



# A Novel Method of Modeling Photovoltaic and Fuel Cell Systems Using Programmable Logic Controller

## KEYWORDS

Programmable Logic Controllers (PLCs), Matlab/Simulink, Photovoltaic cell, Fuel cell, Supervisory Control and Data Acquisition System (SCADA) system

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**ABSTRACT** Renewable energy sources like photovoltaic and fuel cell systems are modeled by using Matlab/Simulink. This conventional way of modeling and simulation offers limitations in simulation time, speed, performance, memory requirements for data logging, and etc. As a solution for all these issues, the proposal is to use Programmable Logic Controllers (PLCs) for modeling and simulation of renewable energy sources. This way of modeling supports real time simulation and an effective control through a Supervisory Control and Data Acquisition System (SCADA) system. This paper focuses on analysis of Photo voltaic cell (PV) and Fuel cell (FC) systems. The simulation results obtained in the proposed PLC simulation are compared with the conventional Matlab/Simulink simulation results.

## 1. INTRODUCTION

Energy demand in developing nations is steadily increasing. It is very important to meet the continually increasing demand of power and ensuring uninterrupted supply. In the mean time, there is a social interest for global environmental concerns such as green house effect and global warming and a reduction in fossil fuel resources. One of the solutions for these issues is to introduce renewable energy, which is generated from sources like wind, sunlight etc using technology like PV Cells, Wind turbines to harness it. Photovoltaic energy is a clean and abundantly available in nature. This system can be used for an abundantly clean generation strategy to supply power for the ever increasing load demand.

The PV cell output depends on the weather factors, mainly the irradiation and the cell temperature. Therefore, the weather factors such as the irradiation and the temperature are utilized for the estimation of the maximum power in this paper. However, like all other good things, a PV array also has some drawbacks as mentioned below [1].

- The PV array output voltage versus the current follows a nonlinear relationship.
- The power of the array varies with solar insolation. This Variation in the generated power causes disturbance for the utility or connected users.
- No power generation is possible during nights.

The above drawbacks are significant. However, if a PV source can be coupled with a suitable auxiliary energy source, these drawbacks can be reduced. A few possible auxiliary energy sources that can work in conjunction with a PV array are FCs, batteries, wind turbines, and diesel generators.

In recent years, fuel-cell generation systems have attracted a lot of attention because of their advantages as power generation systems [2]. Fuel cells are one of the popular sources of clean energy, without any harmful emissions to the environment; they have high power density [3]. Proton Exchange

Membrane fuel cell (PEMFC) is one kind of fuel cells that can work in a comparatively high efficiency and low temperature condition. After many technological advances, PEMFC technology has now reached the test and demonstration phase. The recent commercial availability of small PEMFC units has created many new opportunities to design hybrid energy systems for remote applications with energy storage in hydrogen form [4].

Today the improvements in system communications have stimulated the implementation of hybrid power system using PLCs and control schemes by a centralized supervisory platform commonly known as SCADA system. All the models were implemented in the PLC environment. The initial analysis is performed on realizing the mathematical model of a PV cell and Fuel cell systems. For the realization of these models in PLC, Structured text programming was used which is one of the IEC 61131-3 programming language. PLC and SCADA systems communicate over a protocol which can be transmitted over Ethernet. Speed of communication is 100Mbps.

The organization of this paper is as follows. Section II describes the structure of the proposed system. Section III describes the mathematical models of PV and fuel cell. Section IV presents the simulation of the models using PLC. Section V presents the simulation results. Section VI concludes the main features of the proposed technique and the contributions made.

## II. PROPOSED MODELING AND SIMULATION

The proposed structure for modeling and simulation is shown in the Figure 1. Each renewable energy source is modeled through PLC and the entire system is connected to SCADA for Supervision and user monitoring. The PV cell and Fuel cell modules can be modeled using structured text programming. The realized models can reside in PLC. Since the PV cell and Fuel cell realization had done in PLC and is interfaced to SCADA, user can able to observe the parameters i.e. voltage and power of the modules easily and vary the parameters according to the changes in user requirements.

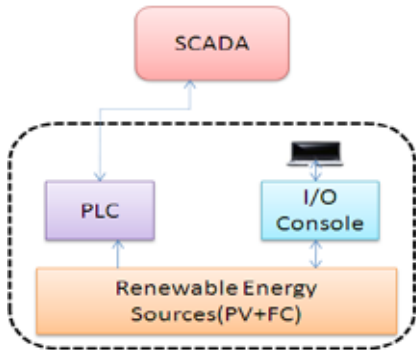


Figure.1. Proposed Structure

III. MATHEMATICAL MODELS

A. Photo Voltaic Cell:

Photovoltaic cell module is the basic element of each photovoltaic system. It consists of many jointly connected PV cells in an array. A number of PV cell models have been developed, but the one diode electrical equivalent circuit shown in Figure. 2(a) is commonly used for cell based or module based

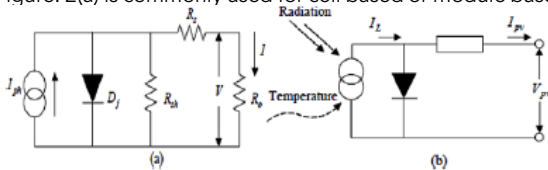


Figure.2. Solar cell (a) Equivalent (b) Simplified circuits

The temperature dependence of the diode saturation current and constant diode ideality factor are included in the modeling. At real PV cells [7], a voltage loss on the way to the external contacts is observed. This voltage loss is expressed by a series resistance (Rs). Furthermore leakage currents are described by a parallel resistance (Rsh). However, the series resistance is very small and the parallel resistance is very large, so we can ignore Rs and Rsh. The PV cell simplified circuit is shown in Figure. 2(b). The voltage-current characteristic equation of a solar cell is given as follows.

$$I = I_{ph} - I_s \left[ \exp\left(\frac{V + R_s I}{V_a}\right) - 1 \right] - \frac{V + R_s I}{R_{sh}} \tag{1}$$

$$I = I_{ph} - I_0 \left[ \exp\left(\frac{qV}{V_t * a}\right) - 1 \right] \tag{2}$$

Where  $I_{ph}$  is the photocurrent; it is generated by the light incidence on the photovoltaic cell. This current varies with irradiation of the sun and is given by

$$I_{ph} = (I_{ph,n} + Ki\Delta T) \frac{G}{G_n} \tag{3}$$

Where,

$I_{ph,n}$  - is the current generated by light at nominal conditions,  
 $Ki$  - is the current temperature coefficient,  
 $G$  - is the actual irradiation,  
 $G_n$  - is the nominal irradiation,  
 $\Delta T$  - is the difference between actual and nominal temperatures (T-Tn).  
 $I_0$  - is the cell's saturation current varies with the cell.

$$I_0 = I_{0s,n} \left(\frac{Tn}{T}\right)^3 \exp\left[\frac{qE_g}{ak} \left(\frac{1}{T_s} - \frac{1}{T}\right)\right] \tag{4}$$

Where  $I_{0s,n}$  is the Diode Saturation current at nominal conditions.

$a$  - is the Diode ideality factor which is a measure of how much a practical diode deviates from ideal diode equation.  
 $V_t$  - is the p-n junction's thermal voltage given by

$$V_t = \frac{KT}{q} \tag{5}$$

Where,

$K$ = Boltzmann constant =  $1.3806503 \times J/K$

$q$  = electron charge =  $1.607 C$

$T$  = Nominal Temperature =  $298.15 K$

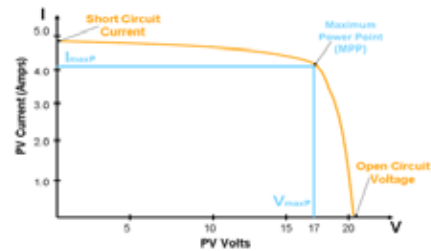


Figure.3. V-I characteristics of a PV cell

B. Fuel Cell:

A fuel cell is a stationary power generator. The fuel cell chosen for this type of application must provide competitive, reliable, and quality power without emitting pollutants such as oxides of nitrogen, carbon or sulphur. It must respond quickly to changes in load and have low maintenance requirements as well as a long cell life [8]. The PEM fuel cell is one of the most promising and certainly the best known of the fuel cell types satisfying above requirements. The PEM fuel cell consists of porous carbon electrodes bonded to a very thin sulphonated polymer membrane. Figure. 4 shows the structure of the PEM fuel cell, As illustrated in figure, this membrane electrode assembly (MEA) is sandwiched between two collector plates, which provide an electrical path from the electrodes to the external circuit [9]-[11]. Flow channels cut into the collector plates distribute reactant gases over the surface of the electrodes. Individual cells consisting of collector plates and MEAs are assembled in series to form a fuel cell stack [11].

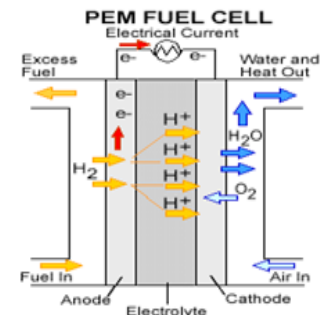


Fig.4. PEM Fuel cell diagram

The potential at active location E is defined via a Nernst equation in expanded form [12] and is given by (6).

$$E_{Nernst} = -\frac{G_{f-liq}}{2 * F} - \frac{R * T}{2 * F} \ln \left( \frac{P_{H_2O}}{P_{H_2} * P_{O_2}^{1/2}} \right) \tag{6}$$

Where  $E_{Nernst}$  is the potential active location,  $G_{f-liq} = -228170 J/mole$  gibbs function in liquid form,  $F = 96439$  faradays constant,  $R = 8.3144$  ideal gas constant,  $T$  = Absolute temperature of the stack,  $PP_{H_2O}$  is partial pressure of water in stack and is given by (7).

$$PP_{H_2O} = 10^x \tag{7}$$

Where

$$X = -2.1794 + 0.02953(T_c - 9.1837) \tag{8}$$

$$* (10^{-5}) * T_c^2 + 1.4454 * (10^{-7}) * T_c^3$$

T is temperature of stack; PP<sub>H<sub>2</sub></sub> is partial pressure of hydrogen in stack and is given by (9).

$$PP_{H_2} = \left( \frac{P_{H_2}}{\exp(1.653 * (i / T^{1.334}))} \right) - PP_{H_2,0} \tag{9}$$

Where i = current density in (A/cm<sup>2</sup>), PP<sub>O<sub>2</sub></sub> is partial pressure of oxygen in stack which is given by (10).

$$P_{O_2} = \left( \frac{P_{air}}{\exp(4.192 * (i / T^{1.334}))} \right) - P_{H_2,0} \tag{10}$$

P<sub>air</sub> is air pressure in atm.

**C. Losses in PEM fuel cell**

The major losses associated with PEM fuel cell are ohmic loss, concentration loss and activation loss. These losses are taken into account while calculating output of the PEM fuel cell. The equations governing these losses are given in the following text:

**1. Ohmic loss**

These are due to the ohmic resistance offered by fuel cell and depend on many factors like resistivity of electrodes, electrolytes etc [12]. Ohmic loss is given by (11).

$$V_{ohmic} = -(R_{ohmic} * i) \tag{11}$$

Where R<sub>ohmic</sub> = ohmic resistance in ohm-cm<sup>2</sup>.

**2. Concentration loss**

Generally fuel cells are connected in series and parallel called stacks to meet load requirements. The input fuel while passing through all the stacks will lose its concentration and it will not be distributed equally to all individual cells. This loss in the concentration of fuel which will affect the output of fuel cell is termed as concentration loss [12]. The equation corresponding to this loss is given by (12).

$$V_{conc} = \alpha_1 * i^k * \log \left( 1 - \frac{i}{i_L} \right) \tag{12}$$

Where i<sub>L</sub> is limiting current density, K = 1.1 mass transport constant and α<sub>1</sub> is amplification constant.

**3. Activation loss**

The voltage over potential required to overcome the energy barrier for the electrochemical reaction to occur is activation polarization. The energy used for this electro chemical reaction is known as activation loss [12]. This loss is of two types, anode activation loss and cathode activation loss. Their respective equations are given by (13) and (14).

$$V_{activ\_a} = \frac{R * T}{(\alpha_a + \alpha_c) * F} \tag{13}$$

$$\log \left( \frac{i}{i_{hor} * ab * (1-s) * (X_{H_2} * P_{gas})} \right)$$

V<sub>activ\_a</sub> is activation loss due to anode, α<sub>a</sub> is anode transfer coefficient, i<sub>hor</sub> is exchange current density, ab is anode specific interfacial area, s is mole fraction of

$$V_{activ\_a} = \frac{R * T}{(-\alpha_c) * F} \tag{14}$$

$$\log \left( \frac{i}{i_{orr} * ab * (1-s) * (X_{O_2} * P_{gas})} \right)$$

Where V<sub>activ\_c</sub> is activation loss due to cathode, i<sub>orr</sub> is exchange current density of oxygen and X<sub>O<sub>2</sub></sub> is mole fraction of oxygen.

**D. Output Voltage Equation of PEM Fuel Cell**

From the Nernst equation (7) and the losses considered above the equation for the output voltage of PEM fuel cell is given by (15).

$$V = E_{Nerst} + (V_{ohmic} + V_{activ} + V_{conc}) \tag{15}$$

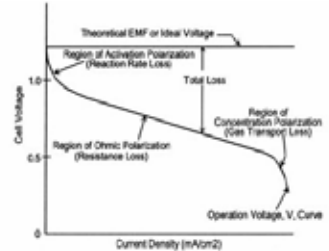


Figure.5. V-I characteristics of a Fuel-cell

**IV. SIMULATION THROUGH PLC's**

As mentioned earlier, structured text programming [13] is used to realize the equations of current and voltage in the PV cell, Fuel cell systems using PLCs. Following figures 5 and 6 shows the realization of PV and Fuel cell models using PLC.

```

//PV Cell modelling
Isci:=0.54;(*Short circuit current*)
Uoc:=0.7;(*Open circuit voltage*)
Isc:=0.001;(*Current temperature coefficient*)
Uoc:=0.07;(*Voltage temperature coefficient*)
T:=300;(*Actual Temperature*)
Tn:=298;(*Nominal Temperature*)
G:=800;(*Actual Irradiance*)
Gn:=1000;(*Nominal Irradiance*)
Uj:=0.06;(*a junction's thermal voltage*)
a:=1;(*Ideality factor of Diode*)
m:=2;(*number of cells*)
//Input current variation from 0 TO 8.55
IF Isci<=0
THEN Ipsc:=Ipsc+0.0001;
END_IF;
//I=Ipsc-REAR(Ipsc);
IF Ipsc>0
THEN
Ipsc:=0.54899784;
END_IF;
//Current in the photocell
C_U:=Ipsc-REAR(Ipsc);(*Actual Irradiance by Nominal Irradiance*)
I:=Ipsc-Tn-REAR(Tn);(*Finding Delta T*)
    
```

Figure.5.PV cell Modeling Using PLC

```

//FuelCell Modelling
Tc:=75;(*Temperature of Stack*)
Tn:=300;(*Nominal Temperature*)
Tc:=300;(*Average Constant*)
Ic:=0.014;(*ideal gas constant*)
R:=8.314;(*gas constant in liquid form*)
Pc:=1;(*hydrogen pressure*)
Pc:=1;(*oxygen pressure*)
Rohmic:=0.02;(*ohmic resistance*)
Ic:=0.014;(*actual current*)
a:=10000;
Ic:=0.02-72;(*Ipsc:=Ipsc-REAR(Ipsc);
Ipsc:=Ipsc+0.01;
Ipsc:=I;
alpha_a:=1;(*alpha_a:=0.5;(*alpha_a:=0.5;(*alpha_a:=0.5;
product1:=REAR(1,145);(*EXP(10,-7);(*EXP(10,3);
product2:=REAR(1,145);(*EXP(10,-7);(*EXP(10,3);
I:=Ipsc-REAR(1,145);(*EXP(10,-7);(*EXP(10,3);
I:=Ipsc-REAR(1,145);(*EXP(10,-7);(*EXP(10,3);
IF I<=0
THEN I:=0.001;
END_IF;
//pH calculation
I:=Ipsc-REAR(1,145);(*EXP(10,-7);(*EXP(10,3);
    
```

Figure.6: Fuel cell Modeling using PLC

Figure. 7 shows the user interface or SCADA interface. SCADA interface [14] is developed in order to view the change in the vital parameters such as PV cell output current and voltage. Also it is provisioned to change the nominal values of the irradiation and temperature.

**Trend Monitoring:**

Trend is the platform where results can be visualized according to the structured text entered by the user. Few adjustments are needed to understand the trends that were obtained in the PLC, the reason being-PLC is used mostly for industrial control application and the default trend configu-

ration is plotted against the time versus given parameters. Hence we cannot directly call a trend against I and V in case of photovoltaic cell or current density against voltage for Fuel cell. The values which are obtained for I and V or current density versus power needs to be captured separately into spread sheet and analyzed further.

Hence the Trend values are taken into historian, this gives the variation in voltage Vs current and Power Vs Voltage characteristics and these results will be stored for future reference.

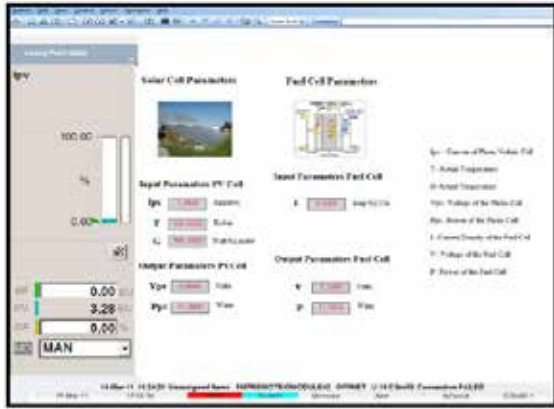


Figure.7. User interface/HMI of PLC display

**V. SIMULATION RESULTS**

The simulation results that are obtained through PLC modeling and MATLAB/SIMULINK modeling of PV cell and Fuel cell are compared.

**A. Results Of PV Cell Model:**

A typical rating of PV panel (Soltech 235W PV panel) was used for simulation of the model proposed. The parameters used in this model are shown in the following Table I:

**TABLE I. PV PANEL PARAMETERS**

Short Circuit Current(Isc)	8.54A
Open circuit Voltage(Voc)	37V
Current temperature Coefficient(Ki)	0.009
Voltage temperature coefficient(Kv)	-0.37
Nominal Temperature(Tn)	298K
Nominal irradiance	1000w/m <sup>2</sup>
Diode ideal Factor	1.2
P-n junction thermal voltage	0.026V

**B. Characteristics Of PV Panel:**

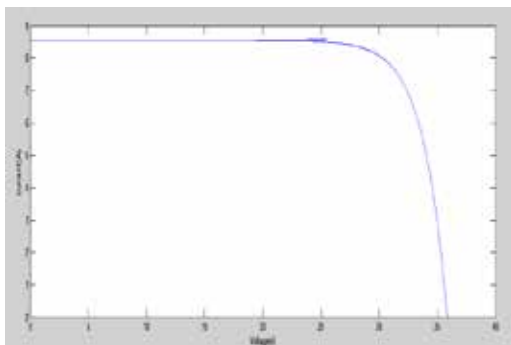
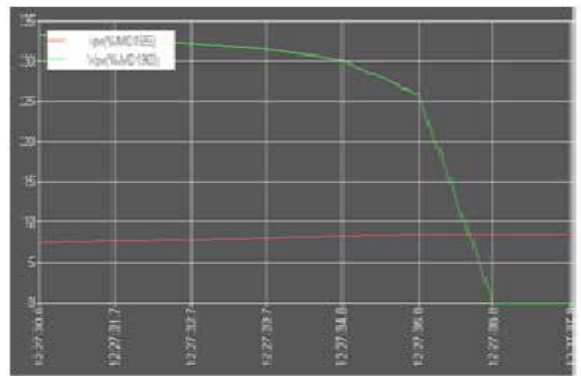


Figure.8.V-I characteristics using MATLAB/SIMULINK



**Real time simulation**

Figure.9.Variation of Current, Voltage in PLC Trend Display

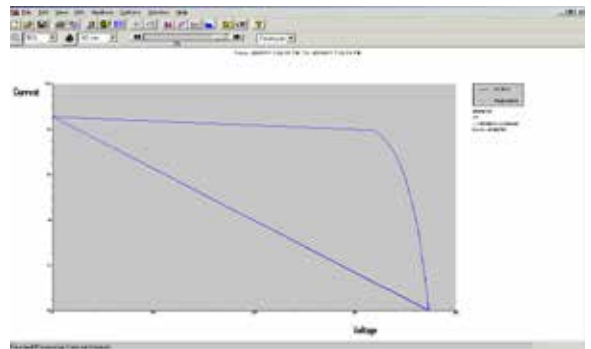


Figure.10.V-I characteristics using Historian

- Figures.8 and 9 shows the V-I characteristics in different simulation environments i.e. by using Matlab/Simulink, PLCs. Figure. 9 show the real time simulation i.e. the variation of current and voltage w.r.t to time. Irradiation is kept constant at 500 W/m<sup>2</sup>,and temperature at 300k, While varying the current of PV cell, output voltage of the PV cell also changes, and the corresponding V-I characteristics are observed.
- Figure. 10 shows the V-I characteristics using historian, since the PLC trend gives the variation of V and I w.r.t to time, for getting V-I characteristics the historian can be used.
- Figures. 11 and 12 describe the P-V characteristics of the PV cell in different simulation environments i.e. Matlab/ Simulink, PLCs. Keeping the irradiance constant at 500 W/m<sup>2</sup> and temperature at 300k while varying the current, the output voltage of a PV cell is varied, the corresponding power can be obtained.
- Figure.13 gives the P-V characteristics using Historian.

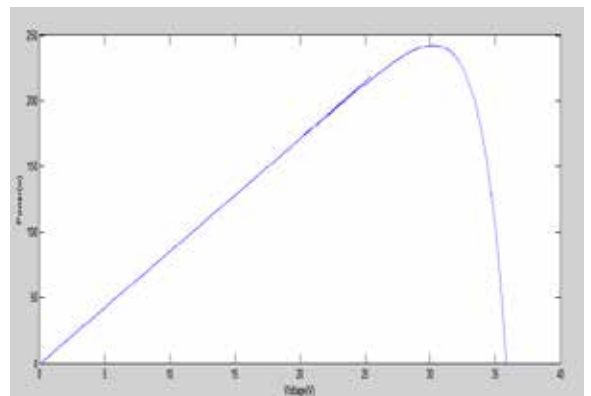
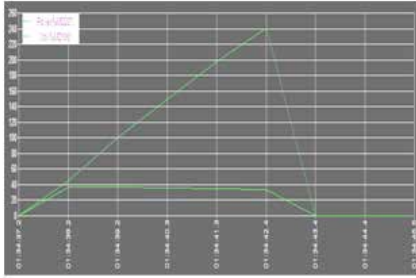


Figure.11.P-V characteristics using Matlab/Simulink



Real time simulation

Figure.12.Variation of Power, Voltage w.r.t to Time in PLC Trend display

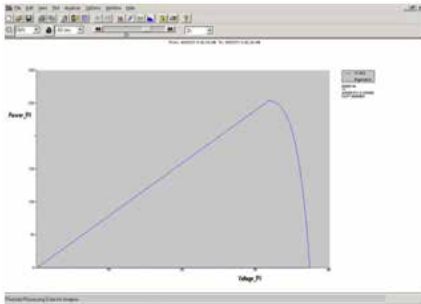


Figure.13.P-V characteristics using Historian

**C. Results Of Fuel Cell Model:**

The PEM fuel cell model is designed based on the output voltage equations as mentioned above. The parameters used in this model are given in the Table II.

§ Figures.14 and 15 shows the V-I characteristics of the fuel cell in different simulation environments i.e. by using Matlab/Simulink and PLCs. The variation in output voltage for varying load current can be observed.

**TABLE II. PARAMETERS OF PEM FUEL CELL MODULE**

Parameter	Value
Temperature	353 K
Total gas pressure	1 atm
Hydrogen pressure	1 atm
Air pressure	1 atm
Saturation	0.6e-12
Anode transfer coefficient	1
Cathode transfer coefficient	0.9
Constant ohmic resistance	0.02 ohm-cm <sup>2</sup>
Limiting current density	1.4 A/cm <sup>2</sup>
Mass transport constant	1.1
Amplification constant	0.085
Gibbs function in liquid form	-228,170 J/mol
Electrode-specific interfacial area	10000
Current density	1 to 1.2 A/cm <sup>2</sup>

**D. Characteristics Of Fuel Cell:**

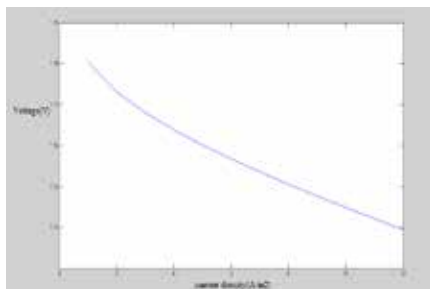
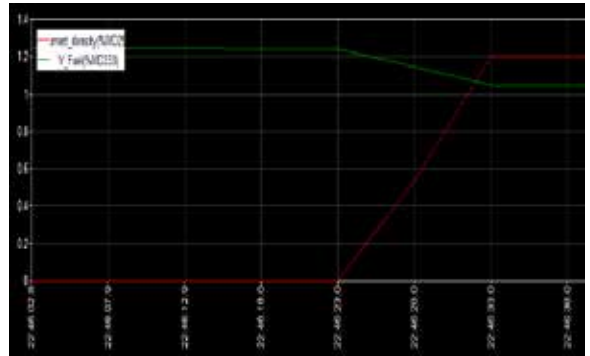


Figure.14.V-I characteristics using MATLAB/SIMULINK



Real time simulation

Figure.15.Variation of Voltage, Current density w.r.t to Time

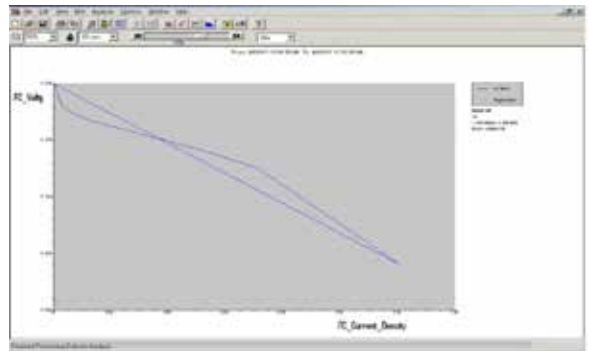


Figure.16.V-I characteristics using Historian

▪ Figure.16 shows the characteristics using historian, since PLC trend display shows the characteristics w.r.t to time, the historian can be used for getting the V-I characteristics.

**VI. CONCLUSION**

Hence in this paper the Photovoltaic and Fuel cell systems dynamics with both the platforms i.e. using conventional MATLAB/SIMULINK and proposed PLC simulations were obtained and compared. From the above plots, the following points are concluded for the proposed method.

- The proposed method supports the real time simulation and simulation capabilities i.e. simulation speed, simulation span were enhanced.
- The proposed method supports real time communication to hardware.
- The system dynamics and fault conditions can be simulated and the action can be taken more realistically.

From the above discussions it is concluded that the proposed method of simulation for renewable energy sources using PLC can effectively supports the real time simulation and effective control strategies via supervisory control and Data Acquisition system.

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