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PLC Based Energy Management and Control Design for an Alternative Energy Power System with Improved Power Quality

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***Abstract*--** **This paper describes modeling and simulation of a renewable energy based hybrid power system in the aspects of improving power quality, energy management and control, because optimal utilization of primary energy sources will increase the level of supply reliability. In order to meet sustained load demands during varying natural conditions, different renewable energy sources and converters are need to be integrated with each other. The paper focuses on the combination of Photo Voltaic (PV) cell System, Wind turbine system, Fuel cell (FC), and Battery systems for power generation, and to improve power quality we are proposing Motor-Generator model instead of using static converters, and an energy management and control unit using Programmable Logic Controller (PLC). Since wind turbine output power varies with the wind speed, the PV cell output power varies with both the temperature and irradiance, and a FC output power varies with input fuel, and so, along with DC Motor, Diesel engine is also coupled to ensure that the overall system performs under all conditions, especially when PV, Wind, FC power is not enough to drive DC motor. Excess energy when available, is converted to hydrogen using an electrolyzer for later use in the fuel cell for the economic use of fuel. The results show that the proposed hybrid power system can effectively manage the optimal utilization of primary energy sources and improves the power quality in both islanding mode and as well as grid connected mode.**

***Keywords*—Hybrid Power system, Renewable energy Sources, DC Motor-Synchronous Generator set, Diesel engine, Islanding (Isolated) mode and grid connected mode, and Energy Management, PLCs.**

I. INTRODUCTION

Energy demand in isolated mode or grid connected mode of applications is steadily increasing. Thus, it is very important to meet the continually increasing demand of power. On the other hand, there is a social interest for global environmental concerns such as green house effect and global warming and a reduction in fossil fuel resources. The solution for these issues can be considered from the recent research and development of alternative energy sources which has excellent potential as a form of contribution to conventional power generation system. 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, and onsite installation. The system consists of PV panels, wind power system and fuel cell system. Electrolyzers are used to absorb the rapidly fluctuating output power with load and generate hydrogen. The generated hydrogen is stored in the hydrogen tank and used as fuel for fuel cells, which reduces the fuel cost.

Combining several different types of power sources will form the system called "Hybrid Power system". Hybrid power systems (HPS) combine two or more energy conversion devices, or two or more fuels for the same device, that when integrated, overcome limitations inherent in either. Hybrid power systems are designed for the generation and use of electrical power. They are available in two modes; namely islanding (isolating) mode and grid connected mode. In general, a hybrid power system might contain alternating current (AC) diesel generators, an AC distribution system, a Direct current (DC) distribution system, loads, renewable power sources, energy storage, power converters, rotary converters, coupled diesel system, dump loads, load management options, or a supervisory.

In the system, the output of the renewable sources cannot feed the load directly because their voltage fluctuations are so large that they will damage the concerned load. So first it needs to be conditioned, for that generally dc-dc/ac-dc converters are used. Thus the varying voltage can be brought to required value and specified variations limits by varying the duty ratio of the converters, and then connected to DC bus.

II. PROPOSED SYSTEM

The DC bus voltage is now used to drive the DC motor coupled to the synchronous generator. Electrical power should be produced exactly at the same time when it is needed. It may not be possible for renewable energy sources like wind, PV, and FC to produce sufficient energy to drive DC motor coupled to synchronous generator at all the time, since their operation depends on varying natural conditions. So, diesel engine is also coupled to synchronous generator to avoid shortages of power.

In the proposed system shown in figure.1, the DC motor, Alternator and Diesel Engine are mechanically connected using an electrical clutch. The DC bus is used for integrating all the sources and storage of energy like PV, Wind, battery, etc. To have an optimum, efficient and reliable operation of the complex system consist of various power sources, a control is needed. Hence microgrid controller which also acts as Energy management unit is designed using PLC. Modeling and simulations are conducted using MATLAB/Simulink [1] to verify the effectiveness of the proposed system.

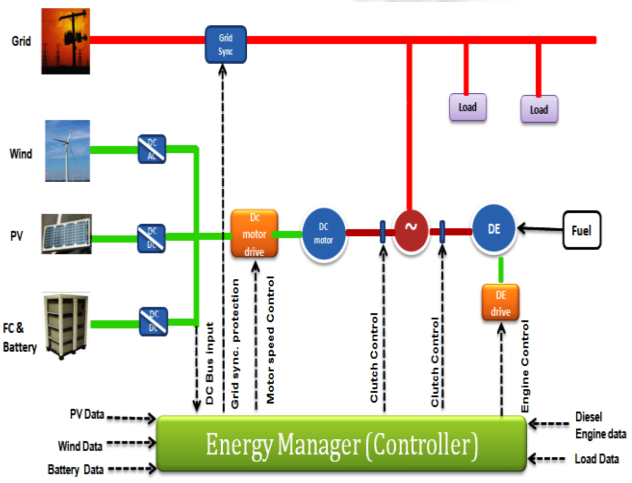


Figure.1. Proposed System Block diagram

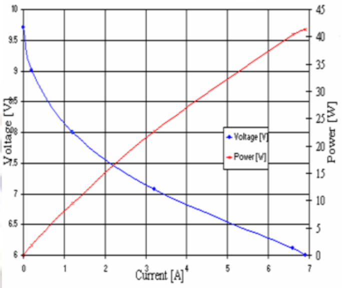
III. MODELING AND SIMULATION

A. Fuel cells

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. It must respond quickly to changes in load and have low maintenance requirement as well as a long cell life [2].The basic building block of a fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on either side. 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,

$$2H_2 + O_2 \leftrightarrow 2H_2O \quad (1)$$

Hydrogen and oxygen pass over each of the electrodes and through means of a chemical reaction, electricity, heat and water are produced.



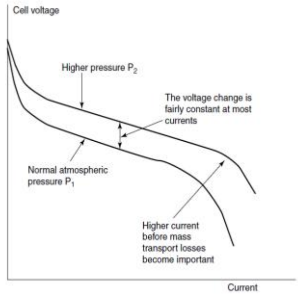


Figure.2. Performance of fuel cell characteristics of fuel   Figure.3. V-I cell with change in fuel pressure

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

$$E = 1.229 - 0.85*10^{-3}*(T-298.15) + 4.3085*10^{-5}*T*(\ln P_{H2} + \ln P_{o2}) \quad (2)$$

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

$$Co_2 = Po_2 / (5.08*10^{6} \exp(-498/T)) \quad (3)$$

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

$$\acute{\eta}_{act} = -0.9514 + 0.00312T - 0.000187\, T \ln(i) + 7.4 * 10^{-5}\, T \ln(Co_2) \quad (4)$$

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

$$R_a = -\acute{\eta}_{act} / i \quad (6)$$

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

$$V = E - v_{act} + \acute{\eta}_{ohmic} \quad (7)$$

The steady state fuel cell model described above indicates that the current drawn, cell temperature, H2 pressure, and O2 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

$$\acute{\eta}_{ohmic} = -i*R_{int} \quad (8)$$

The fuel cell system consists of a stack of 65 similar cells connected in series. Therefore, the total stack voltage is given by $V_{stack} = 65 * V_{cell}$ (9)

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. It also depends upon the volume of the electrodes. If the incoming and outgoing flow rates (mol/s) are known, then the gas pressure within the fuel cell humidifier can be determined using the mole conservation principle. Figure 4, shows the Simulink model of fuel cell.

For the fuel cell anode

$$(V_a/RT)\frac{dPH_2}{dt} = \acute{m}_{H2in} - (\rho_{H2}UA)_{out} - (I/2F) \quad (10)$$

Similarly, the equation for the cathode is

$$(V_a/RT)\frac{dPO_2}{dt} = m_{o2\ in} - (\rho_{O2}\ UA)_{out} - (I/4F) \quad (11)$$

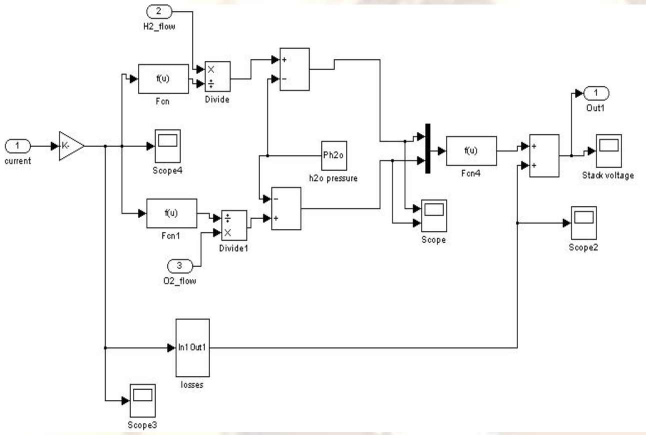


Figure.4.Simulink model of fuel cell

B. Electrolyzer

The decomposition of water into hydrogen and oxygen can be achieved by passing an electric current between two electrodes separated by an aqueous electrolyte [5], [6]. The total reaction for splitting water is;

H_2O (1) +electrical energy = $H_2 + ½ O_2$ (g) (12)

A water electrolyzer consists of several electrolyzer cells connected in series. The current vs. voltage characteristics of an electrolyzer depend upon its working temperature, According to Faraday's law, the production rate of hydrogen in an electrolyzer cell is directly proportional to the transfer rate of electrons at the electrodes, which in turn is equivalent to the electrical current in the circuit.

$$\acute{\eta}H_2 = \acute{\eta}_F\ \acute{\eta}_c\ i_e/2/F \text{ (mol/s)} \quad (13)$$

Faraday efficiency is the ratio between the actual and theoretical maximum amount of hydrogen produced in the electrolyzer. Assuming an electrolyzer working temperature of 40°C, Faraday efficiency (in percent) can be given as

$$\acute{\eta}_F = 96.5 \exp(0.09/I_e - 75.5/i_e^2) \quad (14)$$

The two equations above give a simple electrolyzer model with the assumption that the electrolyzer has an independent cooling system to maintain its temperature at 40°C. For simplification, dynamic modeling of the electrolyzer and fuel cell's auxiliary equipment, such as hydrogen storage vessel, compressor, piping, valves etc., was not considered.

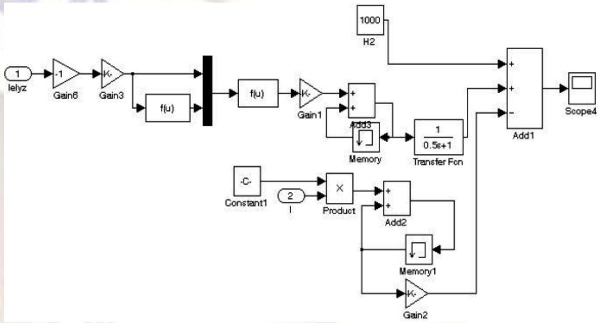


Figure.5. Electrolyzer subsystem model

C. PV Panel

Photovoltaic/solar cell is the device which converts sunlight into electricity directly of which magnitude of current and voltage depends on many factors like temperature, solar irradiation, and wave length of incident photon etc. the solar cell produces DC supply.

A solar cell module is the basic element of each photovoltaic system. It consists of many jointly connected solar cells. A number of solar cell models have been developed, but the one diode electrical equivalent circuit is commonly used for cell based or module based analysis. It consists of a diode, a current source, a series resistance and a parallel resistance. The current source generates the photo-current that is a function of the incident solar cell radiation and temperature [7], [8].

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 [8]. So we can ignore Rs and R_{sh}.

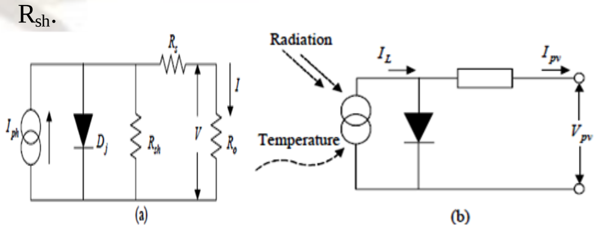


Figure.6. solar cell (a) equivalent circuit (b) simplified circuit

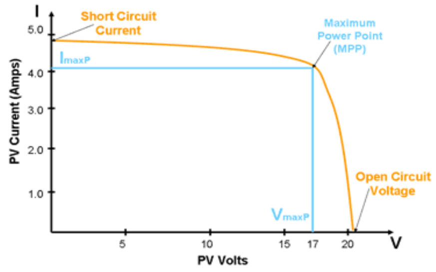


Figure.7. PV array V-I characteristics

PV panel is modeled in Simulink [10]. Figure 8, shows Simulink model of PV panel. The modeling equations used to develop the PV panel model are;

The solar cell current equation is

$$I_{PV} = I_{SC}\left\{1-C_1\left[\exp\left(\frac{V_{mp}}{C_2V_{OC}}\right)-1\right]\right\}+\frac{E_{tt}(t)}{E_{st}}[\alpha(T_a(t)+0.002E_{tt}(t)+1)]-I_{mp} \quad (15)$$

The solar cell voltage equation is

$$V_{PV} = V_{mp}\left[1+0.0539\log\left(\frac{E_{tt}(t)}{E_{st}}\right)+\beta(T_a(t)+0.02E_{tt}(t))\right] \quad (16)$$

$$C_1 = \left(1-\frac{V_{mp}}{I_{sc}}\right)\exp\left(\frac{-V_{mp}}{C_2V_{oc}}\right) \quad (17)$$

$$C_2 = \frac{\left(\frac{V_{mp}}{V_{oc}}-1\right)}{\ln\left(1-\frac{I_{mp}}{I_{sc}}\right)} \quad (18)$$

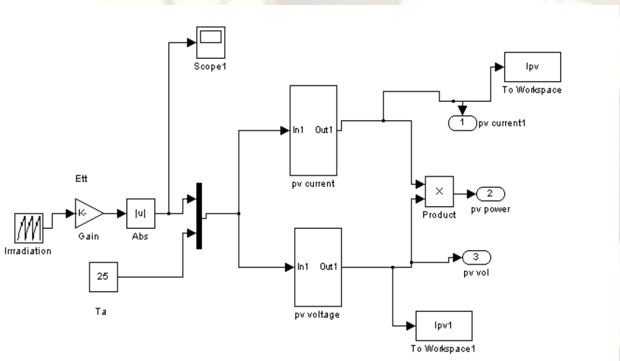


Figure.8. Simulink model of PV panel

D. Wind Power

The power output of wind turbine is relating to wind speed with a cubic ratio. The power curve of the wind turbine AIR 403 studied is nonlinear, [10] which is digitized and the resulting table is used for simulation as Fig. 3. Both the first order moment of inertia (J) and a friction based dynamic model for the wind turbine rotor, and a first order model for the permanent magnet generator are adopted. The dynamics of the wind turbine due to its rotor inertia and generator are added by considering the wind turbine response as a second order slightly under-damped system [7], [9]. Using this simple approach, small wind turbine dynamic is modeled as

$$P_g(s)/P_{wt}(s) = 0.25/(s^2+0.707s+0.25) \quad (19)$$

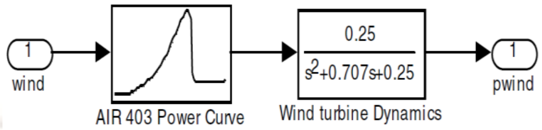


Figure.9. Simulink model of Wind turbine

E. DC Motor-Synchronous Generator set

In order to improve power quality, the DC bus voltage is used to drive motor-generator set as shown in the following figure.10, instead of giving to static converters. This is modeled as figure.12.

Figure.10. Synchronous generator with prime mover DC motor

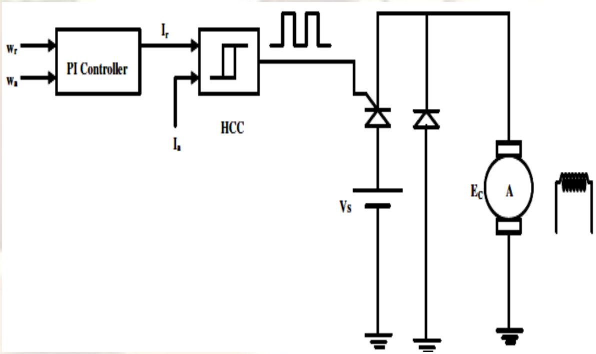


Figure.11. Speed control of a sep excited DC motor

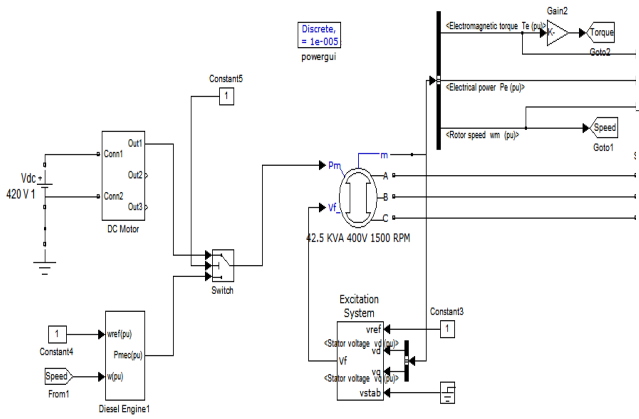


Figure.12. Simulink model of DC motor, Diesel engine-Generator set

F. Diesel Engine setup

To simulate the complete dynamics of a diesel engine system, a very large order model will be required. However for most studies on speed dynamics of internal combustion engines, it is sufficient to use a lower order model [11]. Similar approaches have been adopted in diesel engine simulation studies.

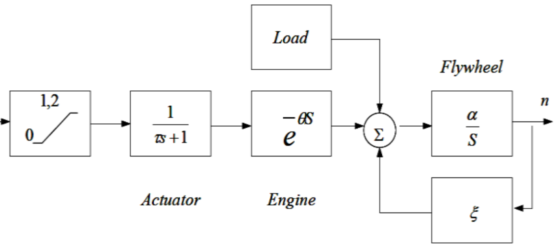


Figure.13. Block diagram of a diesel engine system

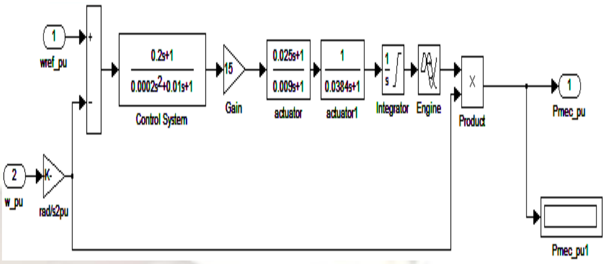


Figure.14. Governor & diesel engine subsystem

G. Proposed Hybrid power system model

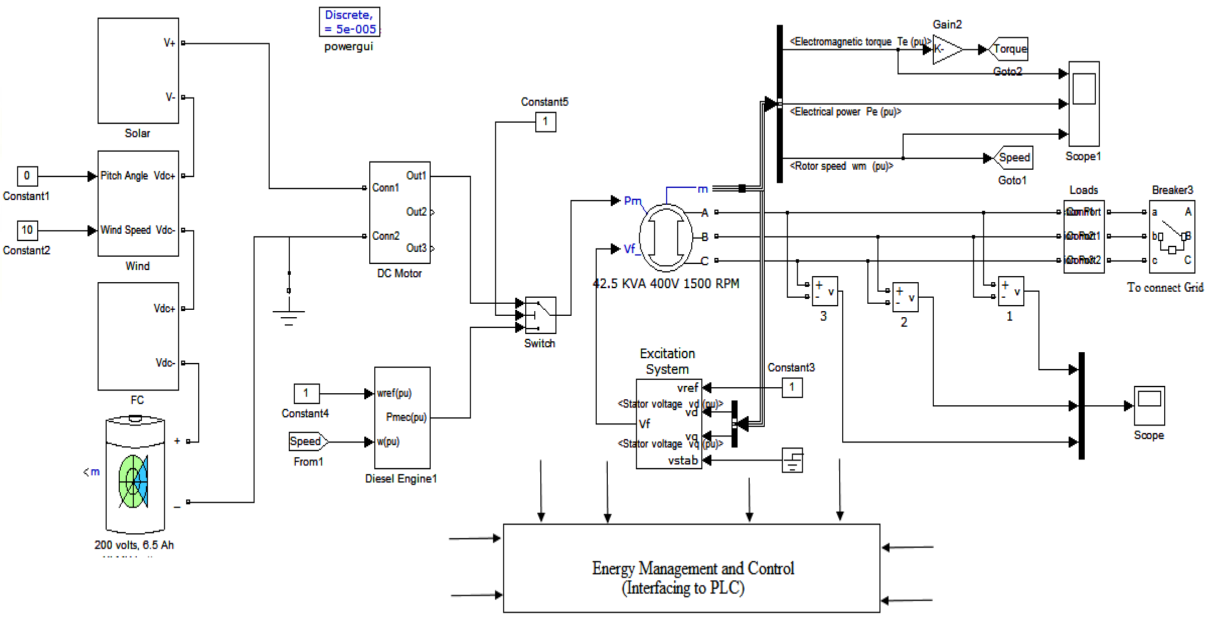


Figure.15. Proposed Hybrid power system model using Simulink

IV. ENERGY MANAGEMENT AND CONTROL SYSTEM

The energy management system (EMS) switches the mode of power supply, and controls the load share according to the condition of wind power, solar radiation, 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 hybrid system is compare with the load. If generated power exceeds the load, then excess power will be collected by the electrolyzer. The electrolyzer can produce H_2 gas and is stored in H_2 reservoir tank. Energy management unit monitors the H_2 reservoir tank. If H_2 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 on-time. If the load is more than the generated power, then the load is connected to the grid. In that case the EMS checks for the frequency and controls it.

In the relatively low capacity of the micro-gird power systems, there are flexible choices for demand side to increase the efficiency of the system operation and economics. Therefore, using demand side management to opportunely control load, would reduce the need of generation capacity and increase the utilization of renewable generation devices and accordingly increase the efficiency of generation investment. Integration of the all blocks by using EMS can provide flexible energy consumption management solution for improving power quality of the renewable energy hybrid micro grid power system. The hybrid power system is based on multi-agents theory [12], so the control subsystem is regarded as an agent. It is composed of programmable logic controller (PLC), human-machine interface (HMI), grid-connected control module, AC multi-function electric power meters, and DC electric power meters, RS485/TCP converter etc., to control and manage the operation of multi-source, such as power grid, wind turbine generation, solar photovoltaic, storage batteries and loads, also to acquire data and communicate with others.

The system is composed of several modules. Their functions are controlled by PLC, the controller of the subsystem, is FBs-40MAT from FATEK. It is responsible for energy management and control of the whole system.

By considering the above mentioned conditions as reference PLC is programmed. More recently, PLCs are programmed using application software on personal computers. The computer is connected to the PLC through Ethernet, RS-232, RS-485 or RS-422 cabling. The programming software allows entry and editing of the ladder-style logic. Generally the software provides functions for debugging and troubleshooting the PLC software, for example, by highlighting portions of the logic to show current status during operation or via simulation. The software will upload and download the PLC program, for backup and restoration purposes. In some models of programmable controller, the program is transferred from a personal computer to the PLC though a programming board which writes the program into a removable chip such as an EEPROM or EPROM.

PLCs have built in communications ports, usually 9-pin RS-232, but optionally EIA-485 or Ethernet. Mod bus, BAC net or DF1 is usually included as one of the communications protocols. Other options include various field buses such as Device Net or Profi bus. Other communications protocols that may be used are listed in the List of automation protocols. Most modern PLCs can communicate over a network to some other system, such as a computer running a SCADA (Supervisory Control and Data Acquisition) system or web browser. PLCs used in larger I/O systems may have peer-to-peer (P2P) communication between processors.

This allows separate parts of a complex process to have individual control while allowing the subsystems to co-ordinate over the communication link. These communication links are also often used for HMI devices such as keypads or PC-type workstations.

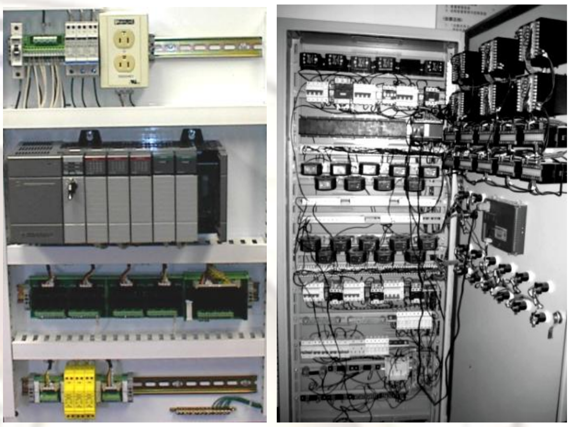
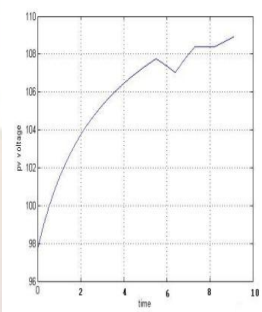


Figure.16. Photograph of the (a) Basic PLC Panel (b) EMS Control box

V. SIMULATION RESULTS OF THE HPS

A. PV and FC



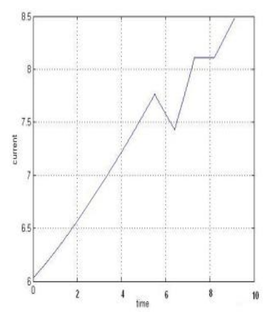
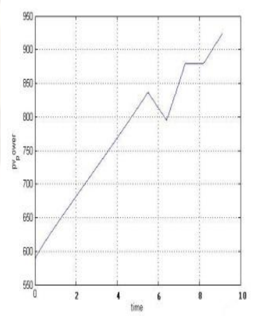


Figure.17. Voltage of the PV panel.
Figure.18. Current of the PV panel.



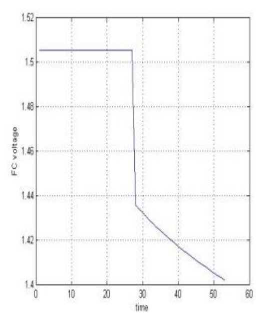
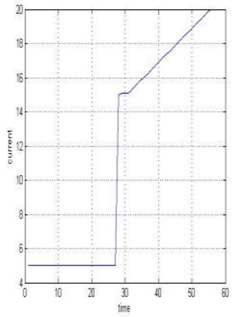


Figure.19. Power output of PV
Figure.20. Fuel Cell stack voltage



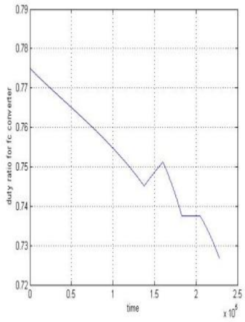


Figure.21. Current drawn from FC
Figure.22.Duty ratio of DC-DC converter.

B. Total Integrated System Outputs

All the components such as PV panel, PEM fuel cell, Wind system, and DC-DC converters, etc., which are individually modeled, and are integrated for simulation. With respect to the variation in natural conditions, the outputs of PV, FC, and Wind turbine systems are primarily controlled by varying duty cycles of DC-DC converters (Figure.22).

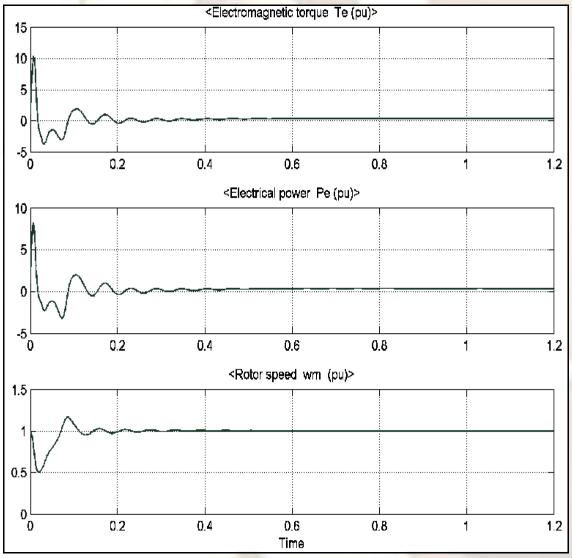


Figure.23. Power output from Hybrid power system.

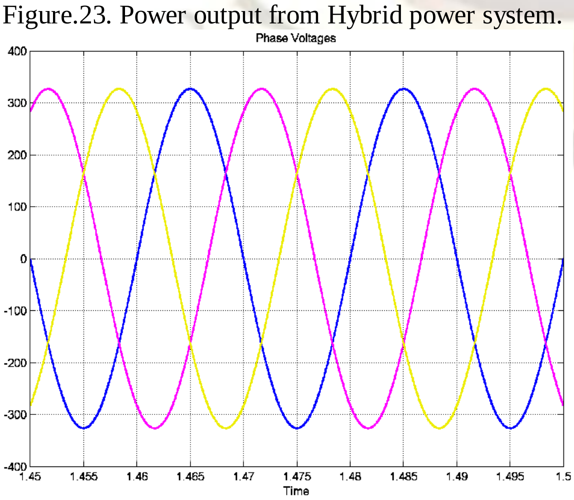


Figure.24. Phase Voltages of Hybrid power system.

VI. CONCLUSION

In this paper, a renewable energy based hybrid power system, its energy management and control system is proposed. It is modeled for an isolated load/grid connected load, with the method of using DC Motor-Alternator setup instead of using static converters. Along with DC Motor, Diesel engine is also coupled to ensure that the overall system performs under all conditions, especially when PV, Wind, FC power is not enough to drive DC motor. This proposed system facilitates improvement in power quality, which ensures continuous and reliable supply to loads. Voltage, Speed, Frequency variations at the output/grid is found to be within the acceptable range, which is shown in Figure 23 and Figure 24. The energy management and control unit is designed using PLC and HMI, which facilitates effective control on the entire power system. Therefore, this system can tolerate the rapid changes in load and environmental conditions, and suppress the effects of these fluctuations and provides optimum utilization of available resources.

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