Modelling, Control and Regulation of Solar Water Pumping System – A Case Study in Vizianagaram district

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Abstract :This paper discusses about the modelling, control and regulation of solar water pumping network. A novel method of water level regulation is provided based on a Fuzzy logic controller. The main objective of this paper is to supply the water according to the needs of the users regardless of dynamic variations in the climatic conditions. The paper focuses on the design and optimization of the power generated from the Photo Voltaic Generator and to regulate the water in the tank. A fuzzy logic controller and algorithm controller are used to control the solar water pumping system. The controller generates the reference speeds necessary for the PWM generator to control each DC/DC boost converter considering water levels in three tanks and instantaneous value of the solar radiation. The performance of the controller is tested on a real time solar water pumping system in vizianagaram district. The system performance is tested under multi-operating conditions such as variable load and weather data using MATLAB/ SIMULINK environment. A comparison analysis is presented between algorithm controller and Fuzzy logic controller.

IndexTerms - Algorithm controllers, DC/DC boost converter, Fuzzy controller, PMDC motor and Solar water pumping system.

I. INTRODUCTION

Recent years, the world is utilizing the solar power applications to every field. They play a major role in agricultural purposes as irrigation systems.The world is facing problems in delivering water to the communities and to the agricultural fields because of deficit in electricity and due to added high price of diesel fuels. So an alternative should be adopted for the supply of water requirements which can be implemented with solar systems.The electrical energized motors driven adoption in renewable photovoltaic water pumping system is one of the most popular methods.

As agricultural technology is changing promptly day to day in the farm machinery, small holding building and manufacture conveniences, many works were being studied in applying the solar water pumping networks. A solar focused water pumping system is construction of PV panels and pumps as basic components. In order to control and enhance the pumping system, many works are done on the choice of the drive system to border to the PV source, such as dc motor, induction motor, synchronous motor. Dc motors are used because they offer cool operation with reduced conversion and little power consumption Thus, the optimization of both using PV power and adjusting the system is presented the persistence of more researches. Renewable energy sources, such as PV, wind, biomass sources and be used in water pumping system.[1].Many technical studies are worked in PV water-pumping systems as discussed in [2]. Previous analysis highlighted the ancient development of PV water-pumping control[3]

Many mechanisms are also developed in sizing PV water-pumping systems [5]. In [5] the author gives a mathematical method PV water-pumping system with more precision. The study concluded that a large variation in temperature had a negative effect on the solar panel leading to a lower-power production and a rise in solar radiation, which positively affected the system. In [5], the author presented a new hybrid technique which composed of battery systems and photovoltaic module by detail modelling and regulation where the batteries are provided with energy storage system. Today many works involved in MPPT (maximum power point tracking) technique in PV solar systems and wind power systems to maximize the energy generated from sources because of the non-linear characteristics of PV cell. The voltage and current of PV cell is affected by the temperature and irradiation. The voltage has positive effect on temperature and current has negative effect. Therefore the maximum point is to be tracked and several works are done in extracting maximum power point tracking (MPPT techniques) in solar cells [6].

A fuzzy control MPPT is developed where the controller generates a control signal for the PWM generator which fine-tunes the duty ratio of the buck chopper to maximize the motor speed and the water discharge rate of centrifugal pumping [7].In the present paper, designing and optimization of Solar Water Pumping System in a real time with fuzzy control is developed. It consists of PV modules connected to pumping motors through boost converter, with the water tank. Here a new technique with fuzzy control is implemented where it applies its efficiency in control of speeds as outputs of the motors by taking solar radiation and water level feedback as inputs. The fuzzy controller in water pumping system is applied in real time and tested for its efficiency. The implemented system with fuzzy controller is suitable for rural communities and an agricultural field for cattle sheds because it is very consistent, reasonable and quiet simple to sustain.

The entire paper is organized as follows. Section2 describes about system under study, and describes the modelling of various components of solar water pumping system such as PV panel dc boost converter, PMDC motor, and centrifugal pump. Designs and application of controllers is presented in section 3.The section 4 discusses the results and analysis and section 5 concludes the paper.

II. SYSTEM UNDER STUDY

2.1 System description

The solar water pumping system [9] shown in figure.1 consists of three boost converters with three PMDC motors and three centrifugal pumps along with water tanks. The main idea of this system containing three motors with single PVG is to optimize the energy utilization and to supply the water according to the needs of the users simultaneously. Another motivation behind the use of three converters and three duty cycle converters is related to the different motors control. The solar panel used here is 1.25kw.The system consists of PMDC motors of rating 300w each. The pumps are of type centrifugal. The water tanks consists of sensors to sense the water levels (set level=3m).The fuzzy controller is used here to regulate the water level in the tanks by controlling the motor speeds by generating the control angle α to set reference speeds as outputs for the DC/DC boost converter taking into solar radiation as input 1 and water level feedback as input 2.

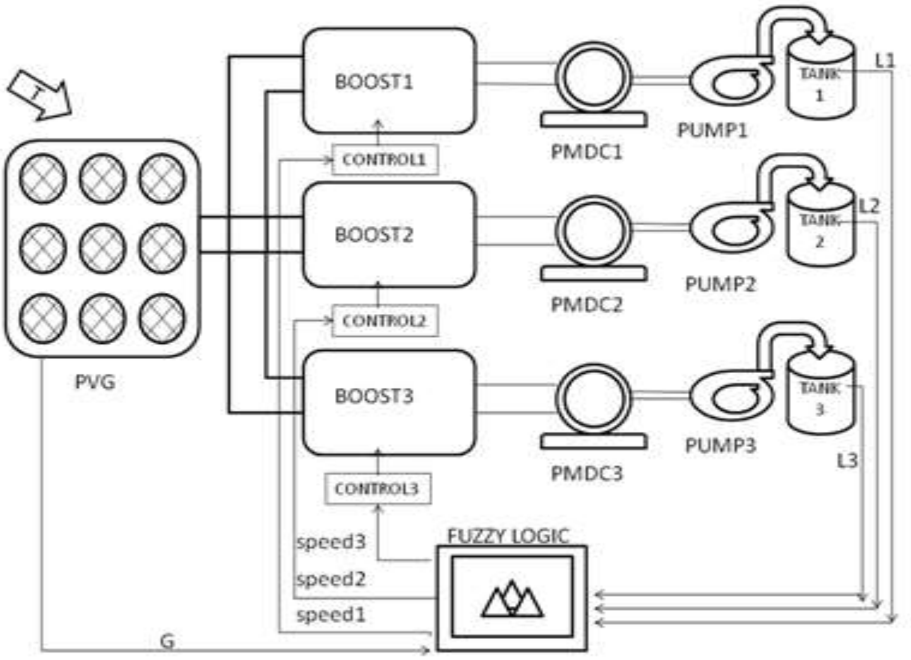


Fig.1.System configuration of solar water pumping system

2.2 Modeling of system component

This section develops an overall control approach for the concert of the PV water-pumping network system, the models of the key components are developed using Matlab/Simulink. The models are developed for a PV panel, DC/DC Boost converter, PMDC Motor, centrifugal Pump, tank and fuzzy controller.

2.2.1 PV panel

According to output characteristic of solar cells, the equivalent electrical circuit of an ideal solar cell can be processed as a current source parallel with a diode [8, 9] shown in figure.2 and figure.3.The mathematic affiliations for the current and voltage in the single diode equivalent circuit can be described with following equations (1) to (5). The specifications of the PV module is given in the following table.

$$I = I_{pv} - I_D\left[\exp\left(\frac{q(V+IR_s)}{kTA}\right)-1\right]-\frac{V+IR_s}{R_{sh}} \tag{1}$$

Where I is the output current of the PV cell and I_D is saturation current of the diode and I_{pv} is cell current.

$$I_D = I_{rr}\left[\frac{T}{T_{ref}}\right]^3 \exp\left(\frac{qE_g}{kqA}\left[\frac{1}{T_{ref}}-\frac{1}{T_{op}}\right]\right) \tag{2}$$

The photocurrent I_{pv} depends on the solar radiation G and the cell temperature T_{op} as follows

$$I_{pv} = \left[I_{SC} + c_t \left(T_{op} - T_{ref} \right) \right] \frac{G}{G_{ref}} \qquad (3)$$

G_{ref}=1000W/m^2

Where I_{SC} is short circuit current of PV panel

The relationship of the voltage and current in PV array is

$$P=IV \qquad (4)$$

$$I = N_p I_{pv} - N_p I_s \left[\exp\left(\frac{A_t V}{N_s} - 1 \right) \right] \qquad (5)$$

Where $At = \frac{q}{AT_{op}k}$

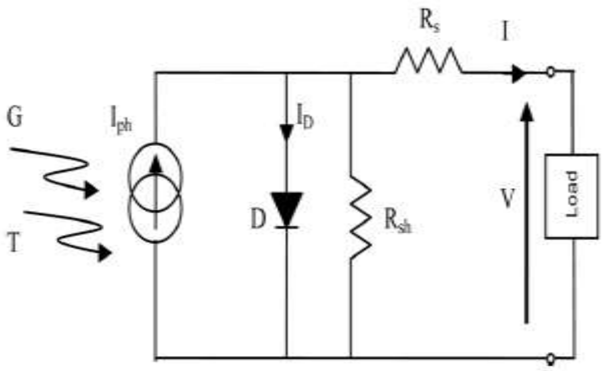


Fig.2 Equivalent electrical circuit of solar cell

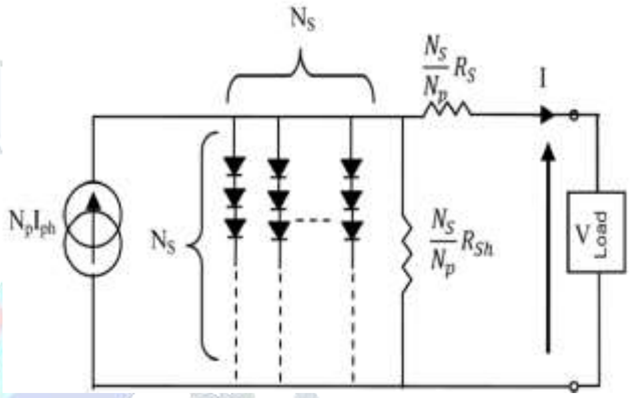


Fig.3.Single diode model of a PV array

When PV cells are arranged together in series and in parallel to form arrays, these cells are usually considered to have the same characteristics. The equivalent circuit of PV array can be shown in figure.3.

Table.I PV Module Specification

Parameter	Value
Type	SM50-H
Eg	1.12
A	1.5
Pmax(w)	50
Imax(A)	3.15
Vmpp(A)	15.9
Isc(A)	3.35
Voc(V)	19.8
Ct	45±2ºC
Ns	33

The power of the chosen PVP is fixed at P_{max}= 1.25kW

The optimal power delivered by the generator is the product of the voltage V with the current I. At a maximum power point, we have

$$P_{\max} = \frac{0.94 N_s N_p h}{A_t} G \ln\left(\frac{0.06hG + I_s}{I_s} \right) \qquad (6)$$

2.2.2 Boost converter

The concert of a photovoltaic system can be improved by using a power converter between the PV generator and the load which is boost converter. The boost converter increases the input voltage coming from solar panel. The DC-DC converter "boost," is controlled by a fuzzy and algorithm controllers in providing (duty cycle α) to adjust the proper voltage to the load. The corresponding circuit for Boost converter [10, 12] is shown in figure.4.The voltage V is applied from PV panel to the boost

converter and the dc motor is applied with V_{dc}. The specifications of the boost converter are given in the table.II.The performance of boost converter is given by following equations (7) to (12).
Transistor T is on

$$L\frac{dI}{dt}=V \quad (7) \qquad C\frac{dV_{dc}}{dt}=I_m \quad (8)$$

Transistor T is off

$$L\frac{dI}{dt}=V-V_{dc} \quad (9) \qquad C\frac{dV_{dc}}{dt}=I_m+I \quad (10)$$

Over one switching period T_s, Eqs. (7) to (10) can be combined and represented as follows:

$$L\frac{dI}{dt}=V+(\alpha-1)V_{dc} \quad (11)$$

$$C\frac{dV_{dc}}{dt}=I_m+(1-\alpha)I \quad (12)$$

Table. II Boost Converter Specification

Parameter	Value
Power(W)	400
Efficiency(%)	90
Inductance(L)(mH)	10
Capacitance(C)(uF)	50
Switching	20
Frequency(K_{HZ})	20

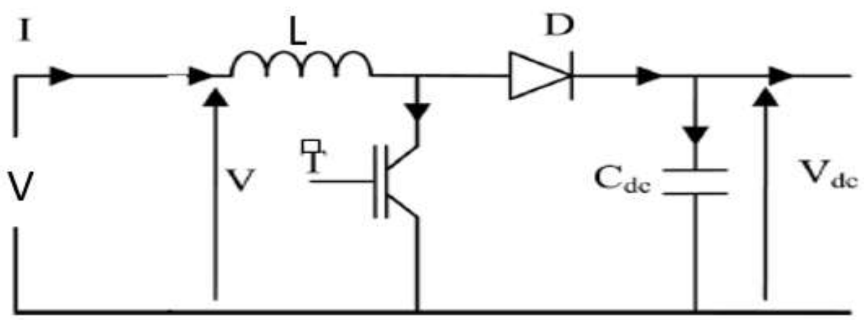


Fig.4.Equivalent circuit for boost converter.

2.2.3 PMDC motor model

Employing DC motors [8, 10] in PV pumping systems instead of AC motors is to improve the utilization of the PV system and introduces greater control flexibility by interposing a DC/DC power converter. A permanent magnet DC motors whose ratings are given in table.III is proposed for this application since it does not require a separate field power supply and gives relatively efficient and low maintenance operation. In addition, the PMDC motor coupled with centrifugal pump has a low starting torque compared to the other PV electro-mechanical systems and may be relatively easily matched with the output characteristics with the PV array. The corresponding circuit of the PMDC motor is shown in figure.5. The dynamic equation of the motor at constant flux is given by [11].

$$V_{dc}=I_m R_s+L_s\frac{dI_m}{dt}+E \quad (13)$$

Where

$$E=K_e\omega \quad (14)$$

In (13), V_{dc} *is* the applied voltage from boost converter, $R_s$is the armature winding resistance, *Ls* the armature self-inductance, I_m Is the motor armature current, *E* is the motor back e.m.f., *Ke* is the back e.m.f. constant and *ω* is the angular speed of the rotor.

Table.III PMDC machine parameters

Parameter	Value
Power(W)	400
Speed(rpm)	3500
Resistance(ohm)	33.5
Inductance(L)(mH)	0.612
K (N m/A)	82.2
J (kg m^2)	2.4
B_M (Nm/rds^{-1})	0.02

$$T_m = K_m I_m = J\frac{dw}{dt} + B\omega + C + T_L \qquad (15)$$

In (15), *Km* is the torque constant, *J* is the moment of inertia, *B* is the viscous torque constant for rotational losses, *C* is the torque constant for rotational losses and *Tm* and T_L are the electromagnetic torque and the load torque, respectively.

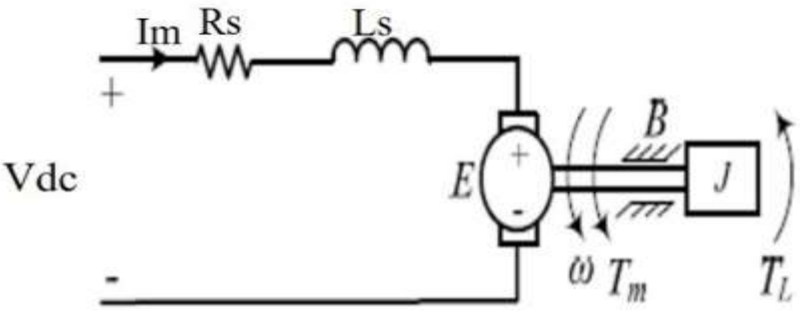


Fig.5. Circuit model for DC permanent magnet motor with pump load

2.2.4 Centrifugal pump

The figure.6.shows the centrifugal pump. In [9, 12] the centrifugal pump is selected because of its longer working periods even for low radiation levels and its load characteristics is are suitable to the maximum power curve of PV Panel.

Fig.6.Centrifugal pump

The speed and load torque of a centrifugal pump and PMDC are related that load torque of the pump is directly proportional to the square of speed of the dc motor as in eq.(16).

$$T_L = k\omega^2 \qquad (16)$$

Where K is proportionality constant

2.2.5 Tank

The water tank is used to store water in the solar water pumping system. The tank has inlet for sucking water as inflows (Q_e) and delivery of water to outside as outflows (Q_s).Flow Q_e is proportional to the speed of the PMDC motor and the flow rate Qs varies depending on the need of the user.
A differential equation for the height of liquid in the tank, L, is given by

$$\frac{dV}{dt} = S\frac{dL}{dt} = Q_e - Q_s \quad (17)$$

Therefore height (L) of water level in the tank can be obtained by eq (18)

$$L = \frac{1}{S}\int\left(Q_e - Q_s\right) \quad (18)$$

Where V is the volume of liquid in the tank, S is the cross-sectional area of the tank. The equation (18) describes the height of liquid, L, and Q_s and Q_e are water outflows and inflows as a function of time.The following table.4 shows the specifications of tank.The tank contains a sensor which gives feedback to the fuzzy controller. The tank has area S and height (L).

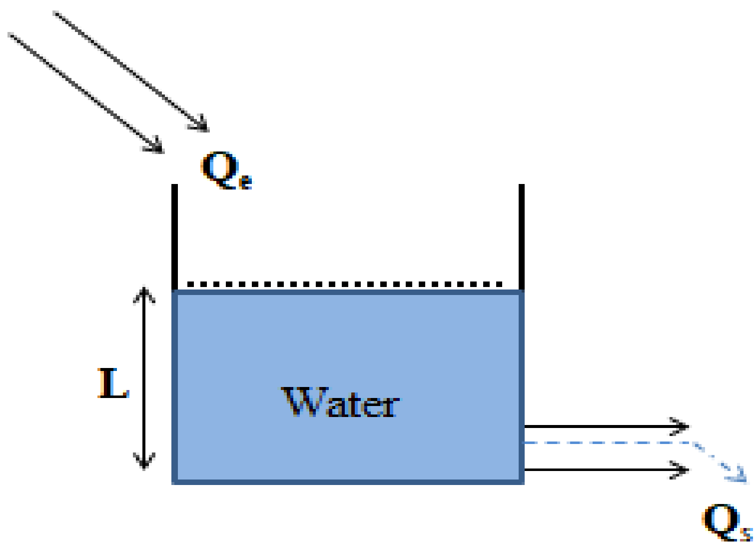


Fig.7.Water storage tank.

Table.IV **Tank parameters**

Parameter	value
Nominalflow (m3/h)	20
Totalhead (m)	10
Height (set level) (m)	3
Area(m^2)	25

III. CONTROLLER

Controllers [9] are applied in solar water pumping system to set the desired speeds of the motors and to regulate the water levels in the tanks. The two controllers used in this paper are fuzzy controller and algorithm controller as shown in figure.9 and figure.10. Though the PI controller was used in earlier methods, but due to added advantage of the fuzzy controller, a proposal had done to be applied in this paper. A fuzzy logic methodology and algorithm controller is applied in solar water pumping system in order to regulate the reference speeds of the motors and to control the water level variations in the water tanks.

3.1 Fuzzy controller:

The Fuzzy logic controller [6, 9] is very simple conceptually. They consist of an input stage, a processing stage, and an output stage as shown in fig.8. Fuzzy rules comprise a set of rules in linguistic form which associate the fuzzy inputs with the fuzzy output. These are based on an expert knowledge and understanding of the system behavior that is required to achieve the control objectives.

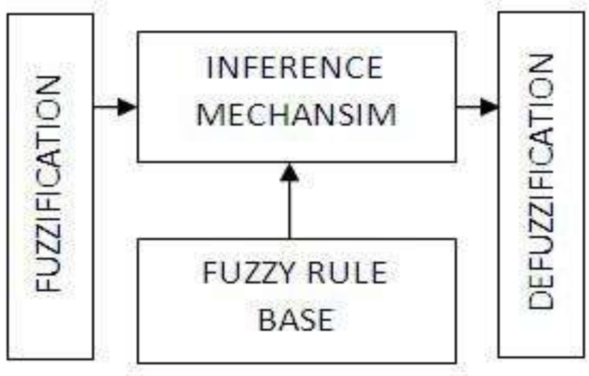


Fig.8. Structure of fuzzy logic controller (FLC)

The fuzzy control rules have been set up using asset of IF-THEN statements as described in Table.V The fuzzy rules are designed to incorporate the following considerations keeping in view of establishing a speed set, based on a measured water level of the three tanks L, and the solar radiation G as inputs and the relative calculated speed ω_{ref} as an output. figure.10 represents the fuzzy-logic architecture. In this application, the fuzzy inference is elaborated and carried out by using Madman's method; whereas, the defuzzification uses the centroid method to compute the output of the fuzzy logic which is the reference speed. The table.V specifies that the rules of the fuzzy controller developed for generating the reference speeds of the motors.The table.V represents the fuzzy rules developed for the control of the motor speeds for regulating the water level variations in the tank. The input variables [9] such as solar radiation consists of membership functions G1-G10 and water tank levels of three tanks consists of membership functions Li, Hi where i=1, 2 ,3 and speeds of motors are S1 to S10. The fuzzy triangular membership functions of are given in fig.11.a, fig.11.b, fig.11.c.

Table.V Rules of fuzzy logic controller

		Solar radiation(Input1)									
Tank levels (Input2)		G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
	L1	S10	S9	S8	S7	S6	S5	S4	S3	S2	S1
	H1	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
	L2	S10	S9	S8	S7	S6	S5	S4	S3	S2	S1
	H2	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
	L3	S10	S9	S8	S7	S6	S5	S4	S3	S2	S1
	H3	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10

The Fuzzy rules used in table.v are used within the fuzzy logic systems to infer an output based on input variables.

Rule is in the form IF x is A THEN y is B where x is input variable and y is output variable and A,B are membership functions. Here the inputs are Solar radiations (G1 to G10) and water tank levels (L_i, H_i) where i=1, 2, 3.

The few rules are as follows:

1) If solar radiation is G1 and water level is L1 then reference speed is S10
2) If solar radiation is G1and water level is H1 then reference speed is S1
60) If solar radiation is G10 and water level is H3 then reference speed is S10

Therefore total 60 rules are possible to obtained different reference speeds.

The conclusion is inferred for input (674; 1.5; 0.482; 0.84),the reference speeds are (239,128,199).

3.2 Algorithm controller

The algorithm controller shown in figure.9 as in [9] is also one of the controller designed to regulate the water levels in the tank and to control the speed of the motors. The algorithm controller sets the reference speeds based on the solar radiation and water levels feedback as inputs. The equations (19-21) describe the reference speeds to be set according to solar radiation and water levels as in [4, 9].

Three operated motors, when the three tanks are not filled:

$$\omega_{refi} = 24.07 + 0.42396G - 0.00081G^2 + 7.7 \times 10^{-7}G^3 - 2.652 \times 10^{-10} \quad (19)$$

Two operated motors, when only one tank is filled:

$$\omega_{refi} = 27.53 + 0.484G - 0.0009357G^2 + 8.9 \times 10^{-7}G^3 - 3.03 \times 10^{-10}G^4 (20)$$

One operated motor, when two tanks are filled:

$$\omega_{refi} = 34.65 + 0.6056G - 0.001171G^2 + 1.114 \times 10^{-6}G^3 - 3.79 \times 10^{-10} (21)$$

The equations obtained (19) to (21) shows the relation between the water levels and solar radiation G in obtaining thereference speeds ω_{refi} for the three situations by using the curve fitting technique, as in [4].The controller algorithm sets the reference speeds to the working PMDC motors. The controller reads the radiation and water levels and compares with the set level water level (3m).The flow of algorithm decides which motor's speeds should be increase or to stop according to the radiation and water levels in the three tanks. When the whole three tanks are not filled, the controller sets the speed of the three motors which is given by eq (19) Similarlyeq (20) and (21) describes the same scenario when only one tank and two tanks are filled.

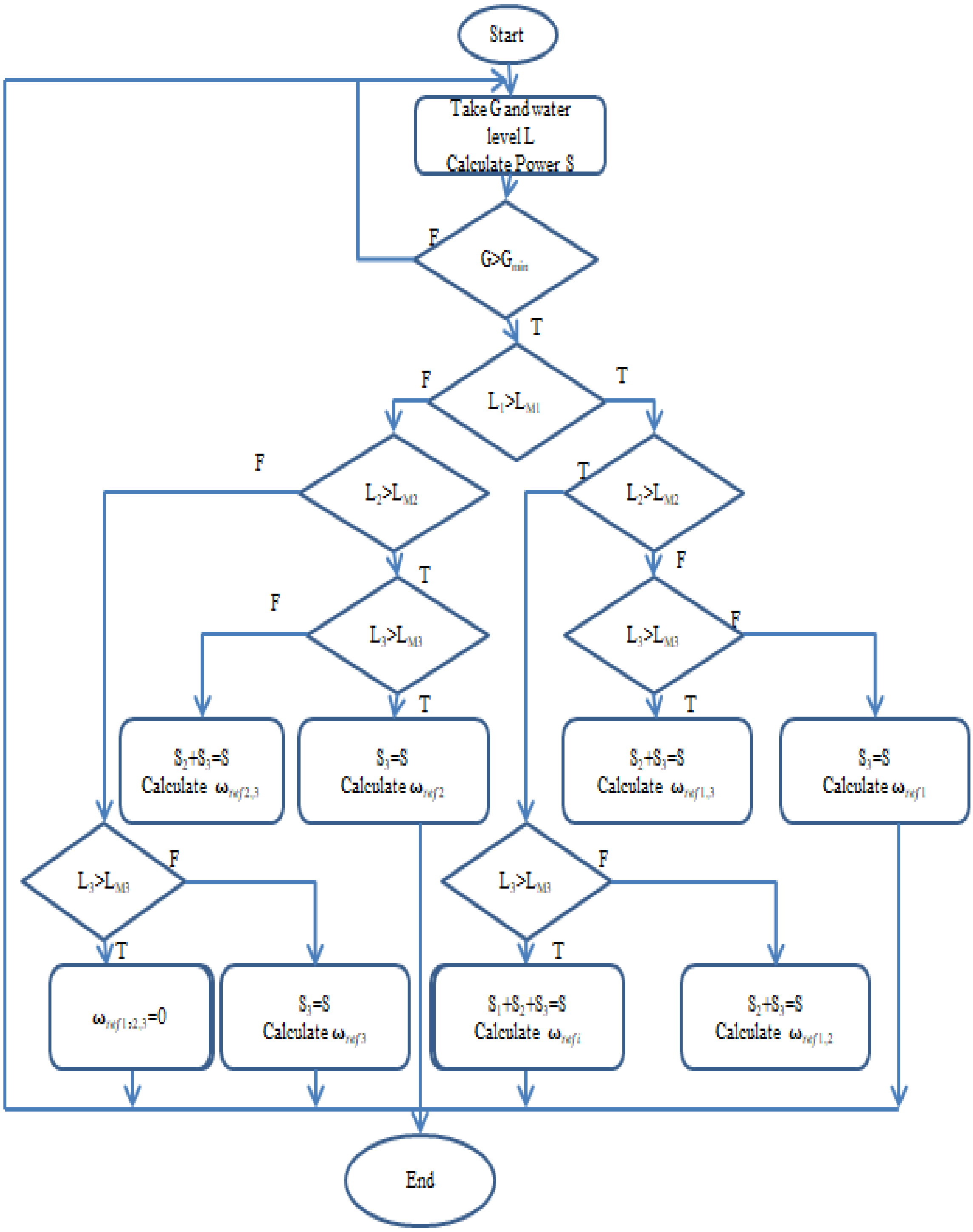


Fig.9.Controller flow chart

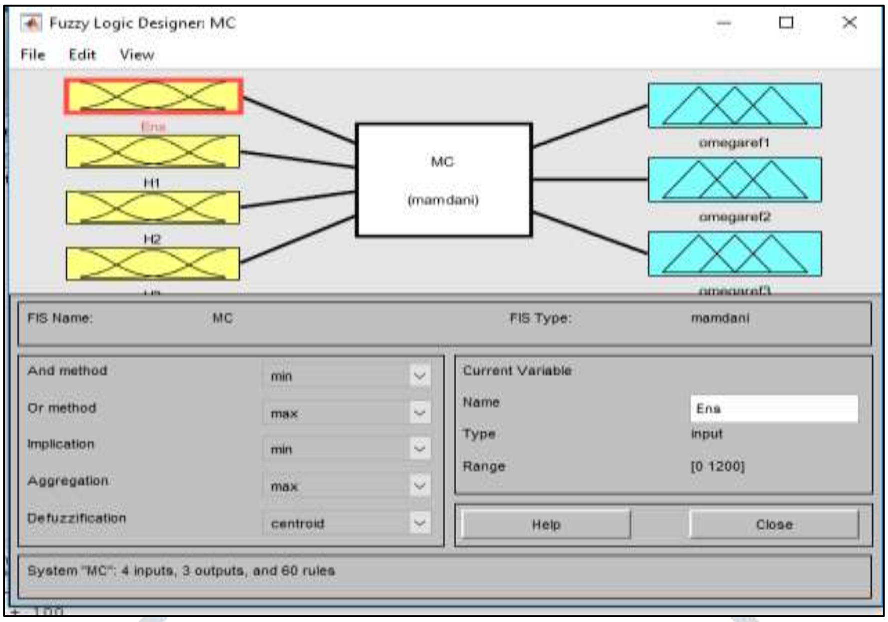
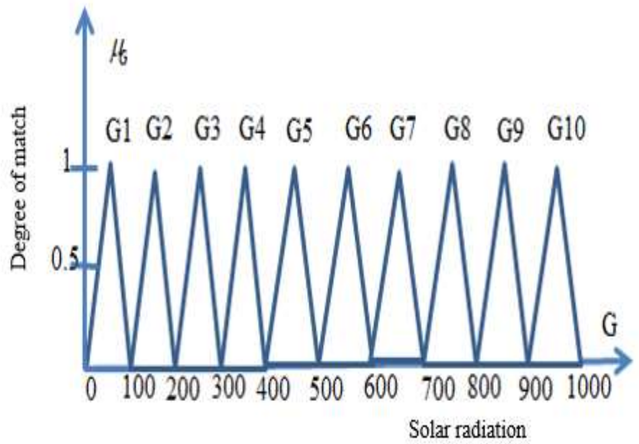
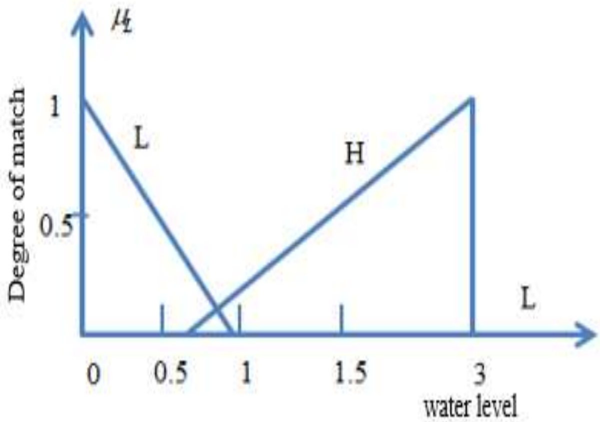


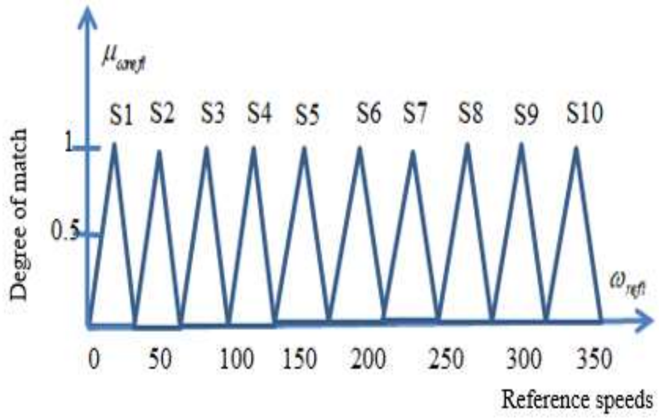
Fig.10.The fuzzy-logic architecture



a) Input variable.1 (solar radiation)



b) Input variable.2 (water level)



c) Output variable (speed)

Fig.11.Fuzzy-logic membership function

IV. RESULTS AND ANALYSIS:

The suggested solar water-pumping system has been established using MATLAB/Simulink. With the developed model, the system performance has been tested using three practical pumping motors and real solar radiation considering a test case of a agricultural field in Vizianagaram as shown in figure.13. The traced solar radiation for 12 months of the year is provided in the figure.12. Solar radiation in vizianagaram district shown in figure.12 occurs from morning 8 am to 4pm. Average annual irradiation: 5.42kWh/m2/day**.** The Maximum peak value is 1000W/m2 (radiation) occurs at 1pm (noon). The variation of daily solar radiation is given in the fig.14.The radiation from 10 am to 3pm daily for solar water pumping system is utilized. The motor starts running with minimum voltage which is available in this duration of time.

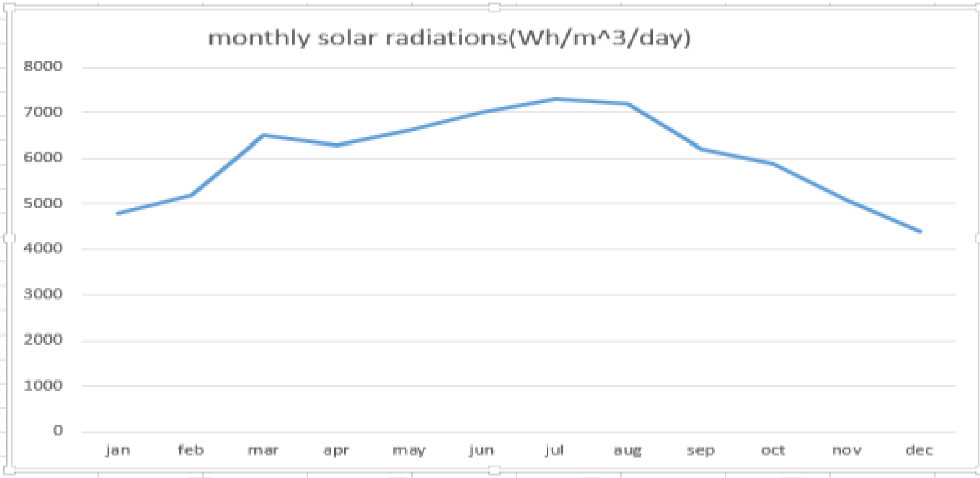


Fig.12.Solar Radiation for 12 months of a year

In this study, the solar plant was selected at vizianagaram consists of three practical PMDC motors of specifications given in table.III along with three centrifugal pumps to supply water to the users according to the demand of water. From figure.14 to figure.22 shows the simulation results of the solar water-pumping network with a fuzzy controller. The system is tested by the fuzzy controller in reaching the reference water level where the water level was set to 3m height in the water tank. The fuzzy controller takes the solar radiation and water level feedback as inputs and generates the reference speeds to the motors.

Fig.13. solar water pumping system at vizianagaram district

The figure.17 shows that the fuzzy controller generates the reference speeds and the PMDC motor traces it which shows the efficiency of the controller. The different discharges (outflows) needed by the users at timely was given in table.VI. The figure.16 represents the variation of the water inflow (Q_e) which signifies the input water flow of the three pumping motors during the day. The figure.15 shows the variation of the water flow (Q_s) of the three tanks during the day, which shows the output water flows consumed by the users. The figure.17 gives the evolution of the real and reference speed of the three pumping motors. figure.18 shows the variation of the water levels of the three tanks during the simulation study.

Following two cases are considered for analysis of the solar water pumping system at Vizianagaram district.

Case1) Qs=0 and Case2) Qs≠0

When the Qs exist i.e. outflows exists, the water levels will changes in the tank according to the needs of the users. When the Qs not exit i.e. if there are no outflows, then entire water will be stored in the tank itself.

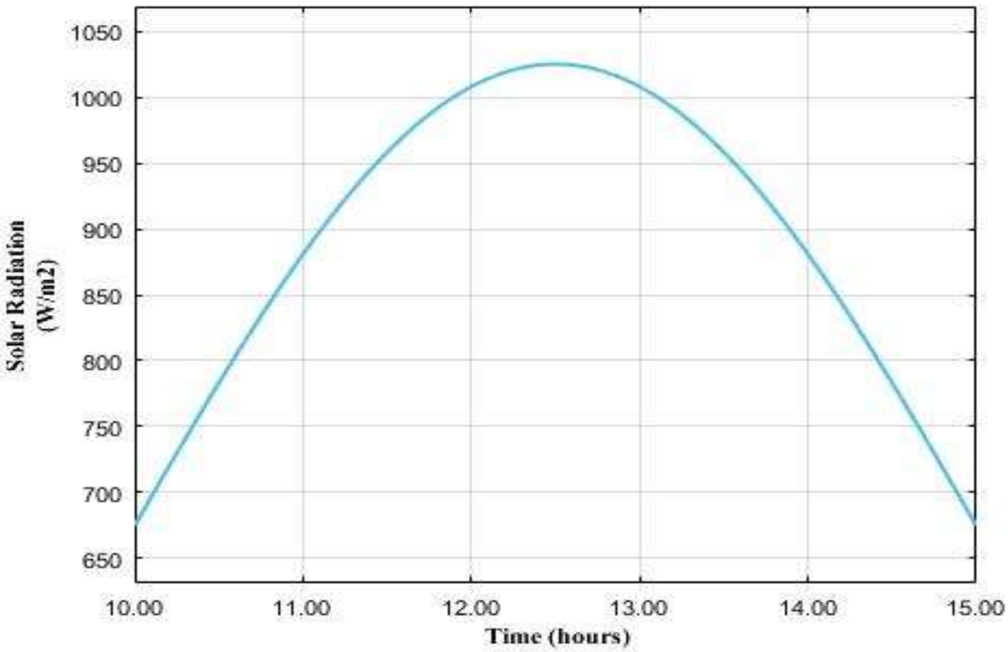


Fig.14.Variation of solar radiation

Case1: When Qs≠0 (when outflow exists) the outflow rate (Qs) in figure.15. varies according to the needs of the user, so it is deliberated as a perturbation i.e. the users were time wise satisfied with their water needs whenever necessary and to be stored in the tanks to the reference value (3m).as shown in figure.18.The following table-VI shows the water needs by the three users during the specific period of times. The water level variations shown for the three tanks are reached to set value (3m) without any error and without any overshoot. Even if there is a disturbance in Qs, the water level will decrease and then it will return to the reference value. The speed of the machine follows the set point as shown in figure.17 without any overshoot showing the efficiency of the controller, which eventually achieves the flow and head. The inflow (Qe) shown in figure.16.is proportional to the speed of each DC motor as shown in figure.17 i.e. the inflows of the pumping system will follows the motor speeds. If the motor speed increases then correspondingly the water inflow to the tanks will also increase.

Case2: When Qs=0 (when outflow not exists)

If the outflows are not exists then the water is pumped into the water tanks. If the water is reaches to set level (3m) then the sensor will senses the controller to stop the motor. The figure.19 to figure.22 shows the efficiency of the fuzzy and algorithm controllers developed in reaching the set point (3m).The water level reaches it reference value (3m) without error and without overshoot shows the realization of fuzzy logic controller. In the figure.19 the fuzzy controller reaches the set point (3m) very effectively with 0.01 error shown in figure.21 where as the algorithm controller in figure.19 touches the set point with 0.32 error shown in figure.22.The table –VII shows the error estimates of the controllers in reaching set water level.

Table.VI. Water discharges (Q_s) needed by the users

Discharge(m^3/hr)	Time(hours)	Time(hours)	Time(hours)
[1] User1(discharges(Q_{s1})	11am to12pm	12.20pm to1.00pm	1.50pm to 2.30pm
[2] User1(discharges(Q_{s2})	12pm to 1pm	1.50pm to 2.30pm	3.00pm to 4pm
[3] User1(discharges(Q_{s3})	11.40amto12.10pm	1.00pm to 1.40pm	3.00pm to 4pm

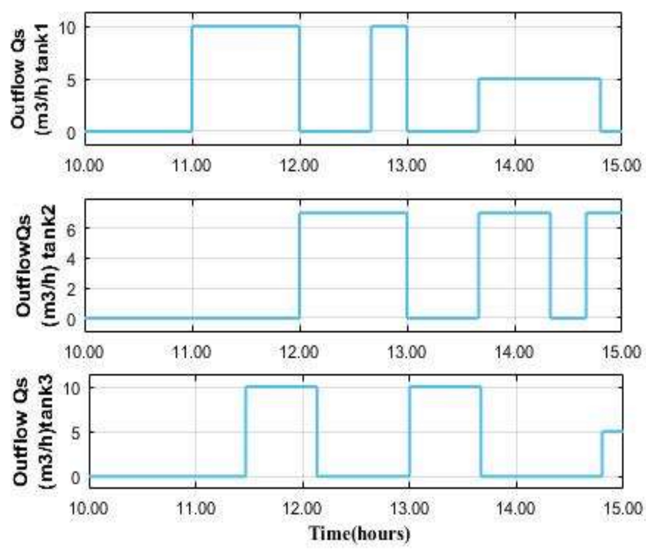


Fig.15.Variation of outflows (Q_S)

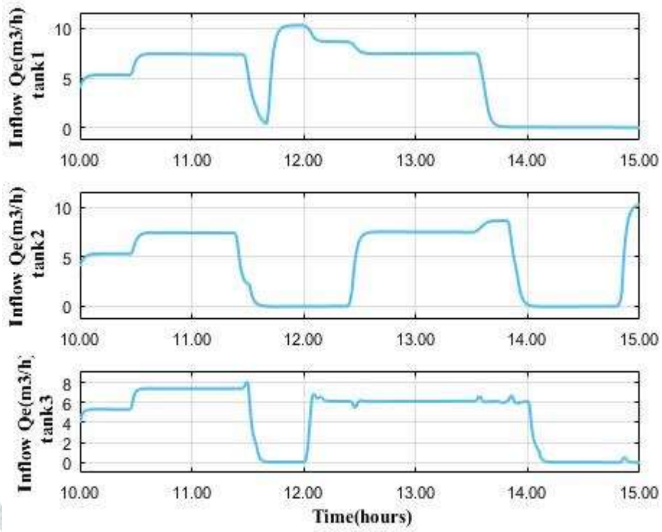


Fig.16. Variation of inflow Q_e

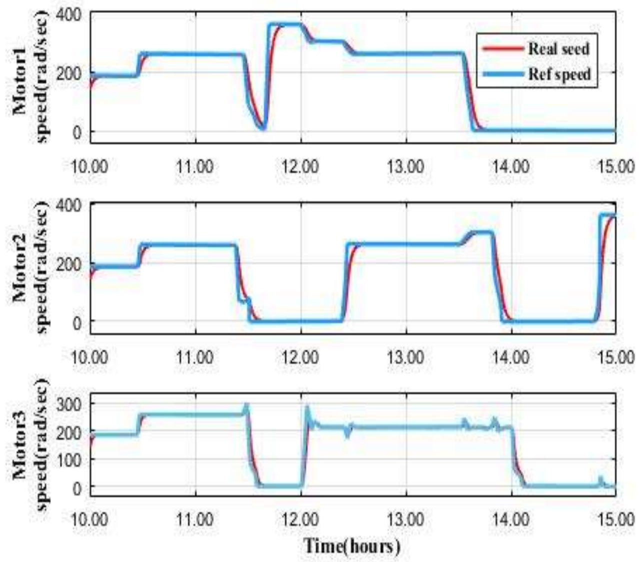


Fig.17. Speed variation of the three motors

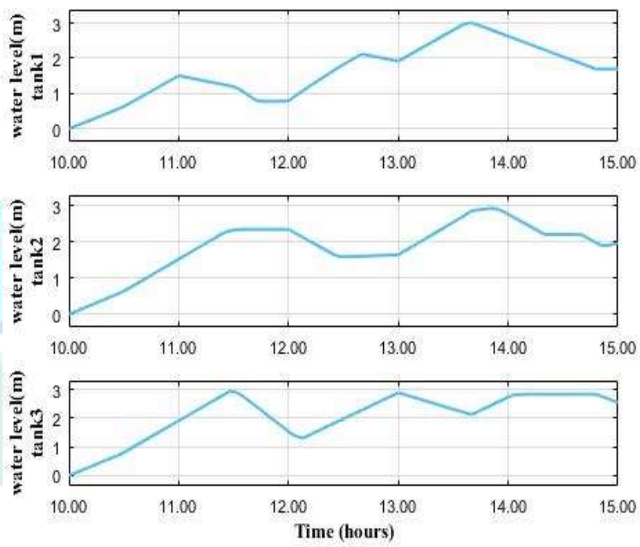


Fig.18. Variation of water level of the three tank

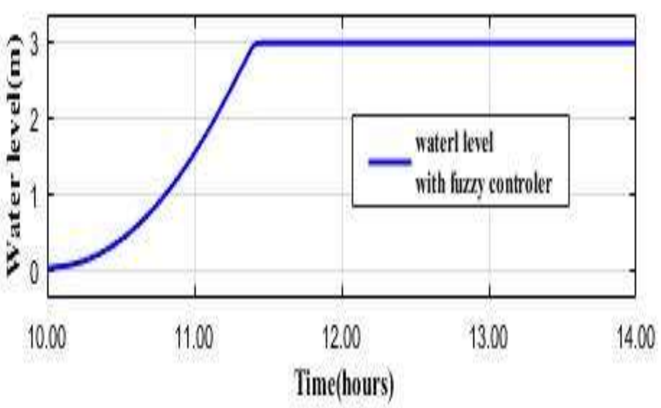


Fig.19. Water level in the tank with fuzzy controllers

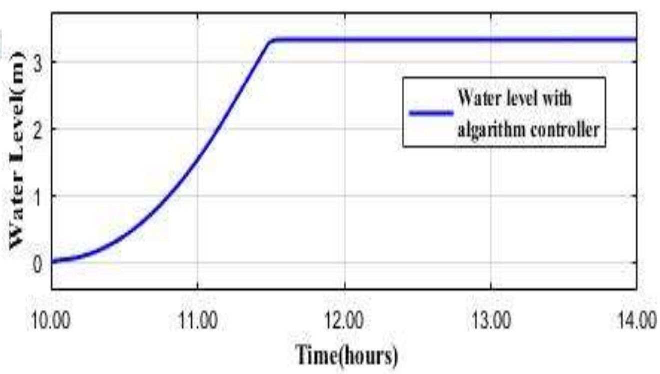


Fig.20. Water level in the tank with algorithm controller

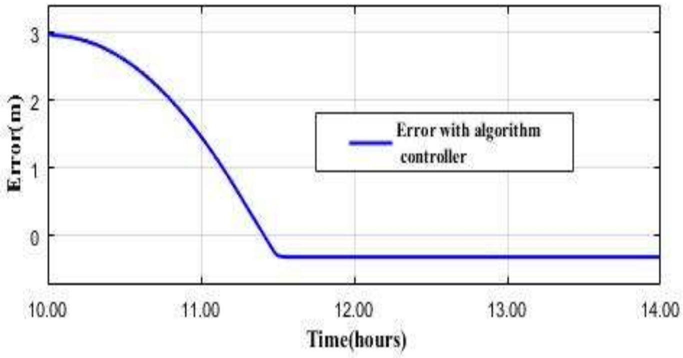


Fig.21. Level error with fuzzy controllers

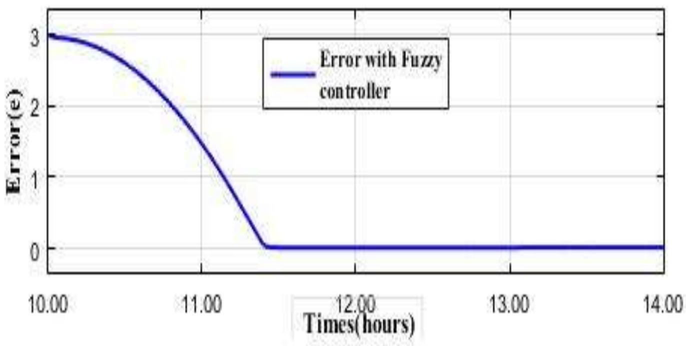


Fig.22. Level error with algorithm controller

Table.VII. Error estimates of water level

Controller	Error(m)
Fuzzy logic	0.01
Algorithm	0.32

V. CONCLUSION

This paper presents a novel method for the regulation of the water level in a photovoltaic pumping system. The fuzzy controller and algorithm controller is designed and simulation model was developed using the real time data of a solar water pumping system supplying water for an irrigation system at Vizianagaram. Simulation study was conducted in MATLAB/SIMULINK environment using designed controllers and it is found that the fuzzy controller works effectively than the algorithm controller. Though the fuzzy controller works better in regulating the water levels in the water tanks but produces some minor error with set water level. To overcome this, the system can be controlled by applying ANN technique which it effectively makes Zero error in reaching the set water level. Further the system can be implemented for multimotor designs by changing fuzzy rules in the controller where the water requirement is more.

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