Optimal sizing method for stand-alone hybrid PV/wind power generation system

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Abstract - This paper recommends an optimal sizing model, to optimize the capacity sizes of different components of hybrid PV/wind power generation systems using a battery bank. The recommended model takes into account the submodels of the hybrid system, the deficiency of Power Supply Probability (DPSP) and the Life Cycle Cost (LCC). With this incorporated model, the sizing optimization of grid-independent hybrid PV/wind power generation system can be accomplished technically and economically according to the system reliability requirements. A case study is conducted to analyze one hybrid project, which is designed to supply residential household located in the area of the CDER (Center for Renewable Energy Development) situated in Bouzaréah, Algeria (36° 48’N, 3° 1’E, 345 m).

Keywords: Hybrid PV/wind system - Unit sizing - Optimization - Economic evaluation.

1. INTRODUCTION

For different regions and locations, climatic conditions, including solar irradiance, wind speed, temperature, and so forth, are always changing. Thus, there exist instability shortcomings for electric power production from photovoltaic (PV) modules and wind turbines.

In order to efficiently and economically utilize renewable energy resources of wind and solar energy applications, the optimum match design sizing is very important for solar-wind power generation systems with battery banks.

The sizing optimization method can help to guarantee the lowest investment with a reasonable and full use of the PV system, wind system and battery bank, so that the system can work at the optimum conditions with optimal configurations in terms of capacity.

Different optimization techniques of hybrid PV/wind systems sizing have been reported in the literature such as dynamic programming [1], multiobjective [2, 3], graphical construction technique [4-6], linear programming [7, 8], probabilistic approach [9-11] and iterative technique [12-14].

In this paper, the hybrid PV/wind system optimization sizing model, is developed based on the Deficiency of Power Supply Probability (DPSP) and the Life Cycle Cost (LCC) concepts. The DPSP technique, which is reputed to be the criteria for sizing, is the probability that an insufficient power supply results when the hybrid system is unable to satisfy the load demand.

Using the DPSP objective function, the configurations of a hybrid system which can meet the system reliability requirements can be obtained. There are three sizing parameters in the simulation, i.e. the capacity of PV system, the rated power of wind
system, and the capacity of the battery bank. The optimum configuration can be identified from the set of the above obtained configurations by reaching the lowest Life Cycle Cost (LCC).

2. GRID-INDEPENDENT SYSTEM DESCRIPTION

A schematic diagram of a stand-alone hybrid PV/Wind system is shown in Fig. 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 terminals are connected in parallel.

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.

![Fig. 1: Block diagram of a hybrid PV/Wind system](image)

3. HYBRID PV/WIND SYSTEM MODEL

3.1 PV generator model

The hourly output power of the PV generator with an area $A_{pv}$ (m$^2$) at a solar radiation on tilted plane module $G_t$ (W/m$^2$), is given by [15]:

$$P_{pv} = \eta_{pv} \cdot A_{pv} \cdot G_t$$

(1)
where $\eta_{pv}$ represents the PV generator efficiency and is given by [16, 17]:

$$\eta_{pv} = \eta_r \cdot \eta_{pc} \cdot (1 - \beta (T_c - T_{ref}))$$  \hspace{1cm} (2)

where $\eta_r$ is the reference module efficiency, $\eta_{pc}$ is the power conditioning efficiency which is equal to 1 if a perfect maximum power tracker (MPPT) is used. $\beta$ is the generator efficiency temperature coefficient, it is assumed to be a constant and for silicon cells the range of $\beta$ is 0.004–0.006 per (°C), $T_{ref}$ is the reference cell temperature (°C) and $T_c$ is the cell temperature (°C) and can be calculated as follows [18]:

$$T_c = T_a + ((\text{NOCT} - 20)/800) \cdot G_t$$  \hspace{1cm} (3)

where $T_a$ is the ambient temperature (°C) and NOCT is the nominal cell operating temperature (°C). $\eta_{pc}$, $\beta$, NOCT and $A_{pv}$, are parameters that depend upon the type of module used. The data are obtained from the PV module manufacturers.

### 3.2 Wind turbine system model

The wind speed distribution for selected sites as well as the power output characteristic of the chosen wind turbine are the factors that have to be considered to determine the wind energy conversion system power output. Choosing a suitable model is very important for wind turbine power output simulations. The most simplified model to simulate the power output of a wind turbine [19] can be described by:

$$P_W(V) = \begin{cases} P_R \left( \left( \frac{V^2 - V_C^2}{V_R^2 - V_C^2} \right) / \left( \frac{V_R^2 - V_C^2}{V_R^2} \right) \right) & V_C \leq V \leq V_R \\ P_R & V_C \leq V \leq V_R \\ 0 & \text{Otherwise} \end{cases}$$  \hspace{1cm} (4)

where $P_R$ is the rated electrical power; $V_R$ is the cut-in wind speed; $V_R$ the rated wind speed; and $V_F$ is the cut-off wind speed. In this study, the adjustment of the wind profile for height is taken into account by using the power law that has been recognized as a useful tool to model the vertical profile of wind speed. The equation can be described by [20, 21]:

$$\frac{V(H)}{V(H_{ref})} = \left( \frac{H}{H_{ref}} \right)^\alpha$$  \hspace{1cm} (5)

where $V(H)$ is the wind speed at hub height $H$, m/s; $V(H_{ref})$ is the wind speed measured at the reference height $H_{ref}$, m/s; $\alpha$ is the power law exponent. The determination of $\alpha$ becomes very important. The value of 1/7 is usually taken when there is no specific site data.
3.3 Battery bank Model

Battery bank storage is sized to meet the load demand during non-availability period of renewable energy source, commonly referred to as days of autonomy. Normally the number of days of autonomy is taken to be 2 or 3 days.

Battery sizing depends on factors such as maximum depth of discharge, temperature correction, rated battery capacity and battery life. The total capacity of the battery bank that is to be employed to meet the load is determined using the following expression [22]:

\[ C_B = \frac{E_L \cdot S_D}{V_B \cdot (DOD)_{\text{max}} \cdot T_{\text{cf}} \cdot \eta_B} \]  

(6)

Where \( E_L \) is the load in Wh; \( S_D \) is the battery autonomy or storage days; \( V_B \) is the battery bank voltage; \( DOD_{\text{max}} \) is the maximum battery depth of discharge; \( T_{\text{cf}} \) is the temperature correction factor and \( \eta_B \) is the battery efficiency.

Depending on the PV and Wind energy production and the load power requirements, the state of charge of battery can be calculated from the following equations:

Battery charging,

\[ \text{SOC}(t) = \text{SOC}(t-1) \times (1 - \sigma) + \left( E_{\text{gen}}(t) - E_L(t) / \eta_{\text{inv}} \right) \times \eta_B \]  

(7)

Battery discharging,

\[ \text{SOC}(t) = \text{SOC}(t-1) \times (1 - \sigma) + \left( E_L(t) / \eta_{\text{inv}} - E_{\text{gen}}(t) \right) \]  

(8)

Where \( \text{SOC}(t) \) and \( \text{SOC}(t-1) \) are the states of charge of battery bank (Wh) at the time \( t \) and \( t-1 \), respectively; \( \sigma \) is hourly self-discharge rate; \( E_{\text{Gen}}(t) \) is the total energy generated by PV array and wind generators after energy loss of controller; \( E_L(t) \) is load demand at the time \( t \); \( \eta_{\text{inv}} \) and \( \eta_B \) are the efficiency of inverter and charge efficiency of battery bank, respectively. At any time \( t \), the charged quantity of the battery bank is subject to the following two constraints:

\[ \text{SOC}_{\text{min}} \leq \text{SOC}(t) \leq \text{SOC}_{\text{max}} \]  

(9)

The maximum charge quantity of battery bank \( \text{SOC}_{\text{max}} \) takes the value of nominal capacity of battery bank \( C_B \), and the minimum charge quantity of battery bank \( \text{SOC}_{\text{min}} \) is determined by the maximum depth of discharge \( DOD \):

\[ \text{SOC}_{\text{min}} = (1 - DOD) \cdot C_B \]  

According to the specifications from the manufacturers, the battery’s lifetime can be prolonged to the maximum if \( DOD \) takes the value of 30–50%. In this paper, the \( DOD \) takes the value of 50%.

4. OPTIMAL SIZING CRITERIA FOR HYBRID RENEWABLE ENERGY SYSTEMS

In the existing literature there are various methods to evaluate the hybrid PV/wind energy system (HPWES) such as energy to load ratio, battery to load ratio, and non-availability of energy. In order to select an optimal combination of a HPWES to satisfy
the load demand, evaluation may be carried on the basis of reliability and economy of power supply. The commonly used methodologies for evaluation of HPWES are as follows.

4.1 Reliability criteria based on DPSP technique

In this study, reliability of the system is expressed in terms of deficiency of power supply probability (DPSP) which is the probability that an insufficient power supply results when the hybrid system (PV array, wind power and energy storage) is unable to satisfy the load demand.

The DPSP technique is considered to be the technical implemented criteria for sizing and evaluating a hybrid PV/wind system employing a battery bank. The technical model for hybrid system sizing is developed using the DPSP technique. The methodology used can be summarized in the following steps:

(a) If the power generated from the PV/Wind system is greater than the load for a particular hour. In this case, the energy surplus is stored in the battery bank and the new state of charge is calculated using Eq. (7) until the full capacity is obtained; the remainder of the available energy is not used.

(b) When the energy demand of the load is greater than the available energy generated by the PV/Wind system, the battery bank will be used to assure the load demand. In this case, the new state of charge at hour $t$ is

In case (b), if the state of charge of the battery bank decreases to its minimum level, $SOC_{min}$, the control system disconnects the load and that deficit called deficiency power supply (DPS) at hour $t$ can be expressed as:

$$DPS(t) = E_{L}(t) - (E_{Gen}(t) - SOC(t) - SOC_{min}) \times \eta_{inv} \quad (10)$$

The deficiency of power supply probability (DPSP), for a considered period $T$ (1 year in this study), can be defined as the ratio of all the $(DPS(t))$ values for that period to the sum of the load demand. This can be defined as [23]:

$$DPSP = \frac{\sum_{t=1}^{T} DPS(t)}{\sum_{t=1}^{T} E_{L}(t)} \quad (11)$$

A DPSP of 1 means that the load will never be satisfied and the DPSP of 0 means that the load will be always satisfied. From the above-described situations, a program is developed in MATLAB to size the components for each configuration, for a particular DPSP specified by the user.

4.2. Economic criteria based on LCC concept

It is pertinent that economic analysis should be made while attempting to optimize the size of integrated hybrid PV/Wind generation systems favouring an affordable unit price of power produced. The economical approach, according to the concept of Life Cycle Cost (LCC), is developed to be the best indicator of economic profitability of system cost analysis in this study.
The LCC is defined as the total cost of the whole hybrid system. Four main parts are considered: PV array, wind turbine, battery bank, and the inverter. According to the studied system, the life cycle cost (LCC) takes into account the initial capital cost ($IC_{cap}$), the present value of replacement cost ($C_{rep}$) and the present value of maintenance cost ($C_{main}$). Thus, LCC may be expressed as follows:

$$LCC(\$) = IC_{cap} + C_{rep} + C_{main}$$  \hspace{1cm} (12)

**4.2.1 The initial capital cost**

The initial capital cost of each system component consists of the component price, the cost of civil work, installation and the connections. In this study, the civil work and installation costs are taken as 40% of PV generator price for PV part and 20% of wind generator price for wind part. Then the initial capital cost for the hybrid system, ($IC_{I}$) is given by:

$$IC_{I} = \left[ (C_{PV} \times C_{Unit, PV}) + (C_{W} \times C_{Unit, W}) \right]$$

$$+ \left[ (C_{B} \times C_{Unit, B}) + (C_{INV} \times C_{Unit, INV}) \right] + C_{0}$$  \hspace{1cm} (13)

Where ($C_{PV} , C_{Unit, PV}$) are the total capacity (W) and unit cost ($/W) of PV array respectively; ($C_{W} , C_{Unit, W}$) are the total capacity (W) and unit cost ($/W) of the wind machine respectively; ($C_{B} , C_{Unit, B}$) are the total capacity (Wh) and unit cost ($/Wh) of the battery bank respectively; and ($C_{INV} , C_{Unit, INV}$) are the nominal capacity (W) and unit cost ($/W) of the inverter respectively; and $C_{0}$ is the total constant cost including the cost of civil work and installation.

**4.2.2 The present value of replacement cost**

The present value of replacement cost of a system component is the present value of all the replacement costs occurring throughout the system lifetime. As the life period of wind generator, battery bank and inverter are shorter than PV system;

The replacement cost of the wind generator, the batteries and the inverter have to be included in the cost analysis of the hybrid system. Considering the inflation rate of component replacements ($f_{0}$) and real interest rate ($k_{d}$), the present value of replacement cost ($C_{rep}$) can be determined as follows [24]:

$$C_{rep} = C_{unit} \times C_{nom} \times \sum_{i=1}^{N_{rep}} \left\{ \frac{(1 + f_{0})}{(1 + k_{d})} \right\}^{N_{i}/N_{rep} + 1}$$  \hspace{1cm} (14)

Where $C_{nom}$ is the nominal capacity of the replacement system component (wind generator in (W); battery bank in (Wh); and inverter in (W)), $C_{unit}$ is the unit component cost (wind generator ($/W), battery bank ($/Wh) and inverter ($/W)), $k_{d}$ is
the annual real interest rate (8 – 10 %) and \( N_{\text{rep}} \) is the number of component replacements over the system life period.

### 4.2.3 The present value of operation and maintenance cost

In its general form, the present value of operation and maintenance cost of the hybrid system \( C_{\text{O&M,Hyb}} \) is expressed as [25]:

\[
C_{\text{O&M,Hyb}} = \begin{cases} 
C_{\text{O&M,0}} \times \left( \frac{1 + f_1}{k_d - f_1} \right) \times \left[ 1 - \left( \frac{1 + f_1}{1 + k_d} \right)^{L_p} \right] & \text{or } k_d = f_1 \\
C_{\text{O&M,0}} \times L_p & \text{for } k_d = f_1 
\end{cases}
\] (15)

Where \( f_1 \) is the inflation rate for operations, \( k_d \) is the annual real interest, \( L_p \) is the system life period in years. \( C_{\text{O&M,0}} \) is the operation and maintenance cost in the first year. It can be given as a fraction ‘ \( k \) ’ of the initial capital cost (\( C_{\text{IC}} \)).

\[
C_{\text{O&M,0}} = k \times C_{\text{IC}}
\] (16)

In this study it is assumed that all prices escalate at the same rate, and use ‘annual real interest rate’ rather than the ‘nominal interest rate’.

The following unit price, maintenance cost and lifetime of each component (PV array, wind generator, battery bank and inverter) in this study are assumed as mentioned in **Table 1**.

The configuration with the lowest (\( LCC \)) is taken as the optimal one from the set of configurations which guarantee the required reliability of power supply.

**Table 1**: The costs and lifetime aspect for the system components

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit price (US$/W)</th>
<th>Maintenance cost in the first year %</th>
<th>Lifetime (year)</th>
<th>Real interest rate ( k_d ) (%)</th>
<th>Inflation rate ( f ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array(^a)</td>
<td>4.84</td>
<td>1% of price</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind generator(^a)</td>
<td>3.000</td>
<td>3% of price</td>
<td>20</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Battery bank(^a)</td>
<td>0.190</td>
<td>1% of price</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inverter(^a)</td>
<td>0.713</td>
<td>0% of price</td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Mean value of the literature data

### 5. RESULTS AND DISCUSSION

#### 5.1 Case study

The recommended methodology has been applied to analyze a stand-alone hybrid PV/wind energy system, which is designed to supply residential household located in the area of the CDER (Center for Renewable Energy Development) situated in Bouzaréah, Algeria (36° 48'N, 3° 1'E, 345 m).

The technical characteristics of the PV module and wind turbine as well as the battery used in the studied project are listed in **Tables 2, 3 and 4**.
The load profile adopted in this research is that represented on figure 3. This hourly energy distribution is considered identical for every day of the year and corresponds to the load profile generally encountered in remote areas in Algeria.

Hourly data of solar irradiation on the horizontal plane, wind speed as well as ambient temperature recorded at Bouzaréah (Algeria) for the year 2003, are shown in Fig. 4. These data are used in system unit sizing, and the generation is assumed to keep constant in each hour interval.

**Table 2: Specifications of the PV module**

<table>
<thead>
<tr>
<th>Type</th>
<th>$V_{oc}$ (V)</th>
<th>$I_{sc}$ (A)</th>
<th>$V_{max}$ (V)</th>
<th>$I_{max}$ (A)</th>
<th>$P_{max}$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arco solar</td>
<td>21.7</td>
<td>2.7</td>
<td>17.3</td>
<td>2.49</td>
<td>43</td>
</tr>
</tbody>
</table>

**Table 3: Specifications of the wind turbine**

<table>
<thead>
<tr>
<th>Type</th>
<th>Rated power (W)</th>
<th>Cut-in speed $V_c$ (m/s)</th>
<th>Rated speed $V_R$ (m/s)</th>
<th>Cut-off speed $V_f$ (m/s)</th>
<th>Tower high (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR 408</td>
<td>21.7</td>
<td>2.7</td>
<td>17.3</td>
<td>2.49</td>
<td>43</td>
</tr>
</tbody>
</table>

**Table 4: Specifications of the single battery**

<table>
<thead>
<tr>
<th>Type</th>
<th>Nominal capacity</th>
<th>Voltage</th>
<th>Round-trip Efficiency</th>
<th>DOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Varta solar</td>
<td>100 Ah</td>
<td>12 V</td>
<td>0.85 %</td>
<td>50  %</td>
</tr>
</tbody>
</table>

5.2 Impact of power reliability on system configurations

The relationships between system reliabilities and system configurations are studied. Figs. 4, 5 and 6 show the results of the relationship between system reliabilities or DPSP values and system configurations for different days of autonomy of the battery bank.

Fig. 4 shows the relationships for a one day-storage battery bank. In this figure, the curves are hyperbolic nature. Each point of them represents a couple (Number of PV modules, Wind turbine power) that guarantees the desired energy autonomy. In the case of a zero value of the DPSP, the corresponding curve is called curve of autonomy of the
system: each point of this curve represents a combination which ensures the total autonomy of the system.

The areas above the curves are also configurations that can ensure the required power reliability. It also shows that when the system reliability is higher; the system configuration (PV module and wind turbine power) is higher too for the same capacity of battery bank.

A similar situation happens to the system for two and three days- storage battery bank (Figs. 5 and 6), but compared to the system with one day- storage battery bank, the PV module and wind turbine power are more moderate. It means the hybrid system with more batteries (3 days of storage capacity) can meet the load demand with less supply failure.
Fig. 3: Meteorological conditions for optimal design (a) solar irradiation on horizontal plane, (b) wind speed and (c) ambient temperature

Fig. 4: System configurations for different DPSP for 1 day of autonomy of the battery bank

Fig. 5: System configurations for different DPSP for 2 days of autonomy of the battery bank
5.3 Impact of system configurations on the LCC

The configurations meeting different desired DPSP requirements under different battery capacities are obtained from the simulation results. After the technical criteria, the Life Cycle Cost (LCC) is utilized as the economic benchmark. The simulation results are demonstrated, and the relationships between the LCC and power reliabilities as well as the system configurations are analyzed.

![Fig. 6: System configurations for different DPSP for 3 days of autonomy of the battery bank](image)

In Figs. 7, 8 and 9, the curves bellow in solid symbols show the results of the relationship between system reliabilities or DPSP values and system configurations for different days of autonomy of the battery bank (already presented in Figs. 4, 5 and 6). Whereas, curves given by the hollow symbols in Figs. 7, 8 and 9, represent the Life Cycle Cost (LCC) under different configurations.

Obviously, one point with the minimum LCC value occurs in each curve which means the best configuration for one certain DPSP value and one certain battery bank. This configuration is considered as the optimal one which meets the system reliability requirement with the lowest LCC value.

On the other hand, a meticulous examination into Figs. 7, 8 and 9 shows that the lowest LCC is found when the capacity of wind turbine and the number of PV modules are both moderate. It is also shown that the LCC for one days’ batterystorage is lower than two and three days’ for the desired DPSP of 0.1 %, 0.3 % and 1 % for the studied case because batteries are much more expensive with a short lifespan.
Fig. 7: System configurations and Life Cycle Cost for 1 day’s storage

Fig. 8: System configurations and Life Cycle Cost for 2 days’s storage

Fig. 9: System configurations and Life Cycle Cost for 3 day’s storage
6. CONCLUSIONS

In this present study, an optimal sizing model is developed to optimize the capacity sizes of different components of grid-independent hybrid PV/Wind power generation system using a battery bank. The recommended model consists of three main parts: the submodel of the hybrid system, the technical submodel developed according to the Deficiency of Power Supply Probability (DPSP) technique for system reliability evaluation and the economic submodel developed based on the concept of the Life Cycle Cost (LCC) which is considered as a good indicator of economic profitability in the field of renewable energy. A set of configurations meeting the desired DPSP can be obtained by using the DPSP submodel. The configuration with the lowest LCC gives the optimal one.

A case study is conducted to analyze one hybrid project, which is designed to supply residential household located in the area of the CDER (Center for Renewable Energy Development) situated in Bouzaréah, Algeria (36° 48'N, 3° 1'E, 345 m). The algorithm input data set consists of hourly solar irradiation on the horizontal plane, wind speed as well as ambient temperature recorded at Bouzaréah (Algeria) for the year 2003, the desired DPSP, load power requirements during the year and specifications of the system devices.

A grid-independent hybrid PV/Wind system is simulated by running the developed program and the relationships between system power reliability and system configurations have been studied. The optimal configurations of the hybrid system are determined in terms of different desired system reliability requirements (DPSP) and the Life Cycle Cost (LCC).

REFERENCES


