

Dimensioning of a battery system to store energy from a hybrid PV/wind/diesel system at 3 kVA

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Abstract. Battery storage presents a considerable challenge in the development of hybrid PV/wind systems. In this work, we present a battery storage dimensioning for a hybrid PV/wind/diesel 3 kVA system. An economic study was carried out by fixing as a criterion the price minimization of one stored kWh. For this study we have taken into account the main battery technologies on the market: GEL batteries, AGM batteries, AGM deep cycle batteries, lithium-ion batteries and lithium iron phosphate batteries. In order to consider a realistic price, we have heeded losses in the battery. We have developed a suitable Matlab program allowing the price calculation of one stored kWh taking into account the battery losses. Two solutions have been identified.

1. Introduction

The current energy situation, characterized by dwindling fossil fuel reserves, global warming due to the emission of greenhouse gases and environmental damage, is encouraging the development of renewable energy sources such as solar and wind. But this energy has a major Achilles heel: its character that can be described as random and intermittent because its production depends entirely on climatic conditions that have become increasingly random. Hybrid systems combining several energy sources with a storage system (combining solar, wind, diesel and batteries), present a promising solution to overcome this random nature. Indeed, such hybrid systems are increasingly used to meet the electricity needs of isolated small and medium cities ensuring total energy autonomy. The combination of solar and wind energies enables us to exploit complementarities between these two sources which are best shared, whether at the daily or annual scale [1]. The most used storage medium for small and medium power hybrid systems are chemical accumulators or batteries. Indeed, chemical storage systems have a good efficiency (close to 100%) and can provide a flexible energy management that can improve the power quality.

The sizing of battery storage in hybrid systems (whether or not connected to the grid) has been the subject of several research projects in recent years. Much of this work concerns the evaluation of optimal storage capacity based on different minimization criteria. The first methods proposed are based on the statistical study of the production deposit data (wind speed, sunshine and ambient temperature) and consumption profile [2] - [3]. Recent methods [4] - [6] are rather based on dynamic



simulations or use sizing software tools such as HOMER developed by the National Renewable Energy Laboratory [7]-[9]. For example, Wang X et al. propose a methodology to determine the capacity of the battery storage system (BESS) required to obtain the optimal level of distributed power of a wind farm and to mitigate the effects of unsteady input power from the farms [10]. Ru Y et al. examine the problem of determining the size of the battery for PV systems connected to the grid for power arbitration and advanced peak shaving. The goal is to minimize the investment in storage of the battery while minimizing the purchase of net power from the grid by storing excess electricity generated by photovoltaic systems when the price is low to sell it to the grid when the price is high [11]. However, few studies detail the practical dimensioning of battery based on their prices and comparing the technologies and capacities available on the market

The case study in this paper aims to size the battery storage for a 3 kVA hybrid PV/wind/diesel system. In order to allow a judicious choice, we carried out an economic study based on the calculation of the price of one stored kWh according to the cost price of the battery and its lifetime. For this price to be as realistic as possible, we have taken into account the losses in the battery.

2. Presentation of the hybrid system

The studied system is a 3 kVA hybrid system developed within the framework of the CNRST-funded GISER project consisting of a 2.5 kW peak PV generator, a 1.5 kVA wind turbine, a 1 kW battery pack in order to ensure the electrical energy needs during the night and a 1.5 kVA diesel generator as a backup power supply in the absence of PV-wind generation and if the batteries are discharged (e.g. figure1).

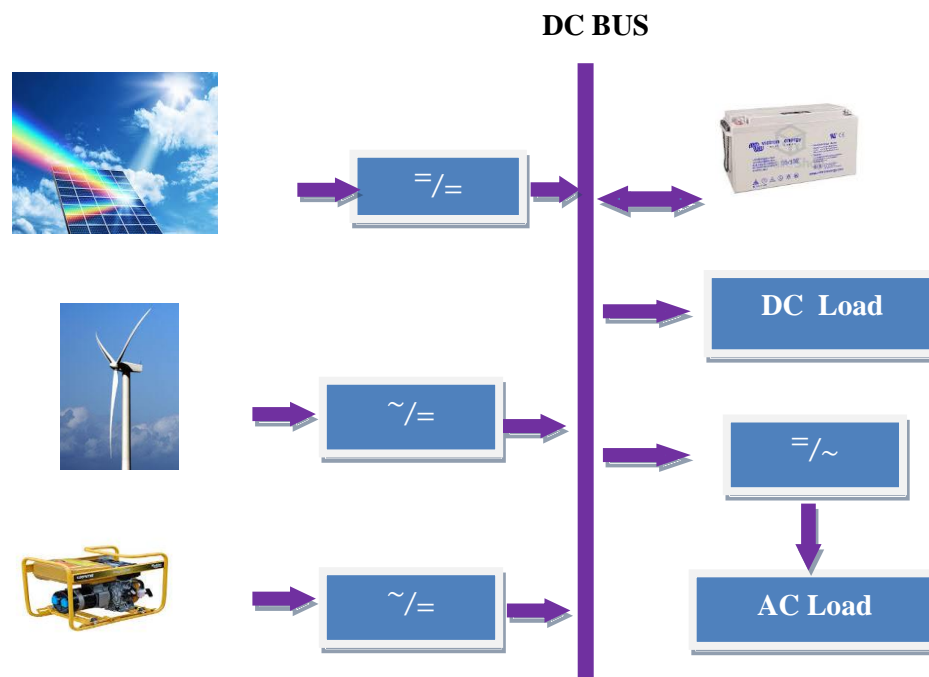


Figure 1. Structure of the studied hybrid system

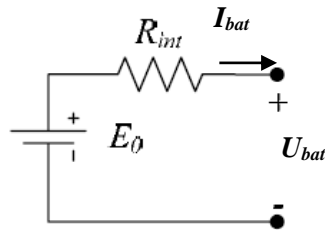
3. Dimensioning batteries

Once the overall storage power has been set, the sizing of the batteries for a given use consists in determining the correct unitary battery capacity (referring to the offers on the market) and the number of batteries needed to meet the energy requirements requested, in respecting the imposed constraints [12].

3.1. Battery features

Before proceeding to the sizing of batteries, it is advisable to present the main characteristics and the battery model to be considered.

3.1.1. Battery model considered. For sizing, it is especially the storage capacity that is important; so we take the simple model of battery shown in figure 2.



With:

E_o : Open circuit battery voltage,

R_{int} : Equivalent internal battery resistance,

U_{bat} : Voltage across the battery

I_{bat} : Battery current

Figure 2. Battery simple model

The power provided by the battery is expressed by:

$$P_{bat} = U_{bat} \times I_{bat} \quad (1)$$

3.1.2. Battery capacity. The nominal capacity (expressed most often in Ah) of a battery is the amount of energy that can be withdrawn from it at a particular constant current, starting from a fully charged state. It is given by the manufacturers under specified conditions of use (temperature T° , I_{bat} et E_o) under two terms C_{nom} and C_n . C_{nom} is the capacity in Ah and C_n (with "n" hours) indicates how long the battery is discharged.

3.1.3. Depth of Discharge (DoD). The depth of discharge is the percentage of the total capacity of the battery that is used during a charge/discharge cycle.

3.2. Calculation of current and total energy to be supplied by batteries

To ensure a useful power $P_u = 1$ kW during a period $T = 12$ h (the night between 6 PM and 6 AM), the battery pack must provide a current I_{bat} and a global useful energy W_u given by:

$$I_{bat} = \frac{P_u}{U_{bat}} = 83.33 \text{ A} \quad (2)$$

$$W_u = P_u \cdot T = 12 \text{ kWh} \quad (3)$$

With: U_{bat} is the nominal voltage of the batteries set at 12V for our case.

By dividing this useful energy by the nominal voltage of the batteries U_{bat} , we obtain the useful storage capacity of the batteries C_u in Ah

$$C_u = \frac{W_u}{U_{bat}} = 1000 \text{ Ah} \quad (4)$$

3.3. Sizing

The sizing of the batteries is made from the maximum storage capacity C_{bat} whose expression according to the useful storage capacity is given by the following formula [13]:

$$C_{bat} = \frac{C_u}{DoD \cdot f_t} \quad (5)$$

Where C_{bat} is the batteries storage capacity in Ah, DoD : Maximum depth of discharge allowable by the batteries and f_t : Temperature reduction factor given by:

$$f_t = \frac{C}{C_0} = 0.01035 \times T_a + 0.724 \quad (6)$$

C : Battery capacity at temperature T_a (in °C) and C_0 : Battery capacity at temperature 26.7 °C.

Thus, the storage capacity of the batteries to be installed depends both on the maximum discharge depth allowed by the batteries considered and on the temperature [13].

We consider an operating temperature of 30 °C and a discharge depth of 80 %, so the battery storage capacity in our case will be:

$$C_{bat} = 1208.3Ah \quad (7)$$

If C_{nom} is the nominal capacity of a battery, the battery pack will consist of N_{bat} batteries associated in parallel and calculated by:

$$N_{bat} = \frac{C_{bat}}{C_{nom}} \quad (8)$$

4. Technical-economic aspects

To choose the technology and the nominal capacity of the batteries to use, we conducted an economic study. As a first step in this study we have established a database for the sizing of batteries by referring to the data of the different websites specialized in the sale of batteries [14] - [20]. For this study we have taken into account the main battery technologies on the market: GEL batteries, AGM batteries, AGM deep cycle batteries, lithium-ion batteries and lithium iron phosphate batteries. For these two last the price proposals are very limited. For the nominal capacities, we took capacities between 80Ah and 220Ah. The main characteristics of the batteries considered are given in Table 1.

Table1. Main characteristics of the batteries considered.

Battery technology		Main Features
Lead Acid Availability on the market Low price	AGM (Absorbent Glass Mat) AGM deep cycle	Low power density Low life (200 to 900 cycles)
	GEL	Low power density Lifetime between 300 and 1300 cycles
Lithium Limited proposals on the market High price	Lithium-ion	High energy density Large number of cycles (1500 to 2500). Risk of explosion
	Lithium iron phosphate (LiFePO4)	High energy density Large number of cycles (2000 to 5000). Fully stable

Then we realized a Matlab program for calculating:

- The number of batteries N_{bat} needed to provide the useful energy W_u according to equation (8).
- The price of one stored kWh according to the price of the battery Pr_{bat} , its lifetime in cycle number N_{cy} , the depth of discharge DoD and the battery nominal capacity C_{nom} for equation (9) and the total storage capacity C_{bat} for equation (10).

$$Pr = \frac{Pr_{bat}}{C_{nom} \times U_{bat} \times DoD \times 2 \times N_{cy} \times 10^{-3}} \quad (9)$$

$$Pr_t = \frac{Pr_{bat} \times N_{bat}}{C_{bat} \times U_{bat} \times DOD \times 2 \times N_{cy} \times 10^{-3}} \quad (10)$$

The factor 2 is used to take into account the charging and discharging of the accumulator [1].

The results obtained are represented in the figures from 3 to 6 below.

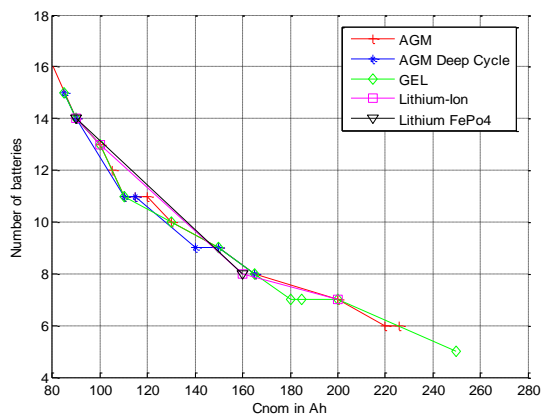


Figure 3. Number of batteries needed to provide storage capacity $C_{bat} = 1208.3Ah$, for the 5 technologies considered.

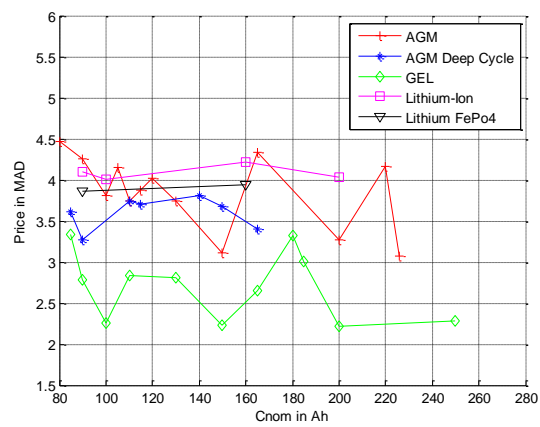


Figure 4. The price of one stored kWh according to the nominal capacity of the batteries and for the 5 technologies considered (using equation 9).

Considering figure 3, we find that the number of batteries decreases as the rated capacity increases. For reasons of congestion, we will limit the number of batteries to 10 batteries maximum so we should choose a nominal capacity greater than 130 Ah.

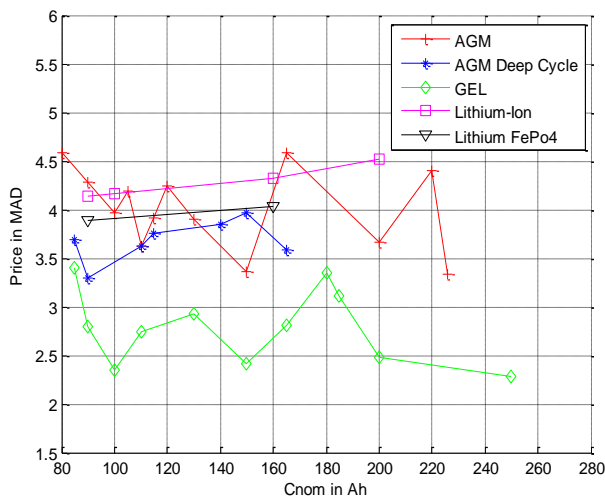


Figure 5. Price of one stored kWh according to the nominal capacity of the batteries and for 5 technologies (using equation 10).

Based on the curves in figures 4 and 5, we find that GEL technology batteries have the lowest kWh price. Especially those rated capacity 100Ah, 150Ah and 200Ah. The slight difference in price between the two curves is explained by the fact that the number of calculated batteries is rounded up to the nearest whole number.

Referring to the battery model of figure 2 we can calculate the losses in the battery by:

$$Ls_{bat} = R_{int} \times I_{bat}^2 \quad (11)$$

However, the internal resistances of the different batteries considered are less than 6 mΩ [14]-[20]. So for the calculation of the battery losses we will use for all the batteries $R_{int} = 6 \text{ m}\Omega$.

According to (2) and (11) we have at most:

$$Ls_{bat} = 41.6 \text{ W} \quad (12)$$

The dissipated energy W_{dp} in 12h is $W_{dp} = 500 \text{ Wh}$ (13)

To consider losses in the price calculation of one stored kWh, equation (10) becomes:

$$Pr_{md} = \frac{Pr_{bat} \times N_{bat}}{(C_{bat} \times U_{bat} - W_{dp}) \times DoD \times 2 \times Ncy \times 10^{-3}} \quad (14)$$

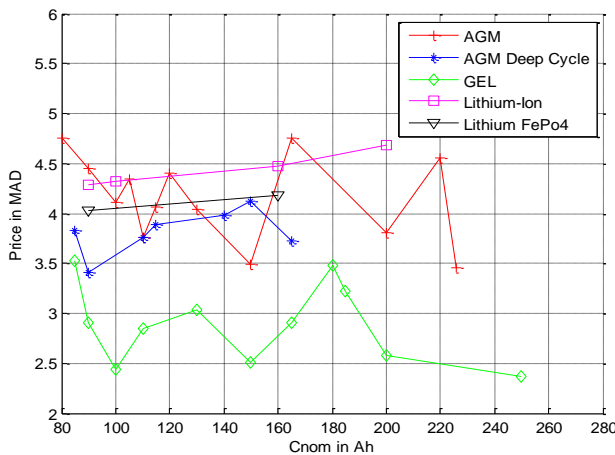


Figure 6. Price of one stored kWh according to the nominal capacity of the batteries and for 5 technologies, calculated taking into account the losses in the batteries.

By introducing the battery losses in the calculation of the price of the one stored kWh we note a very slight increase in the price of the order of 3.5% (The curves in figures 5 and 6 are almost identical) because the losses represent only 4.2%.

According to the results obtained, two solutions appear clearly, either 7 GEL batteries of 200 Ah nominal capacity, or 9 GEL batteries of 150 Ah nominal capacity.

5. conclusion

Battery storage accounts for a large part of the cost of photovoltaic/wind/diesel hybrid installations, which is why optimal dimensioning is required. This work presents an economic study allowing the sizing of battery storage for a 3 kVA hybrid system using as criterion the minimization of the price of the stored kWh. For this study we were interested in the main battery technologies on the market: GEL batteries, AGM batteries, AGM deep cycle batteries, lithium-ion batteries and lithium iron phosphate batteries. A Matlab program calculating the price of one kWh stored taking into account the battery losses has been realized. We have found that GEL technology batteries have the lowest kWh price.

Especially two solutions have been identified: 7 GEL batteries of 200 Ah nominal capacity in parallel or 9 GEL batteries of 150 Ah nominal capacity in parallel.

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