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Analysis of Voltage and Current Variations in Hybrid Power System

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ABSTRACT

In this paper, a detailed dynamic model and simulation of a solar cell/wind turbine/fuel cell hybrid power system is Developed using a novel topology to complement each other and to alleviate the effects of environmental variations. Comparing with the nuclear energy and thermal power, the renewable energy is inexhaustible and has non-pollution Characteristics. Here Ultra-capacitors are used in power applications requiring short duration peak power. The voltage variation at the output is found to be within the acceptable range. The output fluctuations of the wind turbine varying with wind speed and the solar cell varying with both environmental temperature and sun radiation are reduced using a fuel cell. Therefore, this system can tolerate the rapid changes in load and environmental conditions, and suppress the effects of these fluctuations on the equipment side voltage. The proposed system can be used for off-grid power generation in non interconnected areas or remote isolated communities. Modeling and simulations are conducted using MATLAB/Simulink software packages to verify the effectiveness of the proposed system. The results show that the proposed hybrid power system can tolerate the rapid changes in natural conditions and suppress the effects of these fluctuations on the voltage within the acceptable range.

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I. INTRODUCTION

The solar energy, wind energy, hydro power and tidal energy are natural resources of the interest to generate electrical sources. Comparing with the nuclear energy and thermal power, the renewable energy is inexhaustible and has non-pollution characteristics. Extensive and generalized usage of renewable energy is very popular to reduce the pollution we have cause on the earth. The wind and solar energy are welcome substitution for many other energy resources because it is natural inexhaustible source of sunlight to generate electricity [3]. With the increase in the demand, the conventional power plants like thermal, nuclear are unable to meet the demand and increase in the number of poor plants causing on additional pollution to the environment. So it became necessary to tap the electrical energy from the renewable energy resources like solar energy, wind etc for the cleaner and sustainable power. The main problem of using these solar and wind power is to store the energy generated by pv cells and wind turbine rest for future use when no wind is available but the user demand exists.[3] the solar cells 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 the main problem of the wind turbine is that naturally variable wind speed causes voltage and power fluctuations problems at load side. this problem can be solved by using appropriate power converters and control strategies 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] by using an electrolyzer ,h conversion allows both storage and transportation large amounts of power at much higher energy densities[4]. Furthermore, coupling a wind turbine, a solar cell, fuel cells and electrolyzer is effective to decrease the environmental pollution of because of by using natural energy.

In this paper ,a detailed dynamic model and simulation of a solar cell/wind turbine/fuel cell hybrid power system is developed using a novel topology to complement each other and to alleviate the effects of environmental variations. Modeling and simulations are conducted using MATLAB/ Simulink software packages to verify the effectiveness of the proposed system. The results show that the proposed hybrid power system can tolerate the rapid changes in natural conditions and suppress the effects of these fluctuations on the voltage within the acceptable range.

II. DYNAMIC SYSTEM MODELS

A. Solar Cell

In the crystalline silicon PV module; The complex physics of the PV cell can be represented by the equivalent electrical circuit shown in Figure 1 For that equivalent circuit; a set of equations have been derived, based on standard theory [1], that allow the operation of a single solar cell, to be simulated using data from manufacturers or field experiments.

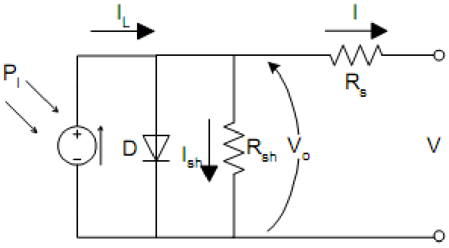

Figure-1 Equivalent electrical circuit of PV module

The circuit parameters are as follows [1]:

- The output-terminal current I equals to the light-generated current I_L, less the diode-current I_d and the shunt-leakage current I_{sh}.
- The series resistance R_s represents the internal resistance to the current flow, and depends on the p-n junction depth, the impurities and the contact resistance.
- The shunt resistance R_{sh} is inversely related with leakage current to the ground.

In an ideal PV cell, $R_s = 0$ (no series loss), and $R_{sh} = \infty$ (no leakage to ground). In a typical high quality one square inch silicon cell, $R_s = 0.05$ to 0.10 ohm and $R_{sh} = 200$ to 300 ohms. The PV conversion efficiency is sensitive to small variations in R_s, but is insensitive to variations in R_{sh}. A small increase in R_s can decrease the PV output significantly.

The equivalent circuit of Figure 2, the current delivered to the external load equals the current I_L generated by the illumination, less the diode current I_d and the ground-shunt current I_{sh}. The load current is given by the expression:

$$I = I_L - I_d - \frac{V_0}{R_{sh}} \tag{1}$$

where:

$V_0 = V_{sh}$ = voltage on the diode and the shunt resistance

I_d = diode Current (A).

The cell could be represented by a voltage-current equation:

$$V = V_0 - R_s I \tag{2}$$

where:

V = cell output voltage (V).

I = load (cell) output current (A). I_L = Photocurrent (A).

I_0= Reverse diode saturation current (A).

The two most important parameters widely used for describing the cell electrical performance are the open-circuit voltage V_{oc} and the short-circuit current I_{sc}. The short-circuit current is measured by shorting the output terminals, and measuring the terminal current under full illumination. The maximum photo-voltage is produced under the open-circuit voltage. The open circuit voltage V_{oc} of the cell is obtained when the load current is zero, i.e., when I = 0.

In this research paper, a model of the PV system with increased accuracy and complexity could be developed by including temperature dependence of the photocurrent I_L and the saturation current of the diode I_0. The series resistance R

$_s$ is included, but the shunt resistance is ignored. The proposed model adopts the simplified single diode version of the two diode model presented [1]. In the proposed model a single diode could be used with adjusting the diode quality factor for the best curve fitting.

The general equation describing the (I-V) characteristics of the PV cell is obtained from Eq.1 by ignoring the last term of the shunt resistance, and using the famous formula used for the diode current [1], as follows:

$$I = I_L - I_0\left(e^{q\frac{V+IR_s}{nkT_r}} - 1\right) \tag{3}$$

where:

I_L = photocurrent(A)

I_0 = diode saturation current(A)

q = electron charge

n = ideality factor

K = Boltzmann constant = 1.38 * 10-23 Joule/kelvin

Tr = rated cell temperature in Kelvin.

Rs = cell series resistance (ohm).

The non-linear Eq.3 describes the PV cell (I-V) characteristics, which adopts the equivalent circuit of PV cell presented in Figure 2 and includes an explicit solar radiation dependency of the photocurrent (I_L). The diode current (I_d) is modeled as a thermally activated device to account for variations of module performance with temperature. Eq.3 is considered as the benchmark model for a certain level of cell operating temperature (T_r) in Kelvin, and Solar radiation level (G_r) in (W/m^2). If those two important environmental variables are taken into consideration, the voltage and current output of the PV cell will follow their changes which should be included in the final PV cell model. When the cell is not illuminated, the relationship between the cell's terminal voltage and current is given by the Shockley equation [1]. When the cell is open circuited and illuminated, the photo- current flows entirely in the diode. The (I-V) curve is offset from the origin by the photo generated current I_L as illustrated in Eq. 3.

The value of the saturation current I_0 at different operating temperatures is calculated as presented in Eq. 4 [1]:

$$I_0 = I_{0(T_r)} * \left(\frac{T}{T_r}\right)^{\frac{3}{n}} * \exp\left(\frac{-qv_g}{nk\left(\frac{1}{T} - \frac{1}{T_r}\right)}\right) \tag{4}$$

$$I_{0(T_r)} = \frac{I_{sc(T_r)}}{\exp\left(\frac{qV_{oc(T_r)}}{nkT_r}\right) - 1} \tag{4.a}$$

An estimate must be made of the unknown ideality factor "n", which takes a value from 1 to 2. A value of 1.3 is suggested as typical in normal operation [1]. The relationship of I_0 in Eq. 4 is complex, but fortunately contains no variables that require evaluation [1]. The photocurrent I_L(A) is directly proportional to solar radiation level G (W/m^2), as presented in Eq. 5 [1]:

$$I_L = I_{L(T_r)}\left(1 + \alpha I_{SC}(T - T_r)\right) \tag{5}$$

$$I_{L(T_r)} = G * \frac{I_{sc(T_{r,}nom)}}{G_r} \tag{5.a}$$

$$\alpha_{I(sc)} = \frac{dI_{sc}}{dT} \tag{5.b}$$

When the cell is short circuited, a negligible current flows in the diode. Hence the proportionality constant i n Eq. 5.a is set so the rated short circuit current I_{SC} at the rat ed temperature is delivered under rated radiation (usually 1 Sun =1 000W/m^2).

The relationship between the photo-c urrent and the temperature is linear in Eq. 5, and is deduced by noting the change of photo-current with the change of temperature with the constant value α_{Isc} specified in Eq.5.b.

The open circuit voltage is varied wit h temperature as illustrated in Eq. 6:

$$V_{oc(T)} = V_{oc(T_r)}\left(1 - \beta_{V_{oc}}(T - T_r)\right) \tag{6}$$

where:

β_{VOC} = the open circuit temperature coefficient (V/sec)

B. Wind turbine

The power output of wind turbine is relating to wind speed with a cubic ratio.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[6].Using this simple approach,small wind turbine dynamic is modeled as

$$\frac{P_g(s)}{P_{wt}(s)} = 0.25/(s^2 + 0.707s + 0.25) \tag{7}$$

C. Fuel Cell

Fuel cell is a complex system consisted of fluid–heat–electrochemistry variables. Also the fuel cell contains macroscopic level fluid flow, microscopic level mass diffusion and transportation and the temperature gradient. Such factors that heat produced by electrochemical reaction, the convection heat transfer to the surrounding atmosphere through the fuel cell surface, the convection heat transfer between fuel cell and anode/cathode channel change the fuel cell temperature. The heat produced during the reaction, will warm up the fuel cell body. For this reason, the mass diffusion within the anode diffusion layer, cathode diffusion layer and membrane will be affected. Occurred variation of gas temperature will change the pressure and flow rate within the channels, which therefore affects the gas diffusion within the diffusion layers. Fuel cell has two important dynamic properties. These properties are fuel/air flow and temperature. State of these dynamic properties will change according to any disturbances on surrounding operating conditions and load changes. The current drawn, cell temperature, H_2 pressure, and O_2 pressure will significantly affect the fuel cell voltage [2].

A mathematical approach is presented for building a dynamic model for a PEM fuel-cell stack. To simplify the analysis, the following assumptions are made [2].

- One-dimensional treatment,
- Ideal and uniformly distributed gases,
- Constant pressures in the fuel-cell gas flow channels,
- The fuel is humidified and oxidant is humidified air. Assume the effective anode water pressure is 50% of the saturated vapour pressure. While the effective cathode water pressure is 100%.
- The fuel cell works under 100 ^{0}C and the reaction product is in liquid phase.
- Thermodynamic properties are evaluated at the average stack temperature, temperature variations across the stack are neglected, and the overall specific heat capacity of the stack is assumed to be a constant.

A fuel cell stack is represented by combining parameters for individual cells [2].

The thermodynamic potential is defined via E as a Nernest equation

$$E = 1.229 - 0.85 * 10^{-3}(T - 298.15) + 4.3085 * 10^{-5} * T(\ln p_{H2} + 0.5 \ln p_{o2})$$

(8)

For hydrogen, there are three relevant contributions to hydrogen flow: the input flow ,the flow that takes part in the reaction and the output flow[15]. The parametric equation for the over-voltage due to activation and internal resistance developed from the empirical analysis is given as:

$$\eta_{act} = -0.9514 + 0.00312T - 0.000187T\ln(i) + 7.4 * 10^{-5}T \ln co_2$$

(9)

$$co_2 = \frac{po_2}{5.08 * 10^6 \, e^{\frac{-498}{T}}}$$

$$R_{int} = 0.01605 - 3.5 * 10^{-5}T + 8 * 10^{-5}i \qquad (10)$$

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

$$V_{cell} = E - V_{act} - \eta_{ohmic} \qquad (11)$$

$$\eta_{ohmic} = i\, R_{int} \qquad (12)$$

$$\frac{dv_{act}}{dt} = \frac{i}{c} - \frac{v_{act}}{R_{ac}} \qquad (13)$$

$$R_a = \frac{V_{act}}{i} \qquad (14)$$

The fuel cell system consists of a stack of 65 similar cells connected in series. Therefore, the total stack voltage is given by

$$V_{stack} = 65\, V_{cell} \qquad (15)$$

Using the mole conservation principle, the gas pressure of the fuel cell anode is given as

$$\frac{V_a}{RT}\frac{dP_{H_2}}{dt} = m\, H_{2in} - (\rho H_2 UA)_{out} - \frac{i}{2F} \qquad (16)$$

The gas pressure of the fuel cell cathode is given as

$$\frac{V_c}{RT}\frac{dP_{o_2}}{dt} = m\, O_{2in} - (\rho O_2 UA)_{out} - \frac{i}{4F} \qquad (17)$$

D. Electrolyzer

Water can be decomposed into small components by electric current passing through the two electrodes separated by a aqueous electrolyte. The electrochemical reaction of water electrolysis is

$H_2O(l)$+electrical energy => $H_2(g)$+1/2 $O_2(g)$ (18)

In the equivalent electrolyzer circuit,the electrolyzer cell hydrogen production rate is directly proportional to electrical current from faraday's law

$$n_{H_2} = \frac{n_F n_c i_e}{2F} \qquad (19)$$

where

η_F is Faraday efficiency,i_e is electrolyzer current,$n_{c\ i}$is the number of electrolyzer cells in series,ie is electrolzer current.

The faradays efficiency is defined as the ratio between the actual and the theoretical maximum amount of hydrogen produced in the electrolyze. The working temperature of the electrolyzer is assumed as 40°C, the faraday efficiency is expressed as

$$\eta_F = 96.5\, e^{(\frac{0.09}{i_e} - 75.5/i_e^2} \tag{20}$$

The electrolyzer model is developed by using simulink.

E. Ultra capacitor

Ultra capacitor is an energy storage device. The construction of the ultra capacitor and the battery are similar to each other. These ultracapacitors are used in power applications where the short duration peak power is required means, it delivers the quick surge of power. An ultracapacitor stores energy in an electric field, rather than in a chemical reaction, it can survive hundreds of thousands more charge and discharge cycles than a battery can. The performance of the fuel cell in hybrid power system at steady state operation exhibits good power supply capability But during the instantaneous and short term peak power demand periods the response of the fuel cell system is relatively poor. To overcome this deficiency of fuel cell system here we present the model of ultra capacitor bank which performs the load sharing with the fuel cell system when they are working simultaneously with the wind turbine and solar cell. The fuel cell system is assisted by the ultracapacitor bank to achieve the good performance and also reducing the cost and size of the fuel system.To make the hybrid power system work effectively the ultracapacitor module is connected in parallel with the fuel cell system because of this the voltage variation due to sudden load changes are reduced.The transfer function given below describes the ultracapacitor which is modeled as a low pass filter.The Ultra capacitor is modeled as using transfer function as below

$$\frac{V_{UC}}{V_{FC}} = \frac{R_c Cs + 1}{(R_s + R_c)Cs + 1} \tag{21}$$

Where capacitance C=108.75μF,series resistance Rc=16mΩ and stray resistance Rs=0.01Ω.

III. SYSTEMS DESCRIPTION

The non-conventional energy based hybrid power system model in simulink is shown in fig 2.The system contains a solar cell of 75W wattage, wind turbine of 400W capacity,proton exchange membrane fuel cell of 500W,Ultra capacitor and an electrolyzer. Wind turbine and solar cell are the main sources to supply load demand. Fuel cell model includes fuel controller.The fuel cell is a accessory generator in this system and supplies insufficient power.Inorder to keepthe supply and demand is balanced. When the supply is bigger than the load need, the electrolyzer model electrolyzes water to produce Hydrogen and store it for further usage.Thus, the system can circulate supply load demand and energy will not be wasted.

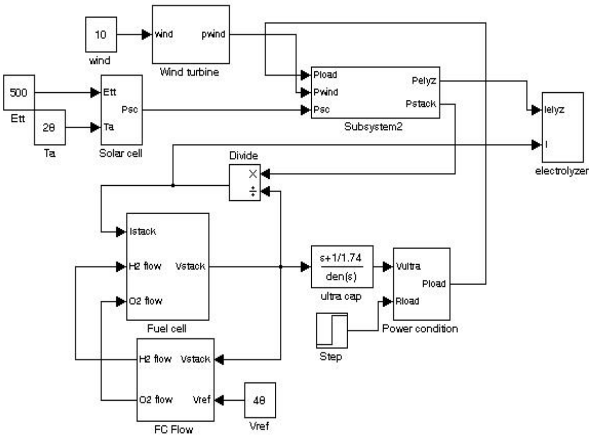

Figure 2. Hybrid power system model in Simulink.

IV. SIMULATION RESULTS

The analysis of the simulation results with step changes in load demand, wind speed, radiation, and ambient temperature are shown in fig 3-6. The initial speed of wind is 6 m/s. At t=5s the wind speed increases from 6 to 12m/s and at t=20s speed decreases to 10m/s initially when the radiation is 400W/$m^2$and temperature 25° the temperature increases to 28° and the radiation also increases to 600W/m^2at 15s. At 10s, the demand of load varies from 350W to 200W and at 15 sec the load changes to 250 W.The changes in available power and load consumption occurs due to this step inputs .The power tracking performance of the hybrid topology with respect to load demand change and environmental variations is shown in figure 3. Hence, the parameter variations in solar cell, wind turbine, fuel cell, ultra capacitor, power converter output and system performance are analyzed.

According to changes in load, the demand of power changes from 350W to 200W at 15s as shown in figure 3. The fuel cell provides power for load requirement because of the output powers of the wind turbine and solar cell are not sufficient enough to supply load demand at t=0 to 15s.However, the captured power increases and the contribution of the fuel cell decreases as the wind speed increases. During this period any excess power is diverted to the electrolyzer. Similarly, contribution of the fuel cell starts at t=20 s, with sudden decrease in wind speed.

As the load and environmental condition varies, the solar cell and fuel cell currents changes as shown in figure 4. The performance of the fuel system reflects these changes. The stack current variation is due to start-up transients and load demand, as the solar cell's and wind turbine's contributions are limited and fixed. During t=10s to t=19s, the fuel cell current decreases to zero because load demand is reduced and the wind turbine increases output power. After t=19s, variation in fuel cell current is due to changes in power demand from the fuel cell with varying availability of wind energy.

Significant variations of the stack voltage is caused due to the change in fuel cell current. Generally, a lower level of current implies higher stack voltage and vice versa. The stack's output variation as shown in figure 5 is reduced by the use of an ultra capacitor connected in parallel with the fuel cell, With variations of the ultra-capacitor voltage between 49 and 62 V, the power converter unit regulates the load voltage.As the fuel of fuel cell the hydrogen is considered. The electrolyzer electrolyzes water to produce hydrogen by the excess power of the system and store it from t=10s to t=19.1s. The variation of hydrogen in storage tank is shown in Fig. 6. The system can circulate supply load demand and renewable energy will not be wasted.

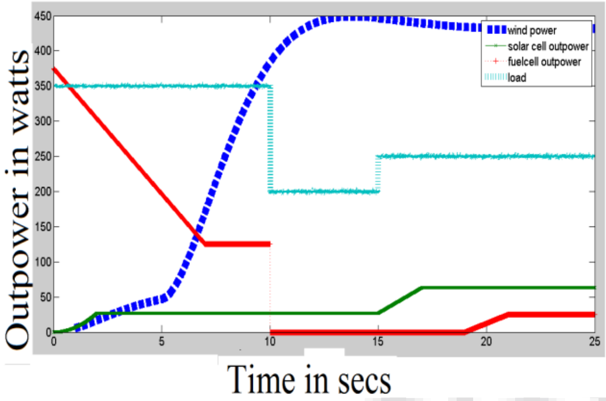

Figure-3 output power of hybrid power system

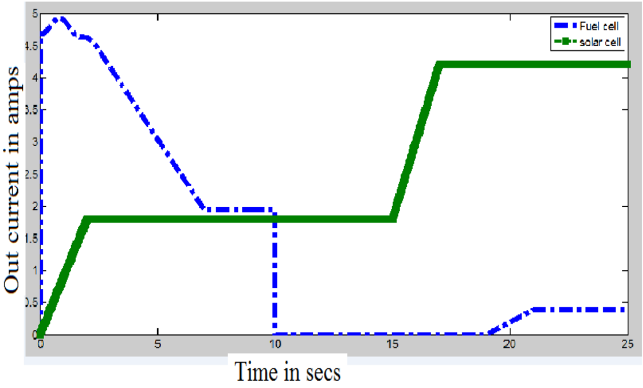

Figure-4 output current of hybrid power system

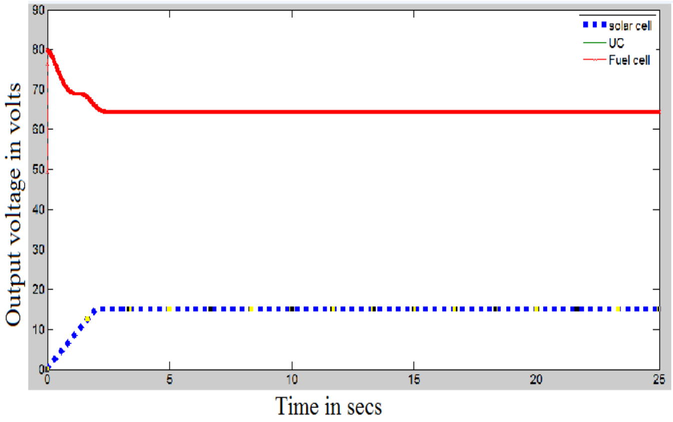

Figure-5 output voltage of hybrid power system

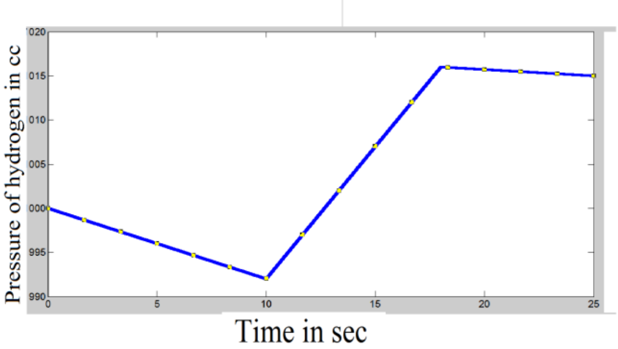

Figure-6 Pressure of Hydrogen in tank

V. CONCLUSION

In this paper, renewable energy based hybrid power system is proposed and modeled with power controllers. The power available from the renewable energy is highly dependent on the environment conditions like wind, solar and its ambient temperature. To meet the demand a FC/UC system is introduced, the power fluctuations obtained from both solar cell and wind turbine varying with speed are reduced using a Fuel cell. This model can be used for off-grid power generation in remote isolated areas.

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