Optimum Sizing of Standalone Hybrid PV/Wind Power Generation System in Egypt

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Abstract: In this study, the I-V and P-V curves of PV system at different solar radiations and ambient temperatures have been determined based on five-parameter equations describing the PV module. Also, the wind turbine performance model has been developed and the predicted power-speed curves have been validated against data sheet and experimental data. Both PV module and wind turbine models have been carried out in PSIM software environment. The sizing of hybrid PV/wind/storage battery power generation system has been implemented in HOMER software environment. The sizing results demonstrate that at meteorological conditions of solar radiation, wind speed, and ambient temperature in Borg Elarab area the PV/storage battery system is more feasible than hybrid PV/wind/storage battery system. Consequently, the PV/storage battery system has Net Present Cost (NPC) of $43571 against $45232 for hybrid PV/wind/storage battery system. In addition, by using fuel cell system with PV/storage battery system the excess electricity production is reduced from 1973 kWh/yr (22.4%) to 986 kWh/yr (8.7%) and NPC is reduced from $43571 to $29744 which corresponds to about 31.73% reduction in system cost.

Keywords: PV module; wind turbine; PSIM software; HOMER; fuel cell
1. INTRODUCTION

Renewable energy sources in energy generation can decrease the costs of system fuel and also can have desirable impact on reliability of system. Therefore, a suitable combination between the system reliability indices and system capital investment costs is required. Maleki and Pourfayaz (2015) [1] evaluated the performance of different evolutionary algorithms for optimum sizing of a PV/WT/battery hybrid system to continuously satisfy the load demand with the minimal total annual cost (TAC). For this aim, all the components were modelled and an objective function was defined based on the TAC. In the optimization problem, the maximum allowable loss of power supply probability (LPSPmax) was considered to have a reliable system, and results were compared in terms of the TAC. An economic evaluation of a hybrid wind/photovoltaic/fuel cell (FC) generation system for a typical home in the Pacific Northwest was performed. A computer program by using a graphical user interface programmed in MATLAB has been developed to size system components in order to match the load of the site in the most cost effective way. A cost of electricity, an overall system cost, and a break-even distance analysis were calculated (Nelson, Nehrir and Wang, 2006) [2]. Kaabeche et al. implemented optimal sizing model based on iterative technique, to optimize the capacity sizes of different components of hybrid photovoltaic/wind power generation system using a battery bank. The recommended model took into account the Deficiency of Power Supply Probability (DPSP) and the Levelised Unit Electricity Cost (LUEC). The flow chart of the hybrid optimal sizing model was illustrated (Kaabechea, Belhame and Ibtiouen 2011) [3]. A system with photovoltaic (PV) arrays, wind turbines, and battery storage was designed based on empirical weather and load data. Simulations using the Hybrid Optimization Model for Electric Renewable (HOMER) was used to determine the feasible set of the optimization problem. The simulation results from HOMER simulator and calculated some cost estimations of an off-grid hybrid energy system with PV/ wind turbine/ storage for the case study were presented (Huang, Low, Topcu, et al., 2011) [4]. This concludes that bulk of the literature deals with simulations for hybrid PV/wind turbine/storage battery using HOMER was implemented to determine the feasibility, sizing, optimization and economic estimation of the systems by Bekele and Tadesse (2012 cited by Li, Ge, Zheng, et al., 2013. Sen and Bhattacharyya, 2014, Rohani and Nour, 2014, Ma, Yang and Lu, 2014, Bhattacharjee and Acharya, 2015 and Amutha and Rajini, 2015) [5-11]. The purpose of the present work is to develop the I-V and P-V curves of PV system at different solar radiations and ambient temperatures based on five-parameter equations describing the PV module. Also, the wind turbine performance model has been developed and the predicted power-speed curves have been validated against data sheet and experimental data. Both PV module and wind turbine models have been carried out in PSIM software environment. The sizing of hybrid PV/wind/storage battery power generation system has been implemented in HOMER software environment. The sizing results of PV/wind/storage battery system at meteorological conditions of solar radiation, wind speed, and ambient temperature in Borg Elarab area are discussed.

2. HYBRID STANDALONE PV/WIND SYSTEM

A schematic diagram of a stand-alone hybrid PV/wind system is shown in Figure 1. Battery chargers, connected to a common DC bus, are used to charge the battery bank from the respective PV and wind input power sources. Depending on the battery charger technology, the maximum available power can be extracted from the PV and wind power sources (Maximum Power Point Tracking, MPPT). The battery bank is used to store the energy surplus and to supply the load in case of low wind speed and/or irradiation conditions. A DC/AC inverter is used to interface the DC battery voltage to the consumer load AC requirements. The energy produced from each PV or wind source is transferred to the consumer load through the battery charger and the DC/AC inverter, while the energy surplus is used to charge the battery bank.

![Schematic diagram of hybrid PV/wind/storage battery system](image)

2.1 PV Module Model

The equivalent circuit of a photovoltaic cell is shown in Figure 2 (Siddiqui and Anif, 2013) [12] where $R_s$ is the very small series resistance, $R_{sh}$ is the quite large shunt resistance, and $D$ is the ideal P–N diode.
I_{ph} is the generated photocurrent source which is influenced by the surface temperature and irradiation. V and I represent the output voltage and current of the cell, respectively.

**Governing Equations**

According to the physical property of P–N semiconductor, the I-V characteristic of a module consists of series-parallel combination of n cells is expressed as follows (Siddiqui et al., 2013) [12]:

$$I = n_p I_{ph} - n_p I_o \left[ \exp \left( \frac{q}{AKT} \left( \frac{V}{n_s} + IR_s \right) \right) - 1 \right] - \frac{V - n_s}{R_{sh}}$$

**Equation 1:** I and V relation of PV cell

$$I_{ph} = \left( I_{sc} + k_{sc}(T - T_{ref}) \right) \frac{q_{rad}}{1000}$$

**Equation 2:** Light generated current

$$I_o = I_r \left( \frac{T}{T_r} \right)^3 \exp \left[ \frac{qE_{gap}}{kA} \left( \frac{1}{T_{ref}} - \frac{1}{T} \right) \right]$$

**Equation 3:** Module reverse saturation current

In Equation 1, q is the electron charge (1.602×10−19, C); k represents the Boltzmann constant (1.38×10−23 J/K), T is the surface temperature of module, A is the ideality factor (A = 1–5), n_s is the number of cells connected in series, and n_p is the number of cells parallelly connected so n = n_sn_p. I_{sc} is the short-circuit current, k_{sc} is the temperature coefficient of the short-circuit current, and q_{rad} is the solar radiation in W/m². The module reverse saturation current I_o is expressed in Equation 3, where E_{gap} is the energy of the band gap for silicon (E_{gap} = 1.1 eV) and T_{ref} is the reference temperature of PV module.

**PSIM Based PV Module Modeling**

Figure 3 shows the electrical model of SF80-A PV module formed by the PSIM software package. The electrical and physical characteristics of SF80-A PV module are described in Appendix A. The series resistance is always neglected in conventional mathematical model to form a simple equation. However, in the proposed PSIM model, the series and shunt resistance are taken into consideration. Therefore, the proposed model can be considered significantly more accurate than the conventional model in simulating the PV module characteristics (Elnozahy, Abdel Rahman, Abdel-Salam, et al., 2015) [13].
Figure 3: Schematic diagram of PSIM based PV module (a) main circuit and (b) inner subcircuit

Figure 4 shows the I–V and P–V characteristic curves of tested SF80-A PV module as obtained by the proposed PSIM electrical model at varying irradiance, $q_{\text{rad}}$ and temperature, $T$. The dependence of the short circuit current on the irradiance is shown in Figure 4a. The effect of temperature on the open circuit voltage is shown in Figure 4b.

Figure 4: I–V and P–V curves of the PSIM based PV module model at varying (a) irradiance at $T = 25^\circ\text{C}$ and (b) temperature at $q_{\text{rad}} = 1000\text{W/m}^2$

2.2 Wind Turbine Generator Model

Figure 5 shows the power curve as described in the data sheet for the Zephyr Z-501 small scale Wind Turbine (WT). Moreover, some wind turbine principal data are reported in Table 1 (Anon., 2015) [14]. Figure 5 indicates the “cut-in” wind speed below which no power is produced, approximately 2.5 m/s. Also important is the “rated” wind speed where the advertised power is obtained; 12.5 m/s. The turbine has a wide region, between 4.5 and 12.5 m/s, where the power increases rapidly, approximating the cubic dependence of Equation 4.
### Governing Equations

Modelling of the WT according to the parameters taken from the datasheet of Zephyr Z-501 will be introduced. Power extracted from the wind \( P_w \) can be calculated as given in Equation 4 where \( A(m^2) = \pi R^2 \) is the swept area by the rotor blades while \( R(m) \) is the radius of the rotor blade, \( \rho \) is the air density (kg/ m\(^3\)) and \( u \) (m/s) is the velocity of the air speed (Lara, Jenkins, Ekanayake et al., 2009) [15].

\[
P_w = \frac{1}{2} \rho A u^3
\]

**Table 1: Principal data of Zephyr Z-501 wind turbine**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine Rotor diameter</td>
<td>1170 mm</td>
</tr>
<tr>
<td>No. of blades</td>
<td>3</td>
</tr>
<tr>
<td>Start of power generation (cut-in) wind speed</td>
<td>2.5 m/s</td>
</tr>
<tr>
<td>Cut-in rotational speed</td>
<td>500 rpm</td>
</tr>
<tr>
<td>Rated output speed</td>
<td>1700 rpm</td>
</tr>
<tr>
<td>Rated output (rated wind speed 12.5m / s)</td>
<td>400 W</td>
</tr>
<tr>
<td>Maximum output power</td>
<td>450 W</td>
</tr>
<tr>
<td>Cut-off speed</td>
<td>14 m/s</td>
</tr>
<tr>
<td>Rated output voltage</td>
<td>12 V</td>
</tr>
</tbody>
</table>

Equation 5: Mechanical power generated by the turbine

\[
P_m = \frac{1}{2} C_p \rho A u^3
\]

Where \( C_p(\lambda, \beta) \) is the power coefficient, which depends on the Tip-Speed-Ratio (TSR), \( \lambda \), and blade pitch angle, \( \beta \) as defined by Equation 6.

\[
C(\lambda, \beta) = 0.5(116\gamma - 0.4\beta - 5) \cdot e^{-2\lambda}
\]

**Equation 7:**

\[
\gamma = \frac{1}{\lambda + 0.08\beta} \cdot \frac{0.035}{1 + \beta^3}
\]

When wind speed, \( u \) changes, the angular velocity of the shaft, \( \omega \) should be adjusted to achieve the best value of \( C_p \). This means that \( \omega \) and the wind speed must somehow be combined into a single variable so that the curve showing the relation between \( C_p \) and \( \omega \) can be drawn. Experiments show that this single variable is the ratio of the turbine tip speed, \( R \omega \), to the wind speed, \( u \). This TSR, \( \lambda \) is defined as (Lara et al., 2009) [15]:

**Equation 8: Tip speed ratio**

\[
\lambda = \frac{R \omega}{u}
\]

According to Equation 8, there is a relation between \( \lambda \) and \( \omega \). Hence, at a certain \( u \), the power is maximized at a certain \( \omega \) called optimum rotational speed, \( \omega_{\text{opt}} \). This speed corresponds to optimum tip speed ratio (\( \lambda_{\text{opt}} \)). The value of the tip speed ratio is constant for all maximum power points (MPPs). So, to extract maximum power at variable wind speed, the WT should always operate at \( \lambda_{\text{opt}} \) in speeds bellow the rated speed. This occurs by controlling the rotational speed of the WT to be equal to the optimum rotational speed (Eltamaly and Farh, 2013).
At different values of wind speed, \( u \), the rotational speed, \( \omega \) should be controlled to operate close to \( \lambda = 8 \) (at \( C_p \) maximum).

**PSIM Based Wind Turbine Generator Modeling**

The power for a certain wind speed is maximum at a certain value of rotational speed called optimum rotational speed, \( \omega_{opt} \). This optimum rotational speed corresponds to optimum tip speed ratio, \( \lambda_{opt} \). In order to track maximum possible power, the turbine should always operate at \( \lambda_{opt} \). This is achieved by controlling the rotational speed of the wind turbine so that it always rotates at the optimum rotational speed. As shown in Figure 6 for TSR calculation, both the wind speed, \( u \) and turbine speed, \( N \) need to be measured, and the optimal TSR must be given to the controller-1. The output of controller-1 is the maximum value of the power coefficient, \( C_{p_{max}} \). Therefore, the maximum power as expressed by Equation 5 can be calculated where \( K_2 \) equals \( 0.5 \rho A \).

Controller-2 keeps the turbine power at optimum value, \( P_{opt} \) by comparing it with the actual turbine power, \( P_{act} \).

The simulation results of wind turbine generator, as shown in Figure 8, indicate good matching between power-speed curve as obtained from data sheet, PSIM model, mathematical calculation based on the maximum power coefficient \( C_{p_{max}} \) and experimental results.

**3. SIZING OF HYBRID PV/WIND SYSTEM**

**3.1 HOMER Simulation**

Sizing of a stand-alone hybrid PV/wind energy system in HOMER software, as shown in Figure 9, which is designed to supply the electrical load demand of the student campus of Egypt-Japan University of Science and Technology (E-JUST) situated in Borg Elarab, Alexandria, Egypt (30°52’ N, 29°34’ 56.9” E). All studied configurations in this section are standalone and fully renewable energy resources (zero emission system). According to Central Bank of Egypt (CBE) (Central Bank of Egypt (CBE), 2015) [17], the average inflation rate, average discount (interest) rate, and annual capacity shortage (i.e. system must meet all of the load all of the time) in Egypt are 8%, 11%, and 0%, respectively. The load profile adopted in this study is that represented on Figure 10. Annual average load consumption of the household is 16 kWh/day at maximum load of 3.4 kW.
Monthly data of solar irradiation on the horizontal plane, wind speed as well as ambient temperature, plotted in Figure 11 during the year 2006, are obtained from National Renewable Energy Laboratory (NREL). The annual wind energy potential for Borg Elarab at 10 m height is 4.94 m/s and the annual total solar radiation on the horizontal surface is 5.12 kWh/m²/day. In this study, the effect of ambient temperature on the PV module performance is taken into consideration (annual average ambient temperature in Borg Elarab is 21.46 °C). The technical characteristics of the PV module and wind turbine as well as the battery, converter, fuel cell, hydrogen tank, and electrolyzer used in the studied system are listed in Table 2.

3.2 Sizing Results and Discussion

Case 1: PV/Storage Battery System

HOMER simulates all the possible system configurations based on the combinations of the components specified to it as input data. Only feasible combinations are displayed according to the total Net Present Cost (NPC) in an increasing order.

Table 3 displays the optimized feasible system configurations according to cost effectiveness at annual average solar radiation, wind speed, and ambient temperature, 5.12 kWh/m²/day, 4.94 m/s, and 21.46 °C, respectively. It is to be noted that the PV/storage battery system has NPC and Cost of Energy (COE) of $43571 and $0.418/kWh against $45232 and $0.434/kWh for hybrid PV/wind/storage battery system, respectively. Consequently, the hybrid PV/storage battery configuration is more feasible (less NPC and COE) than hybrid PV/wind/storage battery configuration. This is due to the small average wind speed (4.94 m/s) in Borg Elarab.

Case 2: Sensitivity Analysis

Table 4 displays optimized feasible system configurations according to cost effectiveness for wind speed as sensitively variable. At annual average solar radiation (5.12 kWh/m²/day) and variable wind speed (4.94, 5.5, 6, 6.5, 7, 7.5 m/s), the feasibility of the system changes according to the change of the annual average wind speed.
Up to wind speed 6 m/s the system configuration consisting of PV modules and storage battery only is more feasible than the other configurations (first three lines, NPC= $43571). When the wind speed reaches 6.5 m/s, the hybrid system consisting of PV modules and wind turbines becomes more feasible and the NPC decreases with increase of wind speed (last three lines, NPC=$42576, $40777, and $37219 at wind speed 6.5 , 7, and 7.5 m/s, respectively). In conclusion, it is better for Borg Elarab area to use renewable power generation system not including wind turbine where the annual average wind speed is low (4.95 m/s). In the other hand, the system has Excess electricity 1973 kWh/yr (22.4%). Therefore, one can reduce this excess electricity and reduce NPC of the system by using fuel cell system as described in the following case.

![Daily Radiation (kWh/m²/day)](image1)

![Average Wind Speed (m/s)](image2)

![Daily Temperature (°C)](image3)

*Figure 11: Meteorological conditions in Borg Elarab (a) solar irradiation on horizontal plane, (b) wind speed and (c) ambient temperature*

| Table 2: Technical characteristics of the hybrid system components |
|------------------|--------------|----------------|-------------------|------------------|
| Components       | Size         | Capital cost ($) | Replacement ($)   | O & M ($/kW.yr) |
| PV               | 1kW          | 2010            | 2010              | 27               |
| Wind turbine     | 1kW          | 2370            | 2370              | 40               |
| Battery          | 1kWh         | 200             | 200               | 10               |
| Converter        | 1kW          | 300             | 300               | 0.0              |
| Fuel cell        | 1kW          | 500             | 500               | 0.0              |
| Hydrogen tank    | 1kg          | 150             | 150               | 0.0              |
| Electrolyzer     | 1kW          | 200             | 200               | 0.0              |

| Table 3: Optimization results of PV–wind hybrid configuration |
|------------------|--------------|----------------|--------------------|------------------|
| PV (kW) | WTG | Battery | Conv. (kW) | COE ($/kWh) | NPC ($) | Ren. Fra. (%) | Elec. Prod. (kWh/yr) | Elec. Cons. (kWh/yr) | Excess Elec. (kWh/yr) |
| 8      | 0   | 45      | 4           | 0.418           | 43571   | 100          | 8815               | 5836             | 1973               |
| 7      | 1   | 46      | 4           | 0.434           | 45232   | 100          | 10042              | 5835             | 3220               |

*Table 4: Optimization results corresponding to the wind speed sensitivity values*
Case 3: Hybrid PV/Wind/Fuel Cell System

Figure 12 shows the fuel cell system which consists of fuel cell (Generator), electrolyzer, and hydrogen tank as attached to PV/wind/storage battery system. The results of sizing optimization of hybrid PV/wind/fuel cell system are illustrated in Table 5. In case of PV/fuel cell configuration, from Tables 3 and 5 it is worth noting that the excess electricity is reduced from 1973 kWh/yr (22.4%) to 986 kWh/yr (8.7%) and NPC is reduced from $43571 to $29744. This corresponds to about 31.73% reduction in system cost. The COE is reduced from $0.418/kWh to $0.285/kWh. This corresponds to about 31.82% reduction in energy production cost.

Figure 12: Hybrid PV/wind/fuel cell system in HOMER

Table 5: Optimization results of PV/wind/FC hybrid configuration

<table>
<thead>
<tr>
<th>PV (kW)</th>
<th>WTG</th>
<th>Batter y</th>
<th>Conv. (kW)</th>
<th>FC (kW)</th>
<th>Elecz. (kW)</th>
<th>Hydrogen tank (kg)</th>
<th>COE ($/kWh)</th>
<th>NPC($)</th>
<th>Hydrogen fuel (kg)</th>
<th>Excess Elec. (kWh/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0</td>
<td>13</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>0.285</td>
<td>29744</td>
<td>72</td>
<td>986</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>13</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>0.293</td>
<td>30499</td>
<td>67</td>
<td>390</td>
</tr>
</tbody>
</table>

Whereas, in case of PV/wind/fuel cell configuration, from Tables 3 and 5 the excess electricity is reduced from 3220 kWh/yr (32.1%) to 390 kWh/yr (3.8%). The NPC is reduced from $45232 to $30499. This corresponds to about 32.57% reduction in system cost. The COE is reduced from $0.434/kWh to $0.293/kWh. This corresponds to about 32.49% reduction in energy production cost.

4. CONCLUSION

In this study, optimal sizing of hybrid PV/wind/storage battery system is carried out. The following conclusions may be drawn from the present study:

A. A model of PV module based on five parameter equations has been implemented to investigate the I-V and P-V curves at different values of solar radiation and ambient temperature. In addition, wind turbine model is developed and validated by comparison against data sheet and experimental results.

B. The sizing optimization results of hybrid PV/wind/storage battery system demonstrate that:

1. The PV/storage battery system has NPC and COE of $43571 and $0.418/kWh against $45232 and $0.434/kWh for hybrid PV/wind/storage battery system, respectively. Consequently, at meteorological conditions of annual average solar radiation (5.12kWh/m²/day), wind speed (4.94 m/s), and ambient temperature (21.46 °C) in Borg Elarab area, the hybrid PV/storage battery configuration is more feasible (less NPC and COE) than hybrid PV/wind/storage battery configuration. This is due to small average wind speed (4.94 m/s) in Borg Elarab.

2. A sensitivity analysis of wind speed variation indicates that the PV/wind/storage battery system became more feasible than PV/storage battery system when wind speed reaches 6.5 m/s.

3. By adding fuel cell system to PV/storage battery system the excess electricity production is reduced from 1973 kWh/yr (22.4%) to 986 kWh/yr (8.7%) and NPC is reduced from $43571 to $29744 which corresponds to about 31.73% reduction in system cost. In addition, COE is reduced from $0.418/kWh to $0.285/kWh. This corresponds to about 31.82% reduction in energy production cost.
5. ACKNOWLEDGEMENT

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6. REFERENCES


