Renewable Energy Hybrid Powered House For Rural Electrification

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Abstract

A photovoltaic/wind/fuel cell hybrid power system for stand-alone applications is proposed Hybrid powered house. Since, there are frequent power cut in our country this proposed model would help to focus in Renewable Energy System. This concept shows that different renewable sources can be used simultaneously to power off-grid applications. The presented Hybrid powered house can produce sufficient power to cover the peak load. Photovoltaic and wind energy are used as major sources and a fuel cell as backup power for the system. The power costing of the system is designed based on the local data of solar radiation and wind availability. The solar radiation and wind availability is taken from Agro Climatic Research Centre, Tamil Nadu Agricultural University for Coimbatore region.

1. Introduction

Providing reliable, environmentally friendly, and affordable energy has been a goal for many countries throughout the world. The rising consumption of energy and falling accessibility of natural resources are increasing the cost and demand of electricity. In addition, as the industry develops, greenhouse gases are becoming a threat to the natural ecosystem [1]. Therefore, renewable energy has received more attention recently. Solar radiation and wind are considered the most preferred renewable energy sources for their availability and inexhaustibility. However, due to the irregular characteristics of natural wealth, it has been a challenge to engender a highly reliable power with photovoltaic (PV) modules and/or wind turbines [2]. To overcome this limitation, previous studies were conducted using a fuel cell as another energy source and simulated results showed that a PV/wind/fuel cell hybrid power system may be a feasible solution for standalone applications [3-5]. Since a multi-source hybrid power system increases energy availability significantly, it becomes advantageous for practical applications that need highly reliable power regardless of location [6], [7]. This paper presents a model of the use of a PV/wind/fuel cell hybrid power system to supply electricity to a Hybrid powered house. The hybrid power system is shown in Fig. 1. The proposed system shows that it is compatible to use hydrogen as an energy hauler with other renewable energy sources such as PV and wind energy. This system will be installed in Karunya University, Coimbatore. PV and wind energy are used as the main energy sources for the system and the fuel cell performs as a backup power for the continuous generation of high quality power. The proposed mobile house demonstrates that it can be used as a stand-alone powersystem in remote areas where there is no access to grid and as a backup power system to cover electricity shortage in certain situations such as natural disasters.

Fig.1. Hybrid Powered House model

The paper is organized as follows. Section 2 discusses the system design strategy and Section 3 presents the system integration of components. Finally, Section 4 concludes the paper and proposes future research plans.
2. Design Strategy

2.1 Load Analysis

System design starts with deciding whether the mobile house is connected to grid or not. Since the system is mobile, it has to be designed as a stand-alone application, independent from grid. Moreover, the load profile of the mobile house is analyzed to ensure that energy sources generate sufficient energy throughout the year. Eq. (1) shows the estimation of average daily energy consumption.

\[ E_d = \sum_{i=1}^{n} I_n V_n D_n \text{ Eq. (1)} \]

Where, \( I_n \), \( V_n \), and \( D_n \) are the current, voltage and duty cycle of each application used in one day, respectively and \( E_d \) shows the total energy demand for the Hybrid powered house. As shown in Table 1, the average daily energy consumption of the Hybrid powered house is calculated as 4220 Wh according to Eq. (1). The total power, 2835W, declares the maximum instantaneous power which the inverter should meet; in order to maintain the stability of the energy flow, an inverter rated at least 2835W is required for the design. To simplify the analysis, daily load was assumed to have constant value throughout the year and in energy supply analysis, December is chosen because the average solar irradiation in December is the lowest for Karunya University, Coimbatore. As shown in Fig. 2, the area under the daily load curve indicates the approximate required energy for a day, which is equal to the result 4220 Wh from Table 1. Annual load of the Hybrid powered house is shown in Fig. 3.

2.2. Availability study

2.2.1. Solar energy

The Karunya University, Coimbatore has the lowest daily irradiance and sunhours in December, as shown in Fig. 4 [9, 10]. The average radiation in December was calculated as 2030 Wh/m²/day when PV panels. Total area on the roof of the mobile house available for PV panels is 8.4 m² and the total energy generated in a day of December can be calculated with Eq. (2).

\[ E_{pv} = \left( \int_{0}^{24} I_r dt \right) S_{pv} \eta_{pv} \eta_{l} \text{ Eq. (2)} \]

\( S_{pv} \) surface area of PV cells = 8.4 m²
\( \eta_{pv} \) efficiency of PV panels = 16%
Ƞb efficiency of batteries = 85%
Ƞi efficiency of inverter = 95%
I, solar irradiance (Wm⁻²R)
\[
\int_0^{24} Irdt \text{ total solar irradiance in a December day} = 2030 \text{Whm}^{-2}/\text{day}
\]
\[E_{pv} \text{ PV panels’ generated power to AC bus in a December day} = 2203 \text{ Wh/day} \]

According to the results from Eq.(2), 2203 Wh/day from the solar radiation can be produced with the available surface on the house roof.

The generated power of PV panels is also a function of temperature; when the temperature increases, the efficiency of the panel decreases. However, this paper does not consider this point because the ±2.6 deviation of the average temperature of 8 in December is assumed to be negligible.

The basic mathematical model is used to calculate the maximum power output from the photovoltaic modules\cite{14, 15}:

\[
P_{pv} = Y_{pv} f_{pv} \left( \frac{\tilde{G}_T}{G_{T,STC}} \right) \left[ 1 + \alpha_p (T_C - T_{C,STC}) \right] \tag{3}
\]

\[P_{PV} \text{ output power of the PV array (kW)}\]
\[Y_{PV} \text{ the rated capacity of the PV array, sense its power output under normal test conditions (kW)}\]
\[100 \text{Wm}^{-2} \text{ solar irradiance, 25°C PV module temperature}\]

\[\alpha_p \text{ the temperature coefficient of power (°C}^{-1})\]
\[T_C \text{ the PV cell temperature in the current time step (°C)}\]
\[T_{C,STC} \text{ the PV cell temperature under standard test conditions(25 °C)}\]

Regarding the meteorological conditions of Karunya University in 2010, the electricity generation from PV panels is highest on June, July, and August, lowest on November, December and January. Annual average PV output power at Fig. 5.

### 2.2.2. Wind energy

Since the energy from the PV panels is not sufficient to provide the average daily energy demand, a wind turbine and a fuel cell can be used to provide the remaining power needed. As shown in Fig. 6, the availability of wind was determined by the average daily wind speed in December in Karunya University at 10-m altitude. The instantaneous power produced from wind is

\[
P_w = \frac{1}{2} \rho AC_p V^3 \tag{4}
\]

Where:
\[\rho \] air density (kgm⁻³)
\[A \] rotor sweep area (m²)
\[C_p \] power coefficient, a function of tip speed ratio and pitch angle
\[V \] wind velocity (ms⁻¹)

The Hybrid powered house used a Ventura 1000 kW wind turbine model which was found suitable for the hybrid power system. The energy produced from wind can be determined as follows.

\[
E_w = (\int_0^{24} P_w dt) \eta_s \tag{5}
\]

Where:
\[P_w \text{ instantaneous power produced (W)}\]
\[\eta_s \text{ system efficiency with battery and inverter = 80%}\]
\[E_w \text{ wind turbines’ generated power to AC bus in a day} = 2177 \text{ Wh/day}\]

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**Fig.4 Solar Irradiance data for December**

f_{PV} \text{ the PV derating factor (%)}

\[\tilde{G}_T \text{ the solar radiation incident on the PV array in the current time step (kWm}^2)\]

\[\tilde{G}_{T,STC} \text{ the incident radiation at standard test conditions(1 kWm}^2)\]
The area under the black dotted curve corresponds to which is 2177 Wh/day (Fig. 8). The energy balance difference between energy production and demand, can be calculated as follows with Eqs. (2), (4), and (5). In terms of meteorological conditions, the electricity generation from wind turbine is highest on February, October, and December, lowest on May, June. Annual average wind turbine output power at Fig. 7.

\[ E_{eb} = (E_{pv} + E_{w}) - E_d \]  \hfill (6)

\[ E_{eb} = \left( \int_0^{24} P_{pv} \, dt \right) \eta_{pv} + \left( \int_0^{24} P_{w} \, dt \right) \eta_{w} - \left( \int_0^{24} P_d \, dt \right) \eta, \]  \hfill (7)

Using Eq. (5), the value \( E_{eb} \) was calculated as 160 Wh which indicate that the Hybrid house has an energy surplus of 160 Wh. When is negative, the fuel cell has to be activated.

### 2.2.3. Fuel cell

A fuel cell is used as a backup power generator for the house. The fuel cell needs to be activated when wind and solar energy is insufficient to supply the demand, depending on the battery state of charge. A FutureE Jupiter 2 kW PEM fuel cell was selected to back up the power of the house. It is 50% efficient and consumes 22 standard liters of hydrogen per minute (slpm) at peak load. Hydrogen storage capacity should be enough for one day autonomy.

The obligatory energy for a day can be calculated as follows:

\[ E_n = \frac{E_d}{\eta_{b} \eta_{fc} \eta_{i}}. \]  \hfill (8)

Where:
- \( E_d \) energy demand = 4220 Wh/day
- \( \eta_{b} \) efficiency of startup batteries = 85%
- \( \eta_{fc} \) efficiency of fuel cell = 50%
- \( \eta_{i} \) efficiency of inverter = 95%
- \( E_n \) hydrogen energy needed for autonomy = 10452 Wh/day = 37.6 Mj/day

Since the lower heating value of hydrogen is 120 Mj/kg, 0.310 kg/day of hydrogen is required for autonomy. Eq. (9) calculates the required amount of hydrogen;

\[ n = \frac{PV}{RTz} \]  \hfill (9)

Where:
- \( P \) pressure (bar)
- \( V \) volume (l)
- \( R \) gas constant \( \frac{1}{2} \times 0.08314 \) (bar.l/K.mol)
- \( T \) absolute temperature (K)
- \( z \) compressibility factor 1.1054 @ 160 bar
n amount of gas (mol)

As a result, two 10-liter tanks may store approximately 121 mol of hydrogen - 0.242 @ 160 bar 15°C-which has 8159 Wh energy. This amount of hydrogen can supply the fuel cell for approximately 19 h. As shown in Fig. 9, manifold and cylinders of PEMFC.

Fig. 9 - PEMFC Cylinder

1 - Regulator 150 bare15 bar
2 - Hydrogen cylinders 150 bar, 1320 sl
3 - Automatic and manual relieves
4 - Check valves

February and July, the fuel cell is not working. The Hybrid PoweredHouse energy needs during these months are supplied by the wind turbine and solar panels. The fuel cell works at its maximum in April. Monthly average the PEMFC output power at Fig. 10.

2.2.4. Batteries

Batteries are used as the energy storing units and the vital capacity can be calculated below

\[ \text{Ih} = \frac{\alpha E_d}{n_s V_s (1 - \text{SOC}_m/100)} \]  
Eq. (10).

Where:

- \( E_d \) = total energy demand = 4220 Wh/day
- \( n_s \) = system efficiency = 80%
- \( V_s \) = system voltage = 24 V
- \( \text{SOC}_m \) = minimum state of charge = 50%
- \( \alpha = \text{days of autonomy} = 2 \)

The required capacity was calculated as 879 from Eq. (10). Because of space limitations, 8 modules of Haze Professional’s 12200 sealed lead acid monoblock gelled electrolyte battery were used so 1.8 days of autonomy is provided. Fig. 11 shows the battery cycle life respect to the depth of discharge.

As shown, (100 - \( \text{SOC}_m \)) of 50% corresponds to approximately 500 cycles. Fig. 12 shows annual state of charge (SOC) of the battery bank.

Fig. 11 - Battery cycle life vs. depth of discharge

Fig. 12 - Annual SOC of the battery bank.
3. System integration

The hybrid power system of the 24/365 powered house consists of an 8 × 1 array of 100 W PV panels, a 1 kW wind turbine, and a 2 kW cell. As shown in Fig. 13, the block diagram of the system demonstrates the integrated components for power generation. In the following, each component of the system is presented and discussed.

For PV panels, Solera GP-100/12 PV modules of E-Sistem - composed of Poly-Si PV modules - were used. Although Poly-Si modules have lower efficiency than Mono-Simodules, Solera models were selected to have better cost efficiency. The wind turbine works in normal mode up to 20 ms⁻¹ of wind speed and after 20 ms⁻¹, the turbine activates a stall control system which enables electromagnetic regenerative braking and lets the wind turbine generate power under the brake control. The turbine is installed on a foldable pole which has a height of 10 m from the ground. Although the turbines with permanent magnet synchronous generators are more expensive, they are more suitable for the mobile applications due to their compact and light structure. The wind turbine is able to automatically change direction to face the predominant wind in order to generate as much power as possible.

A flow diagram, shown in Fig. 14, describes the system operation. Control system, programmed with Lab VIEW, prevents unnecessary switching and minimizes the use of hydrogen as fuel. Control system calculates the total power demand (\( \sum E_{dem} \)) and the total power production (\( \sum E_{prod} \)) for a specific time interval. At the end of the time interval, system checks the hydrogen pressure (\( P_a \)) if the energy demand is greater than the produced energy and SOC is less than 50%. If the hydrogen pressure is over 4 bar, the switch disconnects the system from DC bus as shown in Fig. 14; else the switch stays at position 1 and gives the warning about hydrogen depletion. After the disconnection, the fuel cell startup battery supplies the demand until the voltage level decreases to 49 V. When 49 V is reached, the fuel cell activates to generate power. The switch stays at nullpoint until when the amount of total produced energy is greater than that of total energy demand or battery SOC is greater than 50% at the end of the time interval. When the hydrogen pressure level drops below 4 bar and the SOC is still less than 50%, the switch changes its

The battery bank consists of 8 gel type batteries of 200 Ah at 12 V. Sealed lead acid monoblock gelled electrolyte batteries are more tolerant of deep discharge, overcharge, and a high number of cycles. Due to their negligible gas emission, they are appropriate for residential usage. The sources and storage units are integrated on a single DC bus in order to make the system cost-effective. Having the same voltage level from the PV array and wind turbine allows both sources to be connected directly to the DC bus. Since the output of the PV module is unregulated, a 60 Amp rated Xantrex multifunction DC controller, which is capable of voltage regulation and three-stage battery charging, was used. The Ventura 1000 already has a rectifier with an internal regulator; hence, it gives an output of 24 V which is the same as the PV array. The fuel cell has a 48 V output. Finally, a DC-DC converter was installed to convert the output of fuel cell to 24 V.

The battery bank with a capacity of 19.2 kWh is used in the system to supply the transient power. When the minimum battery state of charge (SOC) is considered, the usable capacity becomes 9.6 kWh which is the sufficient level - according to (9) - for 1.8 days of autonomy. Hydrogen cylinders with a capacity of 8159 Wh at the given conditions were used. Moreover, the hydrogen storage is sufficient for 0.8 day of autonomy when losses are taken into consideration; hence, the total number of autonomous days is 2.6 days. The fuel cell startup battery warms up the fuel cell, and prevents unnecessary switch-on when there is only a short term power demand. When there is a long term power demand, the startup battery functions as a backup power source.
position to 1 and allows the battery voltage to drop below 50% SOC.

Fig. 14 - Flow diagram of the system.

Fig. 15 - Annual excess electricity of the Hybrid powered house.

4. Conclusions

Demonstration of a PV/wind/fuel cell hybrid power system was presented. The hybrid power system increases power availability which is one of the key factors for many applications that need reliable power in remote locations. The system was designed based on the results of a load analysis and a study of the renewable resources available in Karunya, Coimbatore. After the design, the components of the system will be integrated; a PV module (800 W), a wind turbine (1 kW), and a fuel cell (2 kW) will be installed to generate a maximum power of 3.8 kW. The presented system uses PV and wind energy as the primary energy sources and fuel cell energy as a secondary source for power generation. Annual approximate energy production of house is 2510 kWh. Annual approximate energy demand of Hybrid house is 1550 kWh. So there is an excess energy which is shown in Fig. 15. In Hybrid house energy control system, surplus energy is converted to hydrogen via a PEM electrolyzer and stored in a high pressure hydrogen tank until there is a high energy demand which triggers fuel cell unit that converts hydrogen gas back into electricity. Smart energy control system targets to source uninterruptible energy and sustainability property to the Hybrid Powered house.

As a future work, the correlation between the parameters and energy production will be demonstrated, and automatic controls will be designed and installed to optimize the storage efficiency of the system.

References


