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Mathematical Model for Performance Prediction of SPV Powered DC Irrigation System

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Abstract:
Selection of solar powered DC irrigation system is difficult for different sites with varying solar radiation and field conditions. Large numbers of SPV irrigation pumps are already installed; however successful implementation is yet to be achieved. One of the reasons behind this issue is unavailability of performance details. This indicates the need for development of an effective mathematical model of SPV irrigation system, which can predict the performance results by simulation. This paper presents development of mathematical model of SPV powered DC irrigation system using MATLAB/Simulink. Model consists of solar array, DC motor, centrifugal pump and hydraulic pipe network. Model of SPV unit is developed using photo current, saturation current, reverse saturation current and output current. DC motor is modeled using speed, torque and efficiency. Hydraulic power output equation is used to build a centrifugal pump and pipe network is modeled using hydraulic head and loss equations. Further, all the sub models are integrated to establish the complete model. The proposed model is tested with the solar radiation data of BEC campus and comparative analysis is carried with experimental results of the SPV irrigation pumps installed in BEC Energy Park. It is observed that the experimental and simulation results closely match with each other. It is concluded that, developed mathematical model of SPV irrigation pump can be effectively used to predict the performance of the SPV pump details for varying climatic conditions and for different sites.

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I. INTRODUCTION

In the current scenario more number of SPV powered pumps are being installed. But the installations are not successful due to the unavailability of the performance details. The installation of the system requires the system performance results and involves huge capital investment. So there is a need for a mathematical model through which the results can be verified and the model can be used for future installations by which the performance can be predicted before installation.

II. SPV POWERED IRRIGATION SYSTEMS

Solar photovoltaic system has become most developed and efficient system for providing supply to standalone DC irrigation system. The demand of solar energy increased since past few years, due to its reliable, efficient, eco-friendly operation with least maintenance and easy installation process. Solar irrigation system is based on PV technology. Solar photovoltaic unit converts solar irradiation into direct electricity and give input to DC motor. In turn DC motor converts electrical energy into mechanical energy. Output mechanical energy given to pump, where energy converts into hydraulic energy [1]. Further, the pump discharges water to outlet point through pipe network. SPV based AC pumps are also

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employed in a larger scale including a converter. However, due to continuous operation throughout the day with variation in the solar radiation, DC pumps are better option for the irrigation systems where lesser heads are offered for the pump to discharge the water.

Pipe network is a complex interconnected water distribution system which delivers water from one end to other. Usually pipe network analysis is carried to determine the pipe flow rate, pressure head and losses occurring in pipe network.

III. Methodology

The proposed mathematical model is developed in MATLAB simulink. Mathematical model is built for the SPV powered DC irrigation pump, with the SPV panels directly coupled to DC motor supplying the raw voltage to motor. The model includes four sub systems - SPV panel, DC motor, Centrifugal pump and pipe network. Further, all individual models are combined together to form the complete system.

a. Solar Photovoltaic Panel

The solar PV panel is made up of number of solar cells connected. Solar cell is important unit of a PV source and is a simple P-N junction diode, made up of semiconductor material. Solar radiation strikes on solar cell. Semiconductor material converts radiation into electrical energy [2]. The equivalent circuit models characterize the I-V curve of solar array for continuous function of a given set of operating conditions. Single diode model is essential equivalent circuit and most commonly used, which is derived from physical principles and represented by the circuit shown in Fig.1 for a single solar cell [3].

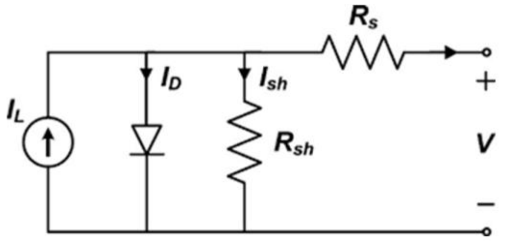

Fig.1: Single diode circuit of solar cell

The solar photovoltaic module is represented by following mathematical equations [4].

The photo current is given by:

$$I_{ph} = [I_{sc} + k_i + (T - 298)]\frac{G}{1000} \tag{1}$$

The saturation current is given by:

$$I_o = I_{rs}\left(\frac{T}{T_n}\right)^3 \exp\left(\frac{q.E_{go}\left(\frac{1}{T_n} - \frac{1}{T}\right)}{n.K}\right) \tag{2}$$

The reverse saturation current is given by:

$$I_{rs} = \frac{I_{sc}}{e^{\left(\frac{q.Voc}{n.N_s.K.T}\right)} - 1} \tag{3}$$

The current through shunt resistance is given by:

$$I_{sh} = \left(\frac{V + I.R_s}{R_{sh}}\right) \tag{4}$$

The total output current of PV module is given by:

$$I = I_{ph} - I_o\left[\exp\left(\frac{q.(V + I.R_s)}{n.K.N_s.T}\right) - 1\right] - I_{sh} \tag{5}$$

Fig.2 presents the complete model of solar photovoltaic panel.

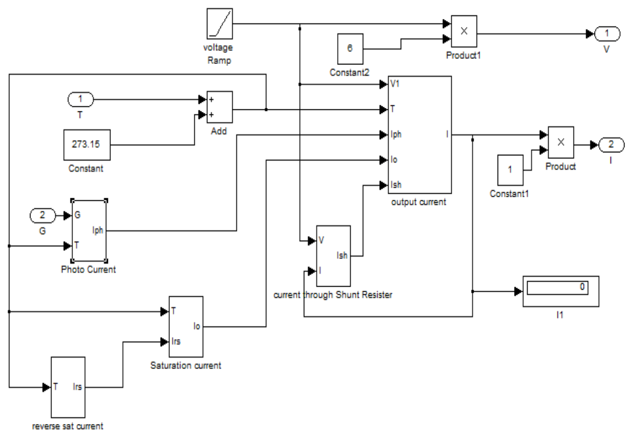

Fig.2: Model of SPV panel

b. DC Motor

A motor converts electrical energy into mechanical energy. In DC motor permanent magnet is supplanted by field winding which creates a flux and armature conductors get exposed to the mechanical force. The direction of motor is given by Fleming's left hand rule. [5-7]

The emf equation of a DC motor is presented by:

$$E_b = \frac{\Phi P N Z}{R_a} \quad (6)$$

The speed equation is given by:

$$N = K\left(\frac{E_b}{\Phi}\right) \quad (7)$$

The torque generated by a DC motor is given by:

$$T_a = 9.55\frac{E_b I_a}{N} \quad (8)$$

Fig.3 presents the complete simulink model of DC motor employed in the irrigation systems.

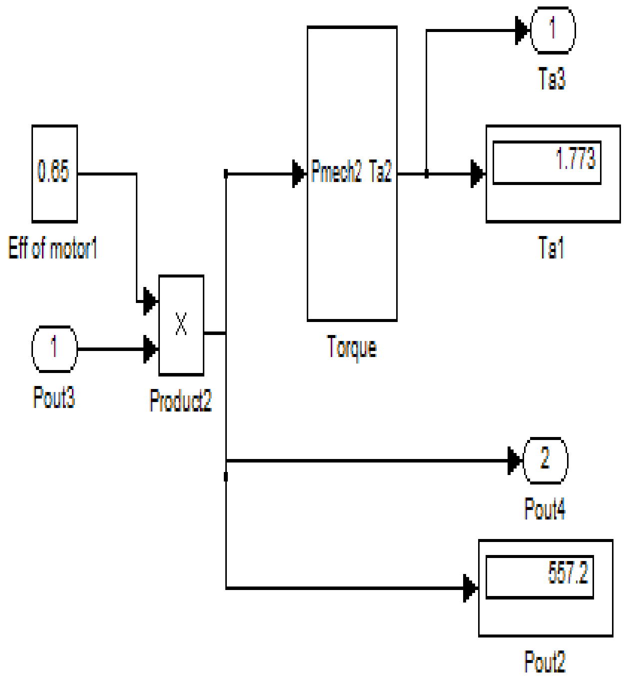

Fig.3: Simulink model of DC motor

c. Centrifugal Pump

The output mechanical power of DC motor is given as input to the centrifugal pump. Pump converts rotational kinetic energy in to hydraulic (hydrodynamic) power and creates a pressure in both suction side and discharge side. Centrifugal pump model is developed by output power equation given by:

$$P_{out} = \rho.g.Q.h \quad (9)$$

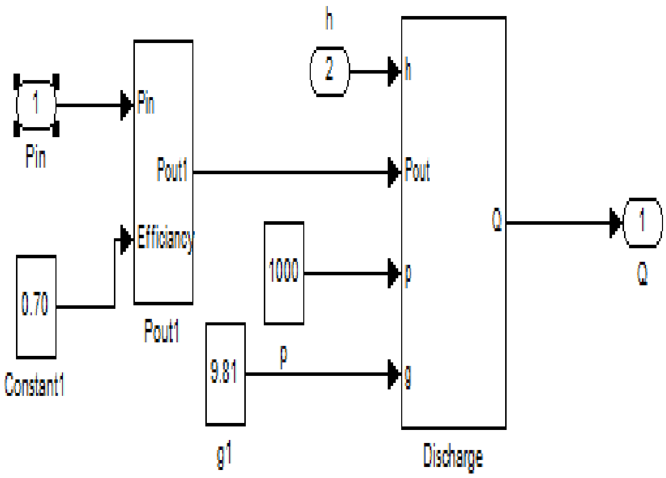

Fig.4: Simulink model of centrifugal pump

d. Pipe Network

Pipe network is final part of irrigation system. Pipe networks are installed to supply the water from source to irrigation area or water reservoir to crops. In sizing the SPV powered pump, loss in the pipe network plays a significant role. Losses in the pipe network are classified as major and minor losses. Total head of pipe network is sum of static head, dynamic head, and loss due to bend, friction loss, entrance loss and exit loss [8]. Fig.5 presents the simulink model of complete Pipe network. Further, the simulink model for complete SPV powered DC irrigation system is shown in Fig.6. The model is combination of all four different sub systems developed.

IV. RESULTS OF PROPOSED MATHEMATICAL MODEL

The performance analysis of 1 HP and 2 HP SPV powered DC irrigation pumps are carried out with varying solar radiations. Further, the experiments are conducted with different discharge heads of 5m, 10m and 15m using 900W and 1800 W solar PV panels connected to 1 HP and 2 HP irrigation pumps respectively. Table. 1, 2, 3 presents the data of SPV irrigation system performance at Bagalkot site with varying solar radiation and discharge heads.

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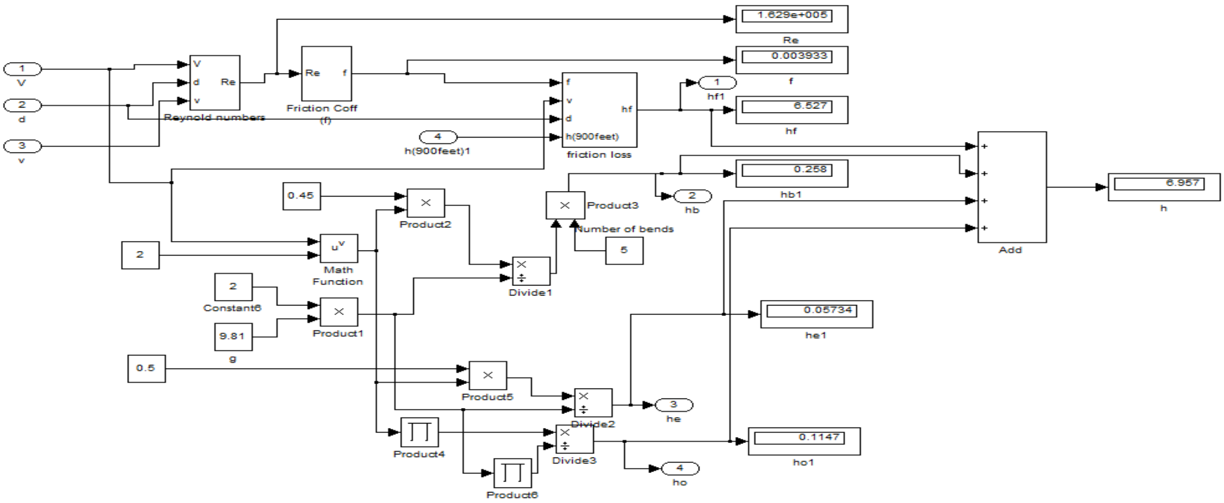

Fig. 5: Simulink model of complete Pipe network

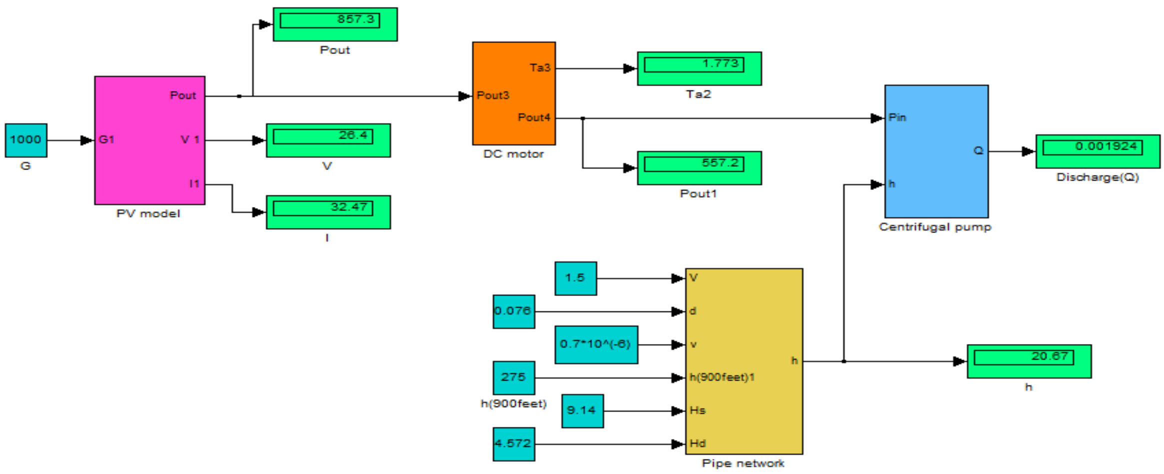

Fig 6: Simulink model of Solar powered DC irrigation system

Table 1: Performance results of the system operates at 5m discharge head in the month of January in Bagalkot site

Time	**Solar radiation (W/m^2)**	**Panel current (I)**	**Electrical Power (W)**	**Torque (N-m)**	**Mechanical Power (W)**	**Discharge water (cu.m/s)**	**Efficiency of solar panel (%)**
09:00	520	16.88	445.6	0.92	289.7	0.0041	4.24
10:00	665	21.59	570	1.17	370.5	0.00528	5.42
11:00	680	22.08	582.8	1.20	378.9	0.0054	5.54
12:00	730	23.7	406.7	1.29	625.7	0.0058	5.95
01:00	806	26.17	690.9	1.42	449.1	0.0064	6.57
02:00	775	25.16	664.3	1.37	431.8	0.0061	6.32
03:00	620	20.13	531.4	1.09	354.8	0.0049	5.05
04:00	477	15.48	408.8	0.84	265.7	0.0037	3.89
05:00	303	9.83	259.6	0.53	168.7	0.0024	2.47
06:00	120	3.88	102.6	0.21	66.71	0.0009	0.97

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Table 2: Performance results of the system operates at 10m discharge head in the month of January in Bagalkot site

Time	Solar radiation (W/m^2)	Panel current (I)	Electrical Power (W)	Torque (N-m)	Mechanical Power (W)	Discharge water (cu.m/s)	Efficiency of solar panel (%)
09:00	530	17.21	454.2	0.93	295.2	0.0021	4.32
10:00	642	20.84	550.3	1.38	357.7	0.0022	5.23
11:00	753	24.45	645.4	1.33	419.5	0.0029	6.14
12:00	820	26.63	702.9	1.45	456.9	0.0032	6.68
01:00	845	27.44	724.3	1.48	470.8	0.0036	6.89
02:00	775	25.16	664.3	1.37	431.8	0.0030	6.32
03:00	638	20.71	546.8	1.13	355.4	0.0025	5.20
04:00	454	14.74	389	0.80	252.9	0.0018	3.70
05:00	428	13.89	366.7	0.25	238.4	0.00170	3.49
06:00	360	11.68	308.4	0.63	200.5	0.00143	2.43

Table 3: Performance results of the system operates at 15m discharge head in the month of January in Bagalkot site

Time	Solar radiation (W/m^2)	Panel current (I)	Electrical Power (W)	Torque (N-m)	Mechanical Power (W)	Discharge water (cu.m/s)	Efficiency of solar panel (%)
09:00	276.5	8.97	236.8	0.93	153.9	0.0018	2.25
10:00	502.2	16.3	430.4	1.38	279.7	0.0019	4.09
11:00	678.4	22.01	581.1	1.33	377.7	0.0026	5.52
12:00	785	25.49	672.9	1.45	437.4	0.0031	6.40
01:00	868	28.18	744.1	1.48	483.6	0.0029	7.08
02:00	841	17.31	720.9	1.37	468.6	0.0022	6.85
03:00	680	22.08	582.8	1.13	378.9	0.0018	5.54
04:00	548	17.79	469.7	0.80	305.3	0.0014	4.46
05:00	356	11.55	305	0.25	198.3	0.0009	2.40
06:00	128	4.14	109.5	0.63	71.77	0.0003	1.04

a. Comparison of Experimental and Simulation Results

1 HP SPV pump is considered for the comparative analysis of the simulation and the experimental data. The parameters like panel current, panel output power, torque of motor, mechanical output power and water discharge are predicted by developed model for varying irradiation. Further, simulink simulation results are compared with experimental results. Both results stay in line with each other. The developed model is used to test the performance of the system at different conditions for different locations in North Karnataka. The only requirement for the model is local solar radiation potential and the hydraulic conditions of the irrigation site.

Table.4, and Fig.7 presents the comparison of current generated by solar PV array.

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Table 4: comparison of panel current

Irradiation (W/m^2)	Panel Current (Experimental)	Panel Current (Simulated)
322	10.3	10.45
378	11.2	12.27
428	14.6	13.89
594	18.1	19.28
612	18.2	19.87
710	19.0	23.05
743	19.1	24.12
825	19.3	26.79

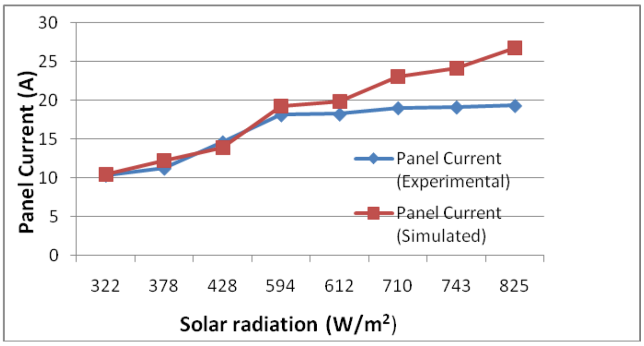

Fig 7: Comparison of Solar Panel current

At the solar radiations up to 650W/m^2, both simulation and experimental values closely match. However, after 650 W/m^2 the simulated values of panel current are slightly higher than experimental value.

Table.5, and Fig.8 presents the comparison of power generated by solar PV array in both cases: it is seen that both values in most of the instances closely match, indicating the effectiveness of the proposed model.

Table 5: comparison of panel Power

Irradiation (W/m^2)	Panel Power (Experimental)	Panel Power (Simulated)
322	201.8	275.9
378	260.9	323.9
428	355.0	366.7
594	447.8	509.1
612	506.3	524.5
710	582.2	608.6
743	591.3	636.9
825	606.9	707.2

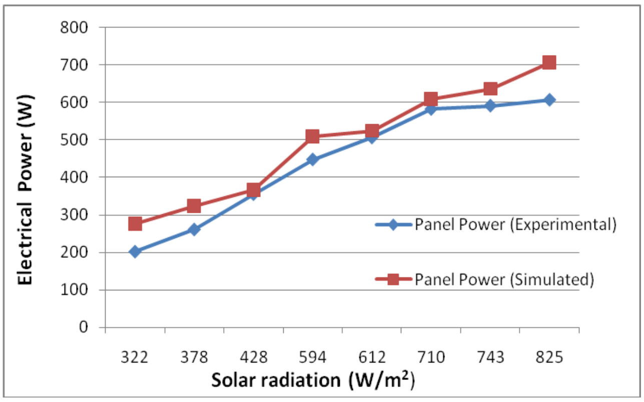

Fig 8: Comparison of Solar Panel power

Table.6, and Fig.9 presents the comparison of water discharge from the pipe network in practical and simulation cases:

Table 6: comparison of rate of water discharge

Solar radiation (W/m^2)	Practical Values (m^3/s)	Simulated Values (m^3/s)	Practical Values (Lit./s)	Simulated Values (Lit./s)
524	0.00156	0.00148	1.56	1.48
574	0.00178	0.00163	1.78	1.63
699	0.00156	0.00198	1.56	1.98
780	0.00170	0.00180	1.70	1.80
820	0.00183	0.00190	1.83	1.90
833	0.00190	0.00210	1.90	2.10
875	0.00182	0.00186	1.82	1.86
888	0.00170	0.00183	1.70	1.83

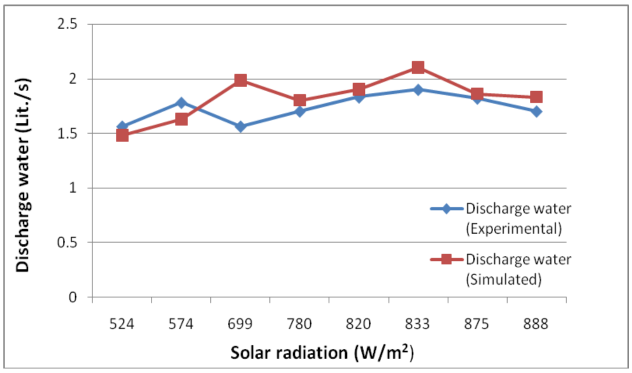

Fig 9: Comparison of Discharge water

V. CONCLUSION

The mathematical model of SPV powered DC irrigation system is developed in MATLAB. Detailed performance analysis of 1HP DC irrigation pump installed in the Energy Park, Basaveshwar Engineering College (A), Bagalkot is carried out experimentally. Voltage, current, power of solar array, speed, torque and efficiency of DC motor, mechanical power, electrical power and hydraulic power are observed with variation of solar radiation. The performance analyses of simulated results are compared with available results. The results almost match with practical results. The model is tested for the performance at different locations and it is observed that the system sizing can be taken up based on the simulation results. The mathematical model is tested under the different effects like temperature, different radiations, and different heads and for different areas. It is concluded that proposed model can be effectively used to predict the performance of SPV based irrigation pumps without carrying out the actual installation.

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