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Closed loop pi control for solar fed switched reluctance motor drive based water pumping system

K. Chinababu[1],Ch. Rajesh[2]
[1](EEE,PG Student, LBRCE/ JNTUK,INDIA)
[2](EEE,.AsstProfessor,LBRCE/ JNTUK, INDIA)

Abstract: This paper demonstrates the utilization of solar photovoltaic (SPV) array produced electrical energy for low cost and efficient water pumping using simple, robust and efficient switched reluctance motor (SRM) drive. For increasing the efficiency of pumping system, an incremental conductance (Inc.) algorithm based MPPT technique is employed with SRM drive. A DC-DC cuk converter operated in continuous conduction mode (CCM) .The Mid-point converter having two split capacitors is used to provide the required voltage pulses for phase windings excitation of all four phases of SRM drive. The mid-point converter operates as an electronic commutator to reduce the switching losses and power dissipation of the converter. Both the inductors of cuk converter are operated in continuous conduction mode (CCM) which results in minimal stress on converter elements. The design of control system for four phase SRM is very complex since it has large torque ripples and non uniform torque at its output. The reduction in torque ripples and speed control requires an effective controller.the simulation of the PI based controller for SRM is performed by using MATLAB/simulink it depends upon the different environmental conditions.

Keywords:SPV Array, MPPT, soft starting, SRM, water pump, incremental conductance (InC) , pi controller.

I. INTRODUCTION

Now a day's solar photovoltaic (SPV) array based water pumping system is usually taken into practice for extracting clean drinking water and irrigation purposes. Improving the efficiency of water pumps has many advantages including increasing the profitability. The variable speed drive method of water pumping system enhances the opportunity to reduce energy requirement [1] An 8/6 configuration of switched reluctance motor (SRM) has become one of the most suitable and prominent machine for water pumping as an adjustable speed drive [2]. The properties of SRM drive [3] which make it suitable for water pumping is its special mid-point converter that is immune to shoot-through fault and only one switch per phase requirement for phase energization. Unlike permanent magnet brushless DC motor and permanent magnet synchronous motor which are giving very deficient performance with unipolar converter control, SRM is suitable for unipolar excitation and low cost applications[4] The complete discussion on different converter topologies convenient for reduced cost SRM drive has been discussed in [5-6] and concluded that mid-point converter is one of the suitable candidate for high efficient low cost SRM drive. An efficient method of MPPT techniquecalled incremental conductance (InC) method of SPV array has been discussed in [7]. Several researchers have demonstrated the water pumping application of SRM motor. An InC algorithm of MPPT has several benefits over others like its simplicity to implement and good performance under varying solar insolation levels [8].

The rotor of SRM contains no conductors or PMs [9]. Because of its high torque density, low inertia, quick response, variable losses, and wide speed range capability, SRM could be a suitable candidate for water pumping powered by SPV array. 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 [10], [11]It consists a storage batteryconnected to the SPV array through a battery voltage regulator (BVR) with the help of two switches. So apart from battery issues, switching losses are also increased. Moreover addition to these losses, absence of MPPT algorithm also decreases the efficiency of system. The switching losses are minimized by using a concept of variable dc-link voltage for speed control of motor drive . A solar-powered pumping system isngenerally in the same price range as a new windmill but tends to be more reliable and require less maintenance. A solar-powered pumping system generally costs more initially than a gas, diesel, or propane-powered generator but again requires far less maintenance and labour . It is common to use diesel to power generatorsin agricultural operations. A switched reluctance motor is a brushless AC motor which has simple construction and does not require permanent magnet for its operation. Hence it has many advantages over other dc or ac machines. The stator and rotor in SRM have salient poles and the of poles depends on the number of phases. Normally two stator poles at opposite ends are configured to form one phase. The number of stator poles is always different from that of rotor poles. SR motor has the phase winding on its stator and concentrated windings are used. The windings are inserted into the stator poles and connected in series to form one phase of the motor. SR motor has the phase winding on its stator only and concentrated windings are used. The windings are inserted into the stator poles and connected in series to form one phase of the motor. In a five phase SRM there are five pairs of concentrated windings and each pair of the winding is connected in series to form each phase respectively.

The flux linkage, inductance and torque characteristics vary with rotor position (i.e. the relative position of the rotor pole with the stator pole). The flux linkage, inductance and torque characteristics of a SR motor are highly non-linear. Positive torque in a SR motor is available at half the rotor pole pitch. Torque production in an SR motor can be explained based on energy conversion process.

The popular electronic method for torque ripple reduction is based on the optimization of control principles. This includes the supply voltage, turn–on and turn–off angles of the converter and current levels. But overall torque will be reduced.Precise control of SRM model is not easy using conventional method (like PI)as its flux linkage, inductance, and torque possess mutual coupling with rotor position and phase current.

II. PROPOSED SYSTEM CONFIGURATION

The proposed solar-PV array fed water pumping system is designed for a 900 w solar PV array using a cukconverter with MPPT control, a mid-point converter, a 750W SRM drive and A four switch split capacitor midpoint converter of 320-V dc link voltage is selected for proposed system. The schematic diagram of proposed SPV array fed water pumping system using cuk converter and SRM drive is shown in Fig.1.Thepurpose of cuk converter is to convert maximum power point voltage coming from SPV array to an adjustable DC supply. A mid-point converter provides the required energy in the form of voltage pulses to excite all four windings of SRM. Soft starting of SRM is also facilitate by adjusting step size of incremental inductance (InC) MPPT algorithim. The CCM base operation of cuk converter improve the efficiency of proposed system.detailed discussion on the suitability of proposed method of water pumping and the The problems present in discontinuous conduction mode like ringing phenomenon which is due to the transition of voltage at the other end of the inductor when the current reaches zero, cause EMI noise, and increased switch voltage rating which are eliminated in CCM operation of dc–dc Cuk converter. The pulses for fundamental switching of the mid-point converter switches are generated from the Hall effect position sensors situated on the stator part of SRMand its helps to reduce the loss associated with switches of a mid-point converter.advantages of using cuk converter and InC method for MPPT are given and pi control use the constant speed and variablespeed of the SRM drive analyzed in the following sections.

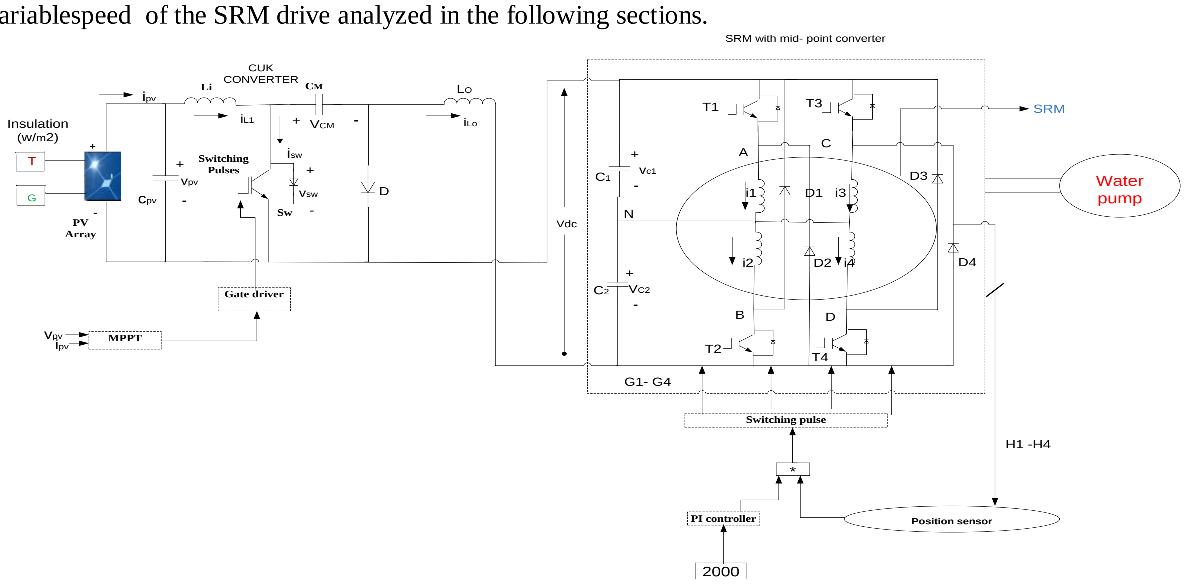


Fig :2.1proposed closed loop pi control spv fed SRM drive water pumping system utilizingcukconverter

III. DESIGN OF PROPOSED SYSTEM

The modeling, simulation and design of proposed water pumping system in MATLAB/Simulink environment with required calculations. The system utilizes cuk converter as a DC-DC converter for implementing an InC-MPPT algorithm operated in CCM. The process to design each part of system is carried out at a standard test condition i.e. 1000W/m2 at 250C. The detailed design procedure for different parts of proposed system isclarifiedin following sub-sections.

3.1 Design of SPV Array

Voltage at MPP, *V*m p = *V*PV	289 v
Power at MPP, *P*m p	900w
Current at MPP, *I*m p = *I*PV	*P*m p/*V*m p = 3.1 A
Number of modules connected in series, *NS*	*V*m p/*Vm*= 17
Number of modules connected in parallel, *NP*	*I*m p /*Im*= 1
Open-circuit voltage, *V*0C	*NS xV*0 = 357 *V*

The model does not take into account the internal losses of the current. A diode is connected in anti-parallel with the light generated current source. The output current I is obtained by Kirchhoff law:

$I = I_{ph}$-I_d

Iph is the photocurrent, Id is the diode current which is proportional to the saturation current and is given by the equation

I_d=I_0[exp($\frac{V}{A.N_s.V_T}$)-1]

V is the voltage imposed on the diode.

$$V_T = \text{k}.\frac{T_c}{q} V_{T_c}$$

$I_0$is the reverse saturation or leakage current of the diode . I0 is the reverse saturation or leakage current of the diode (A), VTc = 26 mV at 300 K for silisium cell, Tc is the actualcell temperature (K), k Boltzmann constant 1.381× 10^{-23}J/K, q is electron charge (1.602 × 10^{-19}C).

$V_T$is called the thermal voltage because of its exclusive dependence of temperature

Ns: is the number of PV cells connected in series

A is the ideality factor. It depends on PV cell technology and A is a constant which depends on PV cell technology.

The equivalent circuit of a solar cell and PV device.

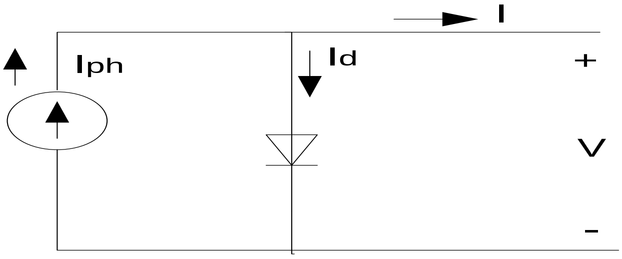


Fig 3.1.1 Ideal single diode model

The thermal voltage ''a'' is presented by equation

a=$\frac{N_{S.A.K.T_c}}{q}$ =N_s.A.V_T
'a' is called ''the modified ideality factor'

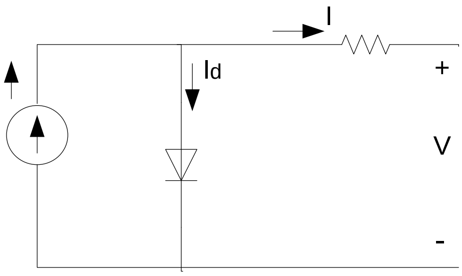


Fig 3.1.2 : Practical model with Rs

- ✓ In reality, it is impossible to neglect the series resistance Rs and the parallel resistance RP because of their impact on the efficiency of the PV cell and the PV module. When RS is taken into consideration, equation

  I_d=I_O[exp($\frac{V+I.R_S}{a}$)-1]

- ✓ It is easy to implement in simulator

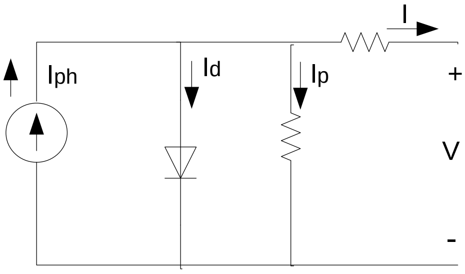


Fig 3.1.3: Practical model with Rs and Rp

By applying Kirchhoff law, current will be obtained by the equation

$I = I_{ph} - I_d - I_P$

I_P, is the current leak in parallel resistor

$I = I_{ph} - I_O[\exp(\frac{V+I.R_S}{a}) - 1] - \frac{V+I.R_S}{R_p}$

It is not easy to determine the parameters of this transcendental equation. But this model offers the best match with experimental values

Table 1:DESIGN OF SOLAR PV ARRAY (25°C, AM1.5, 1000 W/M2)

HB-12100 SPV module

Open circuit voltage, V_O	21V
Short circuit current, I_O	3.55A
Voltage at MPP, V_M	17V
Current at MPP, I_M	3.1A

Determination of the parameters
considered that Iph, I0, RS, RP and the factor ideality are five parameters that depend on the incident solar radiation and the cell temperature

1.Determination of Iph :
The photocurrent depends on both irradiance and temperature

$$I_{ph} = \frac{G}{G_{ref}}(I_{ph_{ref}} + \mu_{sc}.T\ )$$

2.Determination of I_o:

The reverse saturation current is defined by

$$I_O = DT^3{}_C\exp(\frac{-q€G}{A.K})$$

3.2Design and modelling of cuk converter

The dc–dc Cuk converter is designed in such a way that it always operates in CCM regardless of the environmental conditions. The peak and RMS currents are substantially lower in CCM resulting in lower losses in the conduction paths and smaller ringing because the energy stored in inductances is proportionalto the square of the current. The rated dc voltage of the SRM is as, *V*dc = 320 V and the PV voltage at MPP is as, *V*pv = *V*mpp = 289 V. The relationship between the duty ratio *D* of the insulated gate bipolar transistor (IGBT) switch, output voltage *V*dc, and input voltage *V*pvof the Cuk converter is given as . The estimation of the parameters of Cuk converter is summarized.

$$\frac{V_{dc}}{v_{pv}} = -\frac{D}{1-D} \rightarrow \qquad D = \frac{V_{dc}+V_{pv}}{V_{dc}} = \frac{320}{320+289} = 0.52$$

The selected values for dc link capacitors are estimated as

$C1 = C2 = \frac{I(30-\alpha)}{2\omega\Delta V\text{dc}}$

where I = DC link current, ω = rated angular speed of SRM, α = conduction angle, ΔVdc = amount of permitted ripple in the voltage across dc link capacitors $C1$ and $C2$, i.e., 1.5% of Vdc. Considering Pin as 900 W, Vdcas 320 V, f as 50 Hz and $\Delta Vc1 = \Delta Vc2$ as 1.5% of Vc1,2,the obtained value of "I" is 2.34 A and the obtained value of $C1 = C2$ is 2441 μF; hence, $C1$ and $C2$ are selected as 2500 μF.

3.3. Design and Modeling of SRM

The equivalent circuit of SRM is modeled as a currentcontrolled voltage source as shown in Fig. In this equivalent circuit, e(t) is the e.m.f. of the SRM. Due to the saliency on rotor and stator side, SRM has nonsinusoidal current and flux across all four windings against the pulse voltage supply. The modeling is carried out on the supposition that the magnetic coupling between two consecutive windings of SRM is negligible and its phase inductance profile has the nonlinear shape [17], [18]. Fig. 5 shows the developed simulink model for 750W, 8/6 pole, 1500 r/min SRM. ITBL and TTBL are the current and torque lookup table obtained from experimental data. The expression obtained after applying KVL in conducting phase of SRM is as

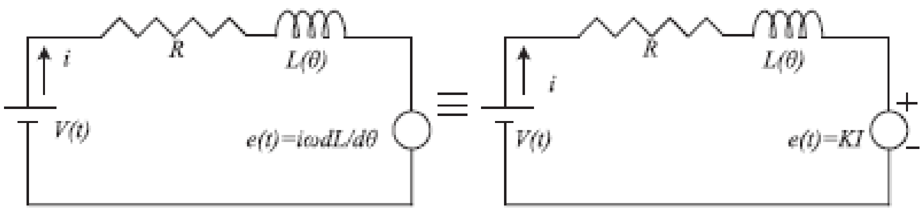


Fig 3.1. Equivalent circuit of SRM.

$V=Ri+\frac{d\psi}{dt} = Ri+\frac{d(Li)}{dt}$

$=Ri+L\frac{di}{dt}+i\frac{dL}{dt}$

$=Ri+L\frac{di}{dt}+i\frac{dL}{d\theta}*\frac{d\theta}{dt} = Ri+L\frac{di}{dt}+i\frac{dL}{dt} + \omega m i\frac{dL}{d\theta}$

where "V" is the terminal voltage, $i$is the current, ψ is the flux-linkage in volt–seconds, R is the phase resistance, L is the phase inductance, θ is the rotor position, and $\omega m$is the angular velocity in rad/s. The last term is sometimes interpreted as a "back-EMF" as follows:

$e=\omega m\,.i\frac{dL}{d\theta}$

The instantaneous electrical power V ×i as follows

$Vi=Ri^2+Li\frac{di}{dt}+\omega i^2\frac{dL}{d\theta}$

The rate of change of magnetic stored energy at any instant is given as follows:

$\frac{di}{dt}\left(\frac{1}{2}Li^2\right)=\frac{1}{2}i^2\frac{dL}{dt} + Li\frac{di}{dt}=\frac{1}{2}i^2\,\omega m\frac{dL}{d\theta}+Li\frac{di}{dt}$

The mechanical power conversion is as follows

$P=T\omega s$

the developed torque is as follows

$T=0.5i^2\frac{dL}{d\theta}$

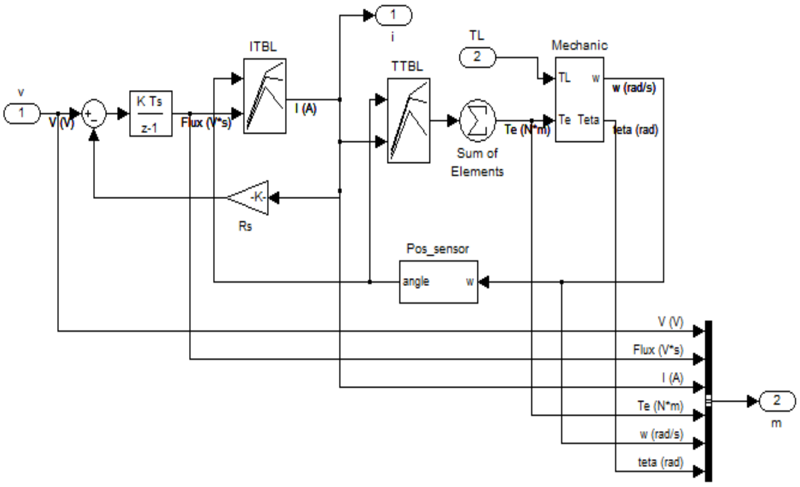


Fig 3.3.2 Developed simulink model of SRM.

III. OPERATION AND CONTROL OF PROPOSED SYSTEM

In the proposed system, maximum power of the SPV array is tracked using InC MPPT technique and the mid-point converter feeding current pulses to the SRM is operated through the electronic commutation. These controllers at the various stages are discussed in brief in following subsections .

4.1MPPT Control

The location of MPP in the *I*–*V* characteristics of SPV array is not predicted in advance and always varies dynamically with insolation levels and environmental conditions The governing equations which explain the operating principle of InC method are as

$$v_{pvref}\,(k) = v_{pvref}\,(k+1) + \text{step, if } \frac{\Delta I}{\Delta V} > -\frac{I_{pv}}{v_{pv}}$$

$$v_{pvref}\,(k) = v_{pvref}\,(k-1) - \text{step, if } \frac{\Delta I}{\Delta V} < -\frac{I_{pv}}{v_{pv}}$$

whereΔI &ΔV = change in PV current and voltage in two consecutive samples

The reference voltage of SPV array is checked for upper and lower limits, which are set to 0.7 *V*ocmax–0.9 *V*ocmax. In case the *V*pvrefis between the limits, it is kept as it is else the *V*pvref is saturated to the nearest limit. The saturation block output is designated as new reference PV voltage (*V*pvrefn). The *V*pvrefn and sensed PV voltage are then used to estimate the duty ratio for the Cuk converter. The governing equation for estimating

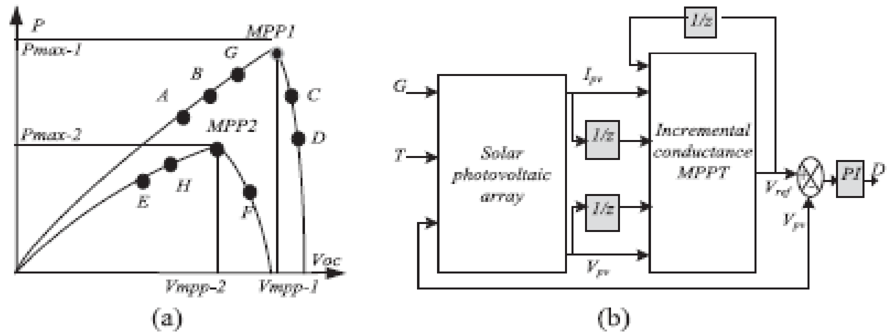


Fig 4.1.1 Explanation of InC method and generation of duty cycle for dc–dc converter by InC algorithm. Diagrammatical explanation of (a) InC method and (b) generation of duty cycle for dc-dc converter.

TABLE 2:ALL POSSIBLE SCENARIO OF INC ALGORITHM

General Condition	First Point	Happened	Duty Cycle	Next Point
Fixed Solar Irradiance Level	MPP-1 B MPP-1 C	A($P_{pv}\downarrow, v_{pv}\downarrow$) A($P_{pv}\downarrow v_{pv}\downarrow$) D($P_{pv}\downarrow v_{pv}\uparrow$) D($P_{pv}\downarrow v_{pv}\downarrow$)	D+ D+ D- D-	B G C Below c
Variable Solar Irradiance	MPP-2 MPP-2 MPP-1 MPP-1	B($P_{pv}\downarrow v_{pv}\uparrow$) C($P_{pv}\uparrow v_{pv}\uparrow$) E($P_{pv}\downarrow v_{pv}\downarrow$) F($P_{pv}\downarrow v_{pv}\uparrow$)	D- D+ D+ D+	G MPP-1 H Below F

Cuk converter duty ratio is as follows

$$D(k) = 1-\frac{v_{pv}}{v_{pv}+v_{pvref}}$$

This reference duty ratio is compared with saw-tooth waveform to generate switching logic for the switch of the Cuk converter.

4.2Control of Mid-Point Converter

The complete switching scheme of a mid-point converter is controlled by three parameters: the advance angle (turn-ON angle), θon, turn-OFF angle, θoff, and value of the effective dc link voltage. The switching angles are defined for each phase based on the rotor position estimation provided by a position Hall sensorslocated on the stator of SRM . A mid-point converter injects unipolar current pulses at desired rotor positions to SRM drive. It also controls the magnitude of current for efficient operation of the motor drive and IGBT switches .The voltage equation at starting is as follows

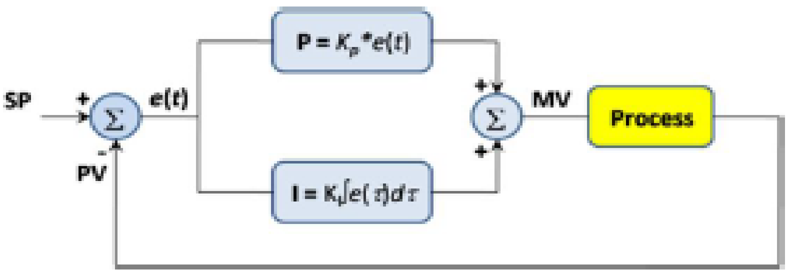
$$\frac{1}{2}V_{dc} = L\left(\frac{di}{dt}\right) = L\left(\frac{di}{d\theta}\right)\left(\frac{d\theta}{dt}\right)$$

$$L\,\omega\left(\frac{di}{d\theta}\right) as\ \omega = \left(\frac{d\theta}{dt}\right)$$

Phase voltage	Phase current	Device status
V_A = Vdc/**2**	i1>0	T1-ON,D1-OFF,D2-OFF
V_A = - Vdc/**2**	-	T1-OFF ,D1-ON, D2-ON
V_A = 0	i1<0	T1-OFF,D1-OFF,D2-OFF

4.3Proportional-Integral (PI) controller

The combination of proportional and integral terms is important to increase the speed of the response and also to eliminate the steady state error



The controller output is given by

$$OP = K\left(\text{error} + \frac{1}{T_i}\int \text{error dt}\right)$$

The Proportional-Integral (PI) algorithm computes and transmits a controller outputsignal every sample time, T, to the final control element. The computed output from the PI algorithm is influenced by the controller tuning parameters and the controller error (Δ).Integral action enables PI controllers to eliminate offset, a major weakness of a P-only controller. Its function is to integrate or continually sum thecontroller error

The proportional term of the PI controller adds or subtracts based on the size of controller error. As error grows or shrinks, the amount added grows or shrinks immediately or proportionately. While the proportional term considers the current size of error only at the time of the controller calculation, the integral term considers the history of the error, or how long and how far the measured process variable has been from the set point over time. Thus the integral action eliminates offset. It continually resetsthe bias value of controller toeliminate offset as operating level changes. Thus the PI controller eliminates offset error and increases the speed of the response.

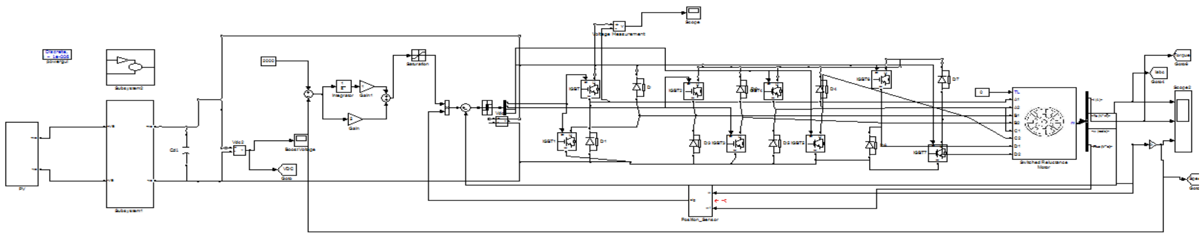
Table 3: Comparison of different types of conventional controllers

controller	Response time	overshoot	Error
On-off	Smallest	Highest	Large
proportional	Small	Large	Small
integral	decreases	increases	zero
derivative	increases	decreases	Small change

In this case, the flux and constant and variable speed from the output is given as input to the PI controller through sum and output of PI controller is given as gate signal to each converter whichcontrols the phases of SRM.The following values are given for PI controller. kp=0.00188

KI=0.299 These values for Kp and Ki are found using trial and error method. PI controller is more suitable during steady state and provides robustness to load disturbance.

Fig 4.3.1**: SIMULATION DIAGRAMClosed loop pi control for switched reluctance motor drive**



IV. RESULT DISCUSSION

The output obtained for four phase SRM using PI controller is shown below. Singleconverter is used for each phase and hence totally four converters for four phases. Thus voltage, current and flux for four phases is obtained. Speed and torque waveform for motor is shown in last two graphs**.**

Speed is controlled by varying the turn on and turn off angle which is given to converter through the PI controller. The tolerance of SRM is small when comparedwith other motors.

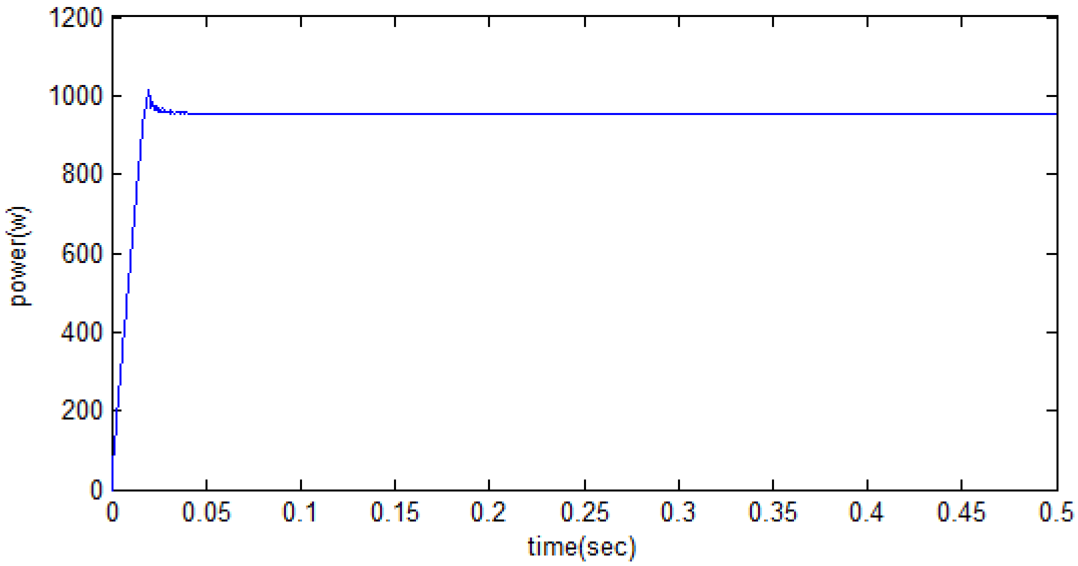


Fig 5.1:solar power waveforme

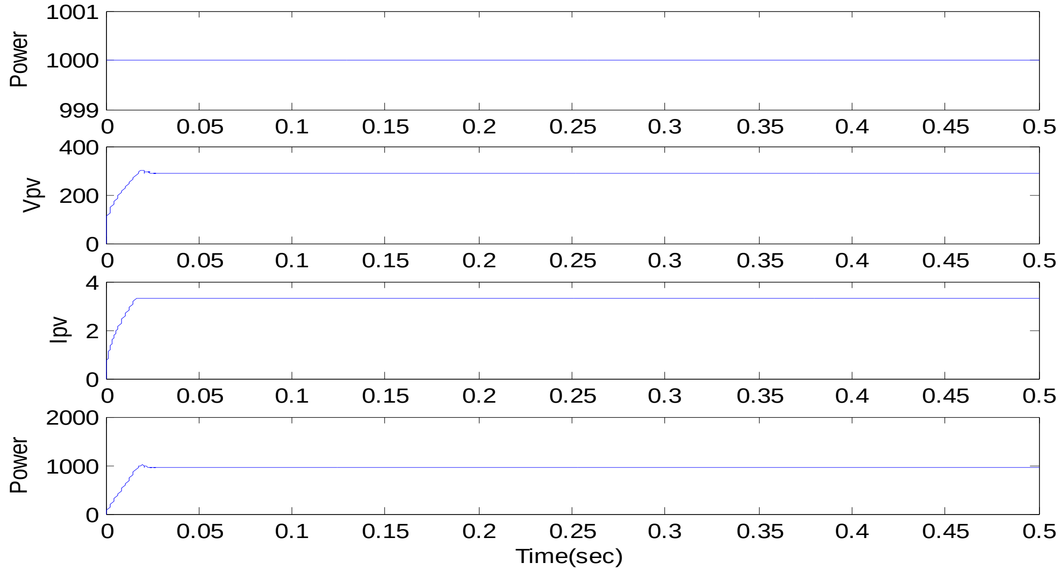


Fig 5.1.1 Performance of SPV array.

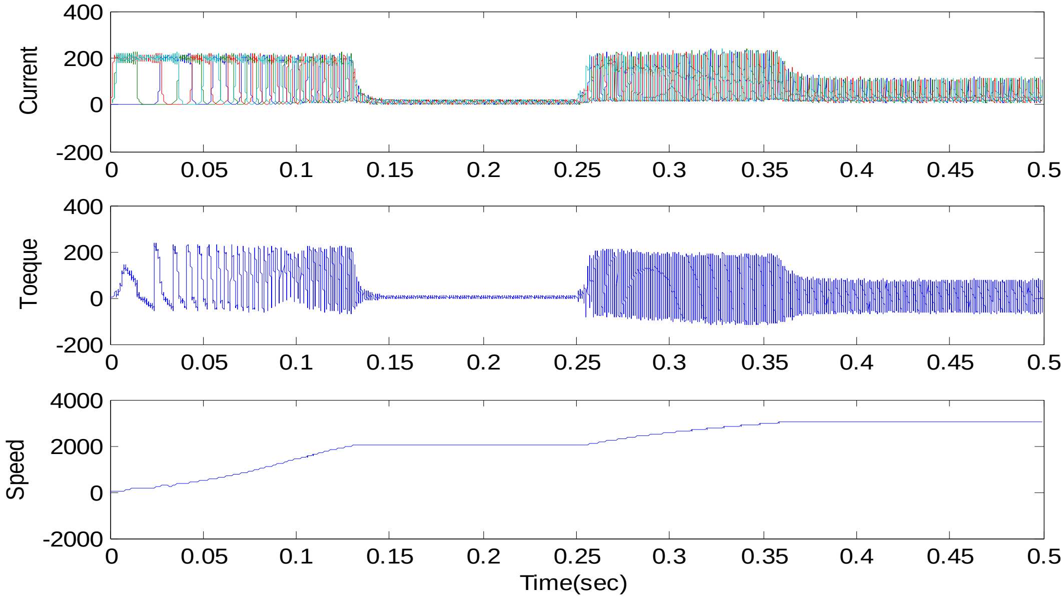


Fig 5.2:performance ofclosedloop pi control of variable speed SRM Drive(2000 rpm -3000 rpm)

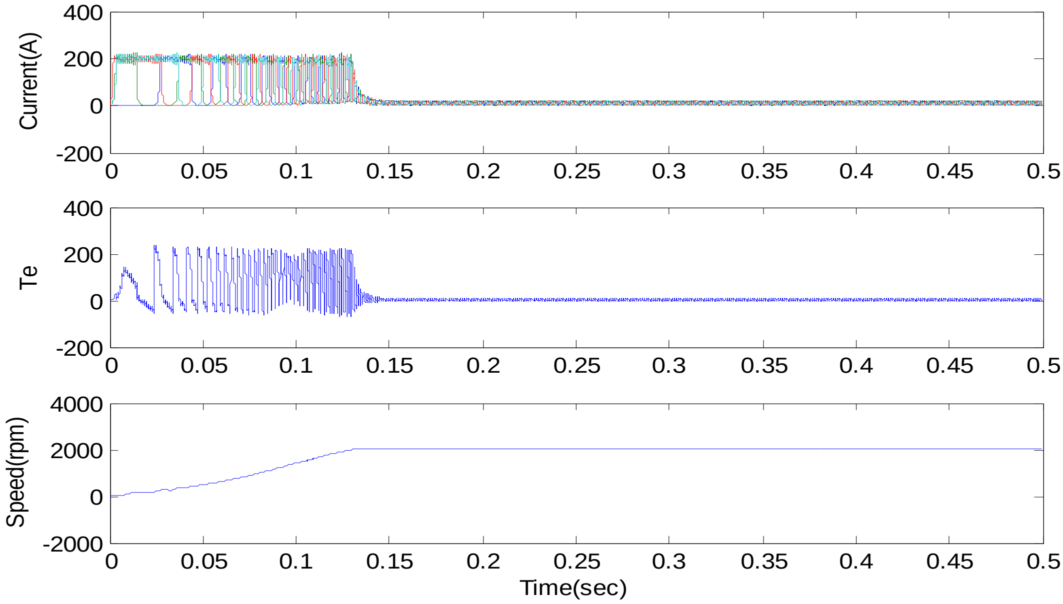


Fig 5.3:performance of closedloop pi control of constant speed (2000) SRM Drive

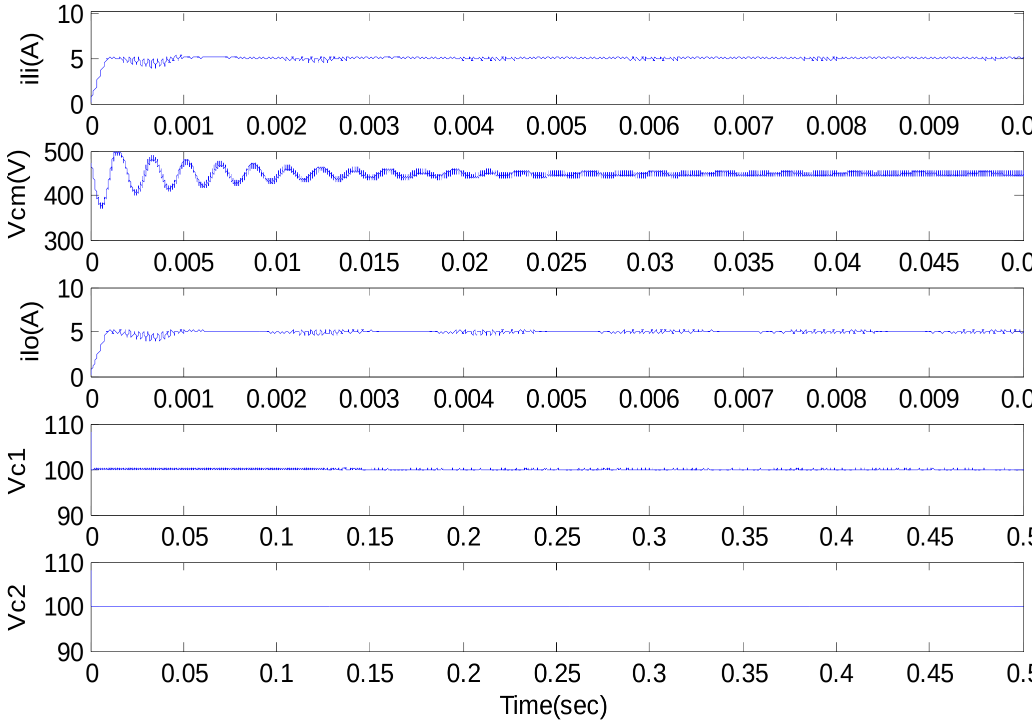


Fig 5.4:Cuk converter parameters response.

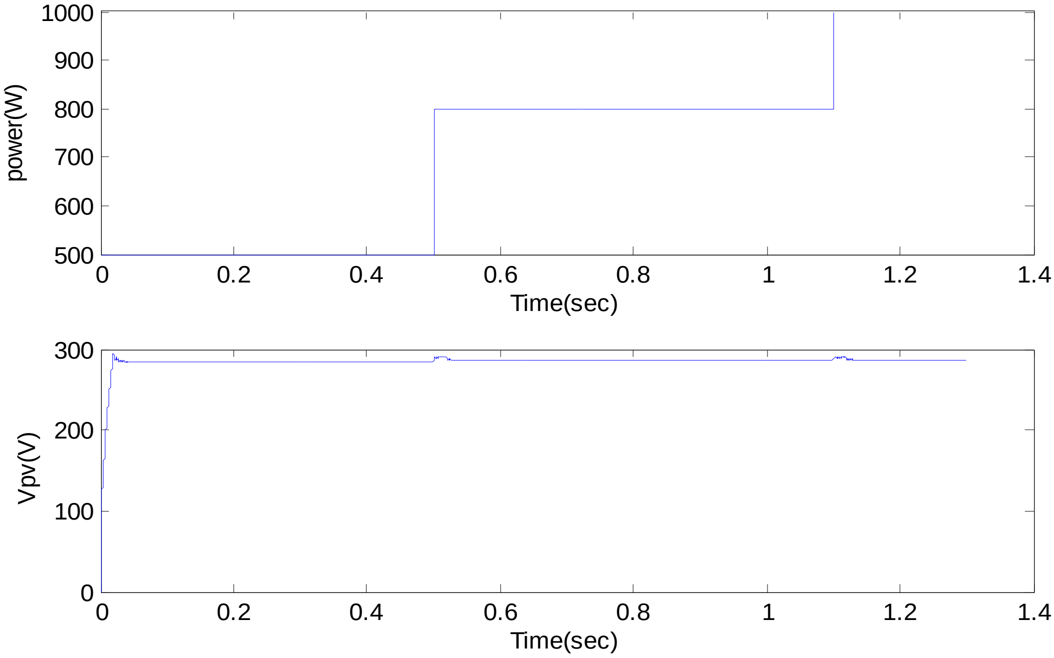


Fig: 5.5 Performance of SPV array and variation of duty cycle for switch of Cuk converter during varying insolation levels

VI.CONCLUSION

In this paper, the speed of foure phase SRM is controlled using PI controller.It is clear that the offset error is eliminated and the speed of the response is increased. this theree phase motor has more advantages such as the reduction in torque ripple with increase in the number of phases and faster response. In 8/6 SRM the torque and speed control performance will be more when compared to other controllers.The CCM operation of Cuk converter has also boosted the efficiency of proposed water pumping system by reducing voltage and current stresses on devices of Cuk converter and increasing power output ofCuk converter by lowering the ringing effect of system.Closed loop pi controller has the advantages of controlling the constant speed and variable speed of SRM drive.

APPENDIX:

A. SRM Specification *:*
750 W, 8/6 pole, Four phase, 1500 r/min, dc link voltage =320 V.

B. Selected Parameters of Solar PV Array
Open circuit voltage, *V*oc = 21 V; Short circuit current, *I*sc = 3.55 A; Maximum power, *P*mp = 900W;Voltage at MPP, *V*mp = 289 V; Current at MPP, *I*mp = 3.1 A; Numbers of modules connected in series, *ns* = 17; Numbers of modules connected in parallel, *np* = 1.

C. Parameter Selection for Design of Cuk Converter
Switching frequency, *f*sw = 20 kHz; Input inductor, *Li* = 6.25 mH; Output inductor, *Lo* = 6.87 mH; Energy transfer capacitor,*Cm* = 3μF; dc link capacitors, *C*1 = *C*2 = 2500 μF.

D. PI controller
Reference speeds 2000 and3000

REFERENCES

[1]. B.N. SINGH, B. SINGH, B.P. SINGH, A. CHANDRA AND K. AL-HADDAD, "OPTIMIZED PERFORMANCE OF SOLAR POWERED VARIABLE SPEED INDUCTION MOTOR DRIVE," *PROC. OF THE INTERNATIONAL CONFERENCE ON POWER ELECTRONICS, DRIVES AND ENERGY SYSTEMS FOR INDUSTRIAL GROWTH (PEDES'96)* HELD AT NEW DELHI, 1996 PP, 58-66.

[2]. K.Y.Lu, P.O.Rasmussen, S.J. Watkins and F. Blaabjerg, "A New Low-Cost Hybrid Switched Reluctance Motor for Adjustable-Speed Pump Applications,'' *Proc. of IEEE 41st IAS Annual Meeting*, held at 8-12 Oct.2006, pp.849-854.

[3]. S. Belliwali, A. Chakravarti and A.B. Raju, "Mathematical modelling and simulation of directly coupled PV water pumpingsystem employing Switched Reluctance Motor,'' *Proc. of IEEE PES Innovative Smart Grid Technologies* - India (ISGT India), 1-3 Dec.2011, pp.no.386-390.

[4]. Mahesh Krishnamurthy, Chris S. Edrington and BabakFahimi, "Prediction of Rotor Position at Standstill and Rotating Shaft Conditions in Switched Reluctance Machines," *IEEE Transactions on Power Electronics*, vol. 21, no. 1, pp. 225-233, January 2006.

[5]. Kim Jaehyuck and R.Krishnan, "Novel Two-Switch-Based Switched Reluctance Motor Drive for Low-Cost High-Volume Applications," *IEEE Transactions on Industry Applications*, vol.45, pp.1241-1248, July-Aug. 2009.

[6]. B. Singh and A.K. Mishra, "Canonical switching cell converter fed SRM drive for SPV array based water pumping," *2nd InternationalConference on Computing for Sustainable Global Development (INDIACom)*, 11-13 March *2015*, pp.932-937.

[7]. D.Sera, L. Mathe, T.Kerekes, S.V. Spataru and R.Teodorescu, "On the Perturb-and-Observe and Incremental Conductance MPPT Methods for PV Systems," *IEEE Journal of Photovoltaics*, vol.3, no.3, pp.1070-1078, July 2013.

[8]. R. Krishnan,*Switched Reluctance Motor Drives: Modeling, Simulation, Analysis, Design and Applications*. Boca Raton, FL, USA: CRC Press,2001

[9]. T. J. E. Miller,*Switched Reluctance Motor and Their Control*. Madison, WI, USA: Magna Physics Publishing, 1993.

[10]. B. K. BOSE, T. J. E. Bose, P. M. Szczesny, and W. H. Bicknell, "Microompouter control of switchedreluctance motor," *IEEE Trans. Ind. Appl.*, vol. IA-22, no. 4, pp. 708–714, Jul./Aug., 1986.

[11]. V. Bist and B. Singh, "PFC Cuk converter-fed BLDC motor drive," *IEEE Trans. Power Electron.*, vol. 30, no. 2, pp. 871–887, Feb. 2015.

