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Harnessing Maximum Power from Solar PV Panel for Water Pumping Application: A Simple Approach

Mrityunjaya Kappali*[1] and R.Y. Uday Kumar [#]

Abstract – *Among alternate sources of electricity, solar photovoltaic (PV) energy is gaining prominence due to its plentiful availability. Water pumping is an important application of solar PV power. However people are not opting for it in large numbers as 'cost per watt' for solar pumping systems is high and the reliability is poor due to complex technology. The cost can be reduced by harnessing more power per unit installed capacity of the solar panel. One of the methods of realizing this is by Maximum Power Point Tracking (MPPT) wherein a power electronic converter is used to match pump with the PV panel. Currently 'panel power' is the widely employed control parameter for MPPT. This approach can be referred to as* $MPPT_{PP}$.

Present paper proposes load voltage as control parameter for MPPT. Varying the duty cycle of the MPPT converter such that load voltage is always maximum leads to harnessing maximum power output. This approach can be referred to as $MPPT_{LV}$. *Here only one parameter i.e. load voltage needs to be monitored.* $MPPT_{LV}$ *is simpler than* $MPPT_{PP}$ *as in the latter case it's necessary to measure both panel voltage and current and then find their product.*

The proposed method is substantiated by theoretical explanation followed by simulation as well as experimentation results. The system considered is a standalone PV source connected to Permanent Magnet (PM) brushed DC motor driving centrifugal pump.

Keywords –Maximum power tracking, MLVPT, PMDC motor pump, PV.

1. INTRODUCTION

In India there are 21 million pumps. Of these 12 million are grid connected and 9 million are diesel driven. There exists a big opportunity for solar pumps to replace the diesel pumps. However, the increase in the number of solar pumps is just 2334 over a span of 10 years, from 5000 in the year 2000 to 7334 in the year 2010 [1], [2]. Major reasons for this poor growth are higher cost per watt and poor reliability due to complex technology. Hence it is necessary to reduce the cost and keep the technology as simple as possible. Cost reduction can be achieved by harnessing more power per unit installed capacity of the solar panel [3].

Solar PV panel exhibits typical voltage versus current (V_p-I_p) (Figure 1) and voltage versus power (V_p-P_p) (Figure 2) characteristics as a function of solar radiation [4]. At each radiation, represented proportionally by the panel short circuit current I_{ph}, there exists a particular operating point at which the output power of the panel becomes the maximum. The process of controlling the operating point of solar PV panel such that it always corresponds to maximum power at the corresponding radiation is referred to as Maximum Power Point Tracking (MPPT). This needs matching between the load and solar panel and can be accomplished by connecting a power electronic converter with variable switching duty cycle (D) between the PV panel and the load [5], [6]. There exist different strategies to vary D [7] and can be broadly categorized as:

a) Interruptive Type: This has mainly two approaches. The first one is to maintain V_p at a value which is a fixed percentage of open circuit voltage (V_{oc}). This requires monitoring of V_{oc}. Another approach is to maintain the panel current (I_p) as a fixed percentage of short circuit current (I_{sc}). This requires monitoring of I_{sc}. These two approaches, though simple, require regular delinking (interruption) of panel from the load for measuring V_{oc} or I_{sc}, leading to loss of harnessed power.

b) Non Interruptive Type: Here the PV panel power (P_p) is monitored continuously. D is varied till P_p becomes maximum. This approach can be referred to as $MPPT_{PP}$. It is more accurate and does not require delinking of panel from load. Hence is widely employed. But for computing power ($P_p = V_p \times I_p$), two parameters *i.e.*, V_p and I_p are to be measured and then multiplication operation is to be performed. This makes the controller comparatively complicated.

Hence there is need for a method which is non-interruptive as well as simple. Present paper proposes a new approach which meets the above requirements. The new proposal is substantiated by theoretical explanation. A real time solar pumping system is considered as an example and the simulation model is developed for the same using Matlab-Simulink (Version 7.7) software tool. The simulation and experimentation are carried out on this system. The results are found to be in close conformity with the theoretical findings thus validating the proposal made.

Section 2 of the paper details the system considered. Simulation of the different components and the system as a whole are presented. Section 3 deals

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with realizing MPPT by monitoring panel power ($MPPT_{PP}$). Section 4 presents the new proposal made. Theoretical background, simulation and experimental testing details are given in support of the proposal. Section 5 presents critical observations and discussion followed by conclusion in Section 6.

2. SYSTEM CONSIDERED

Typical advantage of solar pumping is that storage battery is not a must. Overhead tank itself acts as a storage element [8], [9], [10]. Pumping system having brushed PMDC motor coupled to centrifugal pump is simple and more commonly employed [11]. Hence in the present work, the system considered (Figure 3) is PMDC brushed motor driven centrifugal pump connected to PV panel through MPPT converter with an overhead tank at a height of 5 meters. Details of the different components are given below. Simulation model is developed for each component.

2.1 PV Source

Parallel combination of two panels is used as PV source. Specifications of each panel are: Tata BP Solar make, P_m = 74 W; V_{mp} = 17 V, I_{mp} = 4.4 A; V_{oc} = 21.8 V; I_{sc} = 4.9 A; panel's effective series resistance R_s = 2.13 Ω (found experimentally).

Simulation: PV panel can be represented [12], [13] by a simple equivalent circuit with a current source having a diode in parallel and resistance R_s in series (Figure 4). The current and power are given by the Equations 1 and 2. I_{ph}, being directly proportional to the radiation, is used as a measure of radiation. "V_p-I_p" characteristics found from simulation as well as experimental test are in close conformity (Figure 5) validating the simulation model.

$$I_p = I_{ph} - I_d \quad (1)$$

$$P_p = I_p \times V_p \quad (2)$$

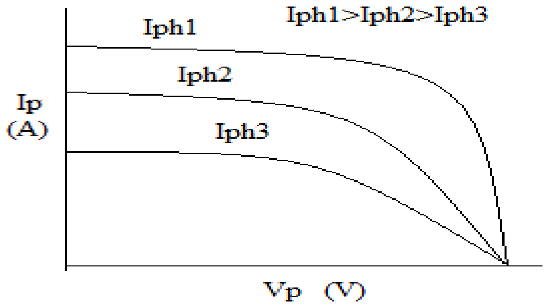

Fig. 1. Typical Vp versus Ip for PV panel.

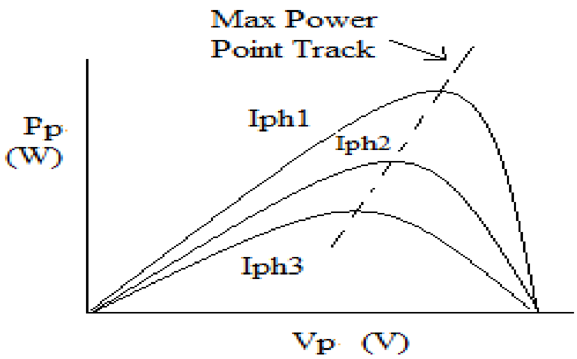

Fig. 2. Typical Vp versus Pp for PV panel.

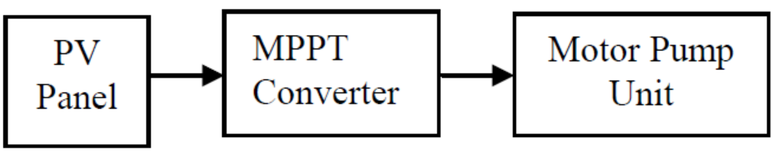

Fig. 3. Solar pumping with MPPT.

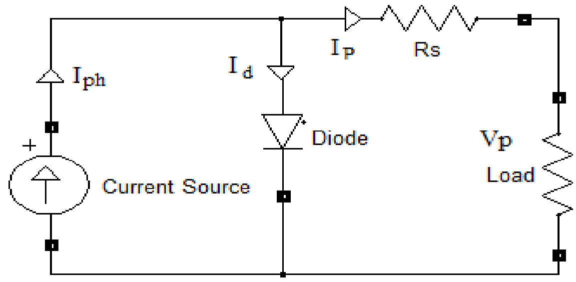

Fig. 4. PV panel simulation model.

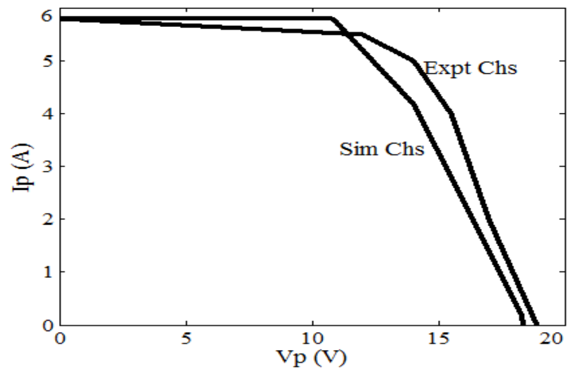

Fig. 5. V_p versus I_p characteristics for PV panel (experimental and simulation).

2.2 Motor-Pump Unit

It is a mono-block of PMDC Motor (brushed) and centrifugal pump with the following specifications: Tata BP Solar make, 12V, 70-100W, Total head: 9 m, Motor inertia: 6.83 x 10^{-3} Kgm^2, Armature resistance: 0.7 Ω, Armature inductance: 0.12 x 10^{-3} H, Voltage constant, K_b = 0.033 V/rad/sec (determined experimentally).

Pump Load Equation: The characteristic "Speed (ω) versus Torque (T)" is obtained experimentally for a head of 5 m and using the pump load (Equation 3) is derived. This is of the same format mentioned in the literature [11].

$$T = 4.8 \times 10^{-6}\ \omega^2 + 0.00019\ \omega + 0.082 \quad (3)$$

Simulation: The DC motor is modeled representing the permanent magnet as separate excitation with constant voltage source (Figure 6).The V - ω characteristics found from simulation as well as experimental test are in close conformity (Figure 7) validating the simulation model developed for the motor-pump unit.

2.3 MPPT Converter

Cuk topology (Figure 8) is chosen for the converter due to its versatility *i.e.* possibility of both step down and step up operations. MOSFET is used as switch. It is designed [14] for switching frequency of 20 kHz with the component values: L_1 = 4.2x10^{-3} H; L_2 = 7x10^{-3} H; C_1 = 1000x10^{-6} F; C_2 = 4x10^{-6} F.

Simulation model is developed (Figure 8). Converter output voltages for an input voltage of 12 V are obtained for different values of D by simulation as well as experimental testing. There is close conformity between both (Figure 9) validating the simulation model developed for the MPPT converter.

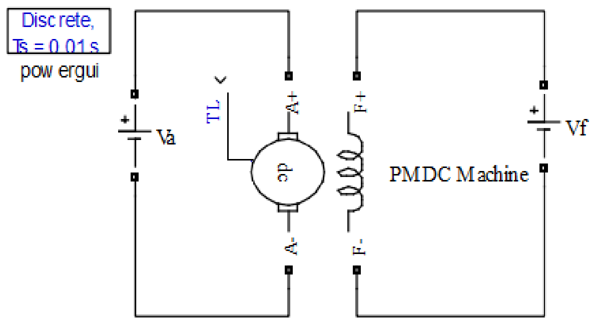

Fig. 6. PMDC motor simulation model.

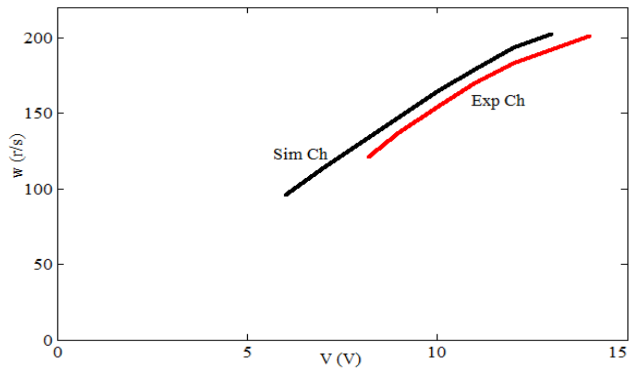

Fig. 7. V versus ω for PMDC motor (experimental and simulation).

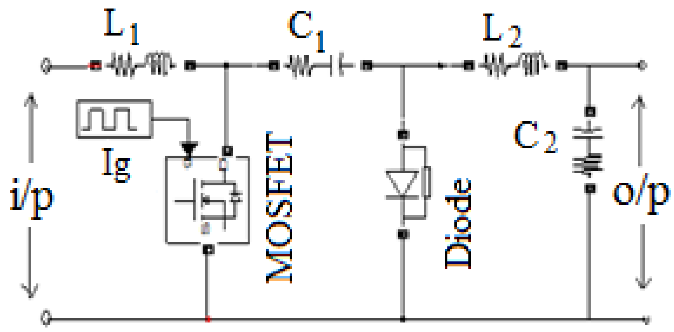

Fig. 8. MPPT converter model.

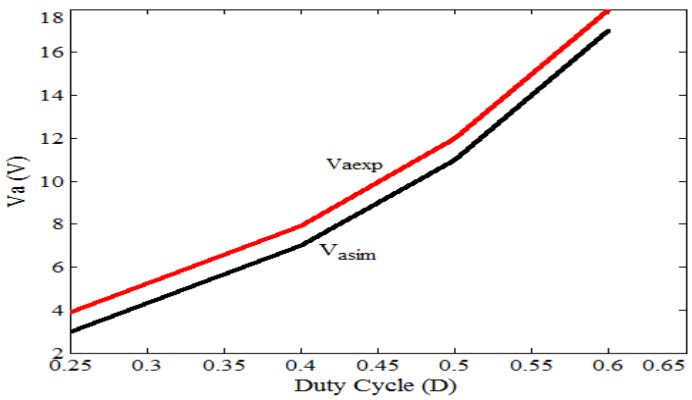

Fig. 9. V_a versus D characteristics for MPPT.

2.4 Total System

Simulation models for the entire solar pumping system are developed using the above basic component models. Both the cases of without and with MPPT converter are considered leading to two types of models: a) Solar pumping system without MPPT converter and b) Solar pumping system with MPPT converter. The latter model is shown in Figure 10.

3. PREVAILING METHOD: MPPT BY TRACKING PANEL POWER ($MPPT_{PP}$)

This section presents realizing MPPT by tracking panel power ($MPPT_{PP}$) which is the prevailing method. Comparison is made with the performance of the system without MPPT converter. Model without MPPT converter is taken first and is run for different I_{ph}. At each I_{ph}, the load power and the pump speed are noted. Then the system with MPPT converter is considered and the simulation is run for different I_{ph}. At each radiation duty cycle D is varied and the operating point corresponding to maximum panel power ($MPPT_{PP}$) is determined. At this condition, the values of panel power and the pump speed are noted and plotted (Figures 11 and 12). It is observed that there is increase in power and pump speed in the system with MPPT converter as compared to the system without MPPT converter.

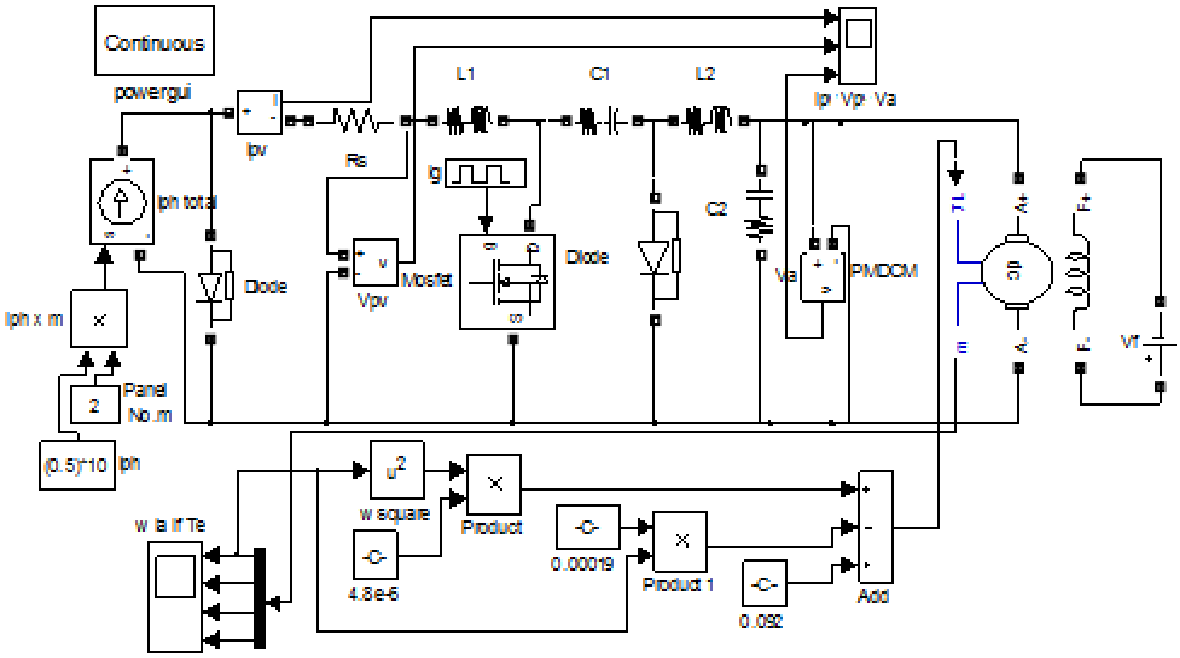

Fig. 10. Simulation model for pump load with MPPT converter.

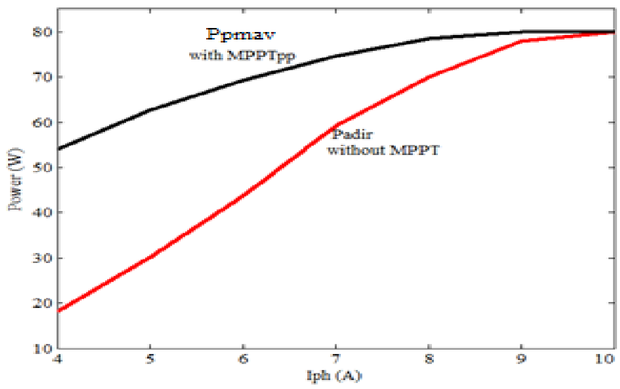

Fig. 11. I_{ph}–P comparison (simulation) for pump load with $MPPT_{pp}$ and without MPPT.

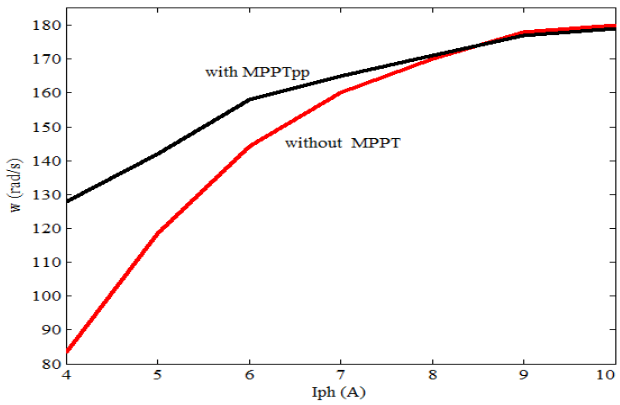

Fig. 12. I_{ph}– ω comparison (simulation) for pump load with $MPPT_{pp}$ and without MPPT.

4. NEW PROPOSAL: MPPT BY TRACKING LOAD VOLTAGE (MPPT$_{LV}$)

The new proposal made is to employ load side voltage as control parameter for MPPT. It is based on the fact that the output power is maximum when the load voltage is maximum. Here only the load voltage is monitored. Duty cycle of the MPPT converter is continuously varied such that load voltage is always maximum. This automatically leads to harnessing maximum power output. This approach can be referred to as MPPT$_{LV}$. It is simpler than MPPT$_{PP}$ as only one parameter *i.e.* load voltage needs to be monitored and there is no need of multiplication.

4.1 Theoretical Background

In this section, it is shown theoretically that the output power is maximum when the load voltage is maximum. For deriving the basic equations, a PV system with resistive load R is considered (Figure 13). The converter acts like a transformer with transformation ratio y = D/(1-D). Let R', V_a' and I_a' be the values of R, V_a and I_a respectively referred to panel side (Figure 14).

For this system the following equations can be written:

$$y = \frac{D}{(1-D)} \tag{4}$$

$$R' = \frac{R}{y^2} \tag{5}$$

$$P_p = V_p I_p \tag{6}$$

$$P_a = V_a I_a \tag{7}$$

$$V_a = y V_a' = y V_p \tag{8}$$

$$I_a = \frac{I_a'}{y} = \frac{I_p}{y} \tag{9}$$

$$R' = \frac{V_a'}{I_a'} = \frac{V_p}{I_p} \tag{10}$$

Assuming 100% efficiency for converter,

$$V_p I_p = P_p = V_a I_a = P_a \tag{11}$$

$$V_a = \sqrt{P_a}\,\sqrt{R} = \sqrt{P_p}\,\sqrt{R} \tag{12}$$

$$V_a = \sqrt{P_a} \tag{13}$$

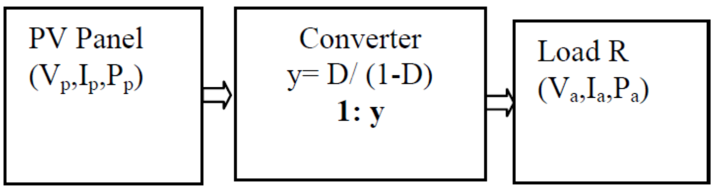

Fig. 13. System with MPPT converter and R load.

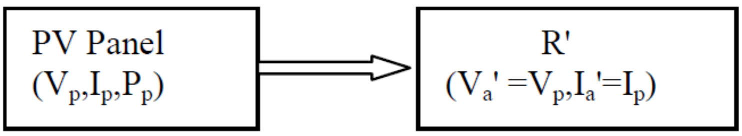

Fig. 14. R load referred to panel side.

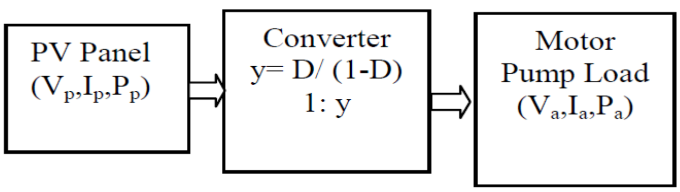

Fig. 15. System with MPPT and pump load.

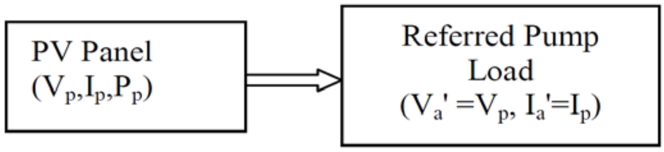

Fig. 16. Pump load referred to panel side.

Hence theoretically, Equation 13 indicates that V_a follows variations of P_a and P_p. As per the typical "V_p-P_p" characteristics (Figure 2), P_p rises from zero, reaches maximum and decreases to zero. So do P_a and V_a. Thus V_a becomes maximum when P_a becomes maximum. Conversely, maximum load power P_a corresponds to maximum load voltage V_a. The equations derived above are applicable to motor-pump load also.

System with Pump Load

For PMDC Motor we can write the following equations:

$$E_b = K_b \omega \tag{14}$$

$$E_b = V_a - I_a R_a \tag{15}$$

$$T = K_b I_a \tag{16}$$

Using Equations 14 to 16, the load in Equation 1 is written in terms of V_a and I_a as shown in Equation 17.

$$4.4\, V_a^2 - 5.75\, V_a - 6.17\, V_a\, I_a + 2.15\, I_a^2 - 36.9\, I_a + 92 = 0 \tag{17}$$

The load can be represented referred to panel side (Figures 15 and 16). The referred load Equation 18 is derived from Equation 17 proceeding in the same way as done for resistive load earlier.

$$4.4y^2 V_a'^2 - 5.75yV_a' - 6.17V_a' I_a' + 2.15\frac{I_a'^2}{y^2} - 36.9\frac{I_a'}{y} + 92 = 0 \tag{18}$$

V_a'-I_a' plots are obtained for different switching duty cycles (D) and then are superimposed with V_p-I_p plot of the panel obtained experimentally at different radiations (Figure 17). The intersection points (operating points) are determined. It can be noticed that by changing D, the operating points can be changed. Using these values, the plots "V_a versus D" (Figure 18) and "P_p versus D" (Figure 19) are obtained. Observing the corresponding values of D in Figures 18 and 19, it is found that at each radiation, panel power is maximum when V_a becomes maximum. This is valid with respect to load power P_a also assuming 100% efficiency for the converter (Equation 11). Thus the theoretical inference "P_a is maximum when V_a is maximum" made for pure resistance load earlier in this section, is valid for pump load also.

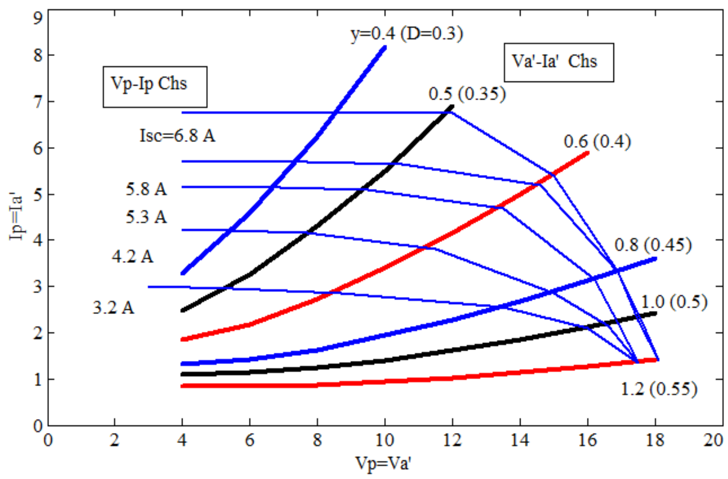

Fig. 17. Panel and pump load characteristics superimposed.

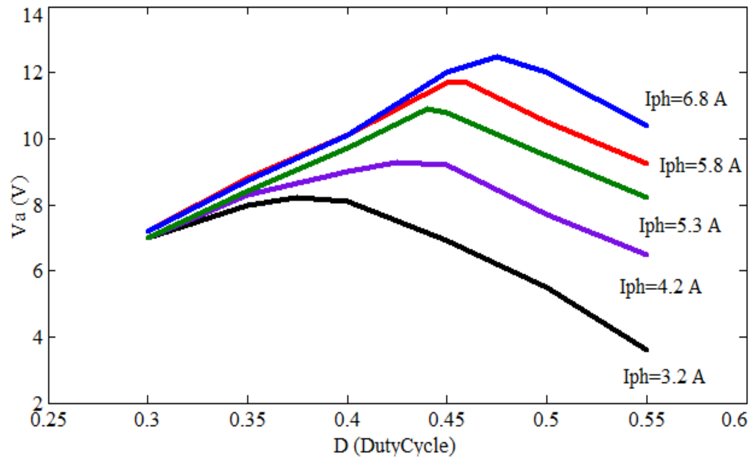

Fig. 18. Duty cycle (D) versus load voltage (V_a) for pump load.

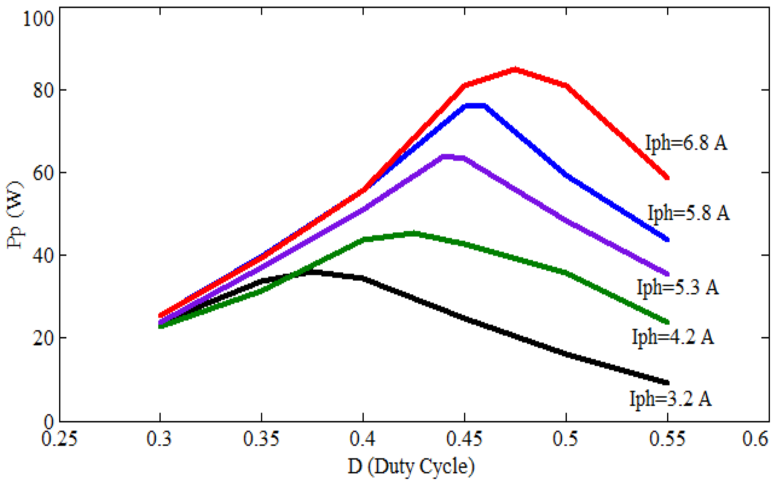

Fig. 19. Duty cycle (D) versus panel power (P_p) for pump load.

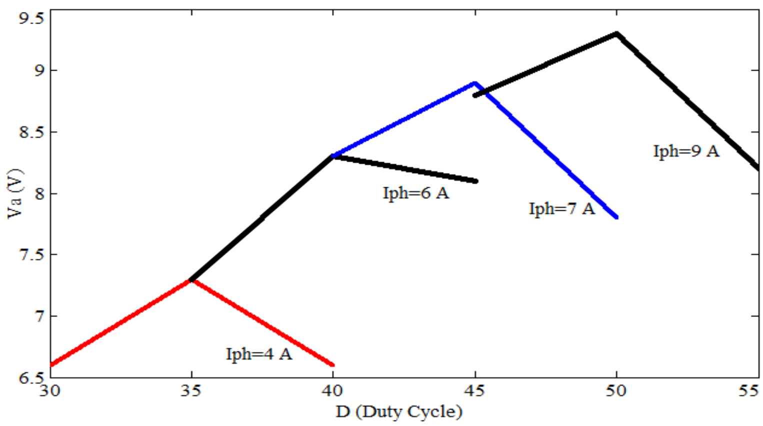

Fig. 20. Duty cycle (%D) versus load voltage (V_a) for pump load (simulation).

4.2 Simulation

Using the model for the entire system (Figure 10), simulation test are carried out for different I_{ph} and at each radiation for different duty cycles D. The plots of load voltage (Figure 20) and load power (Figure 21) as a function of D are obtained. It is found that at each radiation, load power is maximum when V_a becomes maximum. The available maximum panel power (P_{pmav}), the load power with both the methods (P_{ampp} by $MPPT_{PP}$ and P_{amlv} by $MPPT_{LV}$) are obtained (Figure 22). The speeds of the pump for both the approaches (ω_{mlv} and ω_{mpp}) are also determined and plotted (Figure 23). It can be seen that load power and the pump speed obtained with $MPPT_{LV}$ are more than $MPPT_{PP.}$

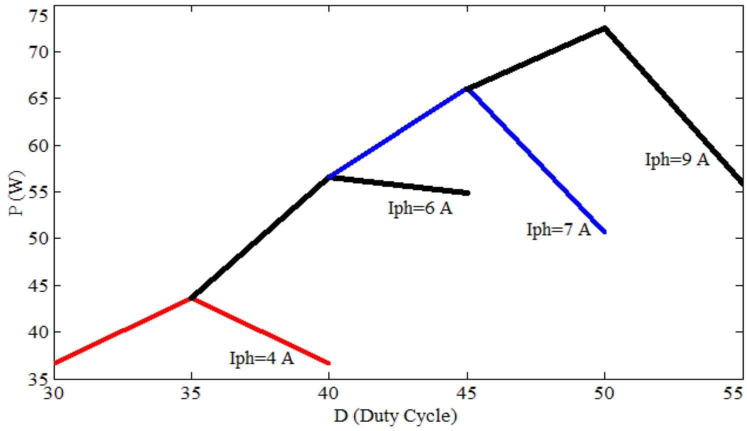

Fig. 21. Duty cycle (%D) versus power (P_a) for pump load (simulation).

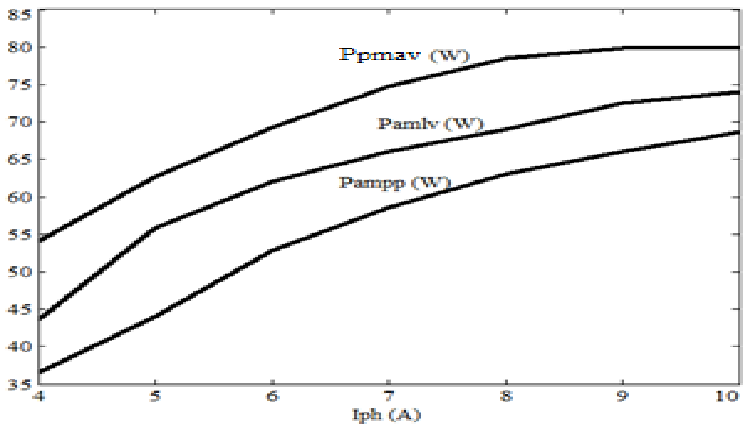

Fig. 22. I_{ph} versus P (simulation) for pump load with $MPPT_{PP}$ and $MPPT_{LV}$.

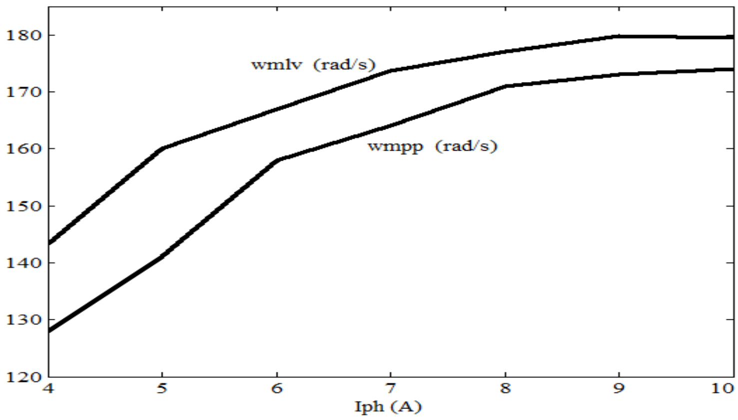

Fig. 23. I_{ph} versus ω (simulation) for pump load with $MPPT_{PP}$ and $MPPT_{LV}$.

4.3. Experimental Testing

Diode (DF400), MOSFET (5NF06), 148 W_p solar PV source, two (2) 100 μF capacitors, two (2) 0.1 mH air cored inductors, pumpset and necessary measuring instruments are connected as per the circuit diagram (Figure 24) for the experimental testing. Pulse width modulated (PWM) signal wave generator is employed along with IR 2110 based driver for triggering MOSFET. Other details of different components are as mentioned in section 3. The actual set up is shown in Figure 25. First the pump is run by connecting it to solar panel directly. Voltage and current readings are taken at different hours of day (Table 1). Load power obtained without MPPT is less (Figure 26). Then the pump is connected through the MPPT converter. The duty cycle of the MOSFET is varied and different parameters like D, V_p, I_p, V_a and I_a are noted. This procedure is repeated for different radiations *i.e.* times of the day. The following characteristics are obtained: a) Load voltage versus Duty cycle (Figure 27) b) Load power versus Duty cycle (Figure 28). Observing the corresponding values of D in Figures 27 and 28, it is found that load power becomes maximum when load voltage becomes maximum. This is still clearer in Figure 29 showing the load power and voltage together.

The panel power and load power with both the methods, $MPPT_{PP}$ and $MPPT_{LV}$, are obtained and plotted (Figures 30 and 31). Load power with $MPPT_{LV}$ is more compared to that with $MPPT_{PP}$. Also, the pump speed with $MPPT_{LV}$ is more compared to that with direct connection (Figure 32). Over a day, with $MPPT_{PP}$, increase in the output energy per day is 27% as compared to the direct connection without MPPT. Increase in the output energy per day is 40% with $MPPT_{LV}$.

Typical waveforms are observed and provided (Figures 33 to 36) to confirm the proper working of the MPPT converter circuit. Figure 33 conveys the working of MOSFET as a switch. It can be observed that MOSFET is ON when the gate signal is high. Figures 34 and 35 represent the inductor voltages. As expected, the time average of the inductor voltage over one cycle is zero. Figure 36 shows the output voltage which is found to be almost constant as per the design expectation of the converter.

Table 1. Experimental results for pump load.

Time of day	Maximum available panel power P_{pmav} (W)	Power to pump by direct connection (without MPPT) P_{adir} (W)	Pump speed ω (rad/s)
10	37.5	9.9	52.8
11	58.8	27.7	78
12	76	46.7	144
13	98	69.5	174.7
14	102	73.4	179.5
15	90	62.6	161.6
16	65	38.8	134.1
17	28.2	9.1	53.7
18	16	3.6	---

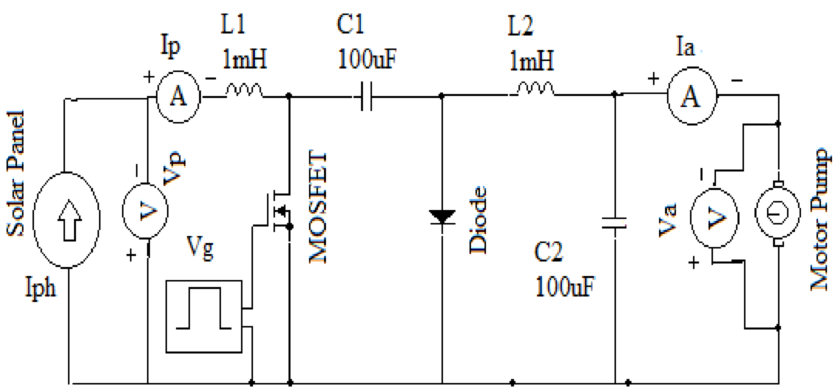

Fig. 24. Circuit diagram for experimental testing.

Fig. 25. Experimental test set-up.

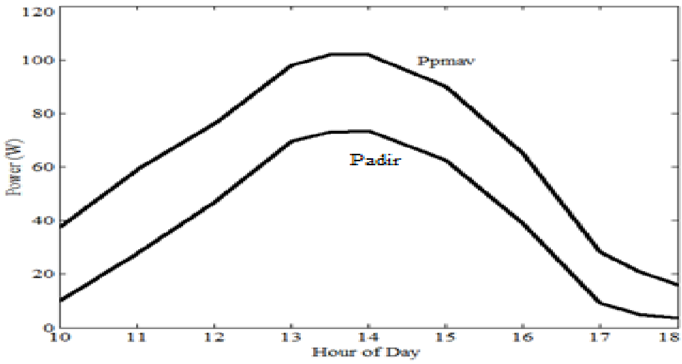

Fig. 26. Hour of day versus different powers for pump load without MPPT converter (experimental).

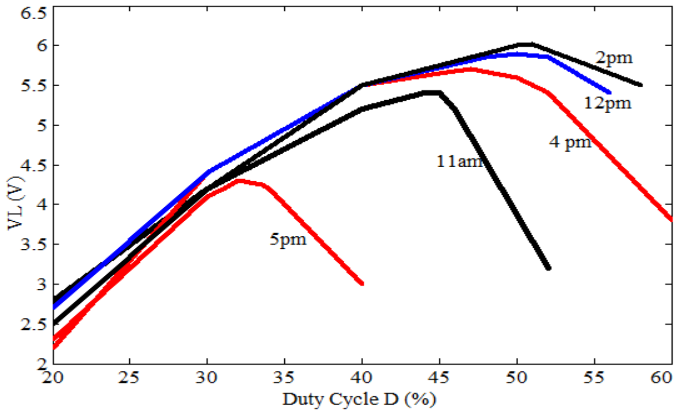

Fig. 27. Duty cycle (%D) versus load voltage (Va) for pump load (experimental).

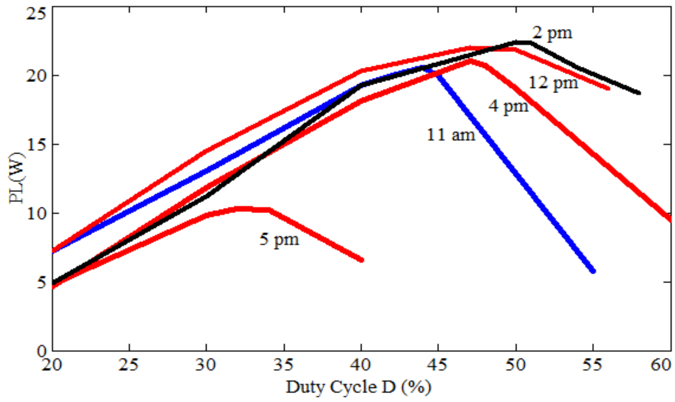

Fig. 28. Duty cycle (%D) versus power (P) for pump load (experimental).

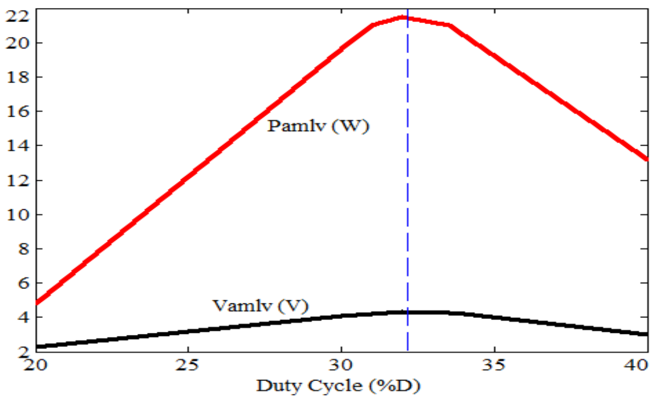

Fig. 29. Maximum power and voltage for pump load at 5pm (experimental).

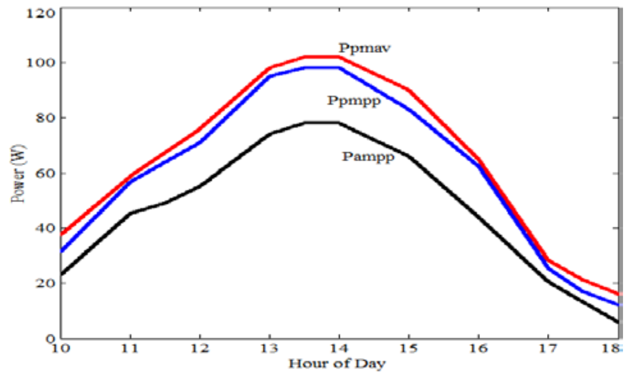

Fig. 30. Hour of day versus different powers for pump load (experimental) with $MPPT_{PP}$.

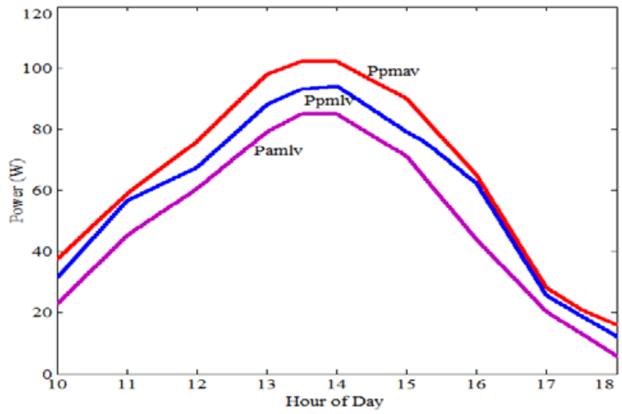

Fig. 31. Hour of day versus different powers for pump load (experimental) with $MPPT_{LV}$.

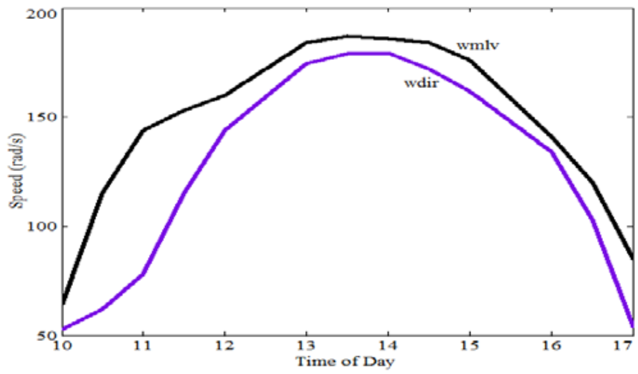

Fig. 32. Hour of day versus ω with $MPPT_{LV}$ and direct connection (without MPPT) for pump load (experimental).

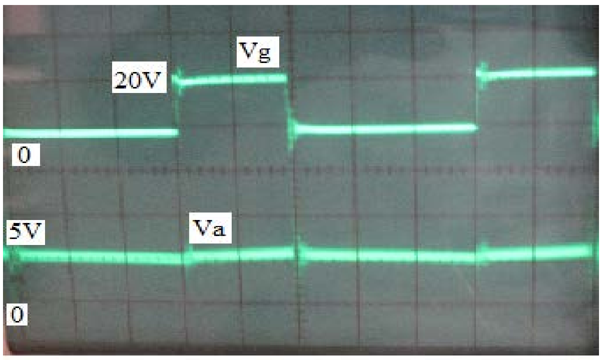

Fig. 33. MPPT converter waveform: time versus gate voltage (V_g) and motor voltage (V_a).

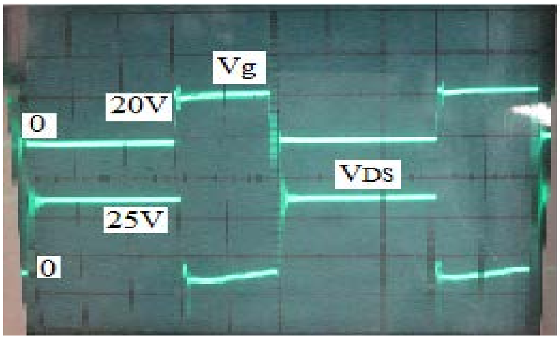

Fig. 34. MPPT converter waveform: time versus gate voltage (V_g) and MOSFET voltage (V_{DS}).

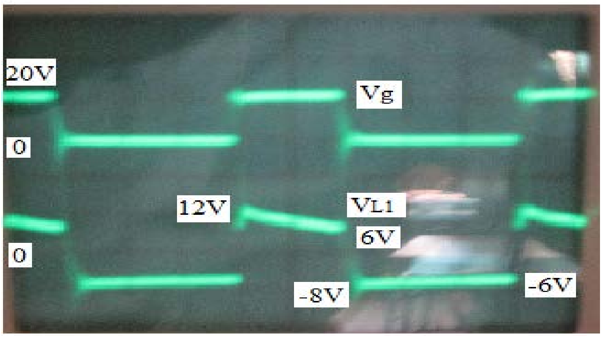

Fig. 35. MPPT converter waveform: time versus gate voltage (V_g) and inductor (L_1) voltage (V_{L1}).

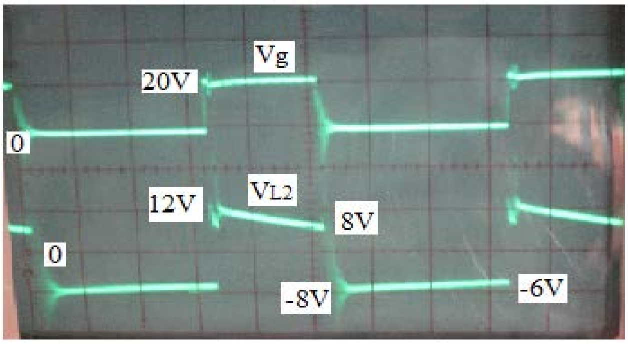

Fig. 36. MPPT converter waveform: time versus gate voltage (V_g) and Inductor (L_2) voltage (V_{L2}).

5. OBSERVATIONS AND DISCUSSIONS

- Looking at the corresponding values of D, it is found from simulation that, at a particular radiation, motor power P_a becomes maximum when V_a becomes maximum (Figures 20 and 21). Experimental results also indicate this feature (Figures 27, 28 and 29).
- This means for a particular radiation, there exists a specific motor voltage at which output power becomes maximum. Hence the motor voltage V_a can be used as a control parameter for varying the duty cycle of the converter in achieving MPPT. V_a can be continuously monitored and D continuously varied so as to realize maximum V_a which automatically ensures maximum output power at the corresponding radiation. This approach can be referred to as Maximum Load Voltage Point Tracking with load voltage monitoring ($MVPT_{LV}$). This is simpler than MPPT with panel power monitoring ($MPPT_{PP}$) which requires measuring panel voltage as well as current and then multiplying them to obtain power value.
- With $MPPT_{PP}$, increase in the output energy per day is 27% as compared to the direct connection without MPPT. Whereas with $MPPT_{LV}$, increase in the output per day is 40%. This feature demonstrates the role of MPPT converter in harnessing more power from the solar panel. It also shows that, not only making the approach simple, proposed new method yields higher power output also. This results in a decrease in the cost per watt of installed capacity of the solar panel.

6. CONCLUSION

Water pumping is an important application of solar PV power. MPPT is opted for harnessing maximum power from the PV panel so as to obtain maximum output from the pump. Widely employed approach for MPPT is to use the PV panel power as control parameter for MPPT converter ($MPPT_{PP}$).

Present paper has proposed load side voltage as control parameter for MPPT. It is shown that varying the duty cycle of the MPPT converter such that load voltage is always maximum, leads to harnessing maximum power output. This approach can be referred to as Maximum Power Point Tracking with load voltage monitoring ($MPPT_{LV}$). Here only one parameter *i.e.* load voltage needs to be monitored. $MPPT_{LV}$ is simpler than $MPPT_{PP}$ as in the latter case it's necessary to measure both panel voltage and current and then find their product.

The proposed method is substantiated by theoretical explanation followed by simulation as well as experimentation results carried out on a real time standalone solar pumping system with PMDC (brushed) motor driving centrifugal pump. Not only making the approach simple, proposed new method yields higher power output also.

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NOMENCLATURE

Symbol/ Abbreviation	Significance
C	Capacitance, F
D	Switching duty cycle of the converter
E_b	Motor back emf constant, V/r/s
Exp.	Experimental
I_a	Load current, A
I_a'	Ia referred to panel side, A
I_m	Panel current for maximum rated power, A
I_p	Panel side current, A
I_{ph} or I_{sc}	Panel short circuit current, A
L	Inductance, H
MPPT	Maximum power point tracking
$MPPT_{LV}$	Maximum power point tracking with load voltage monitoring
$MPPT_{PP}$	Maximum power point tracking with panel power monitoring
P_a	Load side power, W
P_{adir}	Load side power without MPPT converter
P_{amlv}	Load side power with $MPPT_{LV}$
P_{ampp}	Load side power with $MPPT_{PP}$
P_m	Panel side maximum rated power, W
P_p	Panel side power, W
P_{pm}	Panel side maximum power at a particular radiation, W
P_{pmav}	Panel side maximum power available at a particular radiation
R	Resistive load, Ω
R'	R referred to panel side, Ω
R_a	Motor armature resistance, Ω
Sim.	Simulation
T	Motor torque, Nm
V_a	Load voltage, V
V_a'	Va referred to panel side, V
V_{oc}	Panel open circuit voltage, V
V_m	Panel voltage for maximum rated power, V
V_p	Panel side voltage, V
ω	Pump speed, r/s
ω_{mlv}	Pump speed with $MPPT_{LV}$
ω_{mpp}	Pump speed with $MPPT_{PP}$
y	Transformation ratio of the converter (y = D/(1-D))

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