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Sizing and implementation of Photovoltaic Water Pumping System for Irrigation

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ABSTRACT

Solar photovoltaic systems convert energy of light directly into electrical energy. This work presents, a process to compute the required size of the stand-alone solar photovoltaic generator based water pumping system for an existing area. In addition solar photovoltaic generator is connecting voltage source inverter fed vector controlled induction motor-pump system. Perturb and observe are used for harvesting maximum power of PV generator in between buck-boost DC converter and inverter system. In this paper system result is validated by fuzzy logic system and compare with variable frequency drives based PI controllers, driving motor-pump system. The operational performance at 60 m head, VFD based controllers in terms overshoot and setting time and also analysis performance of motor-pump set under different weather conditions. By assessment of system we find that speed and torque variation, overshoot and settling time is more with PI controller, Fuzzy logic controller (FLC) performance have dominance to VFD based PI controller.

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1. INTRODUCTION

The renewable energy resources such as the sun, wind, biomass, tidal and geothermal heat are environment friendly, clean and easily available but these resources harnessing are not possible in large scale level at present scenario. Harnessing energy through these resources using efficient technologies are big task for researchers. Among the all renewable resources, sun energy is the core energy due to the some characteristics such as non-hazardous, undisruptive, endless, and carbon dioxide (CO_2) discharge free. A solar cell or photovoltaic cell is an semiconductor devices that converts the radiance energy directly in to dc electrical energy so that in other way it is just like a transducer. The main applications of PV system are stand-alone grid system and solar water pumping system in remote areas [1].

Many researches published on a stand-alone photovoltaic (PV) water pumping modeling and control system are used for irrigation and drinking water [2-5]. Their performance has been evaluated under varying endure conditions and at different solar insulation levels. In India water irrigation system have been developed and tested around the all state. The demand of water for farming irrigation and livestock water supplies are increasing in MP state rural areas. The traditionally sources for water pumping have Diesel, kerosene and electricity used. In remote areas consistency of fuel supply is problematic, however consistent solar water pumping are now rising on the market. The load matching to the PV array is a serious issue for the efficient functioning of the system [6]. The efficient functioning of the PV water pumping system is usually employed maximum power point tracking (MPPT) controller, to automatically extract maximum power irrespective of the instant conditions of the PV system [7]. The various methods/algorithms are available for Maximum Power Points (MPP) tracking point. The main important methods are Perturb and Observe (P&O), Incremental & conduction (IC), fuzzy logic, neural network etc.[8-9].

The induction motor based pumping systems are more efficient of various climate conditions [10]. This paper is present sizing, analysis of simulation testing and assessment of a stand-alone PV generator pumping system driven three phase induction motor drive system. The motor-pump system was designed to supply a daily average of 35,000 liters/day at 60 m head from a bore well in fruits plant farm.

2. SOLAR WATER (MOTOR-PUMP) SYSTEM ANALYSIS AND DESIGN

Solar water pumping systems are classifying DC and AC motors. DC motors are direct coupling to photovoltaic generator, whereas AC motors are coupled to the photovoltaic generator through inverters (three phase or single phase). AC motors are more robust, less maintenance, low-priced and more reliable as compare to DC motors. There are different varieties solar pumps available in the market. According to water pumping requirement, solar water pumps may be subdivided into three categories: submersible, surface, and floating water pumps. The most common used pump is centrifugal principal based submersible pump. A submersible pump, pumping water from deep wells or bore wells, a surface pump is placed outside the well and draws water from shallow wells, ponds, rivers or tanks, and a floating pump is placed on the water plane and pump water from pool or tank with different height [11-13].

A photovoltaic water pumping system is design: first step calculate total dynamic height, second step calculate hydraulic energy required per day and finally PV generator capacity.

In the first step calculate total dynamic head (TDH), TDH is addition of a perpendicular distance from the water surface level to the water supply end and total friction losses (FL) as shown in Figure 1 (A+B). This FL component can be reduced by removing turns and reduced the water supply velocity. Thus, the TDH is the addition of the perpendicular length and the length representing the friction losses in the pipeline (TDH = A distance + B distance + FL) [14].

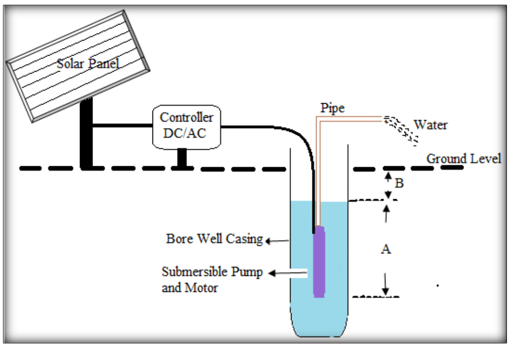


Figure 1. Solar water pumping system

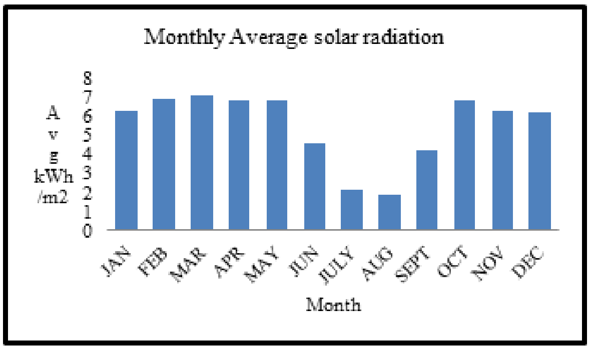


Figure 2. Monthly average solar radiation intensity

In our case study:

TDH= Vertical lift + Frictional losses= (A + B + FL) (1)
TDH = 60 m + (FL- 0.5% of total perpendicular length)
= 60.3 m

The hydraulic energy required per day (KWH) is [15]:

$$E_h = \rho \times v \times g \times TDH \times 10^{-3} MJ \qquad (2)$$
= 20704.005 MJ

We know that, 3.6 MJ= 1 KWH
= 5.751 KWH

ρ is supply water density (1000 kg/m^3); g is the increase of velocity due to gravity (9.81 m/s^2); TDH is the total pumping head in m; v is the volume water required per day is 35,000 liters/day.

Thus, the PV generator power (KW) necessary can be written as

$$P_{pv} = \frac{E_h}{G_t P_e F}\ KW \tag{3}$$
$$= 3.762KW$$

where G_t is the day by day sun energy on PV plane in kwh/mtr^2 (6 hours/day), F is the PV mismatch factor values range between 0.85 and 0.90 and P_e is the everyday subsystem effectiveness which has a typical significance in between 0.20 to 0.60 [16].
Considering operating factor (OF) (to reimburse for the energy falling due to warm, dirt and ageing)

$$= \text{Total PV panel KW /OF} \tag{4}$$

PV panel capacity = 3.762/0.75 =5.016 KW
The total number of PV module required =5016/250 = 20.
5 HP three phase induction motor can be rotate by 5 KW photovoltaic generators with the obtainable 250 W photovoltaic module [17].
Thus PV system efficiency (η_{pv}) is calculating using following equation [18]:

$$\eta_{pv} = \frac{P_{pv}}{A_{pv} G} \tag{5}$$
$$\eta_{pv} = 11.5\%$$

Where A_{pv} is the total plane region of the PV system in mtr^2 shown in table-1 and G is the sun irradiation strength in W/mtr^2. The Photovoltaic array efficiency varies from 8 to 14% percent.

3. THE EXISTING PHOTOVOLTAIC IRRIGATION SYSTEM

A Nursery and fruit plant located Indore city, Madhya Pradesh state is considered as a case study in this research work. The average value of solar radiation intensity in Indore (Latitude and longitude coordinates are: 22.719568N, 75.857727E) is 5.51 kWh/m^2/day, shown in Figure 2 [19].

The size of the Nursery and fruit plant is 5 acres. The farmhouse has cattle and supply drinking water to five homes. A 3ph/5hp/3.70KW submersible (motor-pump) set is used for irrigation the plant. The submersible set is grid connected through controller. The bore well depth is 75 m, the total dynamic head level is 60.3 m and the flow rate is around 35,000 liters/day. Figure 3 illustrate existing PV water pumping system. For optimal sizing of the photovoltaic generator, the hydraulic energy 20704.005 MJ (5.751 KWH) is required per day and the dimension of the solar modules are establish to be 5.01 KW including energy falling due to warm, dirt and ageing. The PV 0.250 KW panel with size of 1.63 mtr^2 gives the requirement of 20 PV panels with total area of 33 m^2 shown in Table 1.

Figure 3. Solar water pumping system of study area

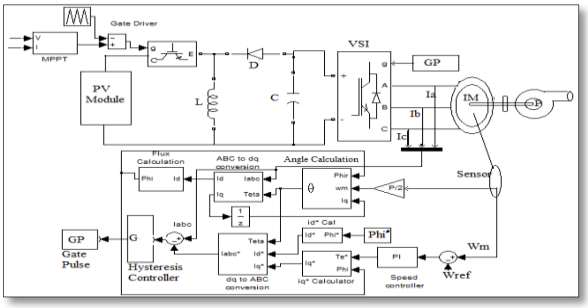


Figure 4. Solar generator Induction Motor pump set

4. MODELLING OF PV PUMPING SYSTEM

The schematic circuit diagram of existing photovoltaic based three phase induction motor-pump system for irrigation system is shown in Figure 4. The complete framework of PV water pumping system including of photovoltaic generator, a buck-boost DC converter, a VSI (3-phase) and submersible pumping system. The semiconductor photovoltaic generator converts sun energy in to DC electricity. The PV generator is linked to the buck-boost topology to control the input voltage of inverter. Three phase inverter is converting DC to three phase AC supply according the motor-pump system requirement.

4.1. Modelling of Solar PV system

The Solar panel (ALP-250W) is modelling using MATLAB/Simulink environment. The solar panel current-voltage and power-voltage characteristic at 25 °C and different insolation are shown in Figures 5-6. ALP-250W panel parameters values are given below Table 1. The PV generator is designed for a 5.01 kW according the requirement.

Table 1. Solar Panel (ALP 250W)

S. No.	Name of Parameters	Value
1	Open-circuit-voltage (Voc)	37.2 V
2	Short-circuit-current (Isc)	8.75 A
3	Current of the panel at maximum power point (Impp)	8.35 A
4	Voltage of the panel at mpp (Vmpp)	29.95 V
5	Power at maximum power point (Pmpp)	250W +- 3%
6	No. of module	20
7	Insolation	1000w/m^2

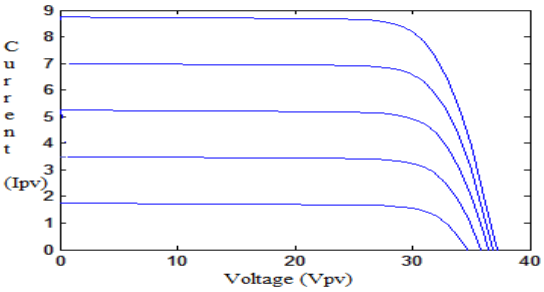


Figure 5. I-V curve at various insolation

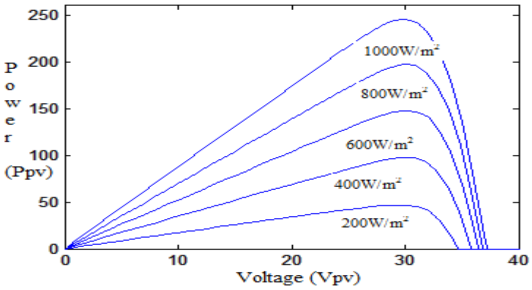


Figure 6. P-V curve at various insolation

4.2. Modelling of DC-DC (Buck Boost) Converter

The DC-DC converter is a converter that vary (less than or greater than) output voltage. The converter output voltage is given below [20]

$$V_o = -\frac{D}{1-D} V_{in} \tag{6}$$

The value of L and C are:

$$L = \frac{V_o D}{\Delta If} \tag{7}$$

$$C = \frac{V_o D}{\Delta V_c f R} \tag{8}$$

L= 34 mh and C= 130 µf.
Where, V_{in}, V_o converter supply and output voltage respectively, D is duty cycle, ΔI is ripple current (10% to output current), $\Delta V_c$is ripple voltage (0.5% of V_o), f on-off frequency and R is load value.

$$\eta_{con} = \frac{V_o I_o}{V_{pv} I_{pv}} \tag{9}$$

4.3. Solar Pump Inverter

The solar pump inverter shown in Figure 4 is convert dc voltage (380-780 V_{dc}) into 3-phase AC variable electrical energy (380 Vrms) and frequency (0-60Hz) to provide the motor-pump system. Vector control technique with PI controller is used for controlling the output voltage of inverter and maintain constant voltage frequency ratio. The solar pump inverter is specially designed for controlling the V/F ratio according variable sun emission level and hotness. The solar pump inverter operates within the defined speed limits minimum pump speed (700 rpm) and maximum pump speed (3500 rpm) inverter stops the pump operation. It is defined by MPPT. The case study used three phase, 4 KW, 0-60Hz, 380Vrms and 13 A rating.

4.4. Modelling of water Pump

In this particular system water pump is used and it is working speed at 2900rpm. The load torque obtainable by the following expression [21]

$$T_l = \frac{K_{pump}}{\omega_m^2} \tag{10}$$

$$K_{pump} = \frac{12.28}{(2\pi\times\frac{2900}{60})^2} \tag{11}$$
$$= 0.133\text{x}10^{-3}\ \text{Nm/(rad/sec)}^2$$

Where T_l and ω_m load torque and rotor (shaft) speed of pump respectively.
Hydraulic pump efficiency can be determined by

$$\eta_{hyd} = \frac{2.725QH}{P_{sh}} \tag{12}$$

The centrifugal pump efficiency depends on the flow-rate and TDH of water. Where, P_{sh} motor shaft power. The overall efficiency of solar motor-pump system (η_{sys}), [18]:

$$\eta_{sys} = \eta_{pv}\eta_{con}\eta_{inv}\eta_m\eta_{hyd} \tag{13}$$

Typically overall efficiency values of solar pump systems in between 3.0 to 4.50%.

5. THE CONTROLLER

In this system, two controllers are used: MPPT for photovoltaic generator to harvest highest energy and 3-phase inverter switching by using PI controller bases AC drive.

5.1. MPPT

The sizing solar energy systems, uses the MPPT control technique to increase the effectiveness of the systems. The output power of the PV cell is proportional to its area and intensity, while the output voltage is constant (p-n diode- 0.6 to 0.7 V). The PV cell characteristics is non linear, its output change by changing the input temperature and insolation so required controller for extract the maximum power. There are number of MPPT strategies available, to derive the height energy from the solar generator. P&0 algorithms are used to extract height energy from the solar system at any moment. Shown in Figures 5-6, the I-V and P-V curve is not constant since intensity and temperature changes during day time.

5.2. Vector control IM drive using PI controller

The Motor-Pump controller is based on speed balance between rotor speed and reference speed. The load energy is equal to the multiplication of speed and torque of the motor. For this particular system inverter is control using Vector Control scheme. The speed error is the deference between required rotator speed and rotor speed (ω_r*- ω_r). This error is feed PI controller, which gives the base torque (T_e*). The base torque is utilize for calculating required current of quadrature axes (i_q*) using following expression,

$$I_q^* = \frac{4}{3P} \times \left(\frac{L_r}{L_m}\right) \times \left(\frac{T_e^*}{\varphi}\right) \tag{14}$$

The required direct axes current I_d^* , and calculated expression as,

$$I_d^* = \left(\frac{\varphi^*}{L_m}\right) \tag{15}$$

Electrical angle θ is obtained as follows

$$\theta = Electrical\ angle = \int(\omega_r + \omega_m) \tag{16}$$

Where, P is number of pole, (L_r) and (L_m) load and mutual inductance of rotor respectively, φ is flux, $\varphi^*$is reference flux, ω_r rotor speed (rad/sec) and $\omega_m$motor speed (rad/sec).
The value of required motor currents $I_a^*, I_{b,}^* and\ I_c^*$ are,

$$I_a^* = I_d^* \cos\theta - I_q^* \sin\theta \tag{17}$$

$$I_b^* = I_d^* \cos\left(\theta - \frac{2\pi}{3}\right) - I_q^* \sin\left(\theta - \frac{2\pi}{3}\right) \tag{18}$$

$$I_b^* = I_d^* \cos\left(\theta + \frac{2\pi}{3}\right) - I_q^* \sin\left(\theta + \frac{2\pi}{3}\right) \tag{19}$$

These motor currents ($I_a^*, I_{b,}^* and\ I_c^*$) are match up to motor stator currents $(I_a, I_b and\ I_c)$ and the difference value is feed pulse generator (hysteresis-band regulator) to generate on-off pulses for inverter [22].

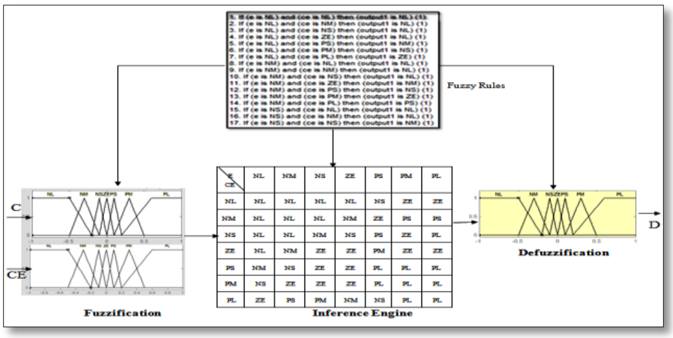
5.3. Proposed Fuzzy logic controller

The main aim of this proposed system is pumping water of the farm in another technique by photovoltaic generator. Fuzzy systems are based on fuzzy logic, boolean or crispy logic to handle the concept of vagueness, uncertainty and imprecision. A fuzzy logic system describes the control action in terms of simple if-then rule. Hence it gives a linguistic or fuzzy model that is developed based on human experienced and expertise rather than a mathematics model. In this study proposed a vector control IM drive with fuzzy controller. In FLC systems are enter two input and one output variable. One input variable is the difference between reference speed and rotor speed (eω(n)), another input variable is difference between error speed and error speed at previous sample (ceω(n))[23-24]:

$$e\omega(n) = \omega_m^*(n) - \omega_m(n) \tag{20}$$

$$ce\omega(n) = e\omega(n) - e\omega(n-1) \tag{21}$$

Where, $e\omega(n-1)$ is error value at before sampling time.



1. If (e is NL) and (ce is NL) then (output1 is NL) (1)
2. If (e is NL) and (ce is NM) then (output1 is NL) (1)
3. If (e is NL) and (ce is NS) then (output1 is NL) (1)
4. If (e is NL) and (ce is ZE) then (output1 is NL) (1)
5. If (e is NL) and (ce is PS) then (output1 is NM) (1)
6. If (e is NL) and (ce is PM) then (output1 is NS) (1)
7. If (e is NL) and (ce is PL) then (output1 is ZE) (1)
8. If (e is NM) and (ce is NL) then (output1 is NL) (1)
9. If (e is NM) and (ce is NM) then (output1 is NL) (1)
10. If (e is NM) and (ce is NS) then (output1 is NL) (1)
11. If (e is NM) and (ce is ZE) then (output1 is NM) (1)
12. If (e is NM) and (ce is PS) then (output1 is NS) (1)
13. If (e is NM) and (ce is PM) then (output1 is ZE) (1)
14. If (e is NM) and (ce is PL) then (output1 is PS) (1)
15. If (e is NS) and (ce is NL) then (output1 is NL) (1)
16. If (e is NS) and (ce is NM) then (output1 is NL) (1)
17. If (e is NS) and (ce is NS) then (output1 is NM) (1)

E / CE	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NS	ZE	ZE
NM	NL	NL	NL	NM	ZE	PS	PS
NS	NL	NL	NM	NS	PS	ZE	PL
ZE	NL	NM	ZE	ZE	PM	ZE	ZE
PS	NM	NS	ZE	ZE	PL	PL	PL
PM	NS	ZE	ZE	ZE	PL	PL	PL
PL	ZE	PS	PM	NM	NS	PL	PL

Figure 7. Schematic diagram of FLC

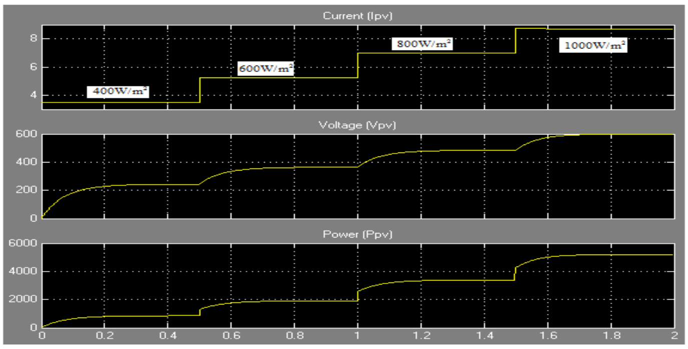


Figure 8. PV generator parameters at various insolations

Open the membership function (MF) editor and add seven MF to two inputs and one output variables to convert these numerical variables in to linguist variables, following seven sets are chosen: Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), Positive Large (PL). Frame the different rules (49 rules) as per the requirement, rules will be there as shown in Figure 7. The FLC output variable is the reference torque after the gain multiplication [25-26].

6. RESULTS AND IMPLEMENTATIONS

6.1. Case-I (PI controller)

According to the case (Nursery and fruit plant) requirement, a photovoltaic irrigation arrangement was designed using MATLAB environment location in Indore total supply water in average to 30m^3/day. The average value of sun energy strength in bore-well location quantity of 5.51kWh/m^2/day considered.

Figures 5-6 shows current-voltage and power-voltage curves of the PV module for motor-pump system under different insolation at constant temperature (25ºC). The experiment was shows that photovoltaic generator operating point precisely placed at MPP and extract maximum power.

Figure 8 shows that the solar generator constraints like voltage (Vpv), current (Ipv), energy (Ppv) for different insolation conditions (400W/m^2 -1000W/m^2) and constant temperature 25°C. The voltage, current and power is increased in increasing the solar insolation and settled at the operating point within 0.04 second.

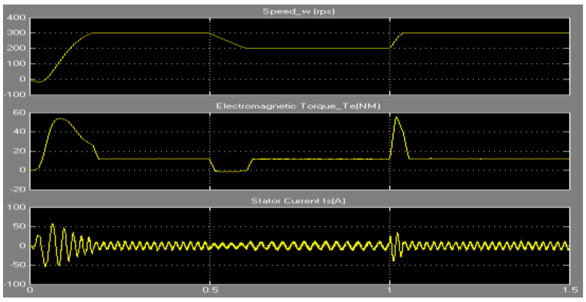


Figure 9. Motor-pump set parameters at various speed

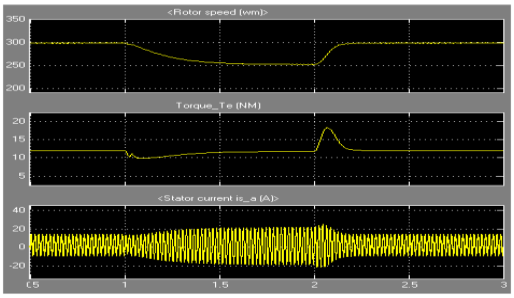


Figure 10. Motor-pump set parameters at various isolations

Figure 9 shows the simulation results for motor side parameters like motor speed, electromagnetic torque and stator current with variation of speed 300radian/second to 200radian/second and 300radian/second for 0.5 second interval. It can be observed that stator current frequency increases or decreases with increase or decrease speed at constant torque.

Figure 10 show the simulation results for motor side parameters like motor speed, electromagnetic torque and stator current with change in solar irradiance. It can be observed that stator current magnitude increases with decrease solar irradiance and settling fraction of seconds. Table-2 shows average efficiency of various stages of PV pump system at constant head. The daily average system efficiency has 3.0% as compare to daily average cells efficiency. The average daily flow rate of the system is about 5.3m^3/hrs, it is fulfill the daily water requirement. Figure 11 show water flow rate and pump efficiency at 400W/m2 to 1000W/m2 insolation. It is clear from graph solar radiation intensity increases, increases water flow rate and pump efficiency.

Table 2. Performance of the PV water pump system for a head = 60 m

Insolation W/m^2	Average η_{pv} %	Average η_{con} %	Average η_{inv} %	Average η_m %	Average flow, Q (m^3/hrs)	Average η_{hyd} %	Average η_{sys} %
400-1000	11.9	94.8	94.5	84.03	5.3	33.6	3.0

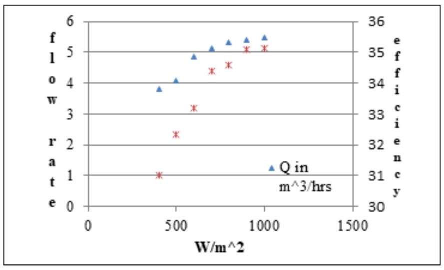


Figure 11. Flow rate and pump efficiency at various insolation

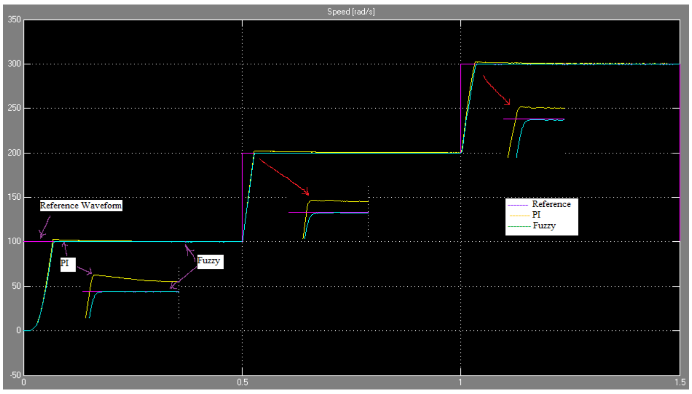


Figure 12. Motor-pump speed variation in each controller

The overall solar-motor-pump scheme efficiency was calculated using expression number (29) as η_{sys} =3.0%. At average PV module efficiency, η_{pv} =11.9% and dc-dc converter efficiencyη_{con}=94.8% was calculated. The inverter efficiency was separately measured to η_{inv} =94.5% and inverter-IM-pump efficiency 26.67% was calculated.

6.2. Case-II Comparison of proposed FLC with conventional PI Controller system

To compare PV pumping system performances of fuzzy logic controller fed water pumping system operation with the existing PI controller simulation is done and the results are shown in Figure 12. The motor-pump speed variations a result was clearly indicated, proportional-integral controller based drive system overshoot is more than the FLC based drive system. Proportional-integral controller based drive system required more settling time as compare to FLC based drive system. In every speed variation FLC based drive reaches operating point earliest as compare to PI based drive.

7. CONCLUSION

The pumping scheme was mounted on a bore in nursery and fruit plant Indore at means rays intensity 5.51kWh/m^3/day, to provide the irrigation and drinking water. The solar water supply scheme has been experienced under various working conditions and the steady-state and dynamic behavior has been found quite suitable for water pumping system. The overall system efficiency is feasible at various environmental situations and 60 mtr water supply (TDH) head. A proposed controller (FLC) compare with traditional PI controller using Matlab environment. The simulation results are confirmed that FLC based pumping system gives more accurate results as compare to PI controller based motor-pump system. The FLC are increasing the performance of the motor-pump system.

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