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Study of Modeling and Control of Renewable Hybrid Energy System with Hydrogen Storage

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Abstract: Renewable energy systems are of importance since being modular, nature-friendly and domestic. This paper involves study ofmodeling and control of wind-photovoltaic-fuel cell hybrid energy system. The hybrid system consists of main components like: wind turbine,photovoltaic array, proton exchange membrane fuel cell (PEMFC), electrolyzer, boost converter, controllers and a power converter. The model for each process component is developed, and all the components are integrated in a MATLAB/Simulink environment.This kind of hybrid system is completely stand-alone, reliable and has high efficiency. Power converter and inverter are used to produce AC output power.Control scheme of fuel-cell flow controller and voltageregulatorsare based on PID controllers. Combination of PV and wind renewable sources has made the advantage of using this system in regions which have higher wind speeds in the seasons that suffers from less sunny days and vice versa. Simulation is carried for step changes in electrical load and wind speeds .Results showed that the ability of the system in adapting itself to sudden changes and new conditions.

Keywords: Wind Energy, Photovoltaic, Fuel Cell, Hybrid Energy Systems.

I. INTRODUCTION

The rapid depletion of fossil fuel resources on a world-wide basis has necessitated an urgent search for alternative energy sources to meet the present day demands. Alternative energy resources, such as solar and wind energies, are clean, inexhaustible and environment friendly, potential resources of renewable energy options. It is prudent that neither a standalone solar nor a wind energy system can provide a continuous supply of energy due to seasonal and periodical variations.
To solve these drawbacks conventional battery storage has been used. But batteries can store a limited amount of power for a short period of time. For long-term storage electrical power produced by wind turbines or PV arrays can be converted into hydrogen using an electrolyzer for later use in fuel cell. So these conventional batteries can be replaced with fuel cells as non-polluting and high efficiency storage devices.

Advantages in wind and PV energy technologies are the main reason of using hybrid Wind/PV configurations, and fuel-cells can be used in parallel with Wind/PV system as the device which can save and generate electrical energy where it is necessary. In addition, the excess heat from a fuel-cell can also be used for space heating or for the residential hot water. Management system is designed for a Wind-PV-Fuel cell hybrid energy system to manage the power flow between the system components in order to satisfy the load requirements.
It is necessary to analyse this system in all aspects such as: cost, efficiency, reliability, dynamic response to load demand and power source sudden changes and its control system. Since, these kinds of hybrid systems are operated under variable conditions such as sudden variations in load demand or wind speed. Therefore in this paper the dynamic response of a Wind- PV-Fuel cell hybrid energy system is analysed under some critical operating conditions. It is assumed that the output power of PV plus wind turbine can supply the nominal load demand, in the case of low wind or lack of ambient irradiation a share of power can be supplied from the fuel cell.
If PV and wind turbine output power exceeds the demand, the excess power is used to produce hydrogen for later use in the fuel cell. The system description, modelling and a study of system dynamics are presented below.

II. SYSTEM DESCRIPTION

The proposed system consists of a PV array, a wind turbine (IG-Phaser type, 1.5MW), a proton exchange membrane fuel cell (PEMFC), an electrolyzer, power converter, three phase load, and controllers. Wind turbine with an AC/DC converter, PV array and fuel cell with DC/DC converter will connect together to a dc bus and after that an inverter will convert this DC power to AC to supply the three phase load.

The load electricity demand is supplied from wind turbine output power plus PV array output in normal operation condition of the system. Each of these two power sources has its own controller. The fuel cell stack consists of 65 individual fuel cells connected in series. Fuel cell controllers are designed to control O2and H2 flow in order to produce more power. DC bus voltage is 200 volt and an inverter that converts the DC power into usable AC power for the system load. A set of differential equations and PID controllers obtained by transfer function is used for the modelling of system components.

A. Power Management Strategy

The block diagram of the overall control strategy for the proposed hybrid energy system is shown in Figure.1. Strategy of system operation is according to the following rules. If load demand (P_{load}) exceeds the available power generated by wind (P_w) and solar sources (P_{pv}), the fuel

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cell (P_{fc}) will come into action. Therefore, the power balance equation is written as:

$$P_{net}= P_w+P_{pv}+P_{fc}$$
$$P_{load}=P_w+P_{pv}+P_{fc},\ P_{net}<0 \qquad (1)$$

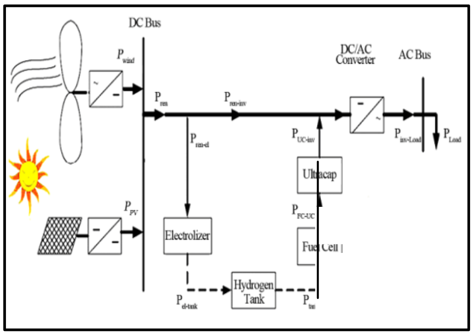

Figure.1 Configuration of hybrid energy system.

If the wind and solar generations exceeds the load demand, then the surplus power is diverted towards the electrolyzer. Therefore, the power balance equation is written as:

$$P_{ele}=P_w+P_{pv}- P_{load},\ \ P_{net}>0 \qquad (2)$$

If the wind and solar generation equals the load demand, then the whole power generated by renewable sources is injected into the load. Therefore, the power balance equation is written as:

$$P_{load}=P_w+P_{pv} \qquad (3)$$

III.WIND-PV-FUEL CELL SYSTEM MODELING

As it can be seen in Figure.2, the system consists of wind turbine, PV arrays, fuel cell stack, hydrogen storage tank, electrolyzer, power converter and controllers. Dynamic component models, used in this study, are summarized in the following sections.

A. Photovoltaic Model:

PV effect is a basic physical process through which solar energy is converted directly into electrical energy. The PV cell, or a solar cell, is presented by an electrical equivalent one-diode model as shown in Figure.3.

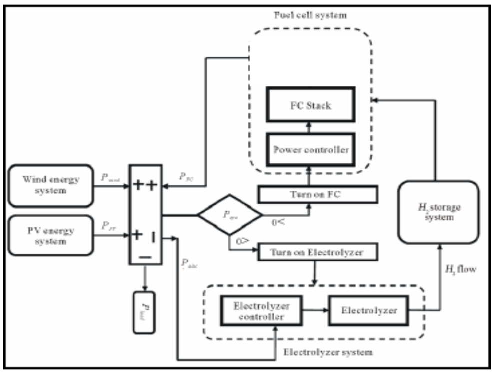

Figure.2 Block diagram of the overall control scheme for the proposed hybrid energy system.

The model contains a current source Isc, one diode and a series resistance Rs(in ohm), which represents the resistance inside each cell and in the connection between the cells.

Relationship between the output voltage Vpv (in volt), and the load current Ipv (in ampere) of a PV cell or a module can be expressed as

$$I_{pv}= I_{sc}- I_D \qquad (4)$$
$$V_{pv}= V_D-(R_S)(I_{pv}) \qquad (5)$$
$$I_D= I_0(e^{(eV_D/mkT_c)}- 1) \qquad (6)$$

Where I_0 is the saturation current, m is idealizing factor, k is Boltzmann's gas constant, T_c is the absolute temperature of the cell and e is electronic charge. V is the diode voltage, I_D is the diode current.

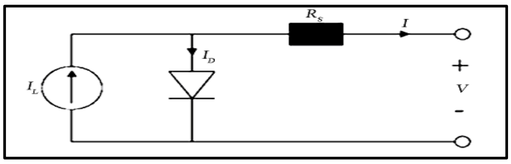

Figure.3 Model for a single solar cell.

The I-V characteristic curves of the PV model for a certain ambient irradiation and cell temperature are given in Figure.4. Effect of cell temperature variation in open circuit voltage is also considered in this model. In Figure.4, Isc is the short circuit current, Voc is the open circuit voltage, A (Vmax*Imax) is the maximum power point on the curve where the load resistance is Ropt, MN and PS are constant current and constant voltage criteria respectively. Here modules consist of NPM parallel branches and NSM solar cells in series. We take NPM and NSM equal to 10,000 and 2000 respectively.

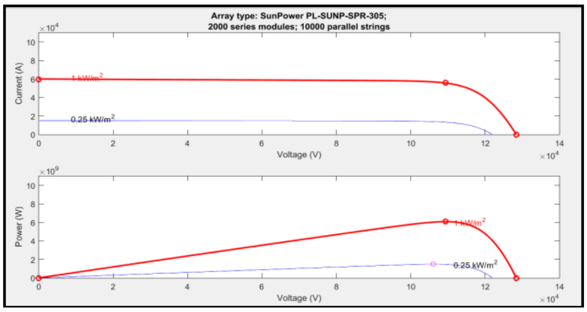

Figure. 4 Current-Voltage curve for PV Module.

B. Wind Energy Conversion System:

The wind energy conversion system (WECS) consists of a turbine to capture the energy in the wind, a drive train to speed up the rotational speed of the shaft, and a generator to convert the mechanical energy into electrical energy.

A variable-speed wind turbine with the capability of continuous adaptation (acceleration or deceleration) of the rotational speed ω of the wind turbine to the wind speed v is used. Wind turbine (IG-Phaser type, 1.5MW) is used.

The WECS model consists of three main parts: wind turbine rotor, drive train, and generator. The wind turbine rotor converts the kinetic energy of the wind into

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mechanical energy by producing torque. Since the energy contained in the wind is in the form of kinetic energy, its magnitude depends on the air density and wind velocity. The wind power obtained by the turbine rotor is given by:

$$P_w = \frac{1}{2}(\rho)\ (A)\ (v_3)\ (c_p(\lambda, \beta)) \qquad (7)$$

Where P_w is the power extracted from the wind, ρ is the airdensity, A is the swept area by the wind, and c_p is the power coefficient which is a function of the tip speed ratio λ and the pitch angle of the rotor blades β. The tip speed ratio is described as:

$$\lambda = \omega_m(R/v) \qquad (8)$$

Where ω_m is the rotational speed and R is the radius of the wind turbine rotor.

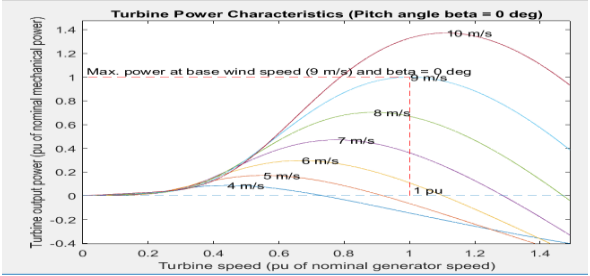

Figure 5. Wind Turbine Output

C. Fuel Cell Model:

Fuel cells are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. Proton exchange membrane fuel-cell (PEMFC) has reliable performance under intermittent supply and is commercially available at large industrial scale capacities. This kind of fuel cell is suitable for large-scale stationary generation and has fast dynamic response with a power release response time of only 1 - 3 s.

In this paper a group of PEMFC stacks is applied to enhance the performance of the hybrid system. The number of stacks is 65. Fuel cell has two PID controller loops; one for O2 and the other for H2 pressure. The controller gains are presented in table 1. The controllers will become activated when the output voltage of Fuel cell drops below 50 V.

Table1.PID Controllers parameters.

Component	K_p	T_i	T_d
Fuel-cell O_2flow controller	3.14	0.5	0
Fuel-cell H2flow controller	5	0.5	0
Boost converter	5	0.5	0
Inverter	0.03	0.15	0

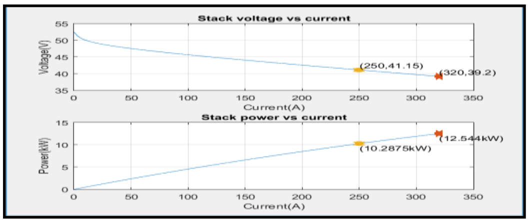

Figure.6 Fuel Cell Stack Output

D.Electrolyzer Model:

The Electrolyzer works through simple water electrolysis. When a direct current is passed between two electrodes submerged in water, which thereby decomposes into hydrogen and oxygen. The hydrogen can then be collected from the anode.

$$\text{Anode Reaction:} H_2O \rightarrow 2H^+ + (1/2)O_2 + 2e \qquad (9)$$
$$\text{Cathode Reaction: } 2H^+ + 2e \rightarrow H_2. \qquad (10)$$

The electrolysis of water using cells with a proton exchange membrane (PEM) is a very efficient method of producing hydrogen. PEM electrolyzers shown in Figure.7 are very simple and compact and have demonstrated higher current density capability than conventional alkaline water electrolyzers. The supplied water to the anode side is decomposed into oxygen gas, hydrogen protons, and electrons. The hydrogen protons are transported through the proton conductive membrane to the cathode side. At the same time, the electrons exit the PEM electrolyzer cell via the external circuit, which supplies the driving force (i.e., cell potential) for the reaction, whereas at the cathode side the hydrogen protons and the external circuit electrons recombine to form hydrogen gas. The production rate of hydrogen in an electrolyzer cell according to Faraday law can be achieved through Equation:

$$n_{H2} = (n_F)(n_c)(i_e/2)\ \text{mol/sec} \quad (11)$$

Where ie is the electrolyzer current, nc is the number of electrolyzer cells in series and nF is the Faraday efficiency. For an electrolyzer working in 40°C; Faraday efficiency can be calculated as:

$$nF = 96.5^{(0.09/i_e - 75.5/i_e{}^{\wedge}2)} \qquad (12)$$

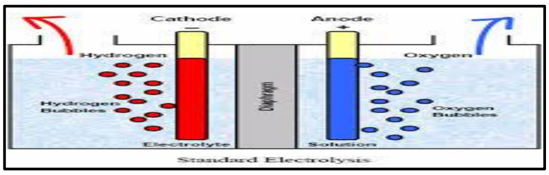

Figure.7 PEM electrolyzer

E. Controllers:

All subsystem controllers are chosen PID type in this system, which have transfer function like in Equation 13. Appropriate controller parameters are available in Table 1.

$$T(s) = K_p(s + T_d * s^2 + 1/Ti)/s \qquad (13)$$

IV. SIMULATION AND RESULTS

The simulated system in Matlab/SIMULINK is presented in Figure 8. It consists of five main subsystems that have been described in previous sections. Wind turbine input and load resistance are two variable inputs of the system .Step changes in load resistance and wind speed are applied to analyze the dynamic response of the system. Load resistance changes at t = 10 s from 35 Ω to 10 Ω and t = 20 s from 10 Ω to 25 Ω as seen in Figure.9. Wind speed changes at t = 20 s from 9 to 12 m/s and returns to 9

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m/s at t = 30 s as it is clear from Figure.10. Simulation is run for 40 seconds. Results are presented in Figures 9 to 14. Figures 9-14 shows the demand power, wind turbine, photovoltaic and fuel cell output powers. As it is clear that demand power increases at t = 10 s and decreases in t = 20 s by change in load resistance. The lack of power in t= 10 s is compensated by an increase in H_2 pressure and as a result a step change in output power of fuel cell.

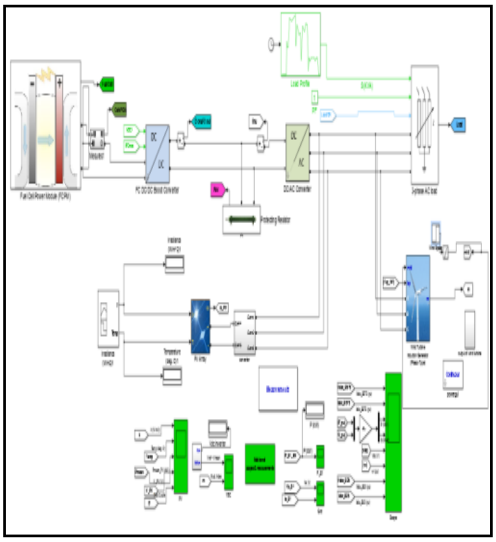

Figure.8 Simulink Model

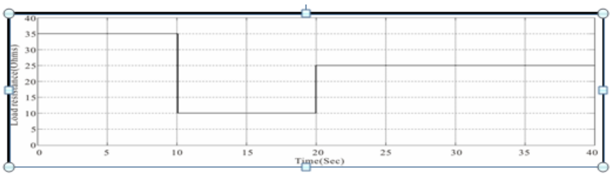

Figure.9Load Resistance v/s Time

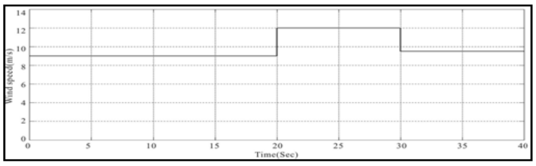

Figure.10Wind Turbine Input

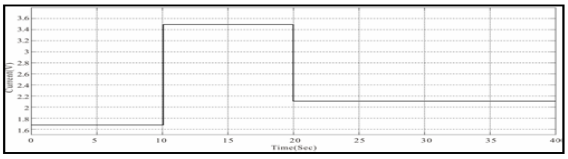

Figure.11PV Current waveform

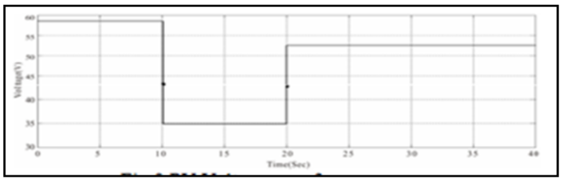

Fig.12PV Voltage waveform

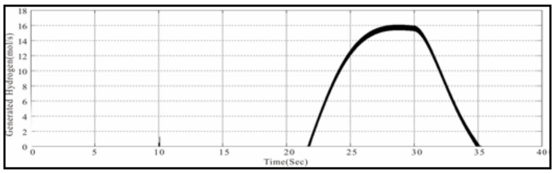

Figure.13Generated H2 by electrolyzer

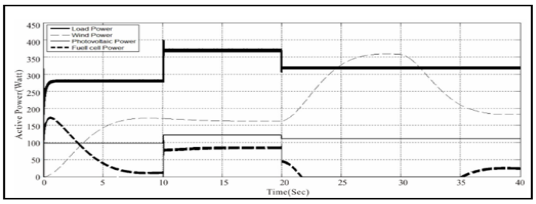

Figure.14Load, fuel cell, PV and wind powers

VI. CONCLUSION

A wind-photovoltaic-fuel cell hybrid energy system for stand-alone operation is studied in this paper. The design and analysis of this demonstration type highlight low emission energy system. System dynamic modeling, simulation, and design of controller is included in paper all system models are described through mathematical aspect. Results show the effectiveness of this hybrid energy system. Such a system shows its ability to supply a variable load without interruption. The system is more reliable in comparison to a wind-fuel cell hybrid system, because of three systems in parallel and their different characteristics. It is more economical to supply the load by this hybrid energy system because it doesn't need the fuel cell to work all day long. The system performance can satisfy the user in all perspectives.

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