

MATLAB/Simulink Versus Refined Real Time Simulation of an Alternative Electrical Energy System in Dynamic Aspects

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ABSTRACT

Dynamic behavior of alternative energy based Hybrid Power System (HPS) is commonly analyzed using Matlab/Simulink. This way of simulation has the limitation in interfacing the model with hardware for real time control, which in turn limits in span of the simulation and consumes more time for simulation. Besides, simulator choice for the designed dynamic model is also constrained. Though, this simulation results may satisfies the system performance, the same may not be implemented practically in real time scenarios. This raises a new thought of modeling the HPS, which can be practically implementable. Hence, this paper proposes an original philosophy for modeling and simulation of HPS with improved simulation capabilities like fidelity, speed, and effective real time control. The method uses Programmable Logic Controllers (PLCs) instead of Matlab/Simulink for modeling and simulation of HPS dynamics. This supports effective control through a real time controller, and also provides Human Machine Interface (HMI). The constituents of HPS are Photo Voltaic (PV) cells, Fuel cell (FC), Diesel generator (DG), Inverter, and Wind Turbine (WT) system, and are combined for islanding mode. For the system, the dynamics are obtained and compared with the conventional simulation. Energy management unit monitors the load conditions and switches the sources accordingly.

Keywords— Hybrid Power System (HPS), Renewable Energy Sources, Programmable Logic Controller (PLC), Energy Management and Control units, Dynamic characteristics

I. INTRODUCTION

In the developing countries like India, energy demand by various classes of consumers is steadily increasing. Thus, it is very important to meet this continually increasing demand with high reliability. On the other hand, there is a social interest for global environmental concerns such as green house effect and global warming, and a considerable reduction in fossil fuel resources. The solution for these issues is to develop alternative energy sources. i.e., to introduce renewable energy, such as Photovoltaic, Fuel cell and wind energy. This is clean and abundantly available in nature, offers many advantages over conventional power generation system, such as low pollution, high efficiency, diversity of fuels, reusability of exhausts [8], and onsite installation. Combining several different types of renewable power sources will form the system called Hybrid Power system (HPS) [10]. HPS combines two or more energy conversion devices, or two or more fuels for the same

device. A generic architecture of a hybrid power system [1] is shown in Figure.1. The reliability of the HPS mainly depends on the dynamic behavior of the renewable energy sources [11]. So, it is very intended to analyze the dynamic characteristics of these units in real time for long hours. Recent research should go on finding the feasible ways of analyzing these dynamic characteristics. With this aspect, this paper proposes such a feasible way of analyzing these desired characteristics efficiently.

Once it is modeled, now the big challenge [14] lies in development of the real time control scheme for the HPS, which is impractical by the conventional MATLAB/Simulink modeling. In order to test the HPS controllers in Hardware in Loop (HIL) model requires, a controller that can interface with a hardware simulator and the inputs and outputs can be processed at real time. The proposed method of modeling and simulation provides an effective means to achieve this. This provides an excellent platform to implement and test the solutions in real time.

Today, the improvements in system communications have stimulated the implementation of the HPS using PLCs, and control schemes by a HPS controller, which is a combination of energy manager and control units.

All the Modules were modeled in the PLC environment. The initial analysis is performed on realizing mathematical model [16] of PV cell, WT system and FC systems.

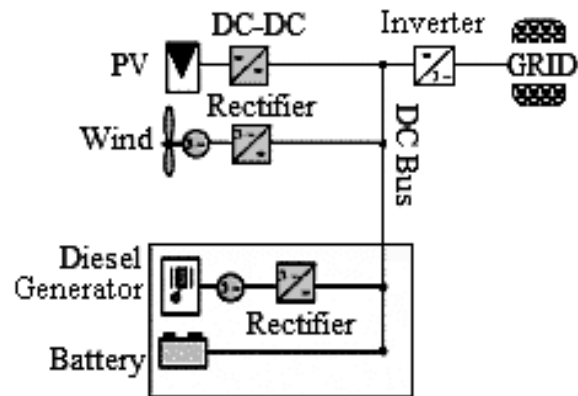


Figure.1. Schematic diagram of Hybrid Power System

To realize and simulate these models under discrete environmental conditions, various critical parameters were fed through the programmer-3 to the HPS controller and the process could be viewed by HMI, as shown in the figure.5. For the PLC realization, structured text or Ladder logic was used in general, which are the IEC 61131-3 programming languages. PLC and HPS controller communicate with each other over a dedicated protocol which can be transmitted over I/O network or Ethernet as shown in figure.5.

II. PROPOSED LABORATORY SETUP AND SYSTEM MODELING

The proposed setup for modeling and simulation of HPS is shown in Figure.5. The major constituents in the setup are; programmer-1, programmer-2, Human-Machine Interface (HMI), programmer-3, PLC simulator, and the HPS controller.

The designed structured text or ladder logic program is dumped into the PLC by the programmer-2, as shown in Figure.5. This code is now simulated. The process is controlled by the HPS Controller, for optimal management of available resources. The HPS controller consists of energy management unit and grid controller unit. This set up facilitates Human Machine Interface (HMI) through Supervisory Control And Data Acquisition (SCADA) system. Historian is the feature that can be connected to SCADA for saving, analyzing the characteristics of the plant over long run. Since the HPS realization had done in PLC and is interfaced to HPS Controller and SCADA, So that the user could be able to observe the parameters easily and vary the parameters according to the changes in user requirements. The detailed objective of each phase in the setup is as follows.

A. Programmer-1

This is the initial phase, and in this phase the proposed system is designed in Matlab/Simulink [1], [15], [16], [17]. The system is developed based on the mathematical equations that describe the individual modules in the HPS. For example the equations (1-18) show the mathematical relations for understanding the working of PV cell, Fuel cell systems. Similarly, these equations could be developed for all the modules in the HPS, and hence for overall system.

1) **Photo Voltaic Cell:** Many jointly connected PV cells as an array forms the photovoltaic system. So, the cell based analysis [8] is done for PV system. It consists of a diode, a current source, a series resistance and a parallel resistance [15], [17]. The current source generates the photo-current that is a function of the incident PV cell radiation and temperature. The diode represents the p-n junction of a solar cell. The temperature dependence of the diode saturation current and constant diode ideality factor are included in the modeling. At real PV cells [5], a voltage loss on the way to the external contacts is observed. This voltage loss is expressed by a series resistance (R_s). Furthermore leakage currents are described by a parallel resistance (R_{sh}). However, the series resistance is very small and the parallel resistance is very large, so we can ignore R_s and R_{sh} [1], [17]. The voltage-current characteristic equation [16] of a solar cell is given as follows.

$$I = I_{ph} - I_0 \left[\exp \left(\frac{V + R_{se} I}{V_t a} \right) - 1 \right] - \frac{V + R_{se} I}{R_{pa}} \quad (1)$$

For an ideal PV cell, the Equation can be rewritten as

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

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

$$I_{os} = I_{os,n} \left(\frac{T_n}{T} \right)^3 \exp \left[\frac{qE_g}{ak} \left(\frac{1}{T_n} - \frac{1}{T} \right) \right] \quad (4)$$

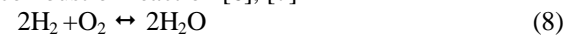
$$V_t = kT/q \quad (5)$$

$$V_{oc} = V_t^* a \left[\ln \left(\frac{I_{ph} - I}{I_0} + 1 \right) \right] \quad (6)$$

Maximum power point [16] is the operating point MPP (V_{max} , I_{max}), at which the power dissipated in the resistive load is maximum:

$$P_{max} = V_{max} * I_{max}. \quad (7)$$

2) **Fuel Cell:** A fuel cell is a device that uses hydrogen as a fuel to produce electrons, protons, heat and water. Fuel cells are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. The fuel cell 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 [2]. In the schematic of fuel cell, gaseous fuels are fed continuously to the anode, and an oxidant i.e., oxygen from air, is fed continuously to the cathode compartment, the electrochemical reactions take place at the electrodes to produce an electric current. A fuel cell is individual small unit of around 1.2V. A group of units are connected in series and in parallel to get required voltage and current ratings, that group is called fuel cell stack [3]. Current fuel cells, when operated alone have efficiencies of about 40-55%. Fuel cell technology is based upon the simple combustion reaction [6], [7]



Fuel cell is modeled with the help of modeling equations given as the thermodynamic potential E is defined via a Nernst equation in expanded form as [3], [4]

$$E = 1.229 - 0.85 * 10^{-3} * (T - 298.15) + 4.3085 * 10^{-5} * T * (\ln P_{H_2} + \ln P_{O_2}) \quad (9)$$

The concentration of dissolved oxygen at the gas/liquid interface can be defined by a Henry's law

$$CO_2 = PO_2 / (5.08 * 10^6 \exp (-498/T)) \quad (10)$$

The parametric equation for the over-voltage due to activation and internal resistance developed from the empirical analysis is given as

$$\eta_{act} = -0.9514 + 0.00312T - 0.000187 T \ln(i) + 7.4 * 10^{-5} T \ln(CO_2) \quad (11)$$

$$R_{act} = 0.01605 - 3.5 * 10^{-5} T + 8 * 10^{-5} I \quad (12)$$

$$R_a = -\eta_{act} / i \quad (13)$$

The combined effect of thermodynamics, mass transport, kinetics, and ohmic resistance determines the output voltage of the cell as

$$V = E - v_{act} + \eta_{ohmic} \quad (14)$$

The steady state fuel cell model described above indicates that the current drawn, cell temperature, H_2 pressure, and O_2 pressure will affect the fuel cell output voltage. A drop in fuel cell voltage can be compensated by an increase in fuel pressure. The ohmic voltage loss in the fuel cell is given by

$$\eta_{ohmic} = -I * R_{int} \quad (15)$$

The fuel cell system consists of a stack of 65 similar cells connected in series. Therefore, the total stack voltage is; $V_{stack} = 65 * V_{cell}$ (16)

The amount of hydrogen and oxygen consumed in the fuel cell depends upon the input and output flow rates and the current drawn out of the fuel cell. The fuel cell anode and cathode equations are respectively as follows.

$$(V_a/RT) \frac{dPH_2}{dt} = m'_{H_2 in} - (\rho_{H_2} UA)_{out} - (I/2F) \quad (17)$$

$$(V_a/RT) \frac{dPO_2}{dt} = m_{o_2 in} - (\rho_{o_2} UA)_{out} - (I/4F) \quad (18)$$

B. Programmer-2

In this phase, the PLC code is developed for total model. The tools available for writing PLC code are; ladder logic, structured text, and function blocks approach. The code is developed by any of these methods. The paper focuses on using structured text for designing PV system, ladder logic for Fuel cell, and etc., for utilizing all the available tools.

1) **Code generation for PV cell:** The inputs that are needed to enter and assumed as follows. Based on those the structured text given below is to be developed and loaded into the PLC.

- Isc: =8.54; (*Short Circuit Current*)
- Voc: =37; (*Open circuit voltage*)
- Ki: =0.009; (*Current temperature coefficient*)
- Kv: =-0.37; (*Voltage temperature coefficient*)
- T: =300; (*Actual Temperature*)
- Tn: =298; (*Nominal Temperature*)
- G: =500; (*Actual irradiance*)
- Gn: =1000; (*Nominal Irradiance*)
- Vt: =0.026; (*p-n junction's thermal voltage*)
- A: =1.3; (*Ideality Factor OF Diode*)

• **Input current variation from 0 to 8.55**

```
IF ipv <= 8.55
THEN ipv := ipv + 0.001;
END_IF;
```

• **Photo current Calculation(Iph)**

```
G_BY_Gn := DIV_REAL (G, Gn);
T_minus_Tn := SUB_REAL (T, Tn);
mul_res := MUL3_REAL (G_BY_Gn, T_minus_Tn, Ki);
Iph := ADD2_REAL (isc, mul_res);
```

• **Diode Reverse Saturation current(Ios)**

```
sub_res_tn_t := SUB_REAL
((cons_one/Tn), (cons_one/T))
exp_ios_num := MUL3_REAL (Q, Eg, sub_res_tn_t);
exp_ios_den := MUL2_REAL (K, a);
Total_exp_res := DIV_REAL(exp_ios_num, exp_ios_den)
Q_ka_Eg_Xpon := EXP_REAL (Total_exp_res);
Tn_by_T := DIV_REAL (Tn, T);
Tn_by_T_Cube := MUL3_REAL (Tn_by_T, Tn_by_T, Tn_by_T);
Ios := MUL3_REAL (iosn, Tn_by_T_Cube, Total_exp_res)
```

• **Output voltage Of PV cell (Vpv)**

```
iph_minus_ipv := SUB_REAL (iph, ipv);
Ad_4_Log := ADD2_REAL (iph_minus_ipv, ios);
Div_4_log := DIV_REAL (Ad_4_Log, ios);
Log Result := LN_REAL (Div_4_log);
Vpv := MUL4_REAL (ns, Vtn, a, log Result);
```

• **Power output OF PV cell**

```
Power := MUL2_REAL (Ipv, Vpv);
```

The figure.2 shows the user interface for entering the structured program, representing the HPS.

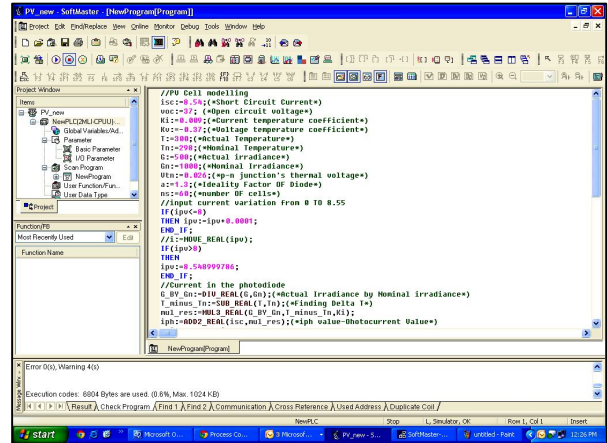


Figure.2. User Interface to enter structured text programming

2) **Code generation for Fuel cell:**

The ladder logic diagrams are developed to model Fuel cell in PLC as shown in figure.3. The figure.4 shows the user interface for entering the ladder logic, representing the HPS.

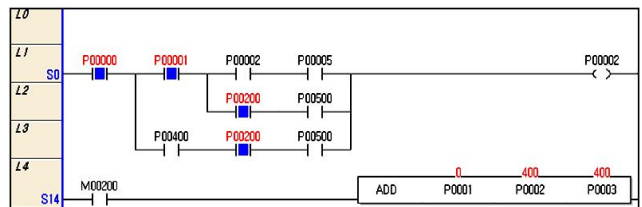


Figure.3. Ladder logic diagram

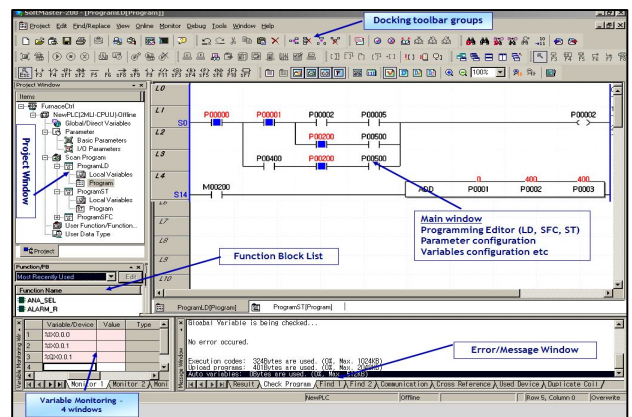


Figure.4. User Interface to enter Ladder logic programming

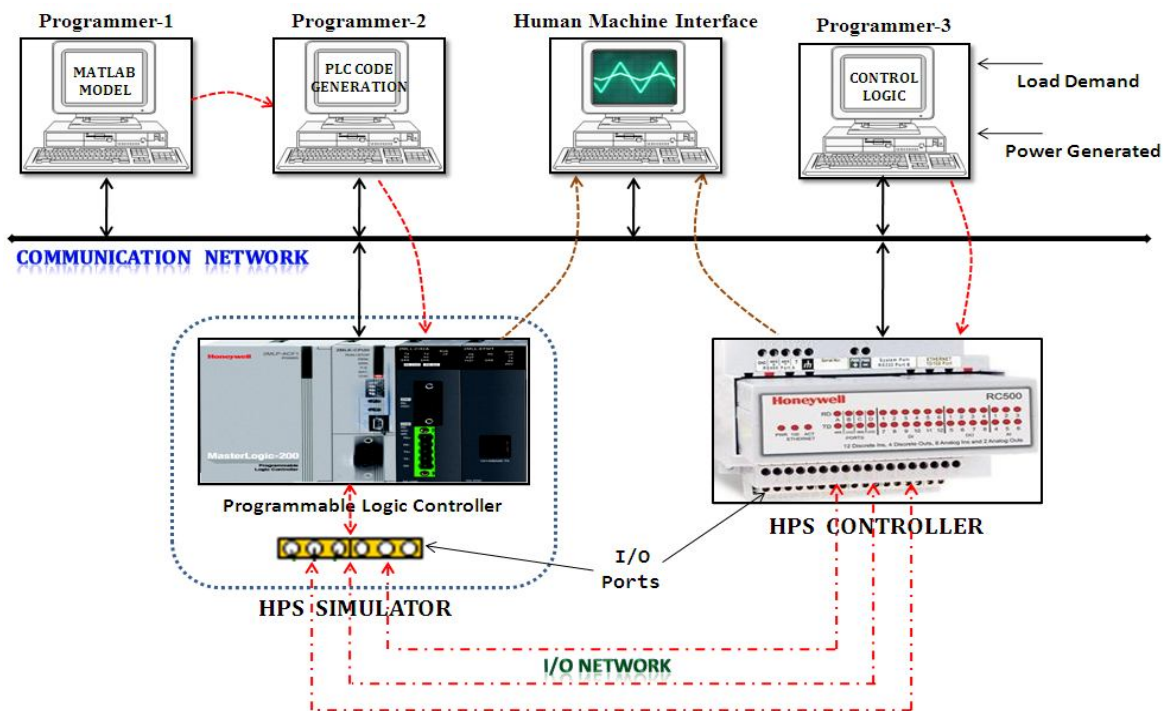


Figure.5. Proposed setup for HPS modeling and simulation

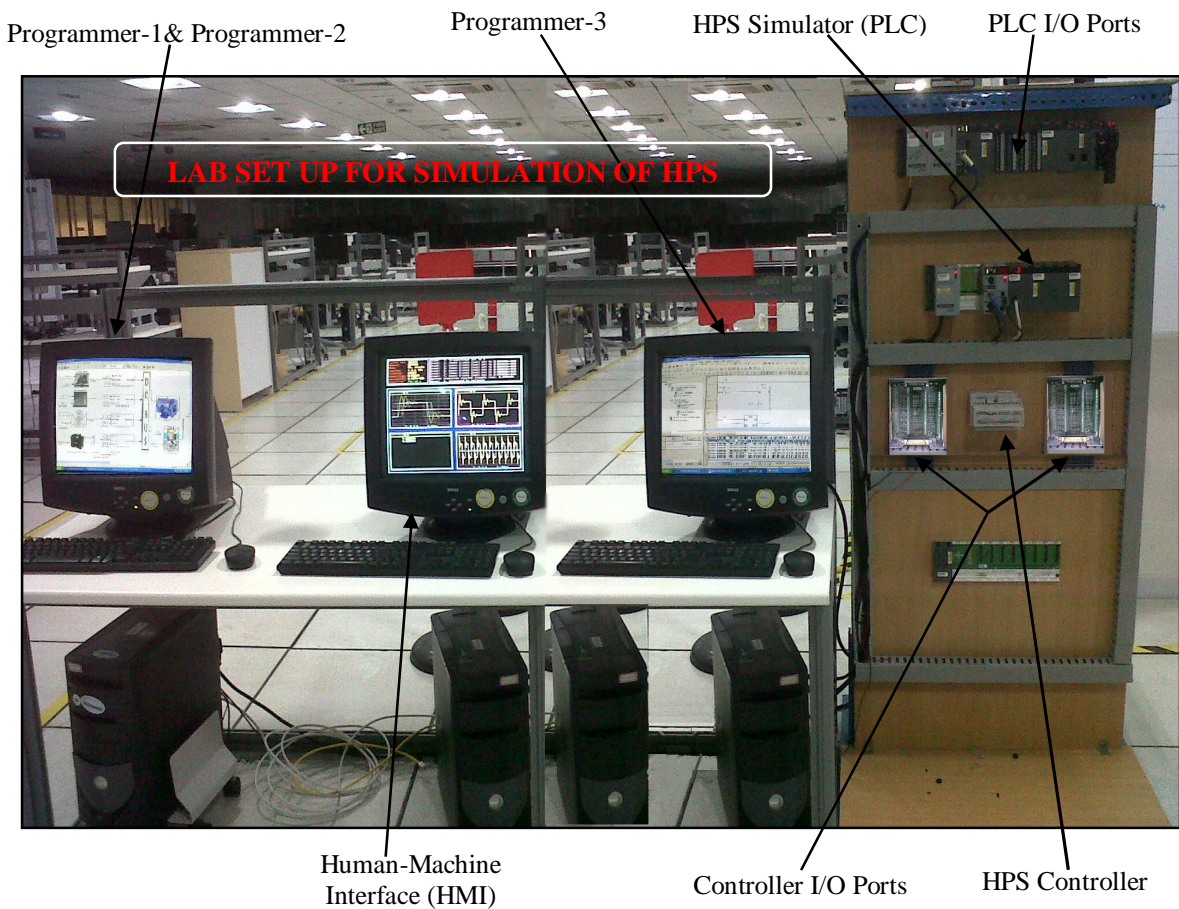


Figure.6. Laboratory setup for HPS modeling and simulation for the proposal

C. PLC Simulator

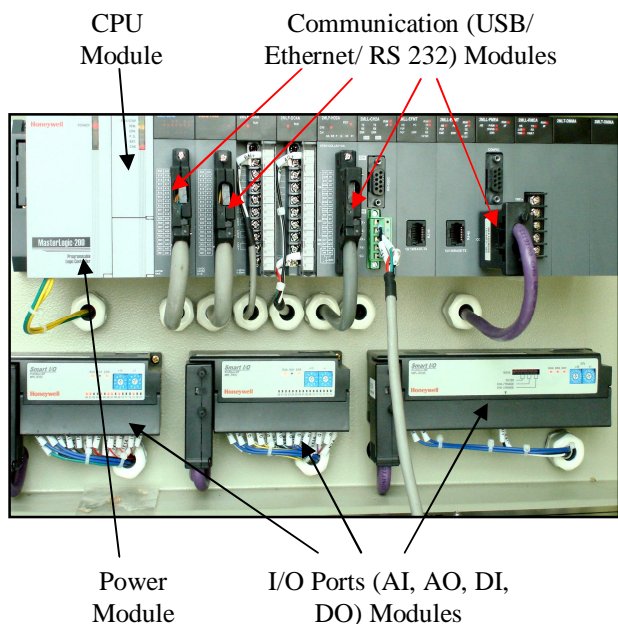


Figure.7. Programmable Logic Controller and its constituents

The PLC used is a master logic 200R series as shown in the figure.7. It has various modules like power supply, processor (CPU), communications, I/O ports. The PLC can communicate with the HPS controller through an USB connector, or Ethernet, or any serial communication devices.

D. HPS Controller

The HPS controller shown in figure.8 consists of energy manager and control units. The energy management system (EMS) [13] switches the mode of power supply, and controls the load share according to the condition of solar radiation, wind power, Fuel cell power and load requirement.

In general wind speed and solar radiation changes at random, in that conditions energy management plays important role. Generated power of HPS is compare with the load. If generated power exceeds the load, then excess power will be collected by the electrolyzer. The electrolyzer can produce H₂ gas and is stored in H₂ reservoir tank. Energy management unit monitors the H₂ reservoir tank. If H₂ reservoir tank is full, and hence excess power is used to charge the battery. The storage batteries compensate the load supply when the output power from the wind power generator, solar and fuel cell is deficient. And its charging status is also monitored by the EMS in-time. If the load is more than the generated power, then the load is connected to the grid. In that case the controller checks for the frequency and controls it. The HPS is based on multi-agents theory [9], [12], so the control subsystem is regarded as an agent. It is composed of PLCs, Human-Machine Interface (HMI), Grid-connected control module, etc., to control and manage the operation of multi-source, such as power grid, solar photovoltaic, storage batteries and loads, also to acquire data and communicate with others.

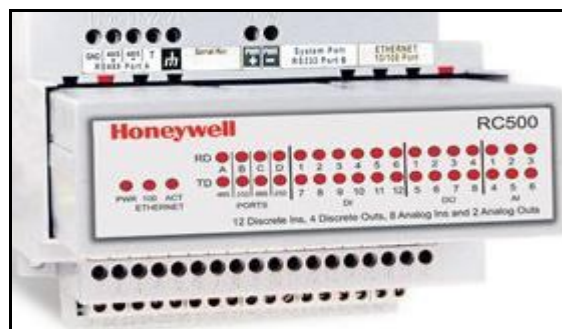


Figure.8. HPS real time controller RC 500

III. SIMULATION RESULTS

The simulation results that are obtained through PLC modeling and MATLAB/Simulink modeling of the system modules are compared.

A. User Interface (UI) Display

The User Interface (UI) displays for viewing results for overall HPS in both the platforms, i.e., conventional MATLAB/Simulink and proposed PLC are given as follows.

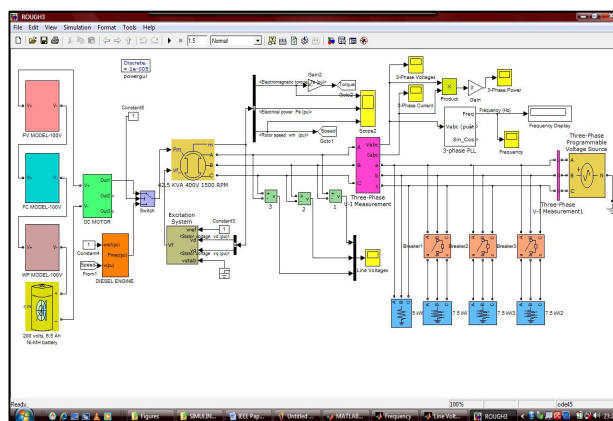


Figure.9. User Interface/Front Panel of MATLAB-Simulink

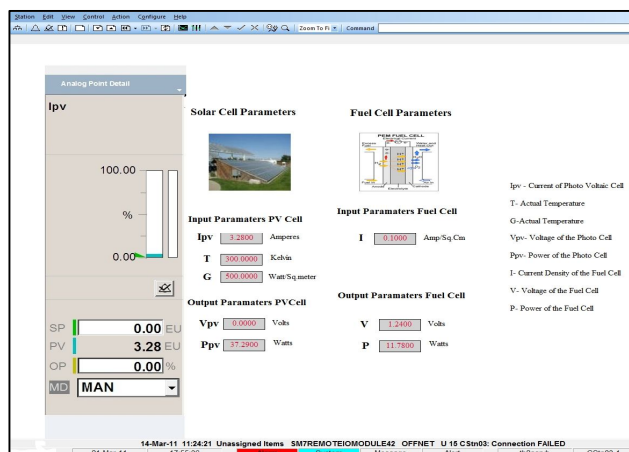


Figure.10. User Interface/HMI of PLC Display

B. V-P Characteristics

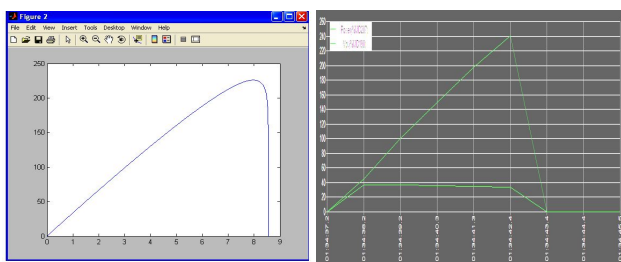


Figure.11. V-P Characteristics in (a) MATLAB-Simulink (b) PLC Trend

C. Voltage and Currents Vs Time

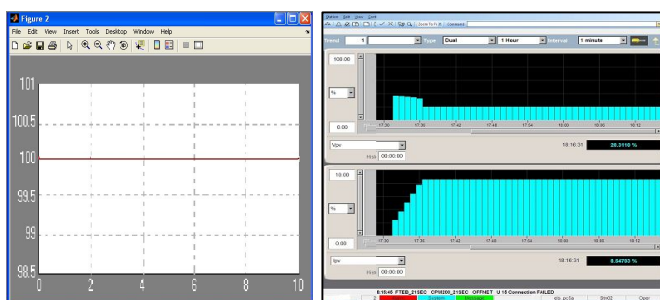


Figure.12. Time Vs V/I plots in (a) MATLAB-Simulink (b) PLC Trend

CONCLUSION

Hence, in this paper a novel method for modeling and simulation of the renewable energy based Hybrid Power System (HPS) was described. HPS Dynamics with both platforms (Conventional MATLAB/Simulink and Proposed PLC Simulations) were obtained and compared. From the plots shown from Figure.9-12, the observations are;

- 1) The simulation capabilities in terms of Simulation speed, Simulation span were enhanced.
- 2) The proposed method possesses high fidelity to design, which supports communication with real time hardware.
- 3) Since real time control devices equipped with specific embedded hardware can be effectively interfaced, hence effective Energy Management is achieved.

Hence, the proposed method of simulation for HPS dynamics using PLC, can effectively supports real time control strategies by connecting through a real time controller, via HMI, and other hardware, over a long period of time. Due to this, all available energy resources could be effectively utilized for economic operation of the plant.

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