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A Hybrid Wind and Solar Energy System with Battery Energy Storage for an Isolated System

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***Abstract:* This paper proposes a hybrid energy system consisting of wind, photovoltaic and fuel cell. Battery storage is designed to supply continuous power and to provide the deficit power when the combined wind and photovoltaic sources cannot meet the net load demand. It works as an uninterruptible power source that is able to feed a certain minimum amount of power into the load under all conditions. Power transfer was different modes of operation, including normal operation without use of battery, which gives the user-friendly operation. A control strategy regulates power generation of the individual components so as to give the hybrid system to operate in the proposed modes of operation. The concept and principle of the hybrid system and its control were described. The simulation results were presented to evaluate the performance and power reliability of the hybrid system.**

Keywords: **Hybrid Generation System, Battery Energy Storage.**

I. INTRODUCTION

With increasing load demand and global warming, many are looking at environment-friendly type of energy solutions to preserve the earth for the future generations. Other than hydro power, many such energy sources like wind and photovoltaic energy holds the most potential to meet our energy demands. While some others like fuel cells are in their advanced developmental stage. The world's fastest growing energy resources, a clean and effective modern technology that provides a hope for a future based on sustainable, pollution free technology. Today's photovoltaic and wind turbines are state-of-the-art of modern technology-modular and very quick to install. These generation systems have been attracted greatly all over the world. The integration of renewable energy sources and energy-storage systems has been one of the new trends in power-electronic technology. The increasing number of renewable energy sources requires new strategies for their operations in order to maintain or improve the power-supply stability, quality and reliability. There are some previous works on hybrid systems comprising of wind energy, photovoltaic and fuel cell have been discussed in [1]-[8]. A maximum power point tracking (MPPT) is discussed on wind and photovoltaic energies in [2]-[7]. Dynamic Modeling and Control of a Grid-Connected Hybrid Generation System was analyzed [6]. Dynamic performance of a stand-alone wind and solar system with battery storage was analyzed [7]. A few systems consider the battery as just a back-up means to use when there is insufficient supply from renewable sources [9]-[11]. This paper focused on system engineering, such as energy production, system stability and reliability. In this paper, an alternative multi-input of a wind turbine generator, photovoltaic (PV) array and fuel cell is proposed for hybrid wind/solar energy systems. This addresses modeling and control of a load-connected wind–PV–battery hybrid system. The wind and PV are used as main energy sources, while the back-up energy source can operate with and without use of battery to get constant power. Three sources are connected to a single PWM voltage source inverter, which holds the output voltages of all the converters at a fixed value by balancing input and output power of the dc links. All the energy sources are modeled using MATLAB software tool to analyze their behavior. A simple control method tracks the maximum power from the wind/solar energy source to achieve much higher generating capacity factors. The simulation results prove the feasibility and reliability of this proposed system.

II. PROPOSED HYBRID ENERGY SYSTEM

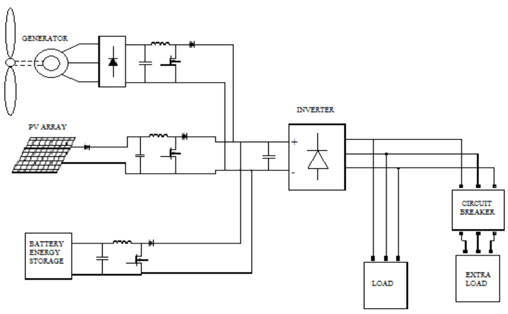

Fig 1: Configuration of Hybrid Energy System

A. Wind Energy Source

The wind turbine captures the wind's kinetic energy in a rotor consisting of two or more blades mechanically coupled to an electrical generator. The equation describes the mechanical power captured from wind by a wind turbine [4] can be formulated as:

$$P_m = 0.5 \rho A C_p v^3 \qquad (1)$$

Where: ρ = Air density (Kg/m^3)
A = Swept area (m^2)
C_p = Power coefficient of the wind turbine
v = Wind speed (m/s)
t = Time (sec)

The theoretical maximum value of the power coefficient C_p is 0.59. It is dependent on two variables, the tip speed ratio (TSR) and the pitch angle. The pitch angle refers to the angle in which the turbine blades are aligned with respect to its longitudinal axis. *TSR* is defined as the linear speed of the rotor to the wind speed.

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$$TSR = \lambda = \frac{\omega R}{v} \quad (2)$$

Where: ω= Turbine rotor speed (rad/s)
R= Radius of the turbine blade (m)
v = Wind speed (m/s)

Fig.2 shows a typical "C_P Vs. λ" curve for a wind turbine. In practical designs, the maximum achievable C_p ranges from 0.4 to 0.5 for high speed turbines and 0.2 to 0.4 for slow speed turbines. Fig.2 shows that C_p has its maximum value (C_{pmax}) at λopt. Which results in optimum efficiency and maximum power is captured from wind by the turbine. Fig. 3 clarifies the output power of a wind turbine versus rotor speed while wind speed is changed from v_1 to v_4 ($v_4>v_3>v_2>v_1$). Fig. 3 shows that if speed is v_1, at rotor speed ω1 maximum power could be captured. While speed increases from v_1 to v_4, similar to the maximum power point tracking rotor speed is also increases from ω_1 to ω_4.

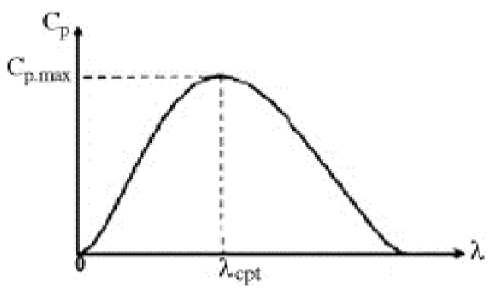

Fig 2: Power coefficient Vs Tip Speed Ratio

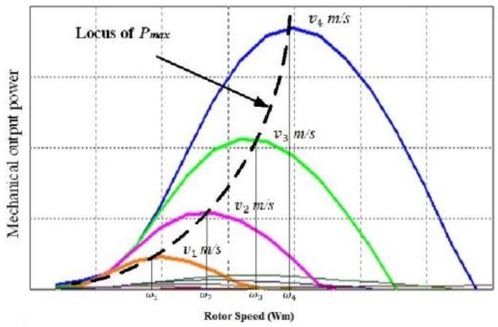

Fig 3: Output Power Vs Rotor Speed of different speeds

For different wind speeds maximum power is generated at a different rotor speeds. Therefore, for every wind speed with the ideal TSR, turbine speed should be controlled. Based on equation (2) the optimum rotor speed can be estimated as follows:

$$\omega_{opt} = \frac{TSR_{opt} V}{R} \quad (3)$$

If C_p is known the torque can be calculated from:

$$T_a = \frac{1}{2}\rho A v^3 C_p/\omega \quad (4)$$

Substituting (2) in (4), the torque can be written as:
For below rated wind speed:

$$T = k_{opt}\,\omega^2 \quad (5)$$

Where: $k_{opt} = \frac{1}{2}\rho A C_p \left(\frac{R}{\lambda}\right)^3$ (6)

For above rated wind speed:
$T = P_{rated}/\omega$; for $P \geq P_{rated}$

B. Photovoltaic (PV) System

A solar cell is the most fundamental component of a photovoltaic (PV) system. The PV array is constructed by many series or parallel connected solar cells to obtain required current, voltage and high power [8]. Each Solar cell is similar to a diode with a p-n junction formed by semiconductor material. When the junction absorbs light, it can produce currents by the photovoltaic effect. The output power characteristic curves for the PV array at an insolation are shown in Fig. 4. It can be seen that a maximum power point exists on each output power characteristic curve. The Fig: 5 shows the (I-V) and (P-V) characteristics of the PV array at different solar intensities. The equivalent circuit of a solar cell is the current source in parallel with a diode of a forward bias. The output terminals of the circuit are connected to the load. The current equation of the solar cell is given by:

$$I = I_{ph} - I_D - I_{sh} \quad (7)$$

$$I = I_{ph} - I_0[\exp(\frac{qV_D}{nkT})] - \frac{V_D}{R_{SH}} \quad (8)$$

Where: I_{ph} = Photo current (A)
I_D = Diode current (A)
I_{sh} = Shunt current (A)
V_D = Voltage across diode (Volt)
I_0 = Diode reverse saturation current (A)
q = Electron charge = $1.6X10^{-19}$ (C)
k = Boltzman constant = $1.38X10^{-23}$ (J/K)
T = Cell temperature (K)
R_s = series resistance (Ω)
R_{sh} = shunt resistance (Ω)

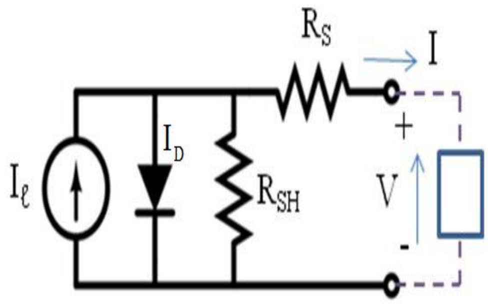

Fig 4: Equivalent circuit of PV Module

The power output of a solar cell is given by

$$P_{pv} = V * I \quad (9)$$

Where: I = solar cell output current (A)
V = Operating voltage of solar cell (volt)
P_{pv} =Output power of solar cell (W)

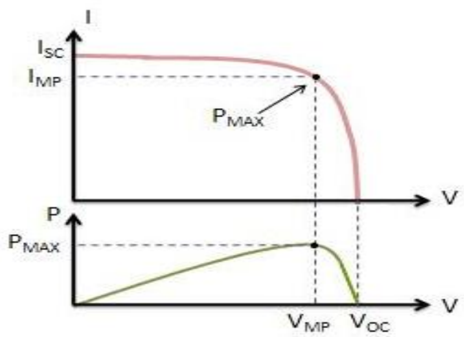

Fig 5: Output characteristics of PV Array

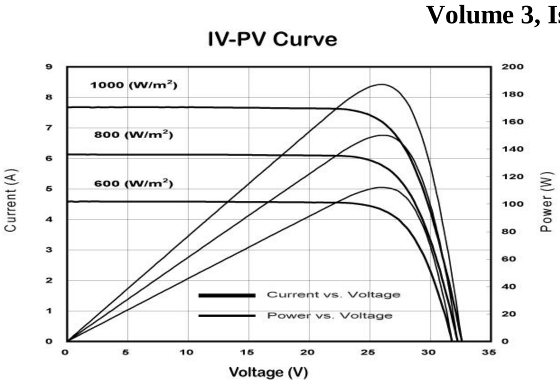

Fig 6: I-V and P-V Characteristics of PV Array at different solar intensities

C. Battery Energy Storage

Battery energy storage system (BESS) are includes batteries, control system and power electronic devices for conversion between alternating and direct current. The batteries convert electrical energy into chemical energy for storage. Batteries are charged and discharged using DC power, regulates the flow of power between batteries and the energy systems is done by a bi-directional power electronic devices. Different types of batteries have various advantages and disadvantages in terms of power and energy capabilities, size, weight, and cost. The main types of battery energy storage technologies are: Lead-Acid, Nickel Cadmium, Sodium Sulfur, Nickel Metal Hydride and Lithium-Ion. Lead-Acid batteries, achieve high discharge rates by using deep-cycle batteries. Low energy density, non-environment friendly electrolyte and a relatively limited life-cycle are the limiting factors to its dominant use in urban renewable energy systems [14]. Overall, with low maintenance requirements, relatively low self-discharge rates, Lead-Acid batteries offer a competitive solution for energy storage applications. Sodium Sulfur batteries have high energy density, high efficiency of charge/discharge and long cycle life. Nickel Cadmium (NiCd) batteries achieve higher energy density, longer cycle life and low maintenance requirements than the Lead-Acid batteries. But, which include the toxic-heaviness of cadmium and higher self-discharge rates than Lead-Acid batteries. Also, NiCd batteries may cost up to ten times more than a Lead-Acid battery [15], making it a very costly alternative. Nickel Metal Hydride (NiMH) is compact batteries and provides lightweight used in hybrid electric vehicles and tele-communication applications. According to [16], NiMH batteries can substitute NiCd batteries in communications. They also provide equivalent cycle life characteristics, are environmentally friendly and can provide for an additional capacity ranging from 25 to 40% [16]. Lithium-Ion technology has the highest energy density amongst all types of batteries [17]. They are currently used in cellular phones, computers, etc. and development of this technology is used in distributed energy storage applications. But, high cost [17] and limited applications of technology. With the high rate of progress in development of lithium-ion technology, it has dominated the electronics market. Because of the sizes it is used in small, medium and large scale renewable energy systems. During coupled operation, Changes in the wind and solar PV generation output will cause an immediate change in the BESS output and BESS must neutralize by quick changes in output power. Rate variation control (or ramp rate control) and it is applied for smoothing real power fluctuations from an associated coupled system. Allowable ramp rates are typically specified by the utility in kilowatts per minute (kW/min), and are a common feature of wind and solar power purchase agreements between utilities and independent power producers. The information is processed by the Battery Energy System controller estimates the state of charge (SOC) of each battery cell and capacity of each battery cell, and protects all the cells operate in the designed SOC range. The amount of electrochemical energy left in a battery is measured by SOC. The SOC information is then used to control the charge- equalization. It is expressed as a percentage of the battery capacity. The electrochemical reaction inside batteries is very complicated and hard to model electrically in a reasonably accurate way. SOC is explained in [10] [11]. SOC is mainly because of differences in chemical and electrical characteristics from manufacturing, aging, and ambient temperatures. When this SOC is left without any control, such as cell equalization, the energy storage capacity decreases severely. Thus, charge equalization is necessary to minimize the mismatches across the battery and extend the battery life cycle. Generally, SOC is maintained between 30%-70% to get the longer life cycle for the battery. The technical and economic advantages of energy storage systems on a smaller scale are as follows:

- Greater use of generally cleaner and more efficient energy sources.
- Improvement of reliability and quality of electricity supply.
- Provision of backup power for critical loads.

II. MAXIMUM POWER POINT TRACKING

Maximum power point tracking technique is used to improve the efficiency of both the solar panel and wind turbine and they adjusted to operate at their point of maximum power. There are different techniques for maximum power point tracking (MPPT) methods have been developed and implemented. Few of the most popular techniques are: Perturb and Observe (hill climbing method), Incremental Conductance method, Fractional short circuit current, Fractional open circuit voltage, Neural networks, Fuzzy logic. The MPPT Technique depends on the initial reference rotor speed for the wind turbine and an initial reference voltage for the photovoltaic array. The corresponding output powers of the two systems are measured. If this power does not correspond to their maximum powers, then their initial reference values are incremented or decremented by one step. If this adjustment leads to an increase in their output powers then the next adjustment is made in the same direction and vice-versa. The above steps are repeated till the maximum power points of the wind turbine and photovoltaic array are reached. Fig. 5 shows the characteristic power curve for a PV array. The

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problem considered by MPPT techniques is to automatically find the voltage V_{MP} or current I_{MP} at which a PV array should operate to obtain the maximum power output P_{MAX} under a given temperature and irradiance.

III. SIMULATION RESULTS

Simulation study was carried out to analyze the dynamic performance of the proposed hybrid energy system design with the complete system is simulated using SIMULINK software. A 10-kW wind/PV/BESS hybrid system was considered. The system parameters used in the simulation study are presented below. All the three energy sources are accurately modeled in SIMULINK so as to predict their actual characteristics. Tables 1, 2 and 3 give the specification of the wind turbine, photovoltaic and fuel cell respectively used for the modeling and simulation.

Table 1: Permanent Magnet Synchronous Generator Specifications

Rated Power Output	8.5 kW
Stator Connection winding	Star
Number of Rotor pole pairs	4
Frequency	50
Stator Phase Resistance	0.425Ω
Stator phase Inductance	8.5mH
Inertia Constant	0.01197kg.m^2
Friction factor	0.001189N.m.s

Table 3: PV ARRAY SPECIFICATIONS

Maximum Irradiance level	1000 W/m^2
Standard Operating Temperature	25°C
Open Circuit Voltage of Each Module	37.1 V
MPPT Voltage	29.6 V
Short Circuit Current of Each Module	8.28 A
MPPT Current	7.6 A
No. of cells in each row	11
No. of cells in each column	2
No. of cells in an Array	22
Total PV Array Rating	9.9kW

Table 2: battery specifications

Battery type	Nickel-Metal Hydrate
Rated Capacity	6.5Ah
Initial State -Of-Charge	60%
Nominal Voltage	300

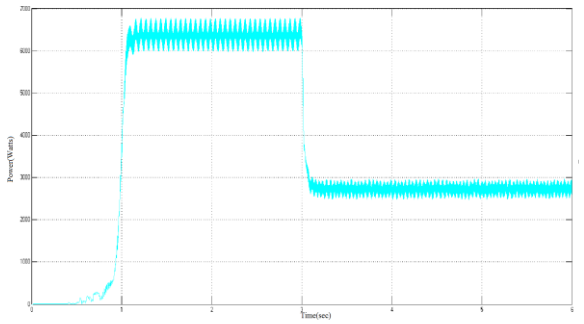

Fig 7: Wind Power output at a different speed of 12 m/s and 9 m/s

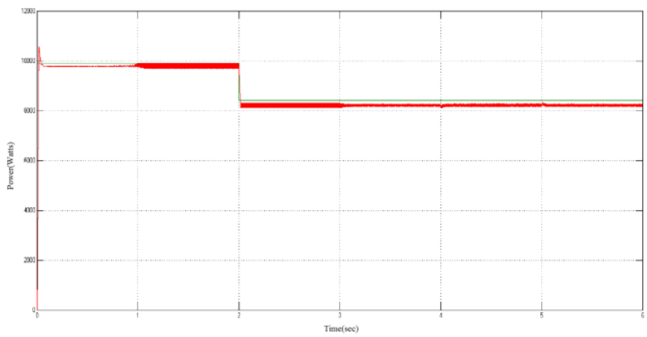

Fig 8: PV Array Output at different Irradiation levels of 1000W/m^2 and 850W/m^2

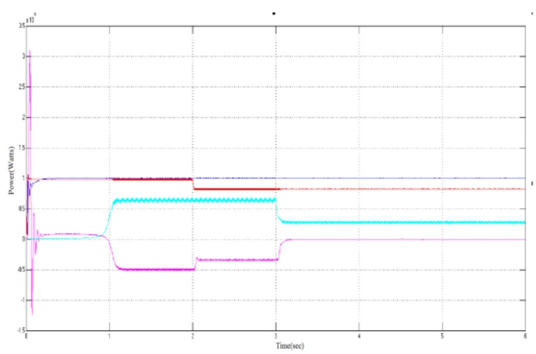

Fig 9: Both Wind & PV Array maintain at a constant load of 10kW

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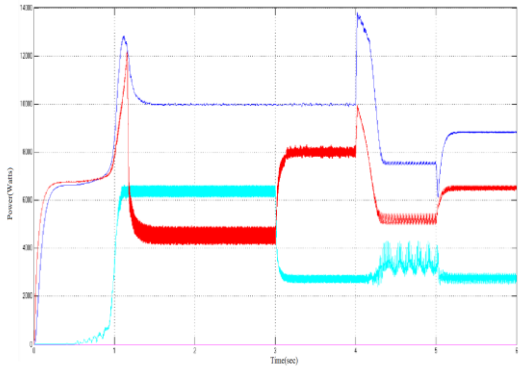

Fig 10: Both Wind & PV Array without using Battery at a load of 10kW and an Extra load of 4kW

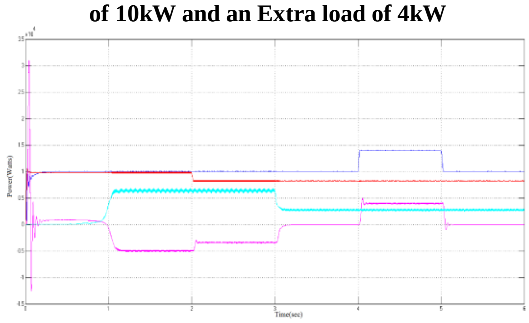

Fig 11: Both Wind & PV Array by using Battery maintain at a load of 10kW and an Extra load of 4kW

IV. EXPERIMENTAL STUDY

In this experiment, Figure 7 shows the output power of the wind and Figure 8 shows output power of the PV arrays. The system under the condition where the wind source has failed and only the PV source is supplying power to the load. Finally the simultaneous operation of the two sources when sudden load is occurred. Sometimes sudden load causes fluctuations. However, this fluctuation must be suppressed. One existing method to solve these issues is to install batteries which absorb power from the system as shown in Fig. 1. Using this method the PV/WT hybrid generation system can supply almost good quality power as shown in Fig. 9 and Fig. 11 are power supplied by the battery. However, this method has disadvantages that they require batteries which are costly. Moreover, they cannot guarantee certainty of load demands at all times especially at bad environmental conditions, where there is no power from the PV and Wind generation system. A 10kW of the load connected hybrid system was developed. Additional load of 4kW is connected by using a circuit breaker in a specified time. Fig. 1 shows the System. It is composed of a PV converter, a wind converter, a BESS converter, and a grid inverter.

V. CONCLUSION

In this paper a multi-input energy system for hybrid wind/solar energy systems have been presented. Dynamic modeling and simulations of the hybrid system is proposed using SIMULINK. A 10-kW hybrid energy system and its supervisory-control system was developed and tested. Load demand is met from the combination of PV array, wind turbine and the battery. An inverter is used to convert output from solar & wind systems into AC power output. Circuit Breaker is used to connect an additional load of 4 KW in the given time. This hybrid system is controlled to give maximum output power under all operating conditions to meet the load. Either wind or solar system is supported by the battery to meet the load. Also, simultaneous operation of wind and solar system is supported by battery for the same load.

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