International Journal of Mechanics and Energy (IJME)
Vol. 1, Issue 1, 2013, ISSN: 2286-5845

Optimal Sizing of Photovoltaic Wind Hybrid Systems

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Abstract: This paper presents an optimal sizing method of an autonomous hybrid wind photovoltaic system. The main objective of this study is to determine the optimal characteristics of a system able to cover the energy demands of a consumer for a given specific location. This method is essentially based on two main phases. The modeling of the autonomous hybrid system is considered the first phase in the process of optimal sizing. The second phase is to optimize the dimensioning of the system based on the lack of energy to generate probability (LEGP), percentage of the surplus of energy produced (PSEP) and the cost of the kilowatt-hour produced (C_{kWh}).

From these two phases, a simulation code has been developed as a working tool able to perform the analysis and optimization of a hybrid system for given load and location.

Therefore, a case study that uses this code was presented to determine the optimal configuration of a system that meets the energy requirements (5kWh/jour) of a house located in Sfax, Tunisia.

Key words: hybrid system, modeling, optimal sizing, simulation algorithm.

1. Introduction

Global problems of the environment, the significant growth of energy needs, the rapid depletion of global resources fuels and steady progress of renewable energy technologies have provided new opportunities for the use of renewable resources. However, solar and wind resources are considered the most promising generators and more. To use these energy resources more efficiently and economically, the optimal sizing of renewable energy systems is important.

Several optimization techniques of hybrid systems have been reported in the literature. For example, S. Diaf [1, 2] presented through its research a simple and useful methodology of optimization design of a hybrid autonomous system (solar wind). The main objective of the study is to find the optimal size of the system. The optimization model developed consists of technical models based LPSP (Loss of Power Supply Probability) and models based on the levelized cost of energy (LCE).

Tina [3] presented a probability approach based on a technique that incorporates the variable nature of resources and demand. The performance of a hybrid (PV-wind) has been studied for the case where autonomous and connected to the network.

The comparison of different types of power conversion chain has been the main objective of the work of O. Gergaud [4] for the search of management strategies of the flow of energy produced by the system. These approaches have been used to achieve the technical and economic optimization of the system.

Yang [5, 6] proposed an optimization technique that follows the model of LPSP (Loss of Power Supply Probability) for a hybrid wind photovoltaic system. Therefore, the main objective of this study is the selection of the necessary power photovoltaic modules, wind turbines and batteries to provide consumer

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demand. This technique is developed based on a genetic algorithm (GA).

Other researchers such as A. Singo [7] have focused their research in the storage modes associated with autonomous energy systems for optimizing the management of the energy produced. The authors compared several types of storage system trying to combine different types for better performance.

Indeed, in this paper, a new method of optimal sizing of autonomous hybrid systems (wind/photovoltaic) intended for a specific location has been developed based on the lack of energy to generate probability (LEGP), percentage of the surplus of energy produced (PSEP) and the cost of the kilowatt-hour produced (CkWh). A simulation code has been developed as a working tool that can analyze and optimize system configurations. The objective of this optimization process is to find the optimum configuration that gives the best compromise between the three considered factors: LEGP, PSEP and Ckwh.

2. Presentation of the hybrid system

A hybrid energy system is composed of a wind turbine, a photovoltaic generator, a storage unit (typically batteries) and a control system which provides control of various components. A schematic presentation of the system is shown in Figure 1.

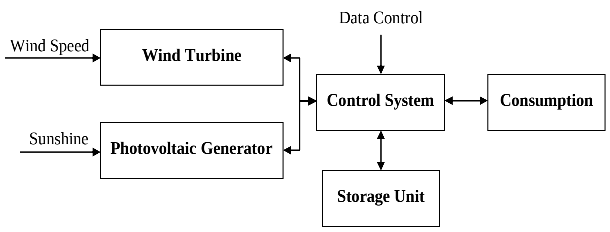

Fig. 1 Presentative diagram of an autonomous hybrid system

3. Hybrid system modeling

In our study, three main sub-systems are included: wind turbine, PV generator and the unit of storage.

In fact, the optimal design of such a system starts with an estimate of the daily consumption of the user. This estimate is the most important factor in determining the characteristics of the system components.

Indeed, the daily energy need B_j represents the sum, for N devices, of the rated power of each device receiver, P_{an}, multiplied by the number of hours of use per day t_j.

$$B_j = \sum_{i=1}^{N} \left(P_{an_i} \cdot t_{j_i} \right) \quad (1)$$

2.1 Mathematical model of the wind turbine

Choose a suitable model is very important for the simulation of the power produced by a wind turbine. There are three main factors that determine power output: the distribution of the wind speed of the selected location (where the machine is located), the power curve of the turbine chosen and the height of the tower.

The power transmitted by a wind P_t is given by the following formula:

$$P_t = \frac{1}{2} \cdot C_p \cdot \rho \cdot S \cdot V^3 \quad (2)$$

The power coefficient, C_p, is a nonlinear function of the specific rate λ and setting angle β.

$$C_p = 0{,}73 \cdot \left(\frac{151}{\lambda_i} - 0{,}58 \cdot \beta - 0{,}002 \cdot \beta^{2{,}14} - 13{,}2 \right) \cdot \exp\left(-18{,}4 / \lambda_i\right) \quad (3)$$

In addition, it is clear that the height of the turbine installation has a large effect on the energy produced, so the wind profile adjustment for height may be considered. Therefore, the wind velocity at a specific height is expressed as follows:

$$\frac{V}{V_{ref}} = \left(\frac{Z}{Z_{ref}} \right)^{\alpha} \quad (4)$$

In general the α value's is between 0.1 and 0.4 depending on the nature of the environment of the installation and its roughness.

2.2 Modeling of the photovoltaic generator

Modeling of the photovoltaic generator is based on the determination of recoverable solar energy. Indeed, the total solar energy, recoverable on an inclined plane, is expressed as follows:

$$E_{s\ ri} = \frac{2}{\pi} \cdot G_i \cdot hi \quad (5)$$

with hi is the maximum duration of sunshine (hours) and G_i is the global radiation received by an inclined plane calculated using this formula [8]:

$$G_i = G_h \cdot k_e \cdot \left(\frac{\cos|\theta - \beta_s - \delta|}{\cos|\theta - \delta|} \right) \quad (6)$$

where:

• G_h is the global horizontal radiation,

• β_s is the angle of inclination of the photovoltaic panel,

• k_e is a correction factor of sunshine. It is often equal to 0.9.

Therefore, the electrical energy produced by photovoltaic inclined surface is calculated through the following formula:

$$E_{pv} = E_{s\ ri} \cdot \eta_t \cdot S_{pv} \quad (7)$$

with η_t is the total efficiency of a photovoltaic panel and S_{pv} is the used photovoltaic surface.

Thus, we denote by Eh the total energy produced by the generators of the system calculated as follows:

$$E_h = E_e + E_{pv} \quad (8)$$

with E_e is the energy produced by the wind turbine and E_{pv} is the electrical energy produced by the photovoltaic generator.

2.3 Mathematical model of the storage unit

The storage units are introduced into the autonomous energy systems to respond to the user energy consumption during periods of unavailability of the renewable energy source. In this study, the batteries are the storage units used.

Battery capacity expressed in ampere-hour is defined as follows:

$$C_B = \frac{B_{jp} \cdot N_{ja}}{P_D \cdot R_T} \quad (9)$$

B_{jp} where is the daily need of consumer ampere-hour, taking into account losses (batteries have losses can reach 10% of the daily consumption).

Every day, the state of the storage unit, during the time t-1 to t, depends on the previous state of charge of the batteries, the amount of energy and the consumption of the user.

During the charging process, the amount of energy available in the storage unit on day t may be described by the following function [9]:

$$E_B(t) = E_B(t-1) \cdot (1-\sigma) + \left(E_h(t) - \frac{B_j(t)}{\eta_{ond}} \right) \cdot \eta_{bat} \quad (10)$$

Moreover, in a discharge state, the energy available in the storage unit to date t can be expressed as [5, 6]:

$$E_B(t) = E_B(t-1) \cdot (1-\sigma) + \left(\frac{B_j(t)}{\eta_{ond}} - E_h(t) \right) \quad (11)$$

E_B (t) and E_B (t-1) are the amount of energy available in the storage unit on days t and t-1 respectively, η_{ond} is the efficiency of the inverter, η_{bat} is the efficiency of batteries and σ is the rate of self-discharge.

4. Criteria of choice and optimization

It is noted that the total energy produced by the system can satisfy or not satisfy daily energy demand. Therefore, different situations may occur.

In the first case ($E_h < B_j$), the lack can be arranged by the energy stored in the batteries. The energy available in the batteries is calculated using the expression (11).

But if the amount of energy available in the storage unit reaches its minimum, E_{Bmin}, the control system disconnects the consumer and the lack of energy to generate, LEG, can be expressed as follows [1, 2, 10]:

$$LEG(t) = B_j(t) - \left(E_h(t) + E_B(t-1) - E_{B_{min}} \right) \cdot \eta_{ond} \quad (12)$$

In the second case ($E_h > B_j$), the excess energy is stored in batteries and the amount of energy in the storage unit is calculated using equation (10) until the total capacity of the unit of storage, E_{Bmax} is reached. In this time, the control system stops the charging process. The rest of energy is not used.

Therefore, we can define a new factor of the surplus. The surplus of energy produced, SEP, is defined as follows:

$$SEP(t) = E_h(t) - \left(\frac{B_j(t)}{\eta_{ond}} + \left(\frac{E_{B_{max}} - E_B(t-1)}{\eta_{bat}} \right) \right) \quad (13)$$

From these two factors (LEG and SEP), we can identify two main criteria of choice for autonomous hybrid system which are the LEGP and PSEP.

The LEGP during a fixed period T, can be defined as the ratio between the sum of the total lack and the total need of the consumer. It can be given by the following expression:

$$LEGP = \frac{\sum_{t=1}^{T} MEP(t)}{\sum_{t=1}^{T} B_j(t)} \quad (14)$$

where T is the period of study (in our case, T = 1 year).

Similarly, PSEP is defined as the ratio between the sum of the excess energy and the total need of the consumer:

$$PSEP = \frac{\sum_{t=1}^{T} SEP(t)}{\sum_{t=1}^{T} B_j(t)} \quad (15)$$

The optimal configuration of the system should make the best compromise between the two objectives considered: the energy produced by the system and the cost of this energy.

Indeed, an economic approach based on the concept of total cost per kilowatt hour of the system is developed to analyze the cost of the system in this study. On the economic point of view, the qualification of this system are the total actualized cost, $C_{t\ a}$, and the annual energy produced by the hybrid system, $E_{h\ a}$. These two criteria are used to calculate the cost per kilowatt hour produced by the system:

$$C_{kWh} = \frac{C_{t\ a}}{E_{h\ a}} \quad (16)$$

The configuration that has the lowest C_{kwh} is taken as the optimal configurations that guarantee the LEGP required.

The total actualized cost is calculated by the following equation [11, 12]:

$$C_{t\ a} = f_a \cdot C_{i\ i} + C_m + C_r \quad (17)$$

with $C_{i\ i}$ is the initial investment cost, C_m is the value of maintenance costs during the life of the system, C_r is the value of cost of replacement of some components of the system and f_a is the actualization factor. This factor is defined by:

$$f_a = \frac{r}{1-(1+r)^{-d_v}} \quad (20)$$

d_v is the duration of system life and r is the actualization rate, r is usually equal to 8% for this type of system.

From the situations described above, an algorithm has been developed. Data input of the algorithm are composed of the values of the wind speed, the number of hours of sunshine, the LEGP required, daily energy needs throughout the year and the technical characteristics of the various components of the system.

5. Case Study

As previously mentioned, the objective of this study is to analyze, from the techno-economic point of view, a hybrid autonomous system. The method mentioned above is used for this analysis. By exploiting the algorithm, a FORTRAN simulation code has been developed.

As a case study, this method is applied to analyze a project that is designed to guarantee the energy demands of a house in the region of Sfax in Tunisia.

For this reason, we relied on the daily data of wind speed and sunshine duration in the region of Sfax provided by meteorological services in the region. In addition, it was determined that for a modern home, the daily energy needs are estimated at 5kWh/jour.

Using these data in the simulation algorithm, different characteristics have been studied for several combinations of the system.

A comparative analysis of different combinations of system components was performed to lead to the best choice of optimal autonomous system.

6. Results and Discussion

The determination of the energy produced by the hybrid system is important for the study of different configurations. The total energy generated by the hybrid system is obtained by the summation of the energy produced by the two generators.

In what follows, we present a comparative study of several configurations of the hybrid system by varying the installed capacity of each type of wind and photovoltaic energy respecting the specificity of the energy potential of the site.

Four types of wind turbines of different powers are studied (P_e = 1-4 kW) coupled to a photovoltaic generator to a power varying between 0 and 1.2 kW.

Note: We recall that the method of analysis of the hybrid system remains valid for different ranges of wind and solar power.

The annual energy produced by a hybrid system for different configurations is shown in Figure 2.

We find that the evolution of annual energy produced by the hybrid system follows a linear course by varying the bottom photovoltaic power and also wind power. The evolution of the energy produced is more important than wind power is high.

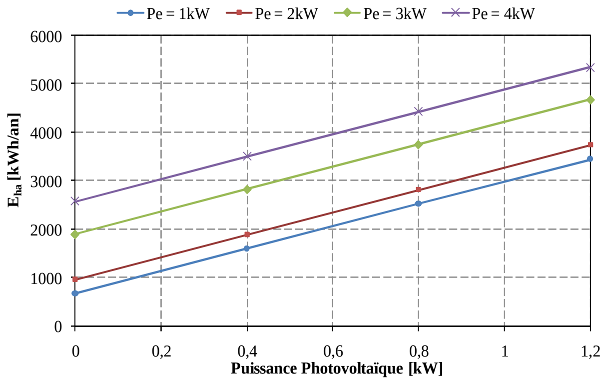

Fig. 2 Variation of the annual energy produced by a hybrid system (wind turbines installed at 12 m)

6.1. Energy efficiency of hybrid system configurations

After determining the amount of energy produced by the hybrid installation (solar and wind), we proceed to study the concept of autonomous hybrid systems productivity based on the energy optimization criteria (LEGP and PSEP).

Figure 3 shows the variation of criteria LEGP and PSEP according to the photovoltaic power and a variety of wind power.

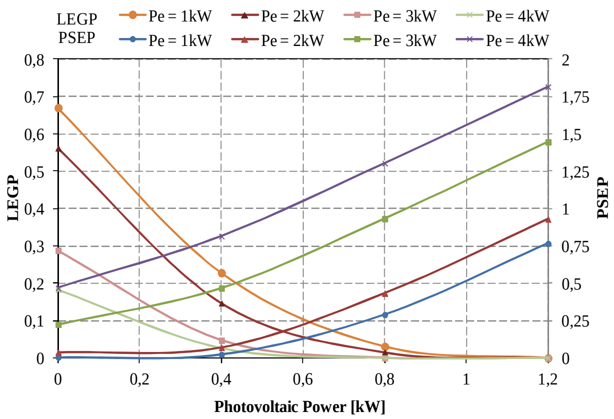

Fig. 3 Variations of MPTP and PSEP according to the photovoltaic power for different wind power

According to the variations of the curves presented in Figure 3, we see that the values of LEGP significantly reduced by increasing the proportion of installed photovoltaic capacity. For all power turbines studied, energy demands of consumers loads are covered from a photovoltaic power about 1.1 kW.

In addition, the variation of PSEP is harmonic with the evolution of LEGP: a decrease in the values of LEGP causes an increase of PSEP values for the same fields of variation of photovoltaic energy.

Comparison of different configurations of the hybrid system, according to the criteria LEGP and PSEP, has shown that in different cases we can find combinations of wind and photovoltaic generators able to fully cover the energy demands of the consumer since we have reach a zero value for LEGP.

However, it remains to confirm the appropriate combination by applying the third criteria of choice: the cost of the kilowatt, C_{kwh}, which is the economic criterion.

6.2. Cost of configurations

After a purely technical analysis of different configurations, determining the cost of the kilowatt-hour (C_{kwh}) is now regarded as the optimization criteria in order to affirm the economic results. In this context, we tried to compare, for the four wind power already studied, the variation of the cost of the kilowatt-hour, C_{kwh}, depending on the installed photovoltaic capacity and LEGP.

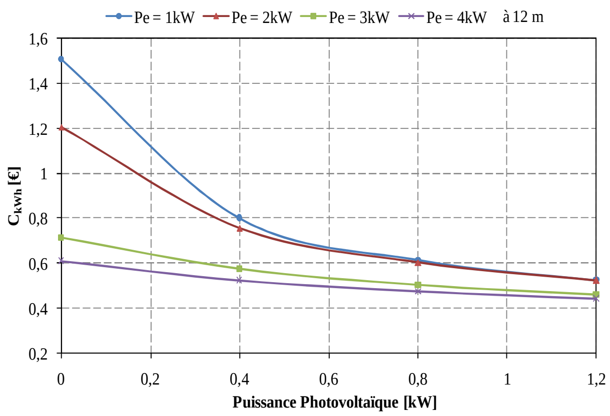

Fig. 4 C_{kwh} variation according to the wind and photovoltaic energy

From Figure 4, we find that the cost of the kilowatt-hour, C_{kwh}, considerably decreases while increasing the installed power (wind and solar). This decrease is more important for lower wind power (between 1 and 2 kW).

To highlight the impact of the lack of energy to generate probability LEGP on the C_{kwh}, we have shown the variation of the minimum cost of the kilowatt-hour produced for different value of LEGP. Figure 5 shows the simulation results on the variation of C_{kwh} according to LEGP for the considered configurations of the hybrid system.

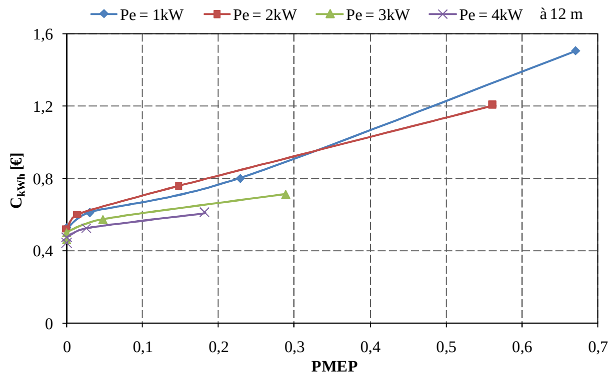

Fig. 5 Evolution of C_{kwh} depending on the LEGP for different cases of the hybrid system

We note from this curve that the cost of the kilowatt-hour is relatively reduced when LEGP is low. This result is very satisfactory for our study that seeks the technical-economic optimization of hybrid systems.

7. Conclusion

To use wind and photovoltaic energy efficiently and economically, an optimal sizing method is developed in this paper based on a simulation algorithm that is able to reach the best results overall sizing of hybrid wind photovoltaic systems.

The main objective of the presented method is to estimate the optimum size of a system capable of performing the energy requirements of a given consumer with minimum cost and high accuracy and analyze the impact of different parameters on the characteristics of the system components.

The proposed method was applied to analyze a hybrid system that provides energy for a house in the region of Sfax in Tunisia. Optimal configurations of the autonomous system are obtained by taking into account the requirements of desired energy criteria and cost of the kilowatt-hour produced.

This dimensioning method can be applied to all sites, taking into account the meteorological data and the application of any installation.

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