Modelling and Control of a Wind-PV-Battery Hybrid Power System

Zaid Bin Siddique, Gagan Deep Yadav[2]

[1]*Research Scholar, YIET Gadhauli, India*

[2]*Assistant Professor, YIET, Gadhauli, India*

Abstract - *Time domain performance analysis results of a standalone hybrid system are presented based on commercial wind generator, photovoltaic generator and battery energy storage system. The hybrid system is designed and modelled using Matlab/Simulink/SimPowSys'" environment, a control strategy has been proposed to control the voltage DC bus and the energy flow between the different energy sources. The wind and photovoltaic generators are controlled locally to obtain the maximum power extraction, while battery energy storage system is controlled using specific control strategy depending on the voltage of the DC bus and energy flow. To test the performance of the system three different cases were analyzed; one case is the examination of the system performance when the solar irradiance in photovoltaic generator is made, the second case wind speed is varied in wind energy generator while the third case includes variable load. The stability of DC bus voltage and voltage total harmonic distribution are taken as system performance indexes. The simulation results ensure the effectiveness of the proposed hybrid system control strategy in following up the variations in load demand and weather data, providing the ground for practical realization.*

Key Words: Battery energy storage system; Hybrid renewable energy systems Photovoltaic

1. INTRODUCTION

The accelerating concerns over global warming and the shortage of conventional energy sources have led to increased interest in distribution Generation Sources (DG) based on green energies. Wind and photovoltaic energy are the most examined and developed renewable energy sources all over the world. Photovoltaic Energy Conversion System (PVECS) is becoming one of the most important renewable energy resources, since it is clean, generated on-site, pollution free and inexhaustible (Grandi et al., 2003; Kuo et al., 2001). The high initial cost, low generation efficiency and lack of reliability are the major disadvantages of PVECS (Shimizu et al., 200°).

Wind Energy Conversion Source (WECS) is a sustainable future energy source which contributes to clean air and global safety, it's costs decrease with time in which the traditional fuels costs increase with time (El-Khattam and Salama, 2004). The generation of electricity utilized from wind is feasible for isolated places far away from the grid. The annual growth rate of wind energy utilization is 30% which is the fastest growth in the world (Ackermann, 2005).

Battery Energy Storage System (BESS) is of a great importance in enhancing hybrid systems, stabilizes and permits the system to run at a constant and stable output despite load fluctuations and it covers the deficiency in energy through instantaneous lacks of primary energy in case of sun and wind sources. Battery technologies have been improved significantly in order to meet the challenges of utility applications (Ribeiro et al., 2001). The high energy density, high energy capability, round trip efficiency, cycling capability, life span and initial cost are key factors of batteries for storage applications (McD owall, 2000).

Different types of battery technologies are available for large scale energy storage system, the lead acid technology is considered a low cost option and mature technology that is suitable in rapid charge/dis charge large bulk storage system but the low energy density and limited life cycle are considered the main disadvantage of this technology (Ribeiro et al., 2001).

Several works have discussed standalone hybrid systems based on renewable energy sources: Energy flow and management of a hybrid WEC S/PVEC S/fuel cell is performed using wind and PV energies as main energy system and battery as backup system.

2. System Configuration

Figure (1) shows the hybrid PV-Wind energy conversion system (with battery storage) proposed in this thesis as a small-scale grid-connected system. The main energy sources for the system are wind and PV generators, while the battery bank works as an energy storage backup source. The utility grid works as a secondary backup supply in this system. The system is intended to be for residential applications, which may be building demand or a water pumping system with domestic demand. The research proposes a power conditioning unit (p.c.u.) which controls such a small-scale system. The small-scale system requires simple controllers and circuits that are easy to implement, and this is the core objective of this study. The present study always considers this to reduce the cost and size of the controllers and the system. The system components could be connected in several ways, depending on the proposed power electronics topology. One option is to connect the sources with the load and the grid via an ac bus bar, using an inverter for every source. This will increase the redundancy of the system, as every source can work independently from the other sources. However, this will increase the overall system cost. Another option, which is proposed in this study, is to connect the sources to a dc bus bar. Subsequently, an inverter will be used to supply the load and connect to the grid. This method is less costly and easier to control for the standalone mode of operation. The sub-system components, power electronics, and control units are outlined in the following sub-sections.

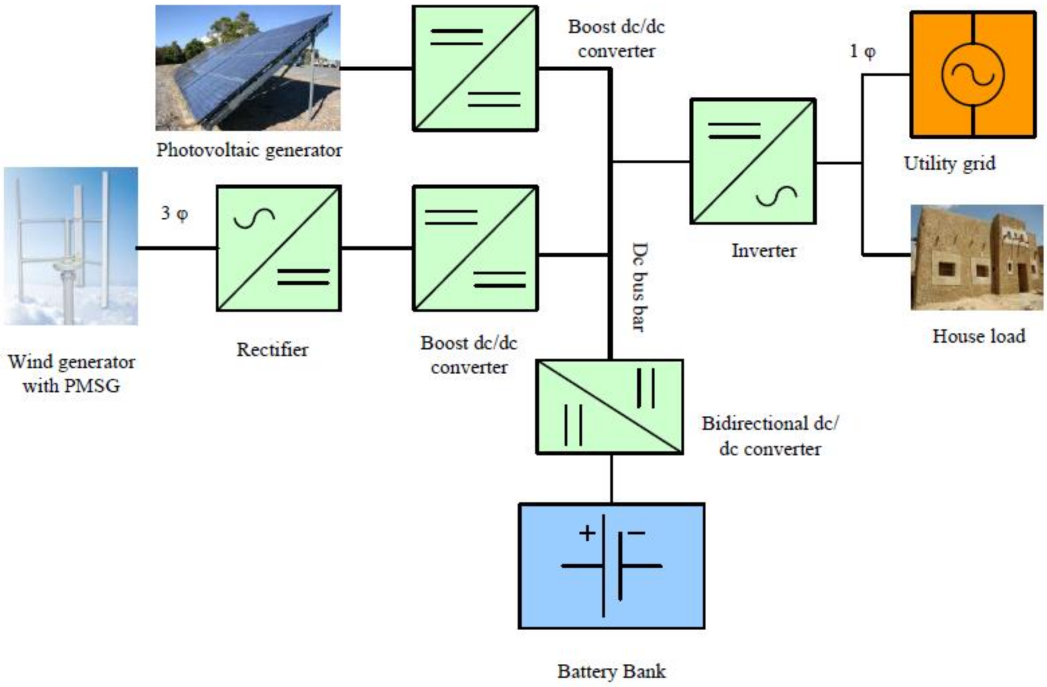

Figure 1 Schematic for the system

3. Modelling of Hybrid System

3.1. PMSG and Wind Turbine Modelling

The electrical circuit dynamics of the generator have little effect on the overall mechanical dynamics and can be ignored in the control design. The equivalent circuit of a permanent magnet generator and the diode rectifier can be simplified as shown in Figure (3.1) viewed from the dc side of the rectifier. The Thévenin series resistance Rw has a value of twice the per phase resistance of the generator, neglecting the commutation overlap in the rectifier as the PM generator used has low inductance. The source emf (ew), is proportional to the generator speed (ωm).

$$e_w = k_w \omega_m \quad (1)$$

where K_w is a constant depending on the machine design. the dc link of the grid inverter represented as a voltage source V_L. The power drawn by the inverter from the dc link maintains the voltage constant; with a passive diode rectifier the power level is to be set by the duty cycle control of the dc-dc converter. The turbine torque is represented by the following equation.

$$T_m = \frac{1}{2}\rho A R v_s^2 C_p(\lambda)/\lambda \quad (2)$$

Taking into account that (λ) was proposed before in Equation (2.2) (see Chapter (2)). With a fixed pitch angle,

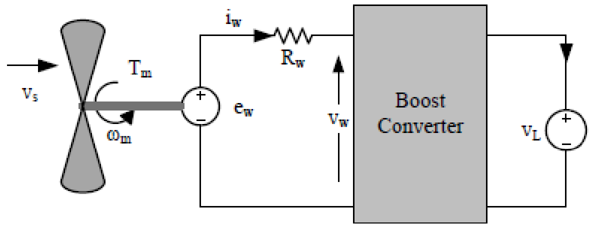

Figure (2) A simplified wind generator system

The Thévenin equivalent of the generator and diode bridge rectifier feeds a boost type dc-dc converter which supplies

the whole operating region of Cp can be approximated in the following quadratic form as a function of λ.

$$C_p = a_1\lambda^2 a_2\lambda + a_3 \quad (3)$$

Neglecting damping and friction, the mechanical dynamics can be reduced to:

$$J\frac{d\omega_m}{dt} = T_m - T_e \quad (4)$$

$$T_e = \frac{P_e}{dt} = \frac{e_w i_w}{\omega_m} = K_w i_w \quad (5)$$

From equations (2), (4) and (5);

$$\frac{de_w}{dt} = -\frac{K_w}{J} i_w + b_1 v_s e_w + b_2 v_s^2 + b_3 \frac{v_s^2}{e_w} \quad (6)$$

Where $b_1 = K_t R a_1 / J$
$b_2 = K_t K_w a_2 / J$
$b_3 = K_t K_w^2 a_3 / (JR)$
$Kt = 0.5 \rho AR$

On the electrical side, the relationship between the dc side voltage of the rectifier and the voltage as the input to the grid side inverter can be simplified as:

$$v_w = (1-d) v_L \quad (7)$$

The average dc side current can be calculated as follows.

$$i_w \frac{1}{R_w} [e_w - (1-d) v_L] \quad (8)$$

3.2 Modeling of PV System

The equivalent electrical circuit of a PV cell is given in Figure 3. It is a one diode model which is also known as the 5 parameter circuit. The cell can be modeled by other equivalent circuits as well; such as 7 parameters but the one diode model is the most commonly used circuit in the literature and the solution of the circuit is not as complicated as is the case in other models. The parameters in the circuit are; I_D, I_L, I_{SH}, R_{SH}, R_S, I and V.

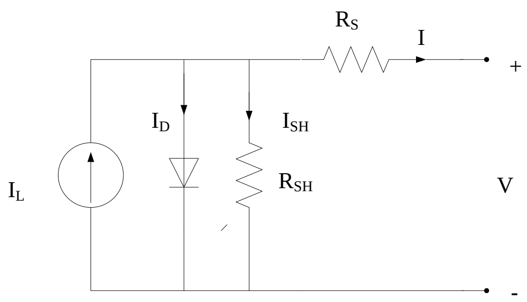

Figure (3) Equivalent circuit of a solar cell.

From the circuit;

$$I = I_{PH} - I_D - I_{SH} \quad (4.1)$$

I_{PH} (photo-generated current) is also called as I_L (light current) which refers to direct current generated by photovoltaic effect. Whereas I is the output current of the cell.

From Shockley's diode equation;

$$I_D = I_0 \left[\exp\left(\frac{V + IR_S}{nV_t} \right) - 1 \right] \quad (9)$$

Where;

$$V_t = \frac{kT}{q} \quad \mathbf{(10)}$$

By Ohm's Law

$$I_{SH} = \frac{V + IR_S}{R_{SH}} \quad (11)$$

After substituting equations (9), (10), and (11) into equation the equation takes the form of;

$$I_D = I_{PH} - I_0 \left[\exp\left(\frac{V + IR_S}{AV_t} \right) - 1 \right] - \frac{V + IR_S}{R_{SH}} \quad (12)$$

Equation (12) is the general solar cell characteristic equation which is available in the literature [26]. From the characteristic equation, it is possible to evaluate cell current for a given cell temperature and voltage. However, analytic solution of the equation is not possible and numerical methods will be used to solve the equation. The parameters that need to be defined before solving Equation (12) are R_{SH}, R_S, A, I_{PH} and I_0. These parameters are specific to every different commercial PV array and will be calculated from the product data sheet values tested at the Standard Test Conditions (STC) or Reference Point which is 1kW/m2 solar irradiation and 25^{o}C cell temperature. Knowing these parameters, solar radiation data and the cell temperature will allow us to calculate the electricity generation of the solar cell. Data sheets of solar arrays supplied by the manufacturers include short circuit current (I_{sc}) and its temperature coefficient (μI_{sc}), open circuit voltage (V_{oc}) and its temperature coefficient (μV_{oc}), voltage (V_{mpp}) at maximum power point (MPP), and current (I_{mpp}) at MPP measured at STC. Equation (12) is given for a single cell. For a PV array including ns number of cells connected in series, the characteristic equation takes the form [26];

$$I_D = I_{PH} - I_0 \left[\exp\left(\frac{V + IR_S}{n_S AV_t} \right) - 1 \right] - \frac{V + IR_S}{R_{SH}} \quad (13)$$

3.4. Battery Energy Storage System

The battery energy storage system (BESS) comprises mainly of batteries, control and power conditioning system (C-PCS) and rest of plant. The rest of the plant is designed to provide good protection for batteries and C-PCS. The battery and C-PCS technologies are the major BESS components and each of these technologies is rapidly developing.

The batteries are made of stacked cells where-in chemical energy is converted to electrical energy and vice versa. The desired battery voltage as well as current levels are obtained by electrically connecting the cells in series and parallel. The batteries are rated in terms of their energy and power capacities. Foremost of the battery types, the power and energy capacities are not independent and are fixed during the battery design. Some of the other important features of a battery are efficiency, life span (stated in terms of number of cycles), operating temperature, depth of discharge (batteries are generally not discharged completely and depth of discharge refers to the extent to which they are discharged), self-discharge (some batteries cannot retain their electrical capacity when stored in a shelf and self-discharge represents the rate of discharge) and energy density. Currently, significant development is going on in the battery technology. Different types of batteries are being developed of which some are available commercially while some are still in the experimental stage. The batteries used in power system applications so far are deep cycle batteries (similar to the ones used in Electric vehicles) with energy capacity ranging from 17 to 40MWh and having efficiencies of about70–80%.

4. Simulation and Results

The hybrid power generation system consists of PV system, Wind Energy Conversion System and Battery Energy Storage System. PV system is subjected to variable solar irradiance. Wind Energy Conversion System is also subjected by variable wind speed. The hybrid system is connected with the load which is also variable. So these perturbances cause the difference in power supply as well as demand also. To take care of these perturbances fuzzy logic based controller is used. Also for getting the maximum output from the wind turbine and PV system their individual controllers are also used to extract maximum power.

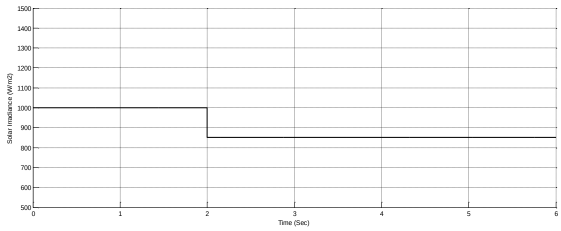

Figure (4) Solar Irradiance

The solar irradiance is variable and it initially 100W/m2 and at time 2 sec it is reduced to 800 W/m2. This cause the dip in PV system. The solar irradiance is reduces as the PV output, i.e. shown in fig. 4.

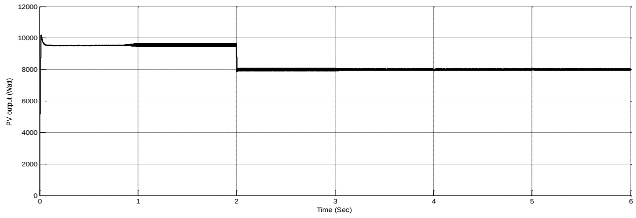

Figure (5) PV output

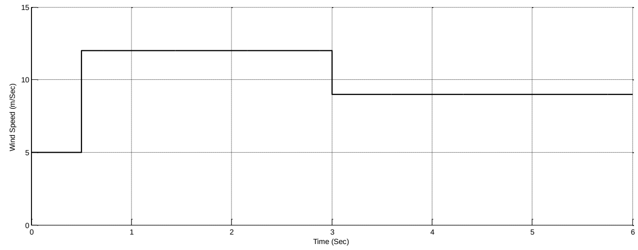

Figure (6) Wind Speed (m/sec)

Figure 6 shows the variations in the wind speed. Initially wind speed is 5 m/sec, which below the cut-in speed. Then at time 0.5 second wind speed rises to 12 m/sec. At time 3 second wind speed is again reduced to 9 m/sec. The wind speed is varies in realization of the random wind speed at a particular location. As the wind speed is not varied as steep as shown in the fig, but it is assumed that the speed is varied steeply for the sake of simplicity.

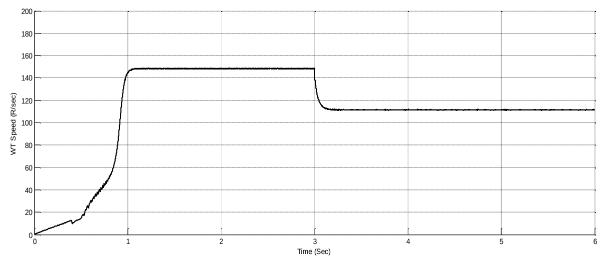

Figure (7) Wind Turbine Speed (rad/sec)

Corresponding WT is shown in fig. 6.4. As the time between (0-0.5 second) the speed is below cut-in speed the WT will not produce any power. This can be seen in fig. 7. At time wind speed increased, the WT speed also becomes more than cut-in speed and WT start producing power. The WT output power is shown in fig. 8.

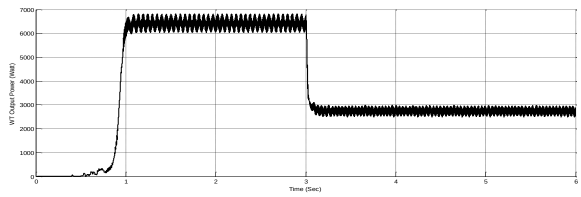

Figure (8) Wind Turbine output power

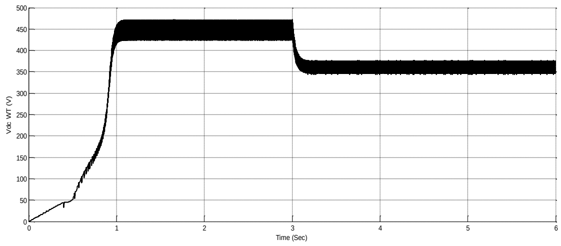

Figure (9) V_{DC} across Wind Turbine

As discussed earlier that wind turbine does not produce power below the cut-in speed, this is also shown in the fig. 8. When wind speed is 12 m/sec, the WT power is around 7000 W. When wind speed is 9 m/sec, then the WT power comes down to 3000 W.

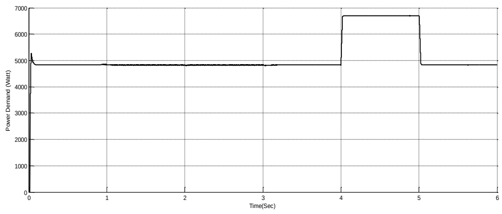

Figure (10) Variation in load

As we know the load is always variable, the variable load is applied to the hybrid power system. Initially 5000 W load is applied which is increased to 6800 W at time 4 second, again the load is reduced to 5000 W at time 5 second. The variation in load is shown in fig. 10.

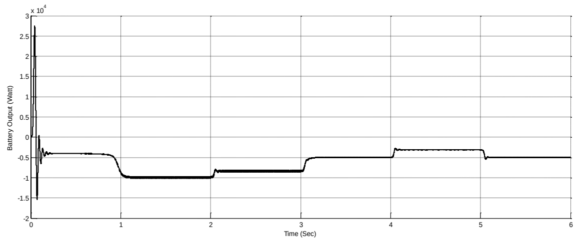

Figure (11) BESS output

The BESS is used as the backup of the system. When there is shortage of the supply then BESS supplies that shortfall in power and when the supply is more than the demand then the BESS system takes that excess power to charge the battery. This is shown in the fig. 11. Fig. 12 shows the current waveform of BESS.

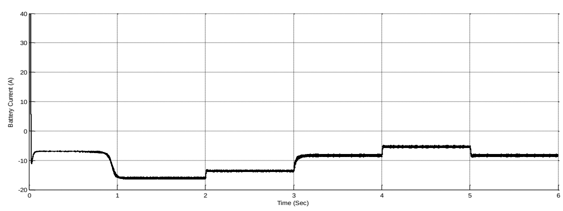

Figure (12) BESS output current

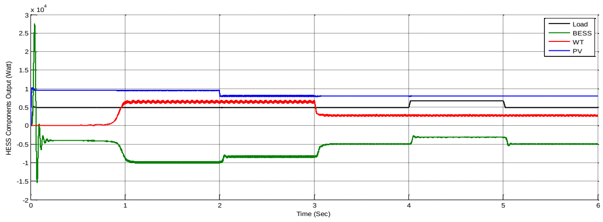

Figure (13) Output power of different components of Hybrid power system

The power output of the different components of the hybrid power system is shown in fig. 613. From the fig. it is found that when there is shortfall in the PV system output or WT output the BESS compensate this shortfall. Also when load is more than the supply the BESS comes in to the action. The BESS always maintained supply equal to the demand.

5. Conclusions

PV cell, module and array are simulated and effect of environmental conditions on their characteristics is studied. Also the wind Energy Conversion System is modeled using PMSG. The effect of wind speed on the performance of the WT system is examined.

Then the BESS using Nickel-Metal Hydride battery system the balance is maintained in supply and demand. The major contributions of the work are:

- Wind energy system has been studied and simulated
- Maximum power point of operation is tracked for both the systems using P&O algorithm
- Both the systems are integrated and the hybrid system is used for battery charging and discharging.
- Fuzzy logic based controller is used for the control purpose.
- Individual MPPT system is used for both WT and PV system.

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