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A PROPOSED DESIGN OF SWITCHED RELUCTANCE MOTOR CONVERTER ADAPTED FOR MPPT OPERATION OF SOLAR PV POWERED WATER PUMP

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ABSTRACT
Photovoltaic energy is widely applied to electrify off -gird zones. One of the most interesting applications of photovoltaic system is the photovoltaic water pumping system (PVWPS). This paper deals with PVWPS employing a switched reluctance motor (SRM) drive. SRM drive offers a number of merits due to its simple construction, highly starting torque and fast response. In addition to that, rotor of SRM has no coils or magnets which results in low copper losses, high robustness and low maintenance. Conventional PVWPS employing SRM consists of a PV array as an energy generator, a DC-DC converter used to operate the PV array at its maximum power point (MPP), a converter for driving the SRM drive, a water pump coupled to SRM. The proposed PVWPS presented in this paper eliminates the DC-DC converter used for maximum power point tracking (MPPT) and adapts the SRM converter to operate the PV array at MPP as well as driving the SRM. Consequently, the cost of the PVWPS is reduced. Modeling, simulation and performance analysis of the proposed PVWPS with adaptive converter are presented to study its effectiveness.

KEYWORDS: Photovoltaic energy;DC-DC converter; Switched reluctance motor; MPPT.

INTRODUCTION

Globally, Renewable energy such as solar, wind, geothermal and hydro energy has gained a deep attention nowadays for electrical applications since it's free, clean and sustainable. PV arrays have occupied an important position in harvesting the solar energy due to simple installation, low maintenance and low operation cost. PVWPS is vastly used in irrigation and building new communities at off grid areas where connecting to the public electrical grid is technically unavailable. Researchers have analyzed and investigated the performance of PVWPS using different types of AC and DC motors. R. Kumar and B. Singh presented a solar photovoltaic powered brushless DC motor (BLDC) suitable for water pumping system [1]. Performance improvement of photovoltaic water pumping system using a three phase induction motor was presented by S. S. Dessouky et al [2]. A. Varshney designed a control system of solar PV array powered water pumping system driven by a synchronous reluctance motor (SyRM) [3]. R. Antonello et al presented a novel off grid PV water pumping system driven by a permanent magnet synchronous motor [4]. PVWPS using switched reluctance motor was presented in many papers: A. K. Mishra designed and developed an efficient solar pumping system with reduced cost depending on SRM [5]; L. Quéval developed a numerical model of photovoltaic SRM prototype with taking into account the nonlinearity behavior of both the SRM and photovoltaic module [6]; Wang proposed a new control strategy with validated results of PVWPS employing SRM [7].

In this paper, the proposed PVWPS consists of a centrifugal water pump which is coupled to a SRM; the SRM is fed from a PV array through an adaptive converter. The adaptive converter has two functions: to drive the SRM and to operate the PV array at its MPP. MATLAB Simulation and performance analysis of PVWPS with the adaptive converter are presented.

1. Modeling of Conventional PVWPS

2.1. PV array mathematical modeling

The power of falling light impinging the PV cell is converted directly to DC energy. PV cells are connected in series- parallel combinations to form a PV module. In order to harvest more solar energy, PV modules are connected together to form PV arrays. Equivalent circuit of a PV array is shown in Fig. 1. Equations (1-4) present a general formula of a PV array modeling [8-10]. Parameters of the used PV array are listed in Table 1.

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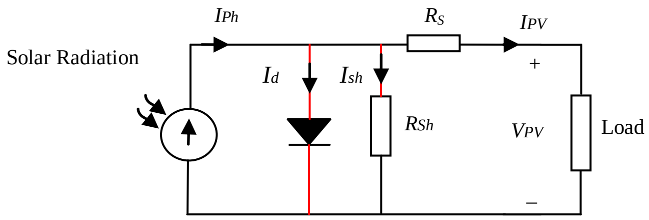


Figure 1: The equivalent circuit of a PV array.

$$I_{PV} = N_P[I_{ph} - I_d - I_{sh}] \quad (1)$$

$$I_{PV} = N_P\left[I_{ph} - I_S\left[exp\left(\frac{q\left(\frac{V_{PV}}{N_S}+\frac{IR_S}{N_P}\right)}{nkT}\right) - 1\right] - \frac{N_P V_{PV} + N_S I_{PV} R_S}{N_S N_P R_{SH}}\right] \quad (2)$$

$$I_{ph} = \left(I_{sc} + K_i\left(T_c - T_{ref}\right)\right) * \frac{G}{G_{ref}} \quad (3)$$

$$I_s = I_{rs}\left(\frac{T_c}{T_{ref}}\right)^3 exp\left(\frac{qE_G}{kn}\left(\frac{1}{T_{ref}} - \frac{1}{T_c}\right)\right) \quad (4)$$

Table 1: Parameters of the used PV array

Short circuit current, I_{sc}	38 A
Open circuit voltage, V_{OC}	195V
MPP voltage, V_{mpp}	159 V
MPP current, I_{mpp}	36.5 A
Ambient temperature, T_{ref}	25 ^{0} C
Parallel modules number, N_P	10
Series modules number, N_s	10

At 250C and 1000 W/m2, I-V and P-V characteristics of the used solar PV array are shown in Fig. 2. Tracking efficiency of a PV array for a stable load at stable environmental conditions is calculated as follows [11]:

$$\eta_{MPP} = \frac{P_{PV\,output}}{P_{MPP}} \quad (5)$$

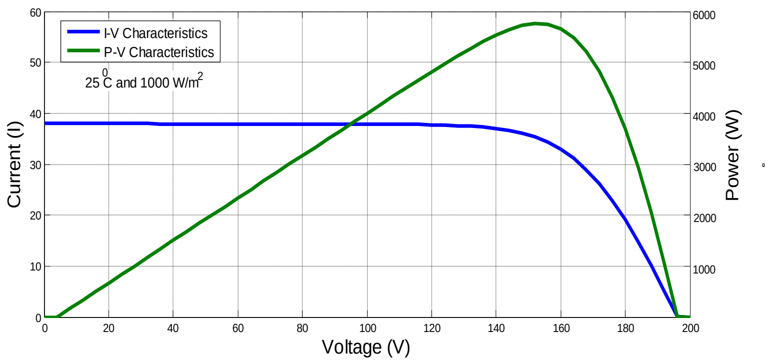


Figure 2: I-V and P-V curves of the studied PV array.

2.2. SRM drive and converter modeling

SRM drive has an unequal number of salient rotor and stator poles. Coils are carried by the stator while the rotor is cage-less and has no magnets. Basically, SRM is excited by a dc source via a driving converter. Therefore, 6/4 SRM drive and the driving converter are studied as one unit of as shown in Fig.3.

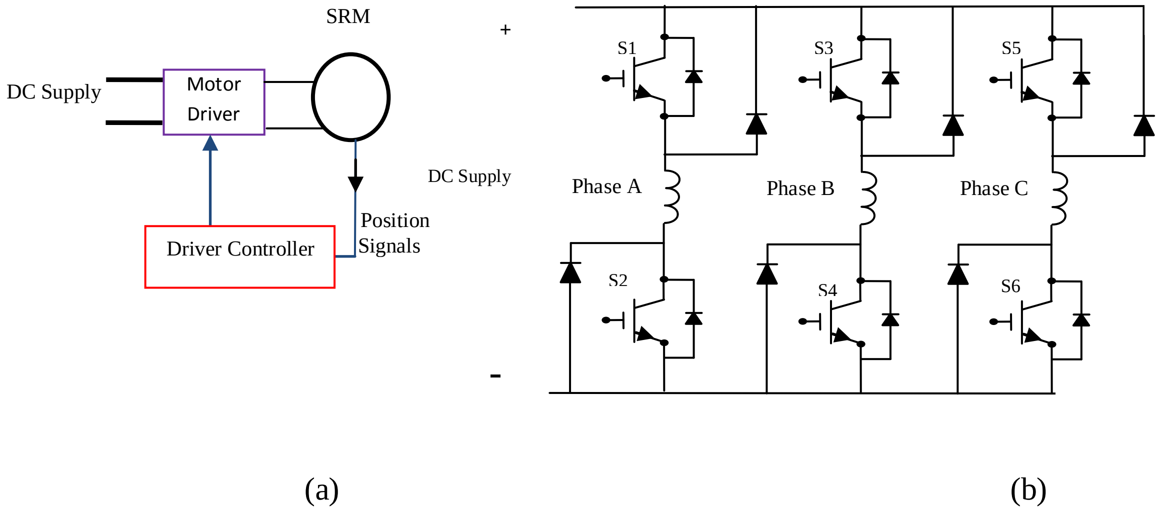


Figure 3: 6/4 SRM drive with the driving converter (a) Symbolic block, (b) schematic circuit.

A rotor position sensor is used to control the turn on angle θ_{on} and the conduction angle θ_{Cond} of each phase switches, thus controlling the energizing of each phase of the SRM drive [12].SRM drive can be mathematically modeled as follows [13]:

$$V = i.R + l(i,\theta)\frac{di}{dt} + e \quad (6)$$

$$e = \omega_m.i.\frac{dl(i,\theta)}{d\theta} \quad (7)$$

$$T_e = \frac{1}{2}i^2.\frac{dl(i,\theta)}{d\theta} \quad (8)$$

$$T_e = T_L + B\,\omega + J.\frac{d\omega}{dt} \quad (9)$$

The SRM parameters used in the simulation are listed in Table 2.

Table 2: Parameters of the studied SRM drive.

Number of stator poles	6
Number of rotor poles	4
Phase resistance, R (Oh m)	0.25
Inertia (kg.m.m)	0.05
Friction (N.m.s)	0.02

2.3. Buck converter modeling

DC-DC converters are used in converting the input dc voltage to another dc voltage of different value. The buck converter shown in Fig. 4 produces an output voltage that is lesser than the input one while the output current is higher than the input one. When the insulated-gate bipolar transistor (IGBT) switch is ON, the inductor current is given by [14]:

$$I_L = \int_0^{DT} \left(\frac{V_{PV}-V_O}{L}\right) dt \qquad (10)$$

when the IGBT switch is OFF, the inductor current is given by [15]:

$$I_L = \int_{DT}^{T} \left(\frac{-V_O}{L}\right) dt \qquad (11)$$

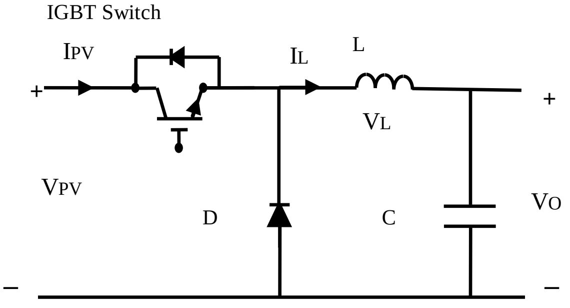


Figure 4: The circuit diagram of the buck converter.

2.4. Centrifugal pump modeling

In general, the centrifugal pump is commonly used in water pumping application. By increasing the speed of the pump more water quantity and pressure can be obtained. Centrifugal water pump can be modeled mathematically as follows [16]:

$$T_L = T_o + C_p \omega_r^{1.8} \qquad (12)$$

$$P_h = \rho g Q h \qquad (13)$$

Parameters of the Centrifugal pump are listed in Table 3.

Table 3: Parameters of the studied centrifugal pump

T_o (Nm)	0.95
C_p	0.001
ρ (Kg/m^3)	1000
h (m)	5

2. Operating PVWPS with conventional MPPT

In this case, the switched reluctance motor is connected to the PV array through a DC-DC converter as shown in Fig.5. The DC-DC converter is operating as a MPPT. Voltage and current transducers are required for the operation of the DC-DC converter.

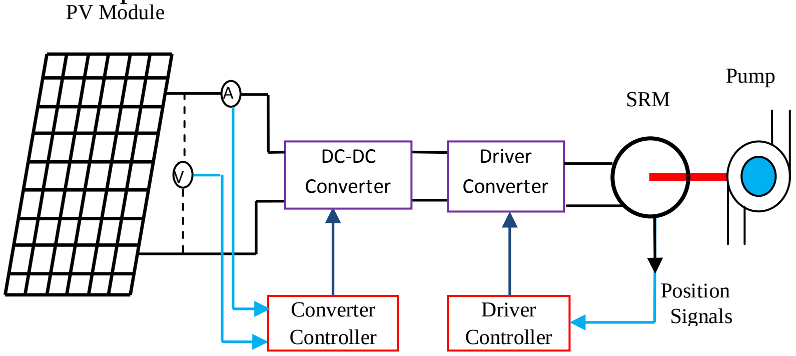


Figure 5: Schematic drawing of operating PVWPS with MPPT.

Many MPPT techniques are developed so that, the PV array can be operated at the MPP. Perturbation and Observation (P&O) technique is commonly used for MPPT. P&O depends on the P-V characteristic of the PV array; where ΔP is zero at the MPP, positive at the left side of the P-V curve and negative at the right side of the P-V curve [17]. The flowchart presented in Fig. 6 explains the control process of continuous modification of the duty cycle *D* in order to operate the PV array at MPP.

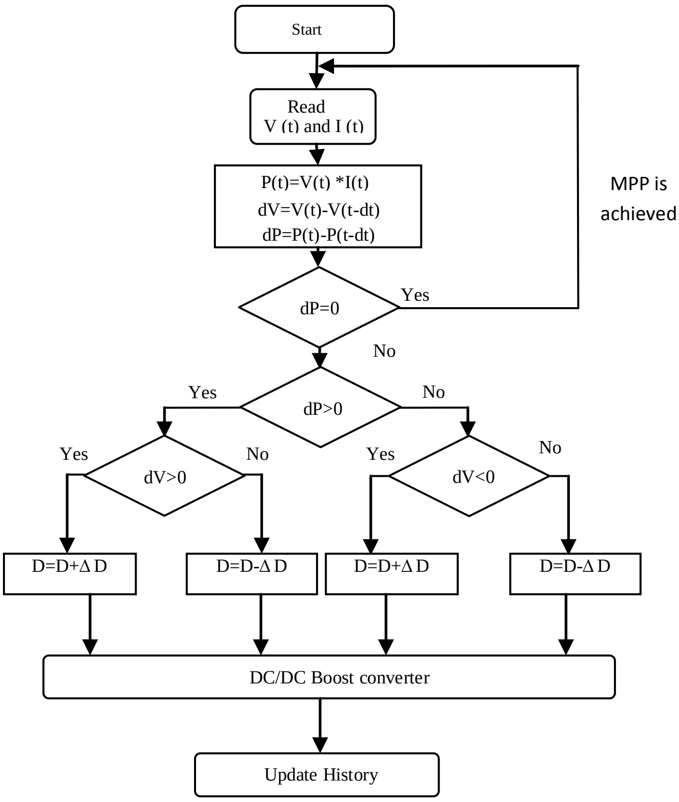
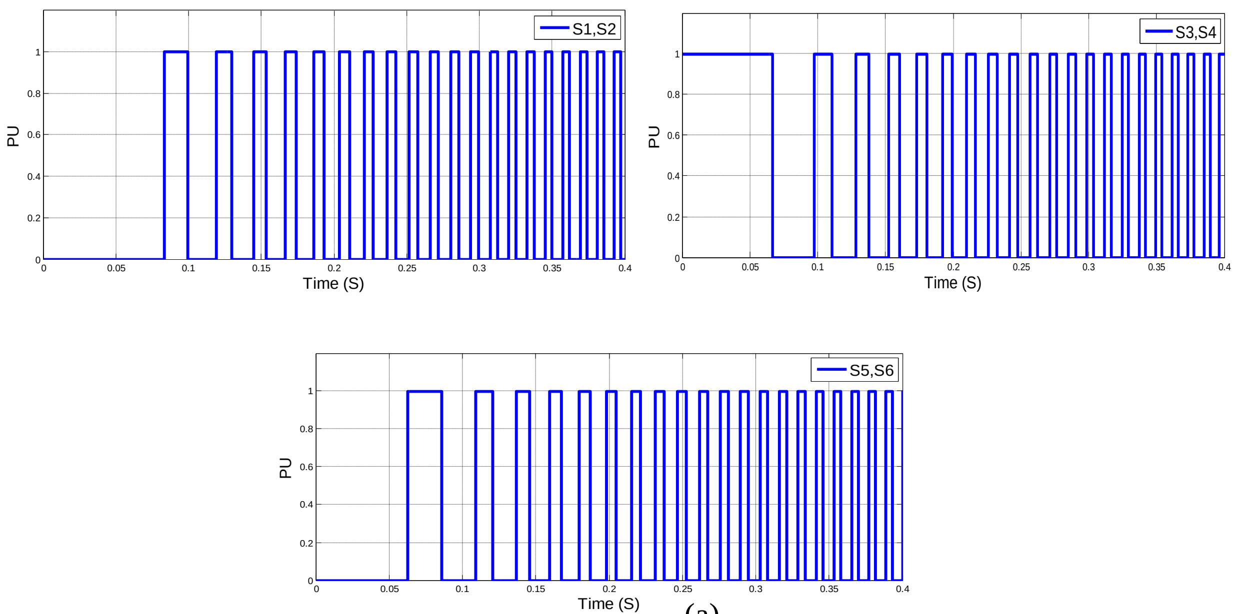
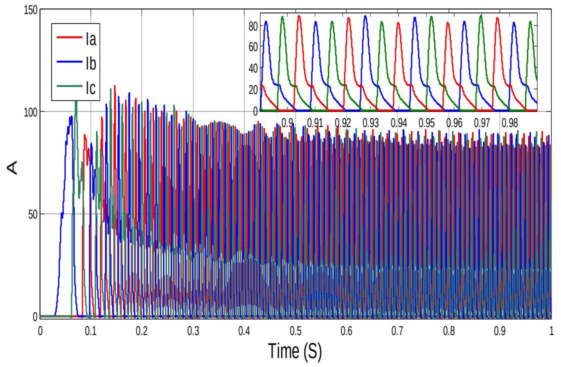


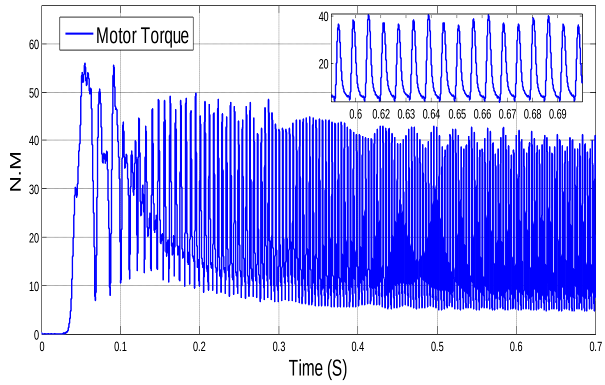
Figure 6: Perturbation and Observation (P&O) algorithm for MPPT.

Behaviors of control signals, motor current, torque, speed, array power, and water flow rate are shown in Fig. 7.

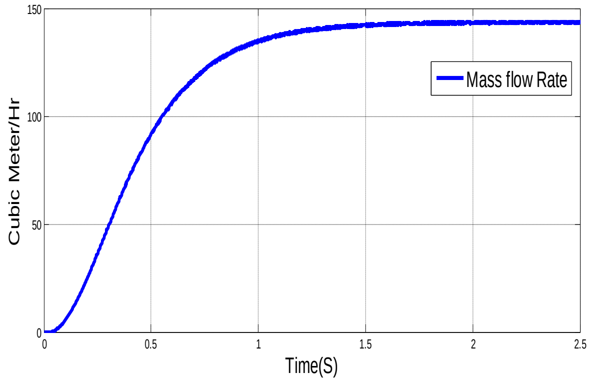


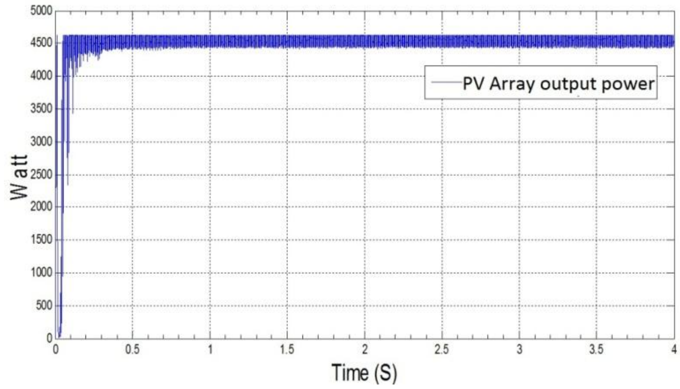
(a)





(b) (c)





(d) (e)

Figure 7: Operating PVWPS with MPPT (a) Control signals, (b) SRM currents, (c) SRM torque, (d) Water florw rate and (e) PV array output power.

3. Operating PVWPS with adaptive converter

In this proposed technique, the SRM is fed from a PV array through the adaptive driver converter as shown in Fig.8. A new control algorithm based on the P&O MPPT is developed to adapt the driver converter as shown in Fig. 9. The adaptive converter has two functions: to drive the SRM and to operate the PV array at its MPP. Behaviors of control signals, motor current, torque, speed, array power, and water flow rate are shown in Fig. 10.

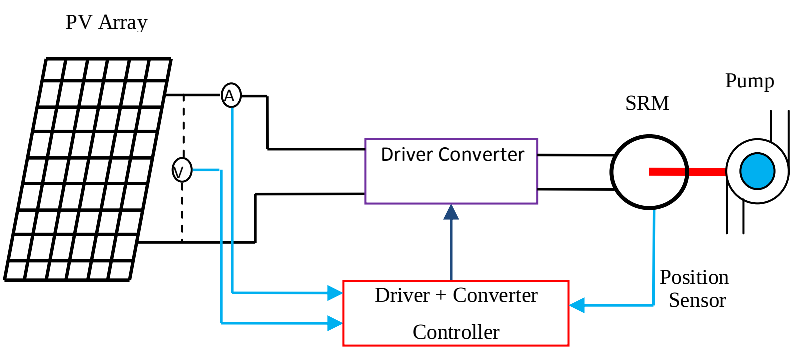


Figure 8: Ciruit diagram of PVWPS with the adaptive converter

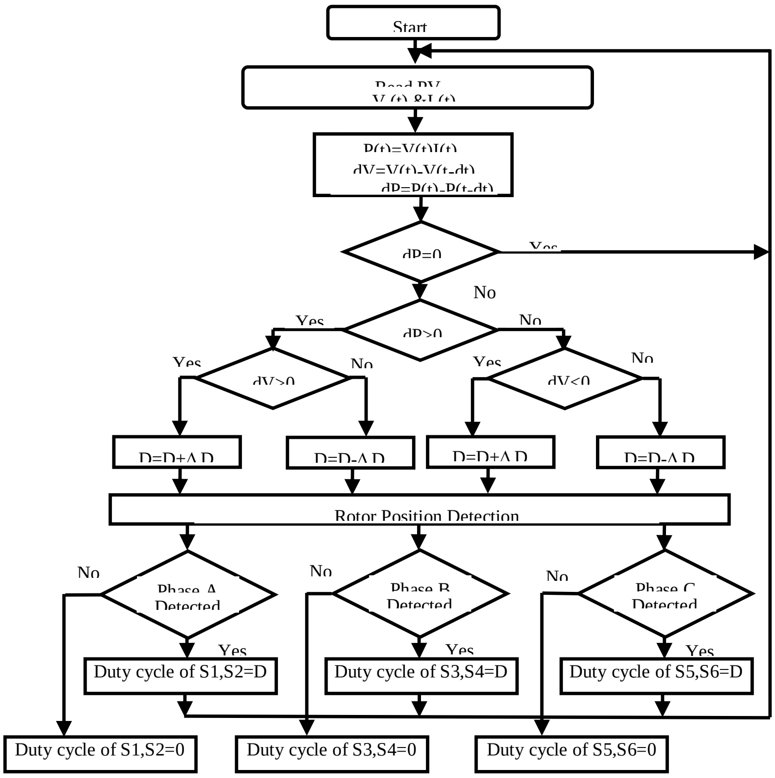
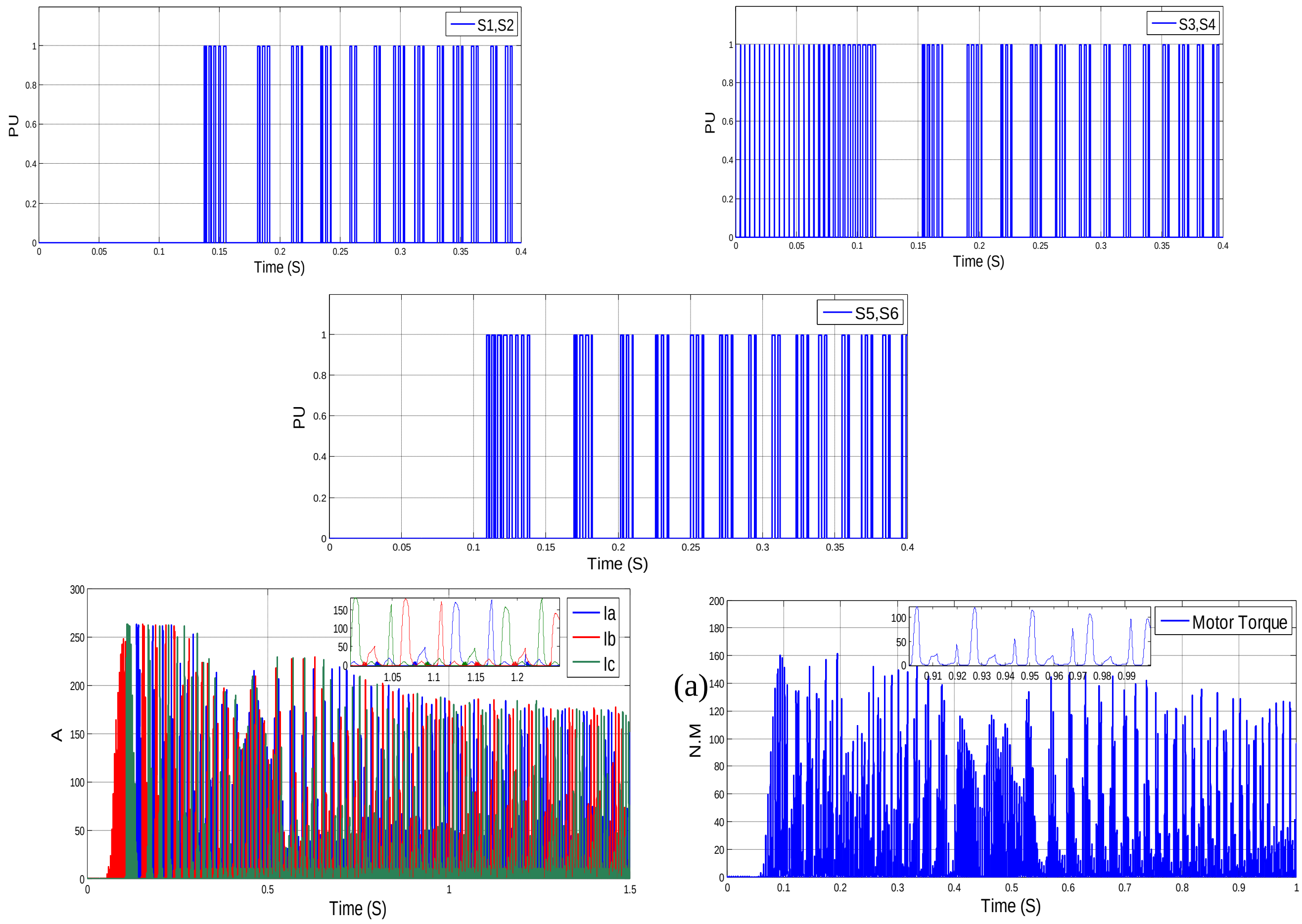
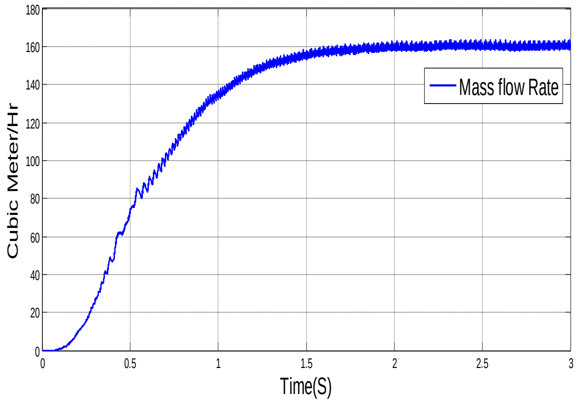


Figure 9: Schematic diagram of the algorithm used in producing the control signals of the adaptive converter.

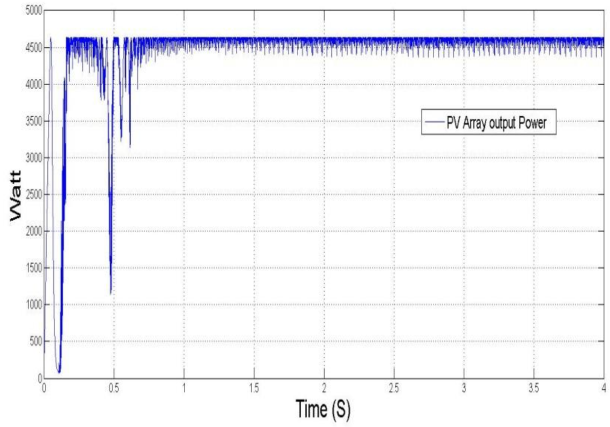


(a)

(b) (c)



(d)



(e)

Figure 10: Operating PVWPS with adaptive converter (a) Control signals, (b) SRM currents, (c) SRM torque, (d) Water florw rate and (e) PV array output power.

Figure 11:

4. Comparative analysis and discussion

Table 4 presents summarized results of the previous simulations. The output power of PVWPS without MPPT is 1950 watts which is far away from the MPP. In addition to that, the output power is highly fluctuated with ΔP=4000 watts. However, PVWPS cost is reduced compared with other cases as DC-DC converter with its voltage and current transducers are not used. In addition to that, switches of the driver converter have low switching frequency up to 77 HZ. As the PV array is operated far away from the MPP, the efficiency of PVWPS without MPPT is 14.58%. PVWPS with MPPT presented a high efficient performance as the produced output power is 4560 watts which is 98.5 % of MPP. In addition to that, the power has low fluctuation around 200 watts. Response time required to operate the PV array at MPP is 0.0790 sec. Switches of the driver converter have low switching frequency up to 111 HZ. However, applying a DC-DC converter to operate the PV array at MPP increases the total cost of PVWPS. As the PV array is operated with MPPT, the efficiency of PVWPS is 42.26%. Efficiency of DC-DC converter is 82.24% which affects highly on the system efficiency. Operating the PVWPS with the adaptive converter presented an effective performance. The output power of the PV array is 4558 watts which is around 98.5% of MPP. In addition to that, the power has low fluctuation around 264 watts. Response time required to operate the PV array at MPP is 0.126sec. Switches of the driver converter have high switching frequency up to 500 HZ. Elimination of DC-DC converter results in losses reduction of the PVWPS and increasing the efficiency up to 48.59%.

Table 4: Comparison among PVWPS without MPPT, with MPPT and with adaptive converter

Index	*Without MPPT*	*With MPPT*	*With Adaptive Converter*
Theoretical MPP	4627	4627	4627
PV Output Power	1950	4560	4558
Power Fluctuation Δ P	4000	200	264
Response Time	N.A	0.079	0.65
MPPT Efficiency	42.14	98.55	98.51
Speed	1120	1730	1800
DC-DC Converter Efficiency	N.A	82.24	N.A
SRM Efficiency	53.33	75.33	70.21
Volume Flow Rate	49.5	143.5	165
Pump Efficiency	64.85	69.21	70.25
Switching Frequency	77.00	111.00	500
System Efficiency	14.58	42.26	48.59

CONCLUSION

Proposed PVWPS driven by SRM was presented in this paper. Conventional DC-DC converter used for MPP has been eliminated. A new control algorithm is developed to adapt the SRM converter in order to operate the PV array at its MPP as well as driving the SRM. The proposed PVWPS with the adaptive converter showed a high effective performance; the converter succeeded to drive the SRM in a manner that kept the operating point of the PV array close to 98.5 % of MPP with no need to use a DC-DC converter. Switching frequency of the adaptive converter switches which goes up to 500 HZ is higher than that in case of using DC-DC converter. In addition to that, response time required to operate the PV array at MPP with adaptive converter is 0.65 sec which is higher than that in case of using MPPT. However, the total cost of the PVWPS is reduced due elimination of the DC-DC converter. Also, Elimination of DC-DC converter results in losses reduction of the PVWPS and increasing the efficiency up to 48.59%. At low irradiance, efficiency of PVWPS with MPPT is higher than PVWPS with adaptive converter, but as the irradiance increases the DC-DC converter losses increases until efficiency of PVWPS with adaptive converter becomes higher than PVWPS with MPPT.

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