Power and Energy Balance in Wind-Solar Hybrid Power System.

C.A. Nwosu, M.Eng. and M.U. Agu, Ph.D.

Department of Electrical Engineering, University of Nigeria, Nsukka, Nigeria.

E-mail: cajethannwosu@yahoo.com
drmarcelagu@yahoo.co.uk

ABSTRACT

In this paper, power and energy balance in a wind-solar hybrid power system having battery and combined heat and power (CHP) sub-units as backups, is presented. A case study for winter and summer seasons are conducted in an urban city in the Netherlands. Load profiles for the periods of winter and summer over a period of 24 hours were developed from a load pattern program developed through load research sampling (LRS). It is observed that within the period under investigation, there exists an instant when the generated energy from the wind-solar hybrid was below energy demand of the load. The battery unit supplies this deficient energy into the system so as to maintain steady power plant. This, however, depends on the state of charge (SOC) of the battery. If the SOC of the two battery sub-units is below a set point, combined heat and power (CHP) unit will be switched into the system, in the context of global energy balance. In another instant, excess energy from the hybrid after meeting the load demand, charges the battery.

(Keywords: hybrid, power, CHP, combined heat and power, renewable energy, energy storage sub-system)

INTRODUCTION

In recent years, much emphasis has been placed on renewable energy as a viable alternative to engine generators for remote power production [1, 2]. The effectiveness of this alternative is met when more than one type of renewable energy source such as photovoltaic (PV), wind, biomass, or small-hydroelectric power systems are combined together with energy storage sub-system in order to ensure steady plant power. In this paper, wind-solar hybrid system which comprises an emulated wind turbine generator, solar PV unit with combined heat and power (CHP) unit, and battery unit as backups is presented. It is anticipated that at one time, there may be little or absence of both wind and solar powers. At these times, the battery unit should be capable of supplying 100% of plant power energy; (however, this will depend on the state of charge (SOC) of the battery) or CHP unit will be switched into the system.

This paper attempts to develop an optimal dispatch strategy such that excess power from the hybrid system is stored in the battery and if the load demand exceeds the hybrid energy the battery supplies the deficient energy into the plant. CHP is used as part of the system to respond to the emergency cases where hybrid energy and stored energy are not sufficient to meet the load. A case study is conducted in Delft University of Technology (TU-Delft), the Netherlands. As a stand alone hybrid system, the power plant is capable of supplying green power to about 15 households in a developed economy or about 100 households with an average of 400 W per household in rural community. With few additional power electronic components, the hybrid power plant can effectively be integrated with a standard grid network.

Wind Unit: The wind turbine emulator consists of an anemometer, voltage source converter, and 37 kW squirrel-cage induction motor. An anemometer is used to measure and convert the wind speed to a proportionate voltage value. A voltage source converter (VSC) supplies frequency of operation to the induction motor.

Photovoltaic (PV) Unit: The PV power unit comprises 180 PV panels and 6 inverters. Two strings of panels are connected in parallel to each inverter, with each string having a total of 15 modules in series. The 6 inverters are connected in parallel to the asymmetric bus of the power plant. Each PV panel is rated at 68 W peak, 16.5 V peak, and open circuit voltage and short circuit current of 21.3 V and 4.4 A, respectively. Tolerance on peak power is ± 4%.

Figure 1: Photograph of the 37kW Induction Motor for Wind Turbine Emulator (WTE), Directly Coupled to a Generator.

Battery Unit: The battery power unit consists of two sub-battery units (battery-1 and battery-2) which are connected in parallel to an autonomous bus. Power from battery-1 is supplied to the autonomous bus through a current source inverter and thus presents itself for control. Power from battery-2 is supplied to the same bus through a voltage source inverter and therefore acts as a local grid by providing the needed voltage and frequency of the power plant. This means that battery-2 is always connected to the bus. Battery-1 may or may not be connected to the grid depending on certain conditions which include: load demand, availability of power from the sun, and then the state of charge (SOC) of the two batteries. The provision of the power plant operating voltage and frequency is a necessity for the induction machines. Each set of battery sub-units is comprised of the battery stacks and power converters and is meant to supply 25 kVA to the power plant.

CHP Unit: The CHP unit comprises a frequency converter, 7.5 kW inductions motor and generator, and a soft-starter. Instead of wind speed conversion as is the case in the wind power unit, a frequency converter aimed at producing a desired frequency capable of developing electromechanical torque for the motor, is used. To appropriately configure the frequency converter, the induction motor and generator was first started and operated on a main grid to determine the appropriate operating conditions including the electromechanical torque and frequency. The parameters were then used in the design of the frequency converter.

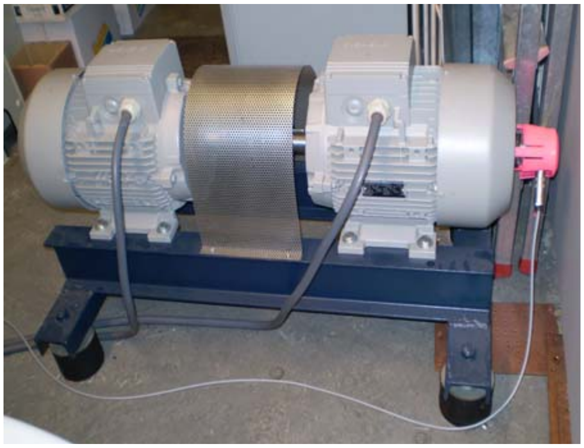

Figure 2: Photograph of the 7.5kW CHP Induction Generator.

Figure 3: Photograph of Part of the Motor and Generator Power Electronics Circuitry.

Under normal operation, the load is supplied by the interconnection of wind and solar power. Surplus energy from the hybrid system is stored in the battery. Battery-2 is constantly connected to the system and supplies the magnetizing current to the induction machine through a voltage source inverter. For a more stable operation of the system, a reactive power compensator is installed which together with the battery unit fulfils the variable reactive power requirement of the induction generator and of the load. As a local grid, the battery through the inverter, determines and sets the voltage and frequency of operation of the hybrid energy system. Any change in real power of the system will depend on the frequency, whereas changes in reactive power will be mainly dependent on voltage. CHP unit is used to compensate for the wind power fluctuations in the context of global energy balance. The objective of this paper is to develop a conceptual framework for effective analysis of power and energy balance in a hybrid system. The analysis adopts an optimal dispatch strategy to find the most economical schedule for combination of hybrid systems with backups, satisfying load balance and resource availability [3].

CONCEPTUAL FRAMEWORK FOR THE ENERGY BALANCE

An optimal dispatch strategy is adopted in this framework such that the battery charges, if the hybrid energy is in excess after meeting the demand and discharges, if load exceeds the hybrid energy [3]. CHP is used as part of the system to respond to the emergency cases where hybrid energy and stored energy are not sufficient to meet the load. The conceptual framework of the energy balance of the system is therefore based on performance of the capacity factor for both wind power and solar power units. Capacity factor is defined as the fraction or percentage of total energy delivered E_D from a facility over a period of time, divided by the maximum energy E_N that could have been delivered if the facility was used at its maximum capacity over the entire period, given by [4]:

$$CF = \frac{E_D}{E_N} = \frac{\int_{t=0}^{T} P(t)dt}{\int_{t=0}^{T} Ndt} = \frac{\int_{t=0}^{T} P(t)dt}{NT} \qquad \textbf{(1)}$$

where t is the time, T is a period of time, P (that depends on time) is the power generation and N is the nominal capacity of the facility and is a constant.

On the other hand, the plant power from the hybrid system can be expressed as the sum of wind power P_W and solar power P_S:

$$P_P = P_W + P_S \qquad \textbf{(2)}$$

taking into account that P_P does not depend on time (since it is a plant power) and considering a period of time T, the energy delivered by the hybrid system can be estimated through:

$$P_P T = \int_{t=0}^{T} P_W(t)dt + \int_{t=0}^{T} P_S(t)dt \qquad \textbf{(3)}$$

and using Equation (1) we can write:

$$P_P = CF_W N_W + CF_S N_S \qquad \textbf{(4)}$$

which gives wind power output as:

$$P_W = CF_W N_W \qquad \textbf{(5)}$$

solar power output as:

$$P_S = CF_S N_S \qquad \textbf{(6)}$$

where CF_W and CF_S are the capacity factors for the wind power and solar power units and N_W and N_S are the rated powers for the wind power and solar power units, respectively.

When there is little or no wind, the solar unit must supply 100% of total power to guarantee plant power output. Therefore the capacity factor for the solar unit $CF_S = 1$. On the other hand, when the wind unit is operating at rated power $CF_W = 1$, the plant power should be equal to the rated power for the wind unit N_W. In standard systems, it is important that the rated power for the wind unit N_W and the rated power for the solar unit N_S must be the same to guarantee plant power P_P:

$$P_P = N_W = N_S = N \qquad \textbf{(7)}$$

In summary, when the wind unit is operating at full capacity, there is no need to generate solar power. Therefore the solar power capacity factor is $CF_S = 0$. In periods of low wind, the solar power capacity factor is $CF_S = 1$ and the wind plant capacity factor is $CF_W = 0$. In fact, the range for the capacity factors is $0 \leq CF \leq 1$. Therefore:

$$CF_W + CF_S = 1 \qquad \textbf{(8)}$$

The rated power for the hybrid wind–solar system N_{WS} is established by the sum of the rated power of wind N_W and the rated power of the solar N_S:

$$N_{WS} = N_W + N_S = 2N \qquad \textbf{(9)}$$

therefore the capacity factor of the hybrid wind-solar system is $CF_{WS} = 1/2$, this is:

$$PP = 0.5 (N_{WS}) = N \qquad \textbf{(10)}$$

according to Equation (7).

WIND POWER OUTPUT

In this paper, the wind power is generated using a wind turbine emulator (WTE), where the characteristics and dynamics of a wind turbine are used to emulate wind turbine rotor and drive train. The wind turbine mechanical shaft is emulated using a standard six-pole 37-kW 400/460V delta/star squirrel-cage induction motor controlled by a voltage source converter. The slip, and hence the rotor speed of a squirrel-cage induction generator varies with the amount of power generated [5]. These rotor speed variations are, however, very small, approximately 1 to 2 per cent almost independent of torque variation [5], [6]. This wind turbine type, therefore, is normally referred to as a constant speed or fixed speed turbine. The aerodynamic model of the wind turbine rotor is based on the $C_p - \lambda$ curve. In a fixed wind operation, the aero-turbine rotational speed is fixed and relates to the tip speed ratio defined as:

$$\lambda = \frac{\omega r}{V} R \qquad \textbf{(11)}$$

where ω_r is the shaft speed in rad.s^{-1}, R is the blade radius in m, and V is the wind speed in m/s. Power output of the wind turbine is related to the cube of the upstream wind velocity and can be expressed as:

$$P_{wt} = 0.5\rho\pi C_p(\lambda)R^2V^3 \qquad \textbf{(12)}$$

where, ρ is air density (kg.m^{-3}), and $C_p(\lambda)$ is the coefficient of power which depends on the particulars of the turbine blade design and can be represented as a function in λ. Substituting for the wind speed, V, from Equation (11) into Equation (12), the power delivered by the turbine can be expressed in terms of the angular velocity, ω_r, and the tip-speed ratio, λ, as:

$$P_{wt} = 0.5\rho\pi C_p(\lambda)R^5 \frac{\omega_r^3}{\lambda^3} \qquad \textbf{(13)}$$

Utilizing Equation (11) with the estimated wind speed, V, and the optimal tip-speed ratio, λ_{opt}, the desired angular velocity of the turbine is determined as:

$$\omega_{r,\,opt} = \frac{\lambda_{opt} \cdot V}{R} \qquad \textbf{(14)}$$

$C_{p,max}$ and λ_{opt} from C_p–λ curve, is determined in this paper using the approximate relationship between C_p and λ given as:

$$C_p(\lambda) = 0.38\left(\frac{116}{\lambda_i} - 5.0\right)e^{\frac{-16.5}{\lambda_i}} \qquad \textbf{(15)}$$

where

$$\lambda_i = \frac{1}{\frac{1}{\lambda} - 0.01} \qquad \textbf{(16)}$$

In wind turbine emulator where an induction motor is used for modeling the turbine gear train, the shaft power P_m of the induction motor usually represents the power of wind turbine.

The 37 kW, 2950 rpm 3-phase induction motor is used to emulate a 2 MW, 17 rpm wind turbine with rotor radius of 37.5 m. From Equation (11), the tip speed is:

$$V_{tip} = \omega_r R = 2\pi R * \frac{rpm}{60} \qquad \textbf{(17)}$$

thus,

$$\lambda = 2\pi R * \frac{rpm}{60V} \qquad \textbf{(18)}$$

Substituting Equation. (15) into Equation (12), we have:

$$P_{wt} = 0.5\rho\pi R^2V^3 * 0.38\left[116\left(\frac{1}{\lambda} - 0.01\right) - 5\right]e^{-16.5\left(\frac{1}{\lambda} - 0.01\right)} \qquad \textbf{(19)}$$

Air density ρ = 1.225 (kg.m^{-3}) is chosen. By substitution of appropriate parameters, Equation (19) can be written in terms of wind speed, Equation (20):

At wind speed V = 17 m/s, the right hand side of Equation (20) yields about 428573 watts. To achieve a maximum power extraction of 37 kW from the emulator, a factor is established to balance both sides of Equation (20) at wind speed of 17 m/s. Thus in p.u., the final relationship between the wind speed and optimal wind power gives Equation (21):

$$P_{wt}(V) = (367.1793215V - 1301.721618) * e^{(-0.2471535V+0.165)} * V^3 \quad \textbf{(20)}$$

$$P_{wt}(V) = 2.333322586 * 10^{-6} * (367.1793215V - 1301.721618) * e^{(-0.2471535+0.165)} * V^3 \quad \textbf{(21)}$$

From measurements, the maximum output power from the electrical generator, P_{gen}, was 35.09 kW at wind speed = 17 m/s. The estimated maximum output power is calculated using the equation:

$$P_{gen} = \eta P_{wt} \quad \textbf{(22)}$$

where η is the efficiency of the electrical generator. An efficiency η of 0.95 is assumed for the 37 kW induction generator for a measured output power of 35.09 kW. In real wind power generation, mechanical gear system provides the needed angular frequency of the generator shaft. In this wind turbine emulator, a 37 kW induction generator is connected to a local grid through a soft-starter interface. In the absence of rotor and gear system to drive the induction generator, an emulator is coupled to the generator. The emulator shall comprise a second 37 kW induction machine whose torque is controlled using a frequency converter to achieve constant nominal torque.

SOLAR POWER OUTPUT

The model of PV arrays can be used to represent the model of the PV system. The building block of the PV system is the solar cell, which is basically a p–n semiconductor junction that directly converts light energy into electricity: it has the equivalent circuit shown in Figure 4. The current source I_{ph} represents the cell photo current; R_{sh} and R_s are intrinsic shunt and series resistance of the cell, respectively.

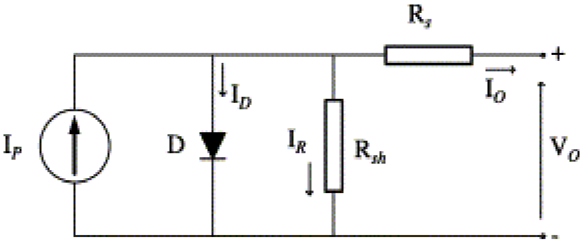

Figure 4: Equivalent Circuit of a PV Cell.

A PV module consists of numbers of PV cells. The performance of crystalline silicon PV modules is a function of the physical variables of the PV cell material, the temperature of solar cells and the solar irradiance exposed on the solar cells. In a whole PV array, there are several strings in parallel. A string consists of several PV modules in series. For practical use, a certain number of PV modules need to be connected to meet the user's demand on voltage and power. The total number for serial connection is determined by the operating DC voltage of the system, while the number of PV modules for parallel connection determines the capacity of the PV array. The voltage V_{PVA} of the PV array is:

$$V_{PVA} = N_{PVS} \cdot V_{PV} \quad \textbf{(23)}$$

and the power output P_{PVA} of the PV array is:

$$P_{PVA} = N_{PVP} \cdot N_{PVS} \cdot V_{PV} \cdot I_{PV} \cdot F_{con} \cdot F_{oth}, \quad \textbf{(24)}$$

where N_{PVS} is the serial connection number of the PV modules; N_{PVP} is the parallel connection number of the PV module strings; and F_{con} and F_{oth} are the factors representing connection loss and other losses such as the loss caused by accumulative dust etc. The PV inverters may be seen as integral part of the PV power unit since the PV arrays and the inverters combine to supply AC power to an asymmetric bus. Six inverters are connected in parallel to the bus. Input to each inverter is about 247.5V DC from two parallel strings of PV Modules. The solar sub-system has altogether, 180 PV modules. Two strings of 15 modules each, connected in series are linked in parallel to one inverter, making a total of 12 parallel modules. Table 1 is the data of PV modules.

Table 1: PV Modules Data.

Open circuit voltage (V_{oc})	21.3V
Short-circuit current (I_{sc})	4.4A
Maximum power	68W
Maximum voltage (V_p)	16.5V
Tolerance on peak power	± 4%

By the maximum voltage and short circuit current ratings of the PV modules, the voltage of each array is:

$V_{PVA} = 247.5V$,

and the power output P_{PVA} of the PV array is:

$$P_{PVA} = (13068 \cdot F_{con} \cdot F_{oth})W$$

From the calculated value of 13068W (subject to connection loss and other losses), the available power at the inputs of the inverters is 12600W out of which only 9600W can be delivered to the grid by the inverters.

MEASUREMENTS AND RESULTS

Load profiles for the periods of winter and summer over a period of 24 hours were developed from a load pattern program developed through load research sampling (LRS). Figure 5 shows the load profiles, while Figure 6 represents the wind-solar hybrid energy generation over a period of 24 hours. Figure 7 displays the wind-solar hybrid energy generation and energy demand over a period of 24 hours.

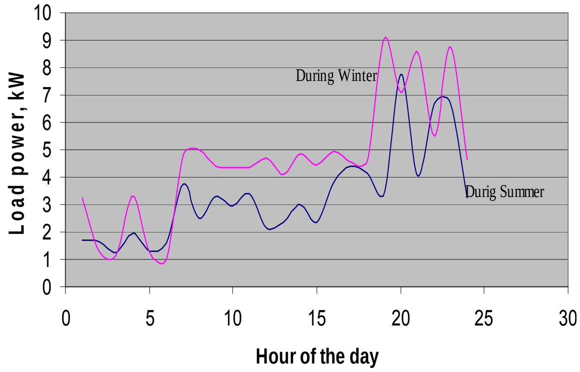

Figure 5: Load Profiles for Periods of Winter and Summer.

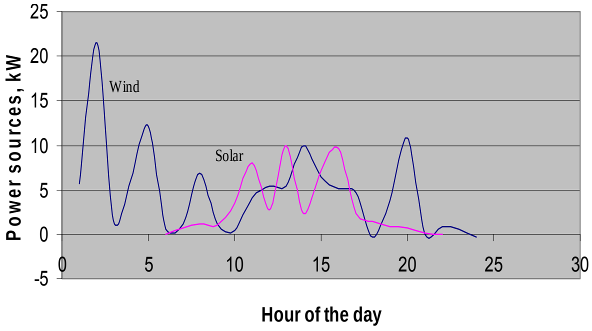

Figure 7. Wind-Solar Hybrid Energy Generation.

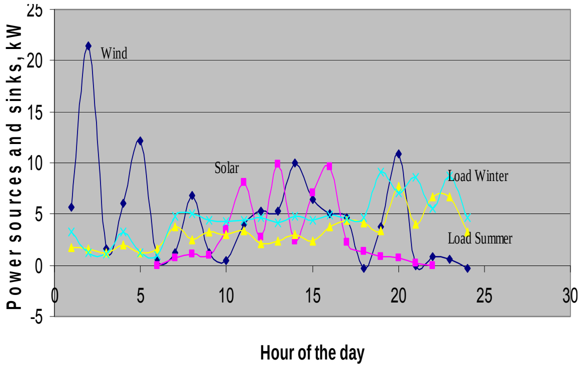

Figure 8. Wind-Solar energy generation and energy demand

EVALUATION OF RESULTS

In order to evaluate the energy balance capability of the hybrid system, we consider two different periods of the day within each of the winter and summer periods, say 0600 and 1600 hours. In this analysis, we have assumed that variation between generated energy in winter and summer is minimal. At 0600 Hours, wind and solar units deliver (0.57 + 0.01) kW or 0.58 kW power to the system. At this same period, the load power demand is 1.60 kW for summer and 1.01 kW for winter seasons respectively. This means that wind-solar hybrid system is deficient of 1.02 kW and 0.43 kW for either of the two seasons (summer and winter) load power demands respectively. However, in the context of global energy balance, the battery unit supplies this deficient power into the system, and this however depends on the state of charge (SOC) of the battery. If the SOC of the two battery sub-units is below a set point, CHP will be switched into the system. This means that the CHP unit must be capable of supplying 100% needed power at any instant. At 1600 Hours, wind and solar units inject (5.03 + 9.67) kW or 14.7 kW into the system when load power demands are 3.8 kW and 4.94 kW for summer and winter seasons respectively. Power from either of the components in the hybrid system is over enough to serve the load demand of either of the two seasons. Excess energy from the sum of the two hybrid components will be stored in the battery by way of charging it.

CONCLUSIONS

The analysis presented in this paper shows that it is possible to guarantee steady availability by power plants given proper combinations of wind and solar energy sources with backups to compensate for source fluctuations. It has been shown that in the absence of enough power from the stochastic sources, the battery backup temporarily assumes a status of a power source in the context of global energy balance. CHP is the alternative power source if the battery SOC is below a set point or if the absence of the stochastic sources persists over a certain period of time. Although the optimization case study was conducted in a winter-summer environment, the scheme promises to be more energy productive in a temperate African environment as ninety-five per cent of the daily global sunshine above 6.5 kWh/m^2 falls on Africa during the winter.

ACKNOWLEDGEMENT

This paper is based on the project work carried out in the Electric Power System (EPS) Laboratory, Faculty of Electrical Power Engineering, Mathematics, and Computer Engineering, Delft University of Technology (TU-Delft) the Netherlands during a research visit to the University. The authors therefore are thankful to the staff of Electric Power System (EPS) and Electric Power Processing (EPP) of the Faculty.

REFERENCES

1. Sudhakar, R. and Painuly, J.P. 2004. “Diffusion of Renewable Energy Technologies – Barriers and Stakeholders’ Perspectives”. *Renewable Energy*. 29(9), July:1431 - 1447.

2. de Lima Montenegro,Duarte, A.R.C., Bezerra, U.H. de Lima Tostes, M.E., and da Rocha Filho, G.N. “Alternative Energy Sources in the Amazon”. *IEEE Power & Energy Magazine*. 5(Jan/Feb):51 – 57.

3. Ashok, S. 2007. “Optimized Model for Community-Based Hybrid Energy System”. *Renewable Energy*. 32(7), June:1155 – 1164.

4. Jaramillo, O.A., M.A. Borja, and J.M. Huacuz. 2004. “Using Hydropower to Complement Wind Energy: A Hybrid to Provide Firm Power”. *Renewable Energy*. 29(11), Sept.: 1887 – 1909.

5. Slootweg, J.G. 2003. “Wind Power Modeling and Impact on Power Dynamics”. Ph.D. Dissertation. Delft University of Technology, TU-Delft: Netherlands. Dec. 2003.

6. Burton, T., D. Sharpe, N. Jenkins, and E. Bossanyi 2001. *Wind Energy Handbook*. John Wiley & Sons, Ltd.: Chichester, UK.

ABOUT THE AUTHORS

Cajethan Nwosu obtained his B.Eng. and M.Eng. degrees in Electrical Engineering from University of Nigeria, Nsukka, Nigeria, in 1994 and 2004, respectively. He is presently working toward his Ph.D. degree in Electrical Engineering. He is currently a Lecturer in the Department of Electrical Engineering, University of Nigeria, Nsukka, Nigeria. His research interests include power electronic converters and renewable energy technologies.

Marcel U. Agu obtained his B.Sc. in Electrical Engineering in 1974 at the University of Nigeria, Nsukka. He also received his M.A.Sc. and Ph.D. in 1978 and 1982, respectively in Power Electronics from the University of Toronto, Canada. He is presently a Professor in the Department of Electrical Engineering, University of Nigeria, Nsukka. His research interests are in power electronics circuits, static electric motor drives, and renewable energy resources.

SUGGESTED CITATION

Nwosu, C.A. and M.U. Agu. 2009. “Power and Energy Balance in Wind-Solar Hybrid Power System”. *Pacific Journal of Science and Technology.* 10(1):110-116.

Pacific Journal of Science and Technology