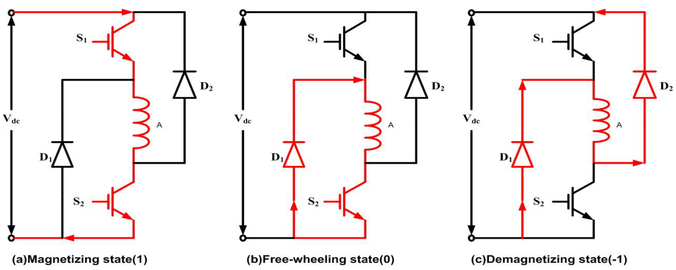

Figure 6. SR motor phase voltage states

Therefore, unlike the conventional ac motor DTC, each phase can have three states, leading to a total of 81 possible configurations. However in order to define eight equal amplitude voltage vectors as in the conventional DTC algorithm, the eight possible voltage vector states based on the vector addition of the voltage vectors in each phase as shown in Fig. 7. In this scheme no other states are allowed by the controller. These voltage state vectors are defined to lie in the center of eight zones N = 1, 2…8, where each are separated by Π/4. If the stator flux linkage lies in the k^th zone, the magnitude of the flux can be increased by using the switching vectors V_{k+1} and V_{k-1} and can be decreased by using the vectors V_{k+3} and V_{k-3}. dψ = 1 means that the instantaneous flux linkage less than the reference value and d ψ = 0 means that the instantaneous flux linkage more than the reference value. Similarly dT=1 means that the instantaneous torque less than the reference value and dT=0 means that the instantaneous torque more than the reference value. Supposing flux linkage rotates in the anticlockwise the switching table of the voltage vector is shown as Table II.

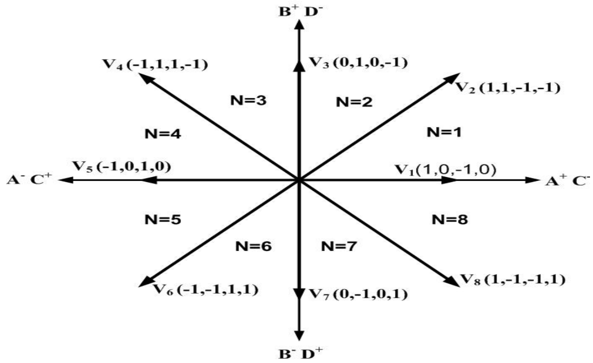

Figure 7. Definition of voltage vectors for DTC

TABLE II. SWITCHING TABLE FOR VOLATGE VECTOR

Sector		1	2	3	4	5	6	7	8
dΨ=1	dT=1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_1
	dT=0	V_8	V_1	V_2	V_3	V_4	V_5	V_6	V_7
dΨ=0	dT=1	V_4	V_5	V_6	V_7	V_8	V_1	V_2	V_3
	dT=0	V_6	V_7	V_8	V_1	V_2	V_3	V_4	V_5

IV. SIMULATION RESULTS AND DISCUSSIONS

The simulation has been carried out in MATLAB/simulink. The conditions considered for the purpose of study include response of the drive for different levels of solar irradiation. The waveforms of the PV voltage and current are shown in fig8. Boost and bidirectional converter is designed for 3.5kW 8/6 SRM. The Simulation parameters are set as follows: the dc link voltage is maintained at 200V, flux is maintained at 0.35wb, torque is maintained at 10N-m and rated speed is equal to1500rpm. The waveforms of phase current, phase flux, flux trajectory and torque is shown in Fig 8-12.

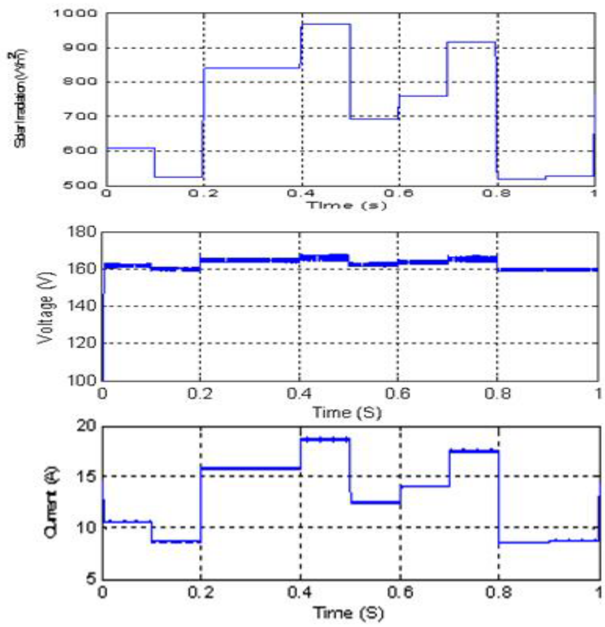

Figure 8. Variation of PV output voltage and current due variation in solar radiation

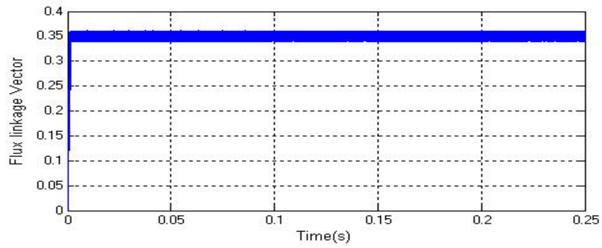

Figure 9. Control of flux vector with in hysteresis band

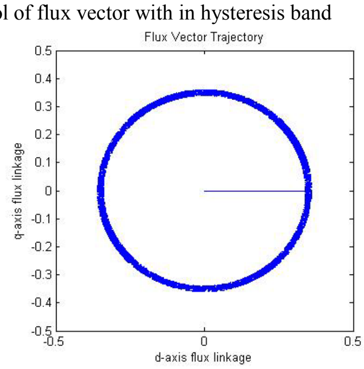

Figure 10. Flux trajectory in d-q plane

V. CONCLUSIONS

The proposed scheme reduces dc link voltage there by reducing capacitor size and insulation level. A single stage conversion is also possible without the use of boost converter. The advantage of using asymmetric bridge converter is freedom to control individual phase independently and no shoot through fault. Torque ripple in the SRM can be eliminated by Direct Torque Control technique. The results indicate that DTC of SRM can directly regulate the torque output of the motor within a hysteresis band.

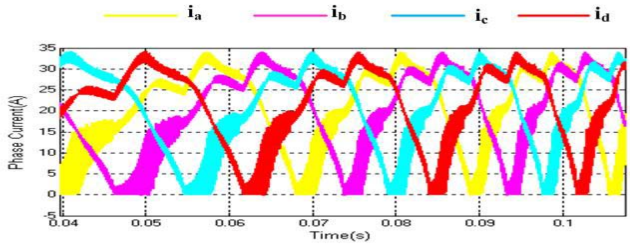

Figure 10. Current waveform of different phases

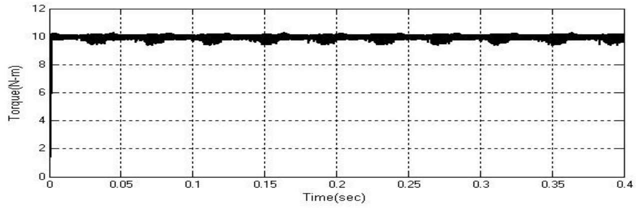

Figure 11. Control of torque in hysteresis band

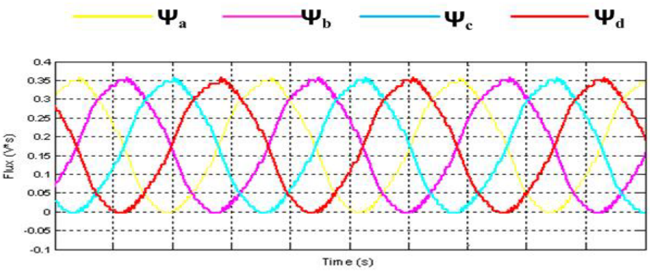

Figure 12. Flux waveform of different phases

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