

## Parameter estimation and control design of solar maximum power point tracking

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### ABSTRACT

Parameters evaluation, design, and intelligent control of the solar photovoltaic model are presented in this work. The parameters of zeta converters such as a rating of an inductor, capacitor, and switches for a particular load are evaluated its values to compare the trade of the existing model and promoted to research in the proposed area. The zeta converter is pulsed through intelligent controller-based maximum power point tracking (intelligent-MPPT). The intelligent controller is a fuzzy logic controller (FLC) which extracts maximum power from the solar panel using the zeta converter. The performance of evaluated parameters based on the solar system and zeta converter is seen by an intelligent control algorithm. Moreover, evaluated parameters of solar photovoltaic (PV) and zeta converter can be examined the performance of fuzzy based intelligent MPPT under transient and steady-state conditions with different solar insolation. The brushless direct current motor-based water pump is used as the direct control (DC) load of the proposed model. The proposed model can enhance the research and assist to develop a new configuration of the present system.

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## 1. INTRODUCTION

Developing of industrial technology in the field of solar and wind energy enhance the demand of these two non-conventional sources of energy [1]. The cost of per unit energy consumption is going down as innovative technologies are continued to change the shape size and layer of the solar panel. The wind-based energy is a complicated as its speed depends on the wind and control algorithm is tedious to design. Whereas, solar is suitable under 40° degree temperature [2]. The region of Kingdom of Saudi Arabia (KSA) is most suitable for the solar photovoltaic (PV) system. Especially the coastal area of red sea region of KSA has favorable temperature throughout the year for solar PV system. Thus, solar PV system can enhance scope of industries and facilitated the household and irrigation system. The water irrigation is used in rural area whereas solar water pumping is used in both rural and urban area [3]. The demand of solar fed water pumping is more for commercial purpose and could be supported to enhance the country gross domestic product (GDP). On the other hand, the designing cost of solar fed water pumping is drastic reducing as power electronics switches cost reduces. The solar PV model integrated with brushless direct control (DC) motor works as standalone system which generates electricity for dedicated systems. Even though many research scholars have explored the solar PV based water pumping with DC and alternative current motors. In [4], brushless DC motor used as water pump connected solar PV via Landsman converter and buck-boost

converter to optimize the power output. In [5], the switch reluctance motors used for water pumping have a high torque/inertia ratio and high efficiency. The performance of all the DC motor and alternating current (AC) motor has a good option for water pumps whereas the drive circuit of the DC motor is complex with the smart converter topology. Moreover, irreversible characteristics of demagnetization of permanent magnets are the limitation of DC motor to use in water pumping [6]. While special machines like brushless DC motor, reluctance motor, and switched reluctance (SR) motor have good options for a water pump. Whereas SR motor is simple in construction as it contains no conductors [7], [8]. It has more advantages over DC motors in designing the solar pump. The design of the stator of the stepper motor is isolated electrically. Thus, the drive circuit of the converter to control the switched reluctance motor is flexible. Special machines like synchronous reluctance and permanent magnet motor have a negligible variable loss ( $I^2R$ ) [9].

There are many research scholars working on solar PV-based water pumping while the designing of the solar PV model, its drive circuit, and control algorithm in the comprehensive form are unavailable in one paper. Thus, authors have evaluated mathematical models of various parameters like solar PV model, DC to DC zeta converter, and maximum power point tracking. These parameters could be helped to understand the trade value of the proposed model and enhance the research interest in the given field. Moreover, tracking efficiency under variable conditions of atmosphere and accuracy of maximum power traction has some limitations. Thus, an efficient technique is needed to extract the maximum power point (MPP) in a solar PV system. An incremental conductance maximum power point tracking (INC-MPPT) method [10], [11] is a good control algorithm. While it has some disadvantages like being sluggish in nature and taking more time to reach a steady state point [12]. This technique is generally used in DC to DC buck-boost converter [13], [14]. Thus, a more efficient technique is needed to improve the results.

A fuzzy logic controller is a soft computing technique that computes the data fast and operates reliably. It tolerates zero oscillation near the MPP [15], [16]. Thus, the authors have selected a fuzzy rule based MPPT. It is good to extract maximum power from the solar PV model [17], [18]. The performance of the control algorithm is seen under a brushless DC motor-based water pump load [19].

The contributions of the authors are as: i) an approach is used to estimate the parameters of the combined proposed model while empirical formula compares its ability, ii) the practical and theoretical data of zeta converter is presented accurately using the proposed approach, iii) solar PV system is designed using seven parameters, iv) the zeta converter is fired using intelligent-MPPT which increases the speed of charging of the battery, and v) the proposed configuration is compared to its results under the variable condition of a solar PV system.

This paper is organized in section 2 proposed method to estimate the parameters of zeta converter is given. In section 3, seven parameters of solar PV system where a comprehensive detail of mathematical formulas of all the related parameters is presented. In section 4, the control algorithm is presented while in section 5 results are discussed and conclusion at last.

## 2. PARAMETERS ESTIMATION OF ZETA CONVERTER

The zeta converter is similar to a buck-boost converter whereas zeta converter has a wide range of duty ratio and non-inverted output [20], [21] which is shown in Figure 1. Three capacitors, two inductors, one power switch, and one diode are required to design a zeta converter while out of three capacitors one is for input capacitor ( $C_{pvin}$ ), the second is for coupling capacitor ( $C_c$ ) and the third is for output capacitor ( $C_{pvo}$ ). On the other hand, two inductors are for coupled inductors  $L_a$  and  $L_b$  whereas a power switch insulated-gate bipolar transistor (IGBT),  $Q$  and a diode,  $D$ . Researchers have evaluated parameters of zeta converters either by empirical method or somehow tedious while the proposed approach is ease to evaluate the given parameters [22]. All these components are considered under the current continuous mode (CCM) to reduce their components' stress.

### 2.1. Duty cycle 1

Assuming ideal condition of zeta converter under CCM, the duty ratio ( $D_t$ ) can be evaluated as (1),

$$D_t = \frac{V_{pvo}}{V_{pv\ max} + V_{pvo}} \quad (1)$$

where  $V_{pvo}$  is output voltage of the zeta converter whereas  $V_{pv\ max}$  is the maximum voltage of solar PV array at maximum power and an (1) can be written as (2),

$$V_{dco} = \frac{D_t}{1-D_t} \left( V_{pv\ max} \right) \quad (2)$$

The given (2) behaves as a buck converter when  $D_t$  is less than 0.5 whereas it behaves as a boost converter when  $D_t$  is greater than 0.5. This paper,  $D_t$  is controlled by the fuzzy logic controller. It is varied as per as per the demand of the brushless DC (BLDC) motor input voltage.

## 2.2. Capacitance 2

The following capacitors of the zeta converter connected in Figure 1 are  $C_{pvin}$ ,  $C_c$  and  $C_{pvo}$ . The design of  $C_{pvin}$ ,  $C_c$  and  $C_{pvo}$  are depends on different electrical parameters. The  $C_{pvin}$  is calculated in (3).

$$C_{pvin} = \frac{Q}{V_{pv \max}} = \frac{I_{pv \max} * t}{V_{pv \max}} \quad (3)$$

The equation (3) shows the basic formula to calculate the capacitance value, where Q is the storing charge capacity and t is the recovery time of the charge. Moreover, for a zeta converter  $C_{pvin}$  is somehow different. It is because of power electronic switches which affect the current  $I_{mp}$  and voltage  $V_{mp}$ . Thus, the  $C_{pvin}$  is formulated in (4),

$$C_{pvin} = \frac{D_t * I_{pvo}}{\Delta V_{pp} * V_{pv \max} * f_{sw}} \quad (4)$$

where  $I_{pvo}$  is the output current to charge the output capacitor of the zeta converter,  $\Delta V_{pp}$  is the output ripple voltage and  $f_{sw}$  is the minimum switching frequency. Similarly, the coupling capacitor  $C_c$  can be evaluated as in (5).

$$C_c = \frac{D_t * I_{pvo}}{\Delta V_{pp} * V_{pv \max} * f_{sw}} \quad (5)$$

The magnitude of output capacitance  $C_{pvo}$  is the input of the voltage source converter (VSC) under the proposed conditions. The  $C_{pvo}$  has been evaluated under the various conditions of the switching frequency. If the switching frequency is higher the BLDC motor get the current nearly sinusoidal and the  $C_{pvo}$  can be evaluated as (6),

$$C_{pvo} = \frac{\Delta I_{Lb(pp)}}{8 * \Delta V_{pvo(pp)} * f_{sw}} \quad (6)$$

where  $\Delta I_{Lb(pp)}$  inductor ripple current which can disturb the function of pulse width modulation (PWM).

## 2.3. Inductor

The following mathematical steps are taken to evaluate the zeta converter inductance ( $L_a$ ,  $L_b$ ). In the first step reactive inductance ( $X_L$ ) has to evaluate using basic formula which is given,

$$X_L = 2 * \pi * f_{sw} * L_{a,b} \quad (7)$$

where  $f_{sw}$  is minimum switching frequency and second way to evaluate  $X_L$  is given as

$$X_L = \frac{V_{dcin} (at \max \text{ input voltage } V_{pv \max})}{\Delta I_{Lb(pp)}} \quad (8)$$

From (7) and (8) the general calculation of inductor value can be explained as under normal condition.

$$L_{a,b} = \frac{V_{dcin} (at \max \text{ input voltage } V_{pv \max})}{2 * \pi * \Delta I_{Lb(pp)} * f_{sw}} \quad (9)$$

While for zeta converter (DC to DC converter), the magnitude of  $L_{a,b}$  also depends on  $D_t$ , thus (9) can be modified,

$$L_{a,b} = \frac{D_t * V_{dcin} \text{ (at max input voltage } V_{pv} \text{ max)}}{2 * \pi * \Delta I_{Lb(pp)} * f_{sw}} \tag{10}$$

$\Delta I_{Lb(pp)}$  is the inductor ripple current and  $V_{dcin}$  is input dc voltage? (10) is the final equation to design the zeta converter inductor  $L_a$  and  $L_b$

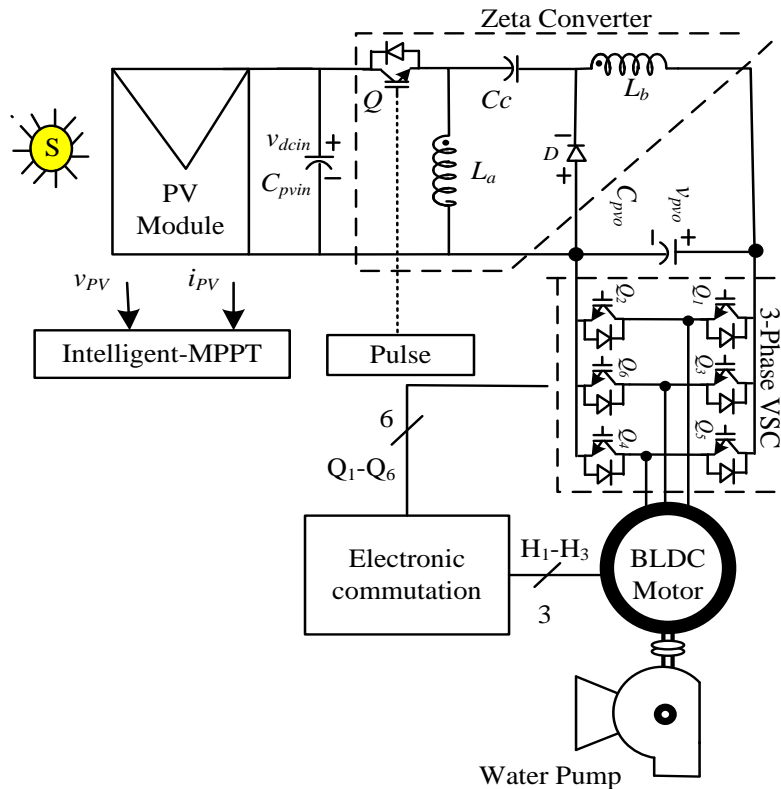


Figure 1. Intelligent MPPT based solar water pump

**2.4. Selecting active components for zeta converters**

The active components are the power electronic switches like uncontrol and fully control. The fully control metal-oxide-semiconductor field-effect transistor (MOSFET) switch, Q, is the best option for zeta converter. It is high frequency and low losses switches for low power system like BLDC motor pump. Whereas uncontrol switch diode D, can stand for both peak current and reverse voltage. In the Table 1 (see in appendix) the complete description is given for zeta converter.

**3. EVALUATION OF SEVEN PRAMETERS FOR SOLAR SYSTEM**

When solar insolation comes in contact with semiconductor device, it regenerates active current ( $I_{ph}$ ). This phenomenon is known as photovoltaic effect. Moreover, standard test condition (STC) is required to design a solar photovoltaic (PV) model which is usually given as,

$$T_c = 25 \text{ }^\circ\text{C} \text{ and } G_{eff} = 1000 \text{ W/m}^2$$

There are various parameters model are available in literature while, the seven parameters model are more attractive than the other parameters [23]. Practical design of seven parameters PV model are shown in Figure 2. The following parameters of practical unit solar cell are explained as:

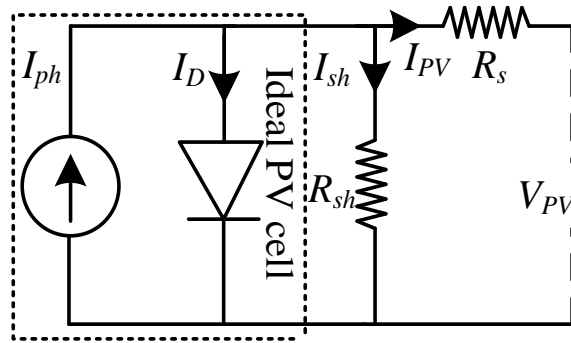


Figure 2. Ideal and practical equivalent circuit of solar PV cell

### 3.1. Short circuit current ( $I_{sc}$ )

It depends on light intensity and produce effective optical power under the range of temperature 25 to 35 °C. The load current  $I$  is maximum when output is shorted or practically voltage is zero. The current  $I$  under such condition is short circuit current  $I_{sc}$ . Mathematical evaluation of these parameters, short circuit current where subscript “st” indicates at standard temperature condition (STC).

$$I = I_{sc, st}, V = 0 \quad (11)$$

In Figure 2, represents the solar model and  $I$  can be evaluated as (12),

$$I = I_{ph} - I_D - I_{SM} \quad (12)$$

where the light generated current  $I_{ph}$  under STC, diode current  $I_D$  and shunt current  $I_{SH}$ . The further explanation of (2) is obtained as (13),

$$I = I_{ph} - I_{rs, st} \left[ e^{\frac{V + IR_s}{a}} - 1 \right] - \frac{V + IR_s}{R_{SH}} \quad (13)$$

where  $I_{rs, st}$  is the reverse saturation current at STC condition and the  $I_{sc}$  can be evaluated as (14)

$$I = I_{ph, st} - I_{rs, st} \left[ e^{\frac{V + IR_s, ref}{a_{ref}}} - 1 \right] - \frac{V + IR_s, ref}{R_{SH, ref}} \quad (14)$$

Applying condition of (11) in (14) to get  $I_{sc}$  at STC.

$$I_{SC} = I_{ph, st} - I_{rs, st} \left[ e^{\frac{I_{sc, st} * R_s, st}{a_{st}}} - 1 \right] - \frac{I_{sc, st} * R_s, st}{R_{SH, st}} \quad (15)$$

### 3.2. Open circuit voltage ( $V_{oc}$ )

The characteristic of open-circuit voltage depends on temperature. It reduces as increases in saturation current. Mathematical equations can be evaluated as (16),

$$\text{At open circuit voltage: } I = 0, V = V_{oc, st} \quad (16)$$

Put the open circuit voltage condition in (15) and the get the open circuit voltage at STC.

$$0 = I_{ph, st} - I_{rs, st} \left[ e^{\frac{V_{oc}}{a_{st}}} - 1 \right] - \frac{V_{oc}}{R_{SH, st}} \quad (17)$$

$$V_{OC} \approx a_{st} \ln\left(\frac{I_{ph,st}}{I_{rs,st}} + 1\right) \quad (18)$$

### 3.3. Ideality factor ( $a_f$ )

The  $a_f$  is an ideality factor to design seven parameters of a solar PV system. It is linearly varied with cell temperature while it shows that solar PV cell how close to ideal solar PV cell. An ideal condition occurs when  $a_f=1$

$$a_f = a_{fst} * \frac{T_c}{T_{c,st}} \quad (19)$$

### 3.4. Light current ( $I_{ph}$ )

An  $I_{ph}$  indicates a light current parameter. It depends on solar irradiance and temperature of PV cell. Mathematically, it is defined as (20),

$$I_{ph} = \frac{G_{eff}}{G_{eff,st}} [I_{ph} + \alpha(T_c - T_{c,st})] \quad (20)$$

where  $G_{eff}$  is effective solar irradiance,  $T_c$  is the solar PV cell temperature and  $\alpha$  is the short circuit current temperature coefficient.

### 3.5. Reverse saturation current ( $I_{rs}$ )

An  $I_{rs}$  indicates reverse saturation current of PV cell. It is due to the flow of minority carriers in PV cell. It depends on various parameters like energy band gap of a semiconductor material, temperature of the PV cell and applied bias voltage. Mathematical, it can be calculated as (21),

$$I_{rs} = I_{rs,st} \left[\frac{T_c}{T_{c,st}}\right]^3 e^{-\frac{\varepsilon * N_s}{a_f st}} \left(1 - \frac{T_{c,st}}{T_c}\right) \quad (21)$$

where  $\varepsilon$  is the material band gap energy and  $N_s$  is the number of cells in series.

### 3.6. Series resistance ( $R_s$ )

Series resistance always with the load which increase the voltage drop across the junction and it controls the position of maximum power point. Three main issues cause series resistance ( $R_s$ ) in solar cells. The first issues are the current movement through emitter and base of the solar cell, second issues are the contact resistance between the silicon and the metal contact and third one is the resistance of rear and top metal contacts. Mathematical value of  $R_s$  can be calculated as (22),

$$R_s = \left(\frac{a_f st}{I_{rs,st}}\right) e^{-\left(\frac{V_{mp,st} + I_{mp,st} * R_{s,st}}{I_{f st}}\right) + R_{s,st} I} * \frac{G_{eff,st}}{G_{eff}} - \frac{a_f}{I_{rs}} * e^{-\left(\frac{V_{mp} + I_{mp} * R_s}{a_f}\right)} \quad (22)$$

where  $V_{mp,st}$  is the voltage at maximum power point at standard temperature.

### 3.7. Shunt resistance ( $R_{sh}$ )

A shunt resistance  $R_{sh}$  is connected parallel to the PV cell. It protects the PV cell from short circuit and limit the current. Mathematically, it can be evaluated as (23),

$$\text{At short circuit condition: } dI_{sc}/dV = -1/R_{sh,st} \quad (23)$$

From (23), the slope of I-V curves is controlled under short circuit condition. Moreover, two more parameters currents at maximum power and voltage at maximum power are needed to understand the characteristics of solar PV which are given.

**3.8. Current at maximum power ( $I_{mp}$ )**

The currents meet at maximum PP of solar cell is called current at maximum power (mp). It is indicated by  $I_{mp}$ . It is somehow less magnitude than the maximum value of currents. The maximum value of the current occurs under short circuit.

**3.9. Voltage at maximum power ( $V_{mp}$ )**

The voltage meet at maximum PP of solar cell is called voltage at mp. It is indicated by  $V_{mp}$  and somehow less magnitude than the maximum value of voltage. The mathematical relation is given as,

$$\text{At the maximum power point: } I=I_{mp}, V=V_{mpo} \text{ and } dP/dV_{mp}=0$$

**3.10. MATLAB model**

The MATLAB model of solar PV is designed using above equations under STC. The basic block diagram is shown in Figure 3. The input voltage is a ramp signal which changes with time. It gives V-I curve to study the characteristics. In Table 2, all parameters' values of solar PV model are given. The output of solar PV model is connected with conventional buck boost converter and zeta converter to compare its performance. The pulses of the converters are generated by fuzzy logic controller at MPPT. It generates maximum power at every pulse of converters.

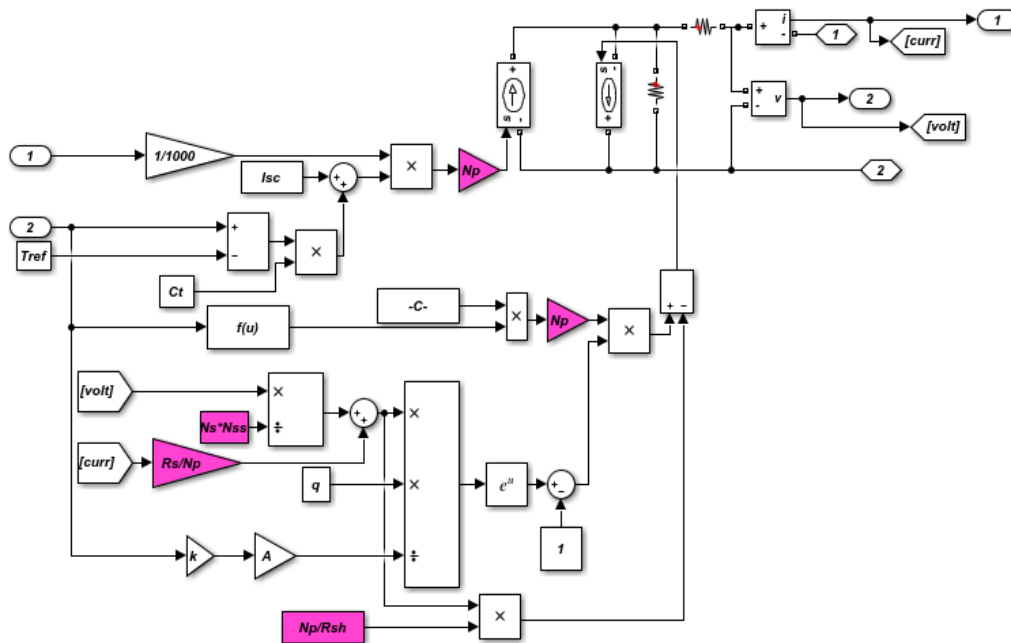


Figure 3. MATLAB model of PV solar based on seven parameters

Table 2. Solar photovoltaic (PV) parameters at 1000 W/m<sup>2</sup> insolation [2]

Parameters	Specifications
Solar power at 1000 W/m <sup>2</sup>	2.5 kW
Maximum voltage ( $V_{pvmax}$ )	220 V
Maximum current ( $I_{pvmax}$ )	10.3 9A
Number of cells in series ( $N_s$ )	$N_s=10$
Number of cells in parallel ( $N_p$ )	$N_p=2$
open circuit voltage ( $V_{oc}$ )	$V_{oc}=21V$
Short circuit current ( $I_{sc}$ )	$I_{sc}=6.4 A$
light current ( $I_{ph}$ )	$I_{ph} = 0.04 A/cm^2$
diode reverse-saturation current ( $I_{rs}$ )	0.00065A
ideality factor ( $a_f$ )	$a_f=1.3$
series resistance ( $R_s$ )	$R_s=0.0053 \Omega$
shunt resistance ( $R_{sh}$ )	$R_{sh}=150 \Omega$
Temperature	$T_{ref}=298;$
Charge in charge (q)	$q=1.602e-19$
Boltzmann's Constant (k)	$k=1.381e-23;$

**4. CONTROL ALGORITHM**

An intelligent control algorithm is taken [24], [25] to pulse the zeta converter switch Q. The switch Q is an electronic switch to generate constant DC voltage which is shown in Figure 1. There are various control approach to design the MPPT while fuzzy logic control algorithm based intelligent controller is a fast and under zero delay [26]. It starts to operate under steady state condition. In intelligent-MPPT algorithm, the active power (P) is calculated from product of voltage (V) and current (I) at each instant k [27]. The power P at k instant is subtract from the P at last instant k-1 to obtain the change in power ( $\Delta P(k)$ ). Correspondingly, the change in current ( $\Delta I(k)$ ) and change in  $Ce(k)$  can be estimated as (24), (25),

$$e(k) = \frac{\Delta P(k)}{\Delta I(k)} = \frac{\Delta P(k) - \Delta P(k-1)}{\Delta I(k) - \Delta I(k-1)} \tag{24}$$

$$Ce(k) = \Delta e(k) = e(k) - e(k-1) \tag{25}$$

where  $e(k)$  and  $Ce(k)$  error in voltage and change in error respectively at sampling time  $k$ . The output of intelligent-MPPT can obtain the changing duty ratio  $\Delta D(k)$  using (24) and (25). The duty cycle ( $D(k)$ ) can obtain as (26),

$$D(k) = \Delta D(k) + D(k-1) \tag{26}$$

The fuzzifier, inference and defuzzifier are the fuzzy process controller. These are used to find the desire value of control algorithm. The fuzzifier receive the input data to analysis it as per user define chart known as membership function (MF). In this work, a grade assign to fuzzifier from 0 to 1 which gives good results. Moreover,  $e(k)$  and  $Ce(k)$  are assigned a set value (-60 100) and (-5 5) respectively to obtain  $\Delta D(k)$ . Whereas inference system is used to evaluate the individual rules. In this case, 25 fuzzy rules of five membership function are taken as linguistic terms using permutations and combinations [28]. At last, defuzzification is used to convert crisp output of duty cycle [29]. In Figure 4, an Intelligent-MPPT model is designed using MATLAB fuzzy logic tool box to extract the duty cycle at maximum power point of the solar system. It is feedback control system. Moreover, it is adoptive in nature to control the duty ratio.

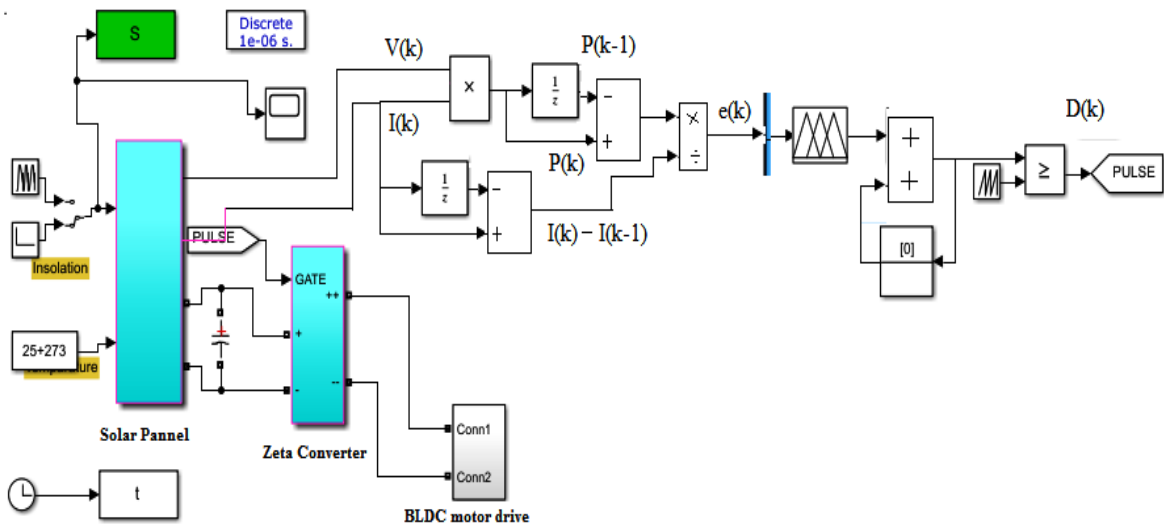


Figure 4. A MATLAB model for intelligent maximum power point tracking

**5. RESULTS AND DISCUSSION**

A solar PV module, zeta converter and Intelligent-MPPT are integrated to get the maximum power for an electronic commutation. An electronic commutation is used to control load of proposed model. The load is a BLDC motor pump as shown in Figure 1.

The MATLAB simulation results are based on seven parameters module of solar system integrated with zeta converter to generate designated voltage level under BLDC load. The estimated parameters of zeta converter and solar PV module are given in Tables 1 and 2. The simulation model is analyzed under standard



condition of solar irradiance (G) and under various condition from 400 to 1000 W/m<sup>2</sup> with constant temperature at 25 °C as shown in Figures 5 and 6. Moreover, a comparative performance of intelligent-MPPT and INC-MPPT are presented in this section to understand the value of the intelligent controller.

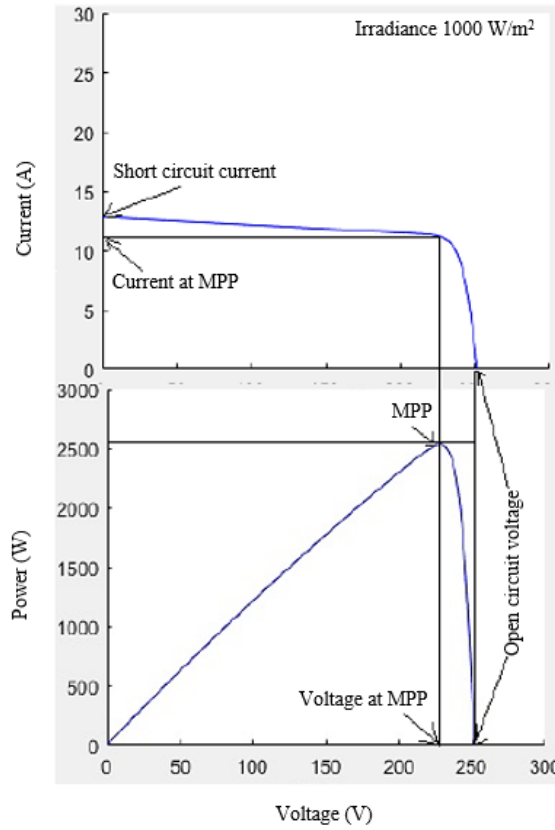


Figure 5. PV current (A) versus PV voltage (V) and power (W) versus voltage (V) curve under standard condition

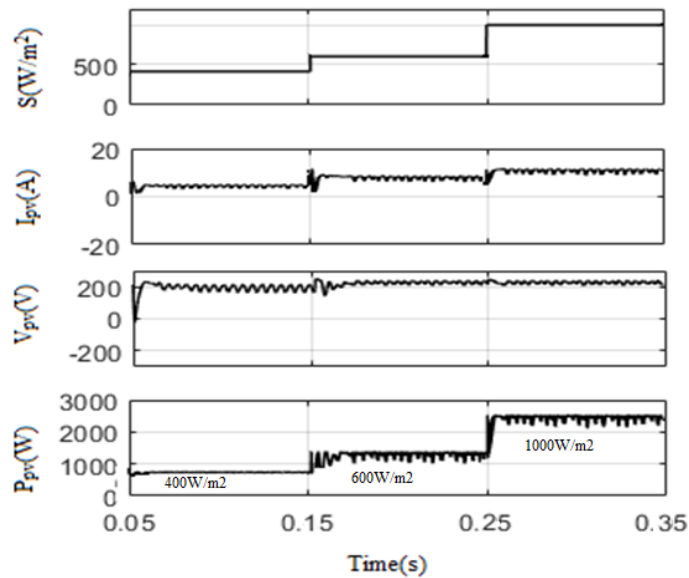


Figure 6. Solar irradiance (S(W/m<sup>2</sup>)), solar current (I<sub>pv</sub> (A)), solar voltage (V<sub>pv</sub>(V)), solar power (P<sub>pv</sub>(W)) under various solar irradiance

**5.1. Performance of intelligent based MPPT**

A comparative result is shown in Figure 7, where the intelligent fuzzy logic controller FLC-MPPT and INC-MPPT are used to pulse the zeta converter with certain duty ratio and maintains output DC voltage. The performance of the intelligent based FLC-MPPT is good and fast without delay while the INC-MPPT has more delay to charge the battery. Moreover, performance of intelligent controller based MPPT under water pump load condition is shown in Figure 8 whereas the performance of INC-MPPT under same load for transient and steady state condition is depicted in Figure 9. The comparative results tell about the satisfaction and good performance of the fuzzy controller as compared to the conventional controller.

**5.2. Performance of intelligent MPPT**

A comparative result in Figure 7 is shown to understand the value of zeta converter performance under intelligent MPPT and INC-MPPT. Zeta converter takes the more time to reach at 0.57 duty ratio while an intelligent MPPT reach very fast at 0.57 duty cycle without overshoot and undershoot. However, in Figure 6, the solar irradiance varies from 400 to 600 W/m<sup>2</sup> and then gain up to 1000 W/m<sup>2</sup>. The DC voltage source continuously maintain the voltage level to vary the duty cycle of zeta converter.

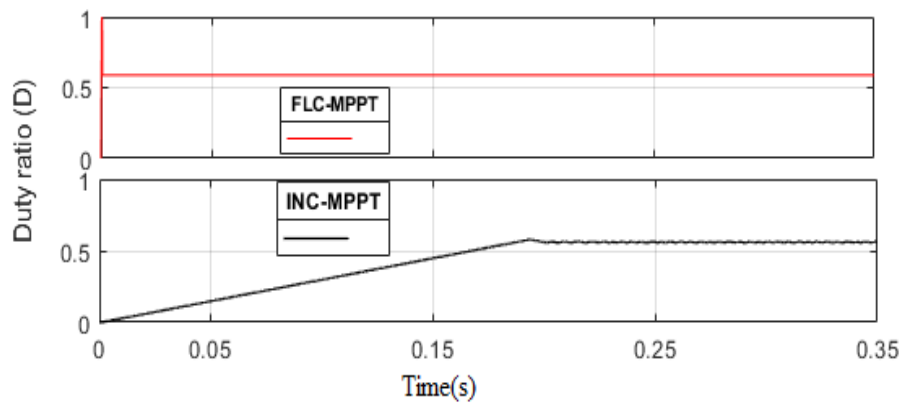


Figure 7. A comparative duty ratio (D) of zeta converter under intelligent based MPPT and incremental conductance based MPPT

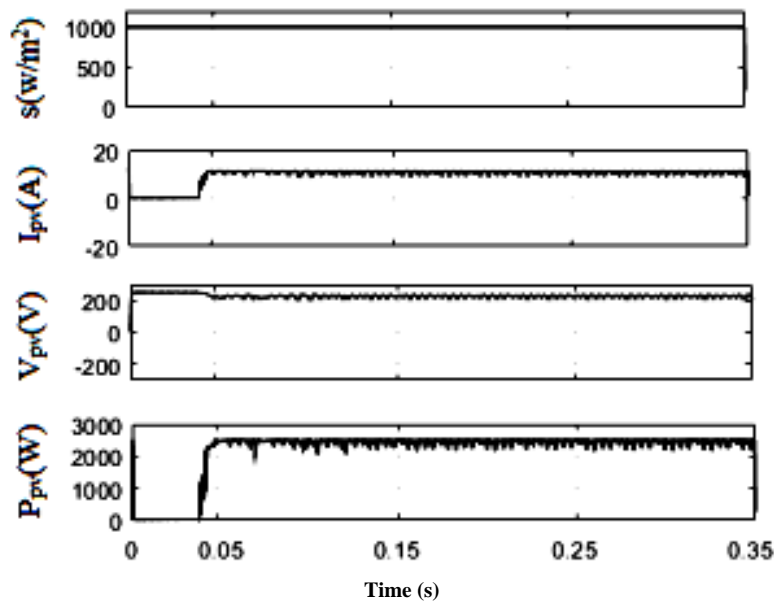


Figure 8. Performance of intelligent controller based MPPT to pulse the zeta converter, Solar irradiance (S(W/m<sup>2</sup>)), PV current (I<sub>pv</sub> (A)), PV voltage (V<sub>pv</sub>(V)), PV power (P<sub>pv</sub>(W)) under BLDC load

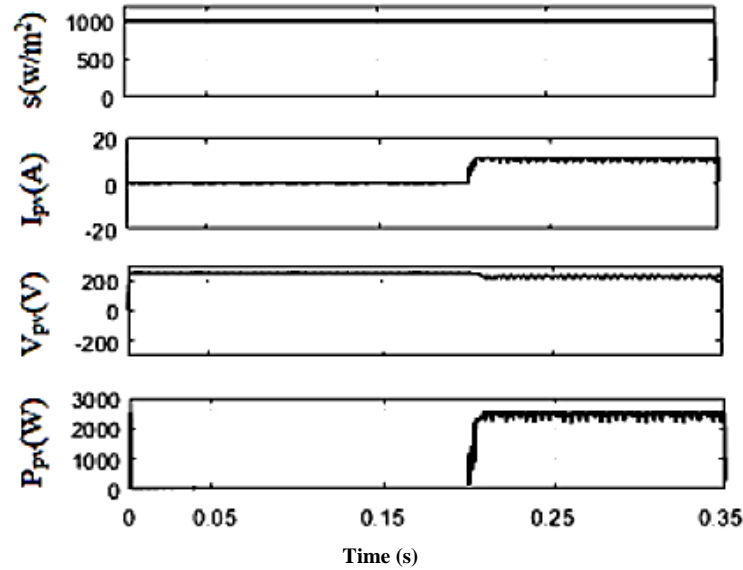


Figure 9. Performance of INC based MPPT to pulse the zeta converter, solar irradiance (S(W/m<sup>2</sup>)), PV current (Ipv (A)), PV voltage (Vpv(V)), PV power (Ppv(W)) under BLDC load

6. CONCLUSION

The estimated parameters of zeta converter and seven parameters based photovoltaic system are designed on MATLAB/Simulink model. The maximum power is extracted using intelligent control algorithm and compare its results with incremental conductance based MPPT. The characteristic of PV current versus voltage and PV power versus voltage are shown in Figure 5. Whereas PV current, PV voltage and power under various conditions of irradiance are shown in Figure 6. Moreover, intelligent-MPPT is compared with INC-MPPT under BLDC-based water pump load. Intelligent-MPPT is reached at 0.57 duty ratio without any delay while INC-MPPT takes 0.21 seconds to reach 0.57 duty ratio. The transient response and steady-state response to extract the power, voltage, and current are fast using intelligent-MPPT as compared to INC-MPPT. Comparative results are shown in Figure 8 and Figure 9. It is seen that each section of the proposed model gives a good performance.

APPENDIX

Table 1. Zeta converter parameters for 2.5 kW solar power

Variable parameters	Mathematical relation	Parameters value	Theoretical value	Practical value
$D_t$	$\frac{V_{pv\ max}}{V_{pvo}}$	$V_{pv\ max}=230\ V, V_{pvo}=300\ V$	$D_t=0.566$	$D_t=0.57$
$C_{pvin}$	$\frac{D_t * I_{pvo}}{\Delta V_{pp} * V_{pv\ max} * f_{sw}}$	$D_t=0.56, I_{pvo}=9.33\ A, \Delta V_{pp}=10\%$ $V_{pv\ max}=230\ V, f_{sw}=20\ kHz$	$C_{pvin}=11.3582\ \mu F$	$C_{pvin}=11\ \mu F$
$C_c$	$\frac{D_t * I_{pvo}}{\Delta V_{pp} * V_{pv\ max} * f_{sw}}$	$D_t=0.56, I_{pvo}=9.33\ A, \Delta V_{pp}=10\%$ $V_{pv\ max}=230\ V, f_{sw}=20\ kHz$	$C_c=11.3582\ \mu F$	$C_c=11\ \mu F$
$C_{pvo}$	$\frac{\Delta I_{Lb(pp)}}{8 * \Delta V_{pvo(pp)} * f_{sw}}$	$\Delta I_{Lb(pp)}=10\%$ of the inductor current $f_{sw}=20\ kHz, \Delta V_{pvo(pp)}=10\%$ ,	$C_{pvo}=58.12\ \mu F$	$C_{pvo}=60\ \mu F$
$L_{a,b}$	$\frac{D_t * V_{dcin} (at\ max\ input\ voltage\ V_{pv\ max})}{2 * \pi * \Delta I_{Lb(pp)} * f_{sw}}$	$D_t=0.56$ $V_{pv\ max}=230\ V$ $\Delta I_{Lb(pp)}=10\%$ of the inductor current $f_{sw}=20\ kHz$	$L_{a,b}=0.0045161\ H$	$L_{a,b}=5\ mH$

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