A novel optimization sizing model for hybrid solar-wind power generation system

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Abstract

This paper develops the Hybrid Solar-Wind System Optimization Sizing (HSWSO) model, to optimize the capacity sizes of different components of hybrid solar-wind power generation systems employing a battery bank. The HSWSO model consists of three parts: the model of the hybrid system, the model of Loss of Power Supply Probability (LPSP) and the model of the Levelised Cost of Energy (LCE). The flow chart of the HSWSO model is also illustrated. With the incorporated HSWSO model, the sizing optimization of hybrid solar-wind power generation systems can be achieved technically and economically according to the system reliability requirements. A case study is reported to show the importance of the HSWSO model for sizing the capacities of wind turbines, PV panel and battery banks of a hybrid solar-wind renewable energy system.

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Keywords: Hybrid solar-wind system; Loss of Power Supply Probability (LPSP); Levelised Cost of Energy (LCE)

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 investment and reliability requirement of the demand load.

There are a number of studies about the optimization and sizing of hybrid PV-wind system since the popular utilization of photovoltaic modules and wind turbines in the 1980s. Generally, there are three main approaches to achieve the optimal configurations of hybrid systems in terms of technical analysis and economical analysis, i.e. the least square method (Castle, 1981; Borowy and Salameh, 1994; Gomaa et al., 1995), the loss of power supply probability (LPSP) method (Abouzahr and Ramakumar, 1990, 1991; Beyer and Langer, 1996; Yang et al., 2003) and the trade-off method (Burke, 1988; Gavanidou and Bakirtzis, 1992; Yang and Burnett, 1999; Chedid et al., 1998; Elhadidy and Shaahid, 1999).

In this paper, the hybrid solar-wind system optimization sizing (HSWSO) model, a novel optimum sizing tool for hybrid solar-wind systems employing a battery bank, is developed based on the loss of power supply probability
(LPSP) concept and the levelised cost of energy (LCE) concept. The LPSP technique, which is considered 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 LPSP 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. Additionally, the orientations of PV modules and the tower heights of wind turbines are also considered. The optimum configuration can be identified from the set of the above obtained configurations by achieving the lowest levelised cost of energy.

2. Model of hybrid solar-wind system

A hybrid solar-wind power generation system consists of a PV system, a wind power system, a battery bank, rectifiers, an inverter, and a controller, other accessory equipment and cables. Sometimes the system loads also include one dump load for safety protection. The power supply from the PV modules and the wind turbine to the demand side, the battery bank and the dump load obey the following priority: first the demand side; second the battery bank; last the dump load.

2.1. Mathematical model for PV system

The power generation simulation model for a PV system is composed of three parts: PV modules, PV array, and the solar radiation on any tilted PV panels for any orientations. The model of PV arrays can be used to represent the model of the PV system.

2.1.1. PV modules

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 this paper, one simplified applicable model for the maximum power output of PV modules is used. The regressed parameters and the model are described as follows:

\[ P_m = -(aG_b + b) \cdot (T_a + 0.03375G_b) + cG_b + d, \]

where \( G_b \) is the total solar radiation absorbed by the PV modules, W/m\(^2\); \( T_a \) is the ambient temperature around PV modules, K; and \( a, b, c \) and \( d \) are constants from regression results for PV modules.
Thus, once the solar radiation on PV panels and ambient temperature are known, the power output of the PV module can be calculated easily and accurately. The parameters in the model can be regressed from site tests, and then the models can be used in the PV module performance simulation.

2.1.2. PV arrays

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 $V_{\text{PVA}}$ of the PV array is:

$$V_{\text{PVA}} = N_{\text{PYS}} \cdot V_{\text{PV}}$$

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

$$P_{\text{PVA}} = N_{\text{PVY}} \cdot N_{\text{PYS}} \cdot V_{\text{PV}} \cdot I_{\text{PV}} \cdot F_{\text{con}} \cdot F_{\text{oth}},$$

where $N_{\text{PYS}}$ is the serial connection number of the PV modules; $N_{\text{PVY}}$ is the parallel connection number of the PV module strings; and $F_{\text{con}}$ and $F_{\text{oth}}$ are the factors representing connection loss and other losses such as the loss caused by accumulative dust etc.

2.1.3. Total solar radiation absorbed by PV modules

The electricity power generated by photovoltaic (PV) systems is directly related to the solar energy received by the PV panels, while the PV panels can be placed at any orientation and at any tilted angles. Most local observatories only provide solar irradiance data on a horizontal plane. Thus, an estimate of the total solar radiation incident on any sloping surfaces or PV panels at any orientation is needed.

In this paper, the Perez model is utilized to estimate the diffuse solar radiation incident on any tilted PV panels ($\gamma, \beta$). The newest improved version of the Perez model (Perez et al., 1990) offers the recommended set of coefficients which are derived from the weather data in many cities. It represents better results than the earlier set. The model accounts for circumsolar, horizon brightening, and isotropic diffuse radiation by empirically derived ‘reduced brightness coefficients’. The brightness coefficients, $F_1$, $F_2$, are functions of sky clearness, $\varepsilon$, and sky brightness parameters, $\Delta$:

$$\varepsilon \equiv \frac{(G_{\text{dh}} + G_{\text{dh}})/G_{\text{dh}} + 1/0410^3}{1 + 1/0410^3},$$

$$\Delta \equiv \frac{G_{\text{dh}} \cdot m}{G_{\text{to}} \cdot \cos \theta_z} = \frac{G_{\text{dh}}}{G_{\text{to}}},$$

where $m$ is air mass.

The sky clearness and sky brightness parameters are used to calculate the reduced brightness coefficients from the relationships and so-called Perez coefficients:

$$F_1 = F_{11} (\varepsilon) + F_{12} (\varepsilon) \cdot A + F_{13} (\varepsilon) \cdot \theta_z,$$

$$F_2 = F_{21} (\varepsilon) + F_{22} (\varepsilon) \cdot A + F_{23} (\varepsilon) \cdot \theta_z.$$  

The angular location of the circumsolar region is determined by the ratio $a/c$.

$$a = \max[0, \cos \theta],$$

$$c = \max[\cos 85, \cos \theta_z].$$

Then the solar diffuse radiation on the tilted surface can be estimated by:

$$G_{\text{dh}} = G_{\text{dh}} \cdot \cos^2 \left( \frac{\theta_z}{2} \right) \cdot (1 - F_1) + G_{\text{dh}} \cdot F_1 \cdot \left( \frac{\theta_z}{c} \right) + G_{\text{dh}} \cdot F_2 \cdot \sin \beta,$$

For the Perez coefficients, there are many sets of values from different studies (Perez et al., 1990, 1987). In this paper, we applied the newest set of coefficients from Perez et al. (1990) which are widely used, as shown in Table 1.

2.2. Modeling of wind energy conversion system (WECS)

There are three main factors which determine the power output of a whole wind energy conversion system (WECS), i.e., the power output curve (determined by aerodynamic power efficiency, mechanical transmission $\eta_m$ and converting electricity efficiency $\eta_e$) of a chosen wind turbine, the wind speed distribution of a selected site where the wind turbine is installed, and the hub height of the wind tower.

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 (Lu et al., 2002) can be described by:

$$P_w(v) = \begin{cases} P_R \cdot \frac{v - \nu_C}{v - \nu_R} \quad (\nu_C \leq v \leq \nu_R) \\ P_R \quad (\nu_R \leq v \leq \nu_F) \\ 0 \quad (v \leq \nu_C \text{ and } v \geq \nu_F), \end{cases}$$

where $P_R$ is the rated electrical power; $\nu_C$ is the cut-in wind speed; $\nu_R$ is the rated wind speed; and $\nu_F$ is the cut-off wind speed.

For small-scale wind turbines, the cut-in wind speed is relatively smaller, and wind turbines can operate easily even when wind speed is not very high.

The variation of wind speed with elevation influences both the assessment of wind resources and the design of wind turbines. A model of the wind speed variation with

Table 1

<table>
<thead>
<tr>
<th>$\varepsilon$</th>
<th>$F_{11}$</th>
<th>$F_{12}$</th>
<th>$F_{13}$</th>
<th>$F_{21}$</th>
<th>$F_{22}$</th>
<th>$F_{23}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1.065</td>
<td>0.008</td>
<td>0.588</td>
<td>-0.062</td>
<td>-0.060</td>
<td>0.072</td>
<td>-0.022</td>
</tr>
<tr>
<td>1.065-1.23</td>
<td>0.130</td>
<td>0.683</td>
<td>-0.151</td>
<td>-0.019</td>
<td>0.066</td>
<td>-0.029</td>
</tr>
<tr>
<td>1.23-1.5</td>
<td>0.330</td>
<td>0.487</td>
<td>-0.221</td>
<td>0.055</td>
<td>-0.064</td>
<td>-0.026</td>
</tr>
<tr>
<td>1.5-1.95</td>
<td>0.568</td>
<td>0.187</td>
<td>-0.295</td>
<td>0.109</td>
<td>-0.152</td>
<td>-0.014</td>
</tr>
<tr>
<td>1.95-2.8</td>
<td>-0.873</td>
<td>-0.392</td>
<td>-0.362</td>
<td>0.226</td>
<td>-0.462</td>
<td>0.001</td>
</tr>
<tr>
<td>2.8-4.5</td>
<td>1.132</td>
<td>-1.237</td>
<td>-0.412</td>
<td>0.288</td>
<td>-0.823</td>
<td>0.056</td>
</tr>
<tr>
<td>4.5-6.2</td>
<td>1.060</td>
<td>-1.600</td>
<td>-0.359</td>
<td>0.264</td>
<td>-1.127</td>
<td>0.131</td>
</tr>
<tr>
<td>6.2-</td>
<td>0.678</td>
<td>-0.327</td>
<td>-0.250</td>
<td>0.156</td>
<td>-1.377</td>
<td>0.251</td>
</tr>
</tbody>
</table>
height is also required in wind energy applications. Generally, two mathematical models can be used to model the vertical profile of wind speed over regions of homogenous, flat terrain (e.g., fields, deserts, and prairies). The first approach, the log law, has its origins in boundary layer flow in fluid mechanics and in atmospheric research. The second approach is the power law which is widely applied by researchers. Here, the power law is utilized. In general, the power law represents a simple model for the vertical wind speed profile. Its basic form is:

$$\frac{v}{v_r} = \left( \frac{z}{z_r} \right)^{-\frac{1}{z}}.$$  \hspace{1cm} (11)

where $v$ is the wind speed at hub height $z$ (the height of the turbine above the ground), m/s; $v_r$ is the wind speed measured at the reference height $z_r$, m/s; $z$ is the power law exponent. $z$ varies with such parameters as elevation, time of day, season, nature of the terrain, wind speed, temperature, and various thermal and mechanical mixing parameters. The determination of $z$ becomes very important. The value of $1/7$ is usually taken when there is no specific site data.

### 2.3. Modeling of battery bank

Pb-acid batteries are usually used for energy storage. The selection of a proper size of the battery bank for these types of applications requires a complete analysis of the battery’s charge and discharge requirements, including load, output and pattern of the solar or alternative energy sources, the operating temperature, and the efficiency of the charger and other system components. Usually, energy losses occur when charging the battery bank, and the efficiency drops when the battery ages and is not operated correctly.

When the total output of the PV arrays and wind generator is more than the energy demand, the battery bank is charged. Usually, two properties of the battery are related to the hybrid system’s performance, i.e. the state of charge (SOC) and the float charge voltage.

#### 2.3.1. State of charge

The battery’s state of charge (SOC) is simulated during the charging process by:

$$\text{SOC}(t+1) = \text{SOC}(t) \cdot (1 - \sigma(t)) + \frac{I_{\text{bat}}(t) \cdot \Delta t \cdot \eta_c(t)}{C_{\text{bat}}},$$  \hspace{1cm} (12)

where $\sigma(t)$ is the hourly self-discharge rate which is determined by the accumulated charge and the battery state of health (Guasch and Silvestre, 2003), the proposed average approximation of 0.02% is used in this study; $C_{\text{bat}}$ is the nominal battery capacity Ah.

The charge efficiency factor, $\eta_{\text{Ch}}(t)$, influenced by the conditions of the battery, i.e. the charging current and SOC($t$), is described by:

$$\eta_{\text{Ch}}(t) = 1 - \exp \left[ \frac{a \cdot (\text{SOC}(t) - 1)}{I_{\text{bat}}(t)/I_0 + b} \right].$$  \hspace{1cm} (13)

where $a$, $b$ and $I_0$ are parameters determined by the working conditions of the battery.

In addition, the charging current at time $t$, $I_{\text{bat}}(t)$, can be described for the hybrid photovoltaic-wind power conversion system (when the power generated by the hybrid system exceeds the load demand) by:

$$I_{\text{bat}}(t) = \frac{P_{\text{PV}}(t, \gamma, \beta)}{V_{\text{bat}}(t)} + \frac{P_W(t, h) \cdot \eta_{\text{in}}(t)}{V_{\text{bat}}(t)} - \frac{P_{\text{load}}(t) / \eta_{\text{in}}(t)}{V_{\text{bat}}(t)}.$$ \hspace{1cm} (14)

The boost rectifier efficiency $\eta_{\text{rectifier}}(t)$ is considered as a constant, 95%, in this study. The rectifier is used to transform the AC power from the wind power generation system to DC power of constant voltage. The inverter efficiency is considered as 92% according to the load profile and the specifications of the ASP TC13/24 Inverter.

During the discharge process, the battery’s state of charge (SOC) is computed (when the power generated by the hybrid system cannot meet the load demand) as follows:

$$\text{SOC}(t+1) = \text{SOC}(t) \cdot (1 - \sigma(t)) - \frac{I_{\text{bat}}(t) \cdot \Delta t}{C_{\text{bat}}},$$  \hspace{1cm} (15)

where

$$I_{\text{bat}}(t) = \frac{P_{\text{load}}(t) / \eta_{\text{in}}(t)}{V} + \frac{P_{\text{PV}}(t, \gamma, \beta)}{V} - \frac{P_W(t, h) \cdot \eta_{\text{in}}(t)}{V}.$$ \hspace{1cm} (16)

Meanwhile, the charged quantity of the battery is subject to the following two constraints:

$$\text{SOC}_{\text{min}} \leq \text{SOC}(t) \leq \text{SOC}_{\text{max}}$$ \hspace{1cm} (17)

and

$$I_{\text{bat,max}}(t) = \max \{ 0, \min [I_{\text{max}}(t, C_{\text{bat}}) \cdot c \cdot (\text{SOC}_{\text{max}} - \text{SOC}(t)) + (\text{SOC}(t) - \text{SOC}_{\text{min}}) \cdot (1 - c) / \Delta t] \}.$$ \hspace{1cm} (18)

The maximum value of the SOC is 1, and the minimum SOC is determined by the maximum depth of discharge (DOD), $\text{SOC}_{\text{min}} = 1 - \text{DOD}$.

According to the specifications from manufacturers, the battery’s lifetime can be prolonged to the maximum if DOD takes the value of 30–50%. In this study, 30% is utilized as the value of the DOD.

The amount of maximum possible battery current rate $I_{\text{bat, max}}$ at time $t$ depends on the battery’s state at each instant time. $I_{\text{max}}$ is given by manufacturers around 20% of the value of nominal capacity, and $c$ is zero during discharge process and one during charge process.

#### 2.3.2. Floating charge voltage of battery

The battery model describing the relationship between the voltage, current and the state of charge is found from the literature (Yang et al., 2003; Yoon-Ho and Hoi-Doo,
The terminal voltage (or floating charge voltage) of a battery is expressed in terms of its open circuit voltage and the voltage drop across the internal resistance of the battery:

\[ V_{\text{bat}}(t) = V_{\text{oc}}(t) + I_{\text{bat}}(t)R_{\text{bat}}(t), \quad (19) \]

where \( V_{\text{oc}}(t) \) is the battery open circuit voltage at time \( t \), \( V \); and \( R_{\text{bat}}(t) \) is internal resistance of the battery, ohms. The open circuit voltage is expressed as a logarithmic function of the state of charge:

\[ V_{\text{oc}}(t) = V_F + b \log(SOC(t)), \quad (20) \]

where \( V_F \) is the full charge rest voltage and \( b \) is an empirical constant.

The variation of the internal resistance of a battery, \( R_{\text{bat}}(t) \), is mainly due to two components, namely, the resistance of the electrode, \( R_{\text{electrode}} \), and the resistance of the electrolyte, \( R_{\text{electrolyte}} \):

\[ R_{\text{bat}}(t) = R_{\text{electrode}}(t) + R_{\text{electrolyte}}(t), \quad (21) \]

where \( R_{\text{electrode}} \) and \( R_{\text{electrolyte}} \) are functions of SOC, which can be expressed as:

\[ R_{\text{electrode}}(t) = r_1 + r_2(SOC(t)) \quad \text{and} \quad R_{\text{electrolyte}}(t) = [r_3 - r_4(SOC(t))]^{-1}, \quad (22) \]

where \( r_1, r_2, r_3 \) and \( r_4 \) are empirical constants. It is noted that as these constants have different values for charging and discharging modes, the values of \( R_{\text{electrode}} \) and \( R_{\text{electrolyte}} \) are therefore different for those two modes as well. All the coefficients in the battery model can be determined by conducting charging and discharging tests on the battery. The values of various parameters obtained for the battery in this study are presented in Table 2.

### 2.4. The load model

The load demand, \( P_{\text{LOAD}} \), determines the requirements of power supply from the hybrid system. The loads can be DC or AC. The load models are simulated according to the dynamic demand loads.

### 3. The reliability model based on the LPSP concept

Two definitions of probability are often used to express the reliability of the power supply of the system. One is the loss of load probability (LLP) defined as the power failure time period divided by the estimated period of time \( T \), and the other is the loss of power supply probability (LPSP) 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 LPSP 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 LPSP technique.

The objective function of the LPSP from time 0 to \( T \) can be described by:

\[ \text{LPSP} = \sum_{t=0}^{T} \text{Power} \cdot \text{failure} \cdot \text{time}(P_{\text{supplied}}(t) < P_{\text{needed}}(t)), \]

where \( N_h \) is the number of time intervals, the number of hours in this study with an hourly weather data input.

Accordingly, the power needed by the load side can be expressed as:

\[ P_{\text{needed}}(t) = P_{\text{load}}(t) / \eta_{\text{inverter}}(t) \quad (24) \]

and the power supplied from the hybrid system can be expressed by:

\[ P_{\text{supplied}}(t) = P_{\text{PV}}(t; \gamma, \beta) + P_{\text{wind}}(t, h) + c \cdot V_{\text{bat}}(t) \]

\[ \cdot \text{MIN} \left[ I_{\text{bat, max}} / \Delta t, C_{\text{bat}} \cdot (\text{SOC}(t) - \sigma - \text{SOC}_{\text{min}}) / \Delta t \right], \quad (25) \]

where \( c \) is a constant, 0 for battery charging process and 1 for battery discharging process.

Using the above-developed objective function according to the LPSP technique, the system configuration can be optimized for certain load profile according to the desired reliability of the system. For a given LPSP value for one year, one set of configurations of a hybrid system can technically guarantee the required reliability of power supply.

### 4. The economic model based on the LCE concept

An optimum combination of a hybrid solar wind energy system must satisfy both the reliable and economical requirements.

Since more concerns are given to the lowest energy cost in commercial projects, the economical approach, according to the concept of the Levelised Cost of Energy, is developed to be the best benchmark of cost analysis in this study.

According to the studied hybrid solar-wind power generation system, the Levelised Cost of Energy is defined as the total cost of the whole hybrid system divided by the energy supplied from the hybrid system. The economic model can thus be expressed accordingly by three parts

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Charging mode</th>
<th>Discharging mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>VF (V)</td>
<td>13.250</td>
<td>12.662</td>
</tr>
<tr>
<td>b</td>
<td>0.810</td>
<td>0.724</td>
</tr>
<tr>
<td>( r_1 ) (Ω)</td>
<td>0.062</td>
<td>0.055</td>
</tr>
<tr>
<td>( r_2 ) (Ω)</td>
<td>-0.046</td>
<td>-0.010</td>
</tr>
<tr>
<td>( r_3 ) (Ω⁻¹)</td>
<td>95.638</td>
<td>4.270</td>
</tr>
</tbody>
</table>

Table 2 Coefficients of the battery obtained from experimental tests
(about PV array, wind generator, and battery banks), which are:

\[
LCE = \sum_{i=1}^{n}(\frac{CO_i}{y_i}) = \frac{CO_{PV}/Y_{PV} + CO_W/Y_W + CO_{Bat}/Y_{Bat}}{E_{an}(\gamma, \beta, h)}
\]

where LCE is the Levelised Cost of Energy, $/kWh; CO_{PV}$ is the sum of capital cost and maintenance cost in the lifespan of the whole PV system; CO_W is the sum of capital cost and replacement or maintenance cost in the lifespan of the whole wind power generation system; CO_{Bat} is the sum of capital cost and the lifespan maintenance cost of battery bank; $Y_{PV}$ is the lifetime year of PV system; $Y_W$ is the lifetime year of wind system; $Y_{Bat}$ is the lifetime year of battery bank; and $E_{an}(\gamma, \beta, h)$ is the annual energy supplied from the hybrid solar-wind system.

The following initial price, maintenance cost and lifetime of the PV modules, wind system and the battery bank are suggested in this study as in Table 3.

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

5. Flow chart of the HSWSO model

The Solar-Wind System Optimization Sizing (HSWSO) model is a simulation tool to obtain the optimum sizes or optimal configuration of a hybrid solar-wind power generation system employing a battery bank in terms of the LPSP technique and the LCE concept, the flow chart of HSWSO model is illustrated in Fig. 1. Generally, the evaluation and optimization approach of the HSWSO model is mainly composed of the following steps:

<table>
<thead>
<tr>
<th>The initial price, maintenance cost and lifespan of the system component</th>
<th>Initial price (US$/kW)</th>
<th>Maintenance cost (US$/kW per year)</th>
<th>Life span (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV modules</td>
<td>3330</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>Wind system</td>
<td>2000</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Battery bank</td>
<td>80</td>
<td>25</td>
<td>4</td>
</tr>
</tbody>
</table>

Fig. 1. Flow chart of the HSWSO method.
(a) The application of hybrid solar-wind power generation system is studied by analyzing the local long term weather data. Good solar resources and wind energy resources validate the potential applications of solar and wind energy resources, while good complementary characteristics between solar energy and wind energy testify the feasibility and reliability of hybrid solar-wind applications.

(b) For system modeling, there are three main parts, PV modules, wind turbines, and battery bank. In the modeling of wind turbines, the height of the tower hub of wind turbine is an important factor which significantly influences the operating performance of wind turbines. With the wind speed at the hub height calculated by Eq. (11) from the input weather data, the power output of the wind turbine can easily be obtained. The modeling of a battery bank is carried out according to the specifications of Pb-acid battery. For a perfect knowledge of the real SOC of a battery, it is necessary to know the initial SOC, then the battery SOC at time $t+1$ can be simply calculated by Eq. (15). The modeling of PV modules includes two main parts: calculation of the total solar radiation on any tilted surface with any orientation, and then the modeling of the maximum power output of PV modules with the calculated total solar radiation.

(c) The last step is to optimize the sizing of hybrid solar-wind power generation system according to the LPSP technique and the LCE technique. The annual LPSP simulation is performed by Eq. (23) with the long-term weather data and the demand load input. Then the system configurations which can meet the desired LPSP requirements or power supply reliability requirements are obtained by changing the number of PV modules, the orientations of PV modules, the capacity (rated power) of the wind turbine, the tower height of the wind turbine, and the capacity of the battery bank. Then the configuration with the lowest value of LCE (calculated by Eq. (26)) for the desired LPSP is the optimal choice. Thus, the hybrid system can be sized both technically and economically according to the system reliability requirements.

6. A case study of the simulation model

A case study is carried out for one project, i.e. the optimization sizing and operating characteristics of the hybrid system for a communication station based in Guangdong of China by running the HSWSO program. This project is to supply power for a telecommunication relay station on a remote island in Shanwei of Guangdong province, China. Its demand load includes 700 W carrier wave (220 V AC) and 55 W microwave (24 V DC). According to the project requirement and technical considerations, 1000 W is chosen as the demand load.

Table 4
Specifications of the PV modules
<table>
<thead>
<tr>
<th>Height (mm)</th>
<th>Width (mm)</th>
<th>PV area (m²)</th>
<th>$I_{sc}$ (A)</th>
<th>$V_{oc}$ (V)</th>
<th>$P_{max}$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1280</td>
<td>357</td>
<td>0.457</td>
<td>2.5</td>
<td>22</td>
<td>50</td>
</tr>
</tbody>
</table>

The specifications of the PV modules are listed in Table 4. For the PV array, the optimization starts from 20 PV modules. The panels are facing south with an inclination angle of 29.5°. Considering the capacity of the demand load, 0.5 kW wind generator is chosen as the starting point with an interval of 0.1 kW. Since the tower heights of wind turbines affect the simulation results significantly, 20 meter high tower is chosen. All the energy losses $F_A$ in a PV sub-system, including connection loss, wiring loss and other losses, are taken as 5%.

7. Simulation results

The relationships between system reliabilities and system configurations are studied, as well as the relationships between the LCE and system configurations. The optimal configurations of the hybrid system are given accordingly for different desired reliability requirements.

7.1. Reliabilities and system configurations

Figs. 2 and 3 show the results of the relationship between LPSP values or system reliabilities and system configurations. Fig. 2 shows the relationships for a one-day-storage battery bank. It is obvious that most configurations of wind turbine and PV modules with low LPSP values (or high system reliabilities) are located in the...
middle area where combinations have moderate numbers of PV modules and moderate capacity of wind turbines. It also shows that LPSP can reach zero only when the rated power of wind turbine (WT) reaches 10 kW and number of PV modules reaches 270 for stand-alone systems with a one-day-storage battery bank. Among these configurations, those meeting the desired LPSP values can be obtained.

For the battery bank with 3-day-storage, the LPSP values can reach zero very soon with fewer PV modules and a smaller wind turbine, as shown in Fig. 3. It means the hybrid system with more batteries can meet the demand load with less supply failure.

From these simulation results, the reliability can be estimated for different combinations of the hybrid solar-wind system.

7.2. LCE and system configurations

The configurations meeting different desired LPSP requirements are obtained from the simulation results. After the technical process, the Levelised Cost of Energy (LCE) is utilized as the economic benchmark. The simulation results are demonstrated, and the relationships between the LCE and system configurations are analyzed.

As shown in Figs. 4 and 5, the curves of the LCE for those configurations meeting the desired LPSPs are plotted. Obviously, one point with the minimum LCE value occurs in each curve which means the best configuration for one certain LPSP value and one certain battery bank. This configuration is considered as the optimal one which meets the system reliability requirement with the lowest LCE value. The grey dashed curves on XY surfaces give the configurations which can meet the system reliability requirements.

A deeper inspection into Figs. 4 and 5 shows that the lowest LCE is found when the capacity of wind turbine and the number of PV modules are both moderate.

7.3. Sizing optimization from the HSWSO model

The minimum Levelised Costs of Energy for different employed battery numbers are given in Fig. 6. The best configuration for an LPSP of 5% happens when the battery bank only employs ten batteries which mean 50% capacity of one day’s power consumption by the demand side. It also proves that the battery bank is heavy in the LCE calculation. Fewer batteries are suitable for low reliable requirement systems with lower cost.

For an LPSP of 1%, the configurations with a 0.5-day-storage battery bank cannot meet the reliability
requirement, but the configurations with more than a 1-day-storage battery bank can. Similarly, the optimal configuration is the system with the fewest batteries of 1-day storage capacity as the battery is very expensive with a short lifespan.

The optimal combination for 100% reliability system comes with a 2-day-storage battery bank, and only the configuration with more than 1.5-day-storage battery bank can meet this reliability requirement.

These results may change for different types of PV modules, different wind turbines, different costs, and different types of batteries. The heights of wind turbines and orientations of PV modules can also influence the simulation results.

Increasing the number of PV panels and capacity of wind turbine could be a better choice than just increasing the number of batteries since batteries are much more expensive with a short lifespan. But, for high reliability systems, too few batteries cannot meet the reliability requirements, which causes high cost because too many PV modules or too large wind turbines are required.

Higher reliability systems are significantly more expensive than lower requirement systems. Choosing an optimal system configuration according to system reliability requirements can help save investment and avoid high capital spending.

8. Conclusions

The HSWSO model is developed in this paper to optimize the sizing of the hybrid solar-wind power generation system employing a battery bank. It includes three main parts: system models for PV system, wind system and battery bank; the technical model developed according to the Loss of Power Supply Probability (LPSP) technique for system reliability evaluation; and the economic model developed based on the concept of the Levelised Cost of Energy for cost analysis.

The system configurations can be obtained in terms of system power supply reliability requirement or system desired LPSP value by using the LPSP model. The one with the lowest Levelised Cost of Energy is considered as the economical optimal configuration. The optimal configuration of the number of PV modules, the capacity of wind turbine, and the capacity of battery bank can be obtained technically and economically by using the HSWSO model.

A hybrid solar-wind system is simulated by running the HSWSO program, and its relationships with system configurations are also analyzed. The optimal configurations of the hybrid system are obtained in terms of different desired system reliability requirements and the LCE.

References


