International Journal of Emerging Research in Management &Technology ISSN: 2278-9359 (Volume-6, Issue-8)

Research Article **August 2017**

Optimal Battery Bank Dimensioning Algorithm for Renewable Systems Electrification of Isolated Sites

Malek Belouda[a, b]

[a] University of Tunis ElManar, Laboratory of Applications of Energetic Efficiency and Renewable Energies - Faculty of Sciences of Tunis, Tunisia

[b] University of Gafsa, National School of Engineers of Gafsa, Gafsa-Tunisia

Abstract—

The penetration of renewable energy systems in remote areas contributes to reply to its accrued demand of electricity. Renewable energy systems as photovoltaic generation systems and wind generation systems are characterized by their unpredictable and intermittent character presenting the main drawback of these systems. Although this advantage, the problems caused by the intermittency of these systems can be resolved by employing a battery energy storage system. To this end this paper proposes and analyses an efficient and optimal methodology dedicated to applications fed by renewable energy systems. Since an optimal energy storage bank sizing is needed in order to assure the continuity and reliability of electricity supply of remote areas from these kinds of energy sources. The first part of this article describes the renewable hybrid system structure and different factors influencing the storage system dimensioning. Different scenarios of renewable sources power generations in order to develop an optimal battery bank sizing algorithm are investigated the second part of this article. The formulation of the algorithm is finally presented and discussed.

Keywords— Renewable energy systems, energy storage, optimal battery bank dimensioning sizing, Ragone graph.

I. INTRODUCTION

Currently, renewable energy systems (PV – wind) with several means of storage (electrochemical accumulators, H2 storage, etc) and sometimes with available energy sources (Diesel generator, fuel cells) are very useful mainly for remote areas, especially for electricity production, water pumping and desalination. The continuity and reliability of electricity supply of these remote areas is quite related to the storage bank which is the responsible of supply consumers in case of loss of energy from renewable energy systems. Therefore, an optimal sizing of these devices is necessary to provide remote consumers continually with electricity and to avoid a prohibitive cost of the system.

This article then proposes an optimal storage device methodology sizing based on electrochemical accumulators associated to a renewable energy systems (PV – wind) subjected to solar radiations and wind speed variations in order to jointly supply a load demand.

Many researchers have presented several methodologies in order to optimally sizing such systems. Aziz et al. [1] have developed a “Firefly Algorithm-based Sizing Algorithm for sizing optimization of a Stand-Alone Photovoltaic system. This “Firefly Algorithm” was used to optimally select the model of each system component such that a technical performance indicator is consequently optimized. Using a linear optimization method, Hesse et al. [2] have established a general method for techno-economic analysis and optimization applied to determine the optimal parameters., a cost-optimal sizing of the battery and power electronics based on solar energy availability and local demand. Others studies have exploited existing algorithms to reach this purpose, Bahramara et al [3] have presented a review of the state-of-the-art of researches, which use HOMER for optimal planning of hybrid renewable energy systems. Hosseinalizadeha and al. [4] have preferred a method based on design by simulating behavior of various combinations of renewable energy systems with different sizing, including wind turbine, photovoltaic, fuel cell, and battery banks.

In [5] and [6], authors have presented a classic design methodology in order to sizing a PV system associated to an electrochemical storage bank. Nevertheless, this approach is also applicable for sizing other systems coupling wind turbines or other energy sources. The concept of this classic design approach is based on averaging over a fixed period (generally one month) of environmental inputs (wind speed profile, irradiation and load profile). Then the main source power (wind, PV ...) to be installed is deduced from this data. Then a number of days for which the system operates autonomously (without the main source production) will be set to determine the storage capacity. Finally, it is ensured, through the choice of this number of days, it guarantees the unremitting supply of the load. Despite its frequent adoption by several designers for integrated storage systems design in intermittent production systems, this conventional design methodology is considered suboptimal. Indeed, the power averaging dissimulates power peaks charging / discharging which can be crucial sizing parameters of the battery bank. Thus, the storage bank is threatened by premature-aging while this design methodology ignores the battery cycling (charge and discharge cycles). In fact, during critical periods (no wind, no solar irradiations ...), the battery bank will be supposed to deep discharge cycles [7 – 8].

Other studies developed in [9] and [10] did not include the battery life problem in their design phase. However, they have an update on the integration of environmental constraints. More recent researches, such as those developed in [11 – 16] have introduced a battery life model in their battery bank optimal sizing.

A numbers of researchers [17-18] have developed integrated optimization solutions by presenting convex modeling steps for the problem of optimal battery dimensioning and control of a plug-in hybrid electric vehicle. Their objectives were to minimize carbon dioxide (CO_2) emissions, from the on-board internal combustion engine and grid generation plants providing electrical recharge power and to minimize the total cost of ownership of a city bus including a battery wear model.

The previous discussion reveals that a number of methods can be found in the literature to size each component of the system generation in order to optimize the power generation or the cost of the system. However, studies focused on the optimization of the storage system in an existing renewable energy system is not accurately fulfilled In the context of this research, we present an optimal battery bank dimensioning algorithm dedicated to a standalone hybrid system (PV – wind) supplying an isolated site. As it will be analysed in this paper, only the power difference (source-load) along time impacts the storage sizing in terms of power and energy. In such a case, all elements (i.e. solar source, wind source, storage device and load demand) are strongly coupled in the system. The proposed methodology is fundamentally based on the decoupling of the battery bank sizing variables (power and energy) in order to achieve an optimal system sizing.

The remaining part of this paper is organized as follows. The renewable hybrid system structure and different factors influencing the storage system dimensioning are described in section 2 which sets the storage system sizing problem. In the third section, battery capacity optimization process is presented. Section 4 is dedicated to the presentation of the developed optimal battery bank dimensioning algorithm.

II. RENEWABLE HYBRID SYSTEM STRUCTURE AND STORAGE BANK DIMENSIONING FACTORS

A. Renewable hybrid system structure

The considered renewable hybrid system consists of a passive wind turbine, a photovoltaic system and a battery bank with low DC output voltage (VDC=48V). This structure is chosen in order to minimize the system cost, to maximize reliability, is considered and to offer an autonomous system operation for remote applications. The figure 1 shows components of the hybrid system.

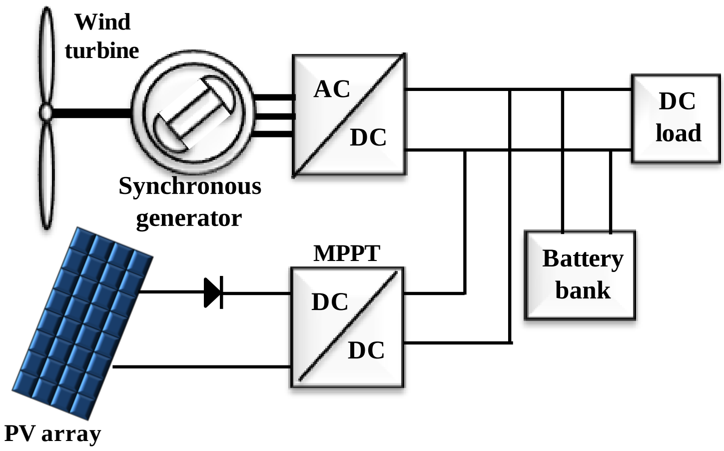


Fig. 1 Renewable hybrid system structure.

B. Storage bank sizing factors

Commonly, batteries are used in applications where storage capacity C_{bat} and discharge current I_{dch} are the primordial factors in their sizing process. Charge current I_{ch} is rarely a determinant factor in the sizing process: this is true if we have the possibility to charge the battery, but false for any hybrid system in which charging is required by the design and the energy management [13]. Thus, in this application discharge current and charge current are determinant factors in the battery bank sizing process. In addition, several couplings between sizing parameters are presents if the sizing process is constrained by the charge power P_{ch}, the discharge power P_{dch} or by the battery useful energy E_U (i.e. total energy of the battery). We propose, in the remainder of this section, a sizing methodology allowing decoupling the various sizing parameters and optimizing the sizing process result.

In this study, a lead acid Yuasa NP 38-12I [19] is considered as battery element. The basic characteristics are summarized in the Table I. These batteries can be used over a broad temperature range permitting considerable flexibility in system design and location:

- Charge: _15 °C to50 °C
- Discharge: _20 °C to 60 °C
- Storage: _20 °C to50 °C (fully charged battery)

Table I Basic Characteristics Of A YUASA NP 38-12I Lead Acid Battery Element

Nominal capacity C_3	30.3 (Ah)
Nominal voltage V_0	12 (V)
Nominal discharge Current I_3	10.1(A)

The total storage energy E^0_{bat} which can be stored by this battery element is given by :

$$E^0_{bat} = C_3.V_0 = 363{,}6Wh \qquad (1)$$

The specified currents are given for a nominal utilization. In this study, we have chosen to utilize the battery in the limits of $2.C_3$ in discharge phase and $1.C_3$ in charge phase. Thus, in generator convention we have:

$$\begin{aligned} I^0_{dch} &= 2.C_3.h^{-1} = 60{,}6A \\ I^0_{ch} &= 1.C_3.h^{-1} = 30{,}3A \end{aligned} \qquad (2)$$

In reality, the battery voltage varies depending on the State Of Charge (SOC), nevertheless we consider that this variation is of rather weak influence in the storage bank sizing process. In the following, the voltage of a battery element is assimilated to the nominal voltage V_0. By making this approximation, the limitations in discharge and charge powers will be, for a battery element equal to 12V:

$$\begin{aligned} P^0_{dch} &= I^0_{dis}V_0 = 727{,}2W \\ P^0_{ch} &= I^0_{ch}V_0 = 363{,}6W \end{aligned} \qquad (3)$$

Consider a battery sized to an E_{bat} storage capacity. The technological constraints impose stringent limits in charge power P^0_{ch} and discharge power P^0_{dch} . We shall introduce the two variables μ_{dch} which represents the minimum discharge time corresponding to the discharge time at the maximum discharge power P^0_{dch} assuming that the battery is initially full and μ_{ch} which represents the minimum charge time corresponding to the charge duration at the maximum charge power P^0_{ch} assuming the battery is initially empty. Considering a maximum discharge current at $2.Ch^{-1}$ and a maximum charge current at $1.C.h^{-1}$. Thus $\mu_{dch} = 0.5h$ and $\mu_{ch}=1h$. These two new variables link powers and storage capacity by E_{bat} by the following inequalities:

$$\begin{aligned} E_{bat} &\geq \mu_{dch}.P^0_{dch} \\ E_{bat} &\geq \mu_{ch}.P^0_{ch} \end{aligned} \qquad (4)$$

These inequalities, arising from charge / discharge minimum times expression, define a validity domain of the batteries sizing delimited by the energy-power region (Ragone graph). This is referred to as a graph of the technological constraints, to refer to the whole of the power energy domain containing the validity domain of the batteries sizing. This graph is shown in figure below, which illustrates an example of a 30 kWh battery which may be obtained with the previous charge and discharge current limits charged at -30 kW and discharged at 60 kW.

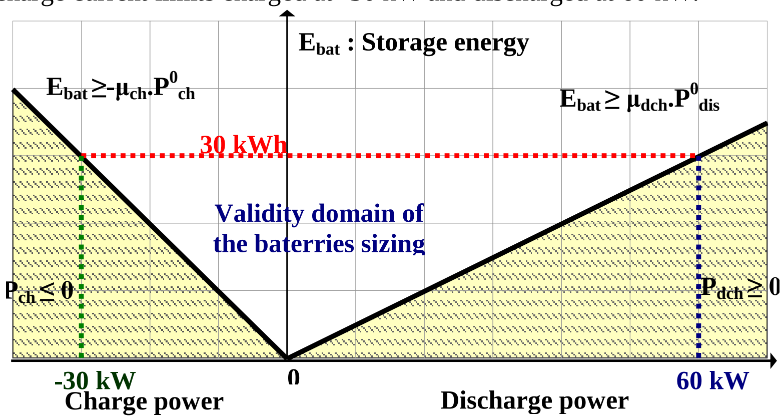


Fig. 2 Technological constrainsts graph (Ragone graph).

III. BATTERY CAPACITY OPTIMIZATION

The battery power $P_{bat}(t)$ results of the difference between the renewable source power $P_{RS}(t)$ and the load power $P_{load}(t)$:

$$P_{bat}(t) = P_{load}(t) - P_{RS}(t) \qquad (5)$$

In terms of battery power, it is important to distinguish between charging and discharging phases. The batteries must supply all required power during the discharge phases (positive part according to the sign convention). This means that we have to integrate the entire battery power. The charging phases are certainly useful in avoiding too much "digging" the SoC of the batteries, but their taking into account is not an obligation. This is a very important point because in configurations where renewable source power is high, the indiscriminate consideration of all "storable" energy can lead to excessive over-sizing of the storage elements for a "need for overload".

A. Useful energy calculation by simple integration

To illustrate this phenomenon, we consider a theoretical battery power $P_{bat}(t)$ shown in Figure 3. This power has a negative mean value, therefore according to the sign convention used, which corresponds to a positive energy with overall surplus recharge energy. The relative energy calculation associated with $P_{bat}(t)$ by simple integration is written as below:

$$E_{bat}(t) = -\int_{0}^{t} P_{bat}(\tau).d\tau \tag{6}$$

The battery bank sizing is inherent to the useful energy ΔE_U which depends only its extremes levels. In this example, the useful energy ΔE_U calculated by simple integration is equal to $9.U_E$ (see Figure 3), the energy balance of the integrated profile being positive (the initial energy level is lower than the final level). This means that not all the stored energy could be used, so that ΔE_U of $9.U_E$ potentially leads to an oversize of the accumulator.

Energy calculation by simple integration stores energy as much as possible. However, in practice, when the battery pack is full, it is no longer possible to charge it. Observing the energy curve $E_{bat}(t)$ shows that at no time the battery bank is considered full. It is as if all available energy has to be stored. It is therefore necessary to modify the calculation mode and go through a "saturated integration" to calculate the truly useful energy.

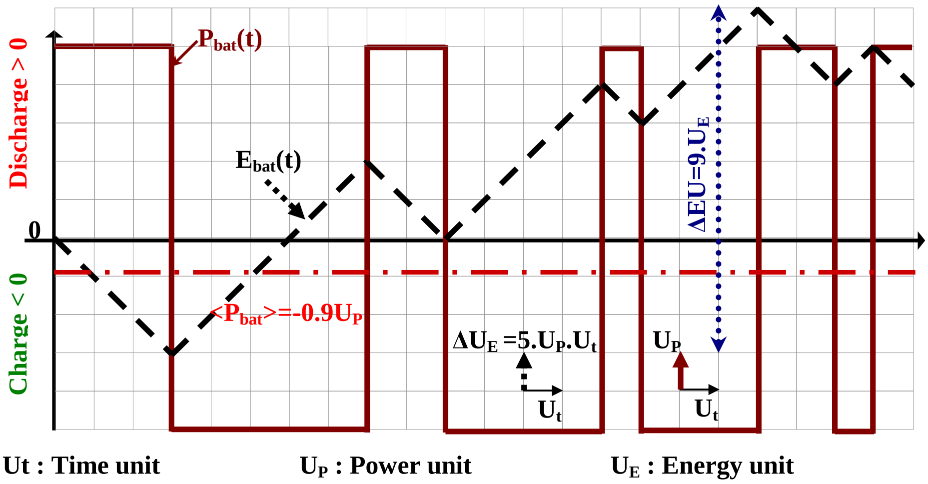


Fig. 3 Useful energy calculation by simple integration

B. Saturated integration principle

If $P(t)$ is a continuous function of time representing a power profile of duration D and $E(t)$ the saturated integral of $P(t)$. Taking into account the used sign convention (generating convention: discharge phase: positive, charge phase: negative), we note:

$$\forall t \in [0\ D]; \qquad E(t) = -\int_{0\ sat}^{t} P(\tau).d\tau \tag{7}$$

If $P(n)|_{n=0..N}$ and $E(n)|_{n=0..N}$, with $D=N.Ts$, The samples of $P(t)$ and $E(t)$. T_S is the sampling period. These expressions can be expressed as follow:

$$\forall n = \{0..N\}\ ,\quad P(n) = P(n.T_S)\quad et \quad E(n) = E(n.T_S) \tag{8}$$

At each time $t = n.Ts$, we define the quantity of exchanged energy between the instants $(n\text{-}1).T_S$ and $n.Ts$ as:

$$\begin{cases} e(0) = 0 \\ \forall n = 1..N\ ,\quad \delta e(n) = -\frac{1}{2} T_S (P(n-1) + P(n)) \end{cases} \tag{9}$$

The saturated integral $E(t)$ of the power profile $P(t)$ is defined as:

$$\begin{cases} \qquad\qquad e(0) = 0 \\ \forall n = 1..N \quad E(n) = \begin{cases} 0 & : \quad if\ (n-1) + \delta e(n) \geq 0,\ \ (case\ 1) \\ E(n-1) + \delta e(n) : else & ,\ \ (case\ 2) \end{cases} \end{cases} \tag{10}$$

Indeed, by definition $\forall n,\ E(n) \leq 0$. When $\delta e(n)$ is strictly negative (power to be supplied), since E(n-1) is necessarily negative or zero then the sum is strictly negative or zero. Therefore, energy is provided (Case 2). On the other hand, when $\delta e(n)$ is positive (power to be stored), it is effectively stored only if it does not cause the energy level to overflow from the initial level $E(0) = 0$.

C. Useful energy calculation by saturated integration

To take into account the limited capacity of the battery bank to be sized and the fact that only the minimum useful energy is required to be stored, the useful energy is calculated by saturated integration. The principle of this integration is to consider that the device is full at the beginning (SOC = 100%), this means that the initial charge level is as high as possible. This energy level is arbitrarily set to zero (since this is a relative level, its highest value is any whenever it is greater than any level). The useful energy is the peak-to-peak amplitude of the energy curve.

Applying this method to the same power considered in the previous example, Figure 4 shows the energy level evolution in the battery.

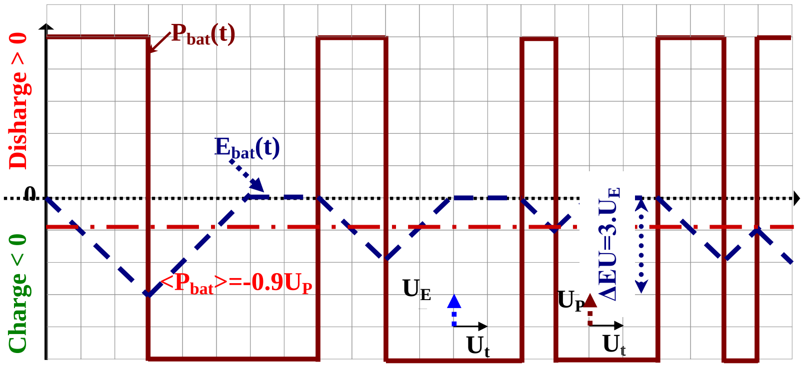


Fig. 4 Useful energy calculation by saturated integration

The useful energy needed for consumption is the difference between the maximum value (here zero) and minimum value of $E_{bat}(t)$. It will be noted that any demand for power is satisfied and results in a battery discharge from the initial state to the final. The charging power is absorbed as long as the energy level is lower than the ceiling level (zero). But when the energy level is at the ceiling (zero), the charging phases are ignored until the level drops again after a discharge phase: in terms of real-time system management, this would correspond to "Bypass" the renewable source as soon as the accumulator is full. This process therefore minimizes useful energy without failing in the power necessary for the system autonomy.

D. Sizing methodology

In order to highlight the complexity of the battery bank sizing problem, we will proceed to study three deliberately chosen real cases. For each case, we consider different scenarios of load and supplied power for a period of three days and with an averaging time of 15 minutes.

The first battery sizing factor is the useful energy ΔE_U which is given by:

$$\Delta E_U = \max\left(E_{bat}(t)\right) - \min\left(E_{bat}(t)\right) \tag{11}$$

But ΔE_U does not represent the total storage capacity of the battery. Indeed, for optimum use, the battery should be used between a minimum state of charge (SOC) (typically 25%) and at most 100% of its total storage capacity. This corresponds to a Depth Of Discharge (DOD) of 75%. The total battery storage capacity ΔE_{tot} is then given by:

$$\Delta E_{tot} = \frac{\Delta E_U}{DOD} \tag{12}$$

In addition to this battery total storage capacity, there is also other sizing factors: the maximum discharge power P_{dchmax} of $P_{bat}(t)$, (maximum in absolute value) and the minimum charge power P_{chmax}, of $P_{bat}(t)$. These sizing factors are given by:

$$P_{dchmax} = \max_t\left(P_{bat}(t)\right)$$
$$P_{chmin} = \min_t\left(P_{bat}(t)\right) \tag{13}$$

1) Case 1 : Battery dimensioning constrained by the useful energy

This case presents a situation in which the average power supplied by the renewable source is equal to the load power average. Figure 5 shows of the various sizing powers and the stored energy curves.

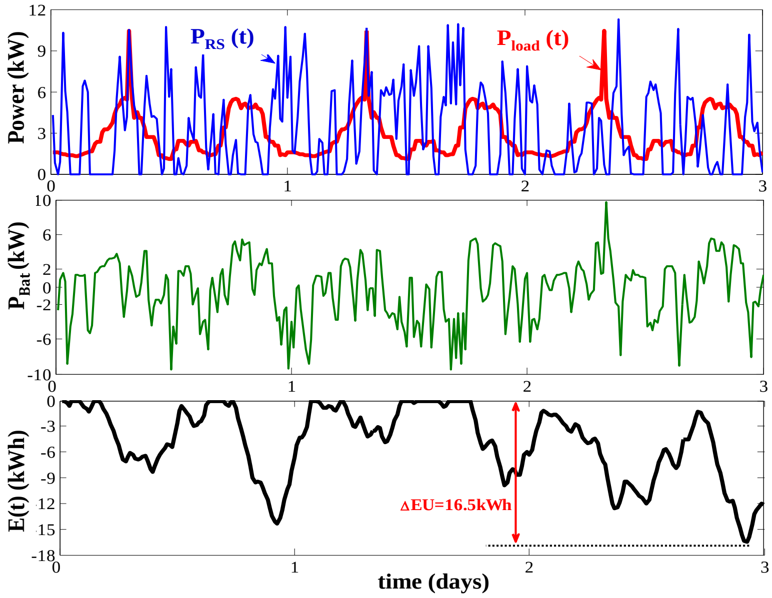


Fig. 5 Case 1 : Battery bank sizing factors evolution.

In this first case P_{dismax}=9.76 kW and P_{chmin} = -9.56 kW. Energy curve $E_{bat}(t)$ is calculated with saturated integration, Useful energy ΔE_U = 16.5 kWh and the total storage capacity ΔE_{tot} is equal to 22 kWh (16.5/75%). These sizing values are reported on the Ragone graph of the batteries technological constraints established above.

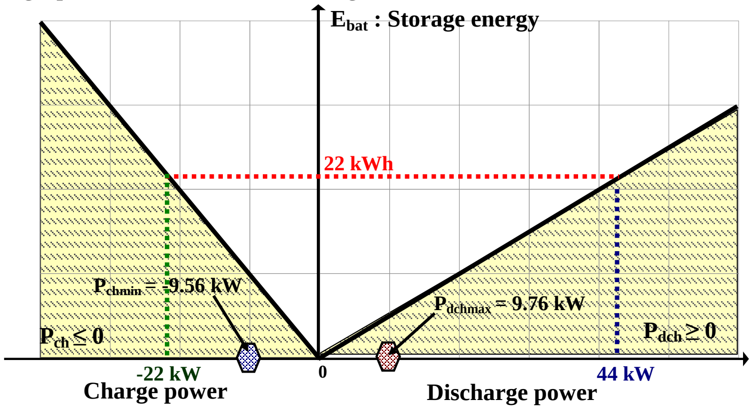


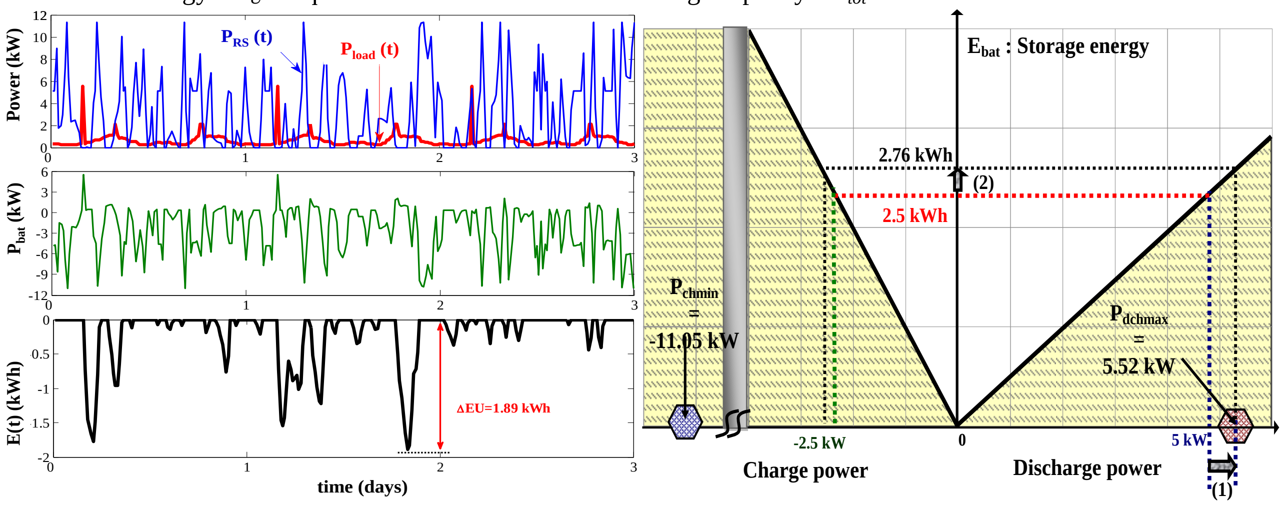
Fig. 6 Case 1 : Battery dimensioning constraint by useful energy (Ragone graph).

Figure 6 shows that the power limits -9.56 kW in charge and 9.76 kW in discharge are never reached. Energy dimensioning therefore covers power requirements: we are talking about "dimensioning constrained by useful energy".

2) Case 2 : Battery dimensioning constrained by discharge power

This case presents a particular situation, for which there is overall more power supplied by the renewable source compared to the low load power. Figure 7_(a) shows the evolution of the different dimensioning powers and the stored energy. The maximum discharge power P_{dchmax}, the minimum charge power P_{chmin} are respectively equal to 5.52 kW and 11.05 kW.

The useful energy ΔE_U is equal to 1.89 kWh and the total storage capacity ΔE_{tot} is 2.5 kWh for 75% DOD.



(a) (b)

Fig. 7 Case 2 : (a) Battery bank sizing factors evolution, (b) Battery dimensioning constrained by discharge power (Ragone graph).

These new dimensioning values are reported on the Ragone graph of the batteries technological constraints. Figure 7_(b) shows that neither the 11.05 kW nor the 5.52 kW (discharge power and charge power limits) are covered by the 2.5 kWh total storage capacity. In other words, the energy dimensioning does not allow crossing the thresholds of charge and discharge powers imposed by the battery power. As explained above, discharge is the most constraining part of the battery power and must be considered as a priority. It is therefore necessary, in the first place, to satisfy this discharge power. For this purpose, the total storage capacity will be increased from 2.5 to 2.76 kWh in order to reach the peak power of 5.52 kW = (5.52 kW = 2.76 kWhx2h^{-1}), while remaining within the validity zone of the battery sizing. It is therefore a dimensioning constrained by the discharge power. However, at 2.76 kWh of total storage capacity, the battery bank covers peak discharge but is not sufficient to cover the charge capacity of 11.05 kW. The question arises, therefore, whether the battery capacity must be increased again in order to satisfy its charge constraints.

3) Case 3: Battery dimensioning constrained by charge power

In this case, we consider a battery sizing that satisfies the energy and discharge power requirements, but whose charge power limitation does not cover the charge power.

Figure 8_(a) shows the evolution of the different dimensioning powers and the stored energy. The maximum discharge power P_{dchmax}, the minimum charge power P_{chmin} are respectively equal to 5.5 kW and 27.8 kW. The useful energy ΔE_U is equal to 16 kWh and the total storage capacity ΔE_{tot} is 21.3 kWh.

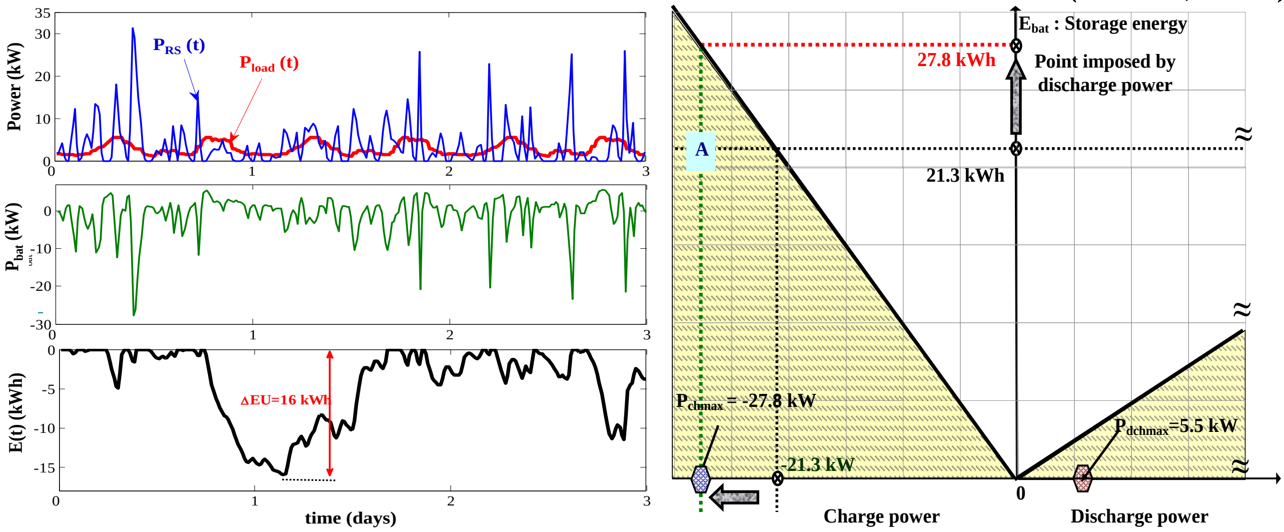


Fig. 8 Case 3: (a) Battery dimensioning constrained by charge power, (b) Battery dimensioning constrained by charge power (Ragone graph).

Figure 8_(b) presents the report of the new dimensioning values on the Ragone graph of the batteries technological constraints. This figure shows that the 5.5 kW discharge capacity limit is largely covered by the 21.3 kWh total storage capacity, while the charge capacity -27.8 kW is not covered. In other words, the sizing energy does not allow crossing the threshold of charge power imposed by the power of the battery.

To remedy this problem, as in the second case, it is possible to increase the storage capacity of the pack to cover the peak charge ratings. This would make 27.8 kWh of storage capacity, an increase of 30%. Knowing that the charge power is not an absolute constraint, such an increase seems excessive.

A second possibility consists in ignoring the power peaks and clipping the charge to the limit (in this case -21.3 kW) that is admissible by the 21.3 kWh (Figure 9_(a)).

The report of these new dimensioning values on the Ragone graph of the batteries technological constraints Leads to a sizing covering the discharge power and the charge power by the 21.3 kWh of total storage capacity.

But in reality, clipping charge power tends to increase the useful energy required. As a result, the battery storage capacity must increase to compensate for the missing energy: this is an iterative process that we describe below. This situation does not appear in this example. For this we will consider a situation in which the total storage capacity is increased to 25 kWh when clipping P_{ch} to -21.3 kW.

By pointing these values directly to the Ragone graph (Figure 9_(a)), it can be seen that with this storage capacity and by limiting the charge power to -21.3 kW, we obtain a point B well situated in the validity zone. But this point is not optimal because it is too far from the border zone (in any optimization problem, border areas are the most optimal).

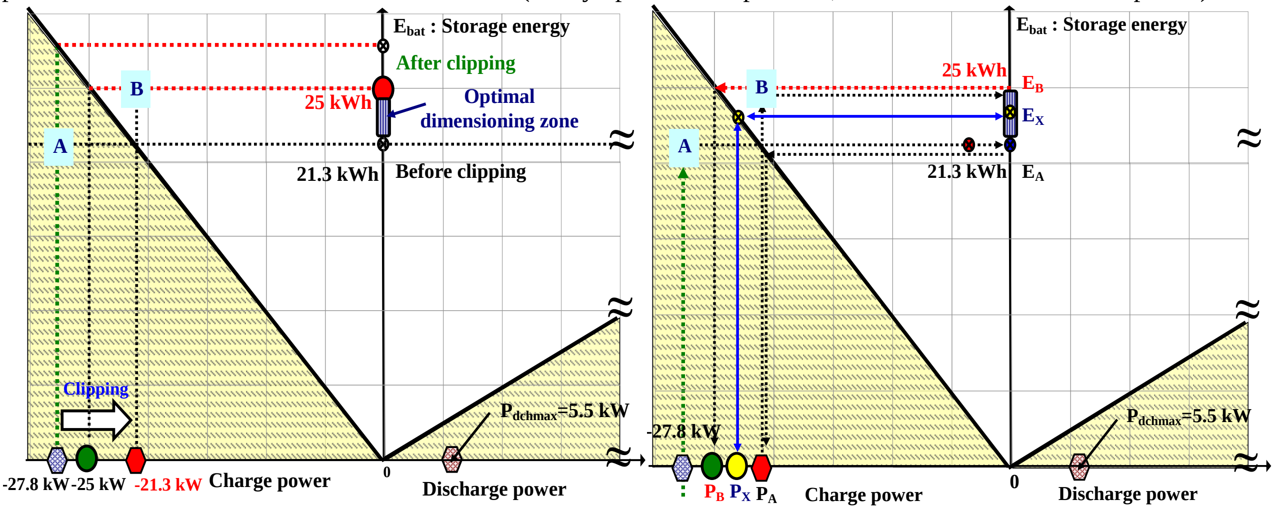


Fig. 8 (a) Dimensioning obtained by charge power clipping, (b) Optimal dimensioning research.

Beyond 25 kWh of storage capacity, the battery bank largely covers the discharge powers and the clipped charge powers -21.3 kW. In reality, with a storage capacity of 25 kWh, the charge capacity can rise to -25 kW. We had clipped the charge to -21.3 kW. If we decide to increase the charge limitations from -21.3 kW to -25 kW, the storage capacity will decrease. We could play this long before converging to an optimal sizing point. The situation is summarized in Figure 9_(b).

At point A, the storage capacity E_A is not sufficient because it corresponds to a much higher charge power (in absolute value) than it can't admit. At point B, storage capacity E_B is sufficient but not necessary. Indeed, it is certain that the optimum dimensioning point X lies between the points A and B. The characteristic of the point X is: When the charge power phases are clipped to P_X, the total capacity E_X is such that the point X of coordinates (P_X, E_X) lies within the validity zone closest to the boundary line. The determination of the point X passes by a numerical formalization of the problem, then by the elaboration of a dichotomous search algorithm.

IV. OPTIMAL BATTERY BANK DIMENSIONING ALGORITHM

On the basis of the different cases studied previously, we have developed the batteries dimensioning algorithm. As shown in Figure 13, we have simplified the algorithm as much as possible by encapsulating complex processes.

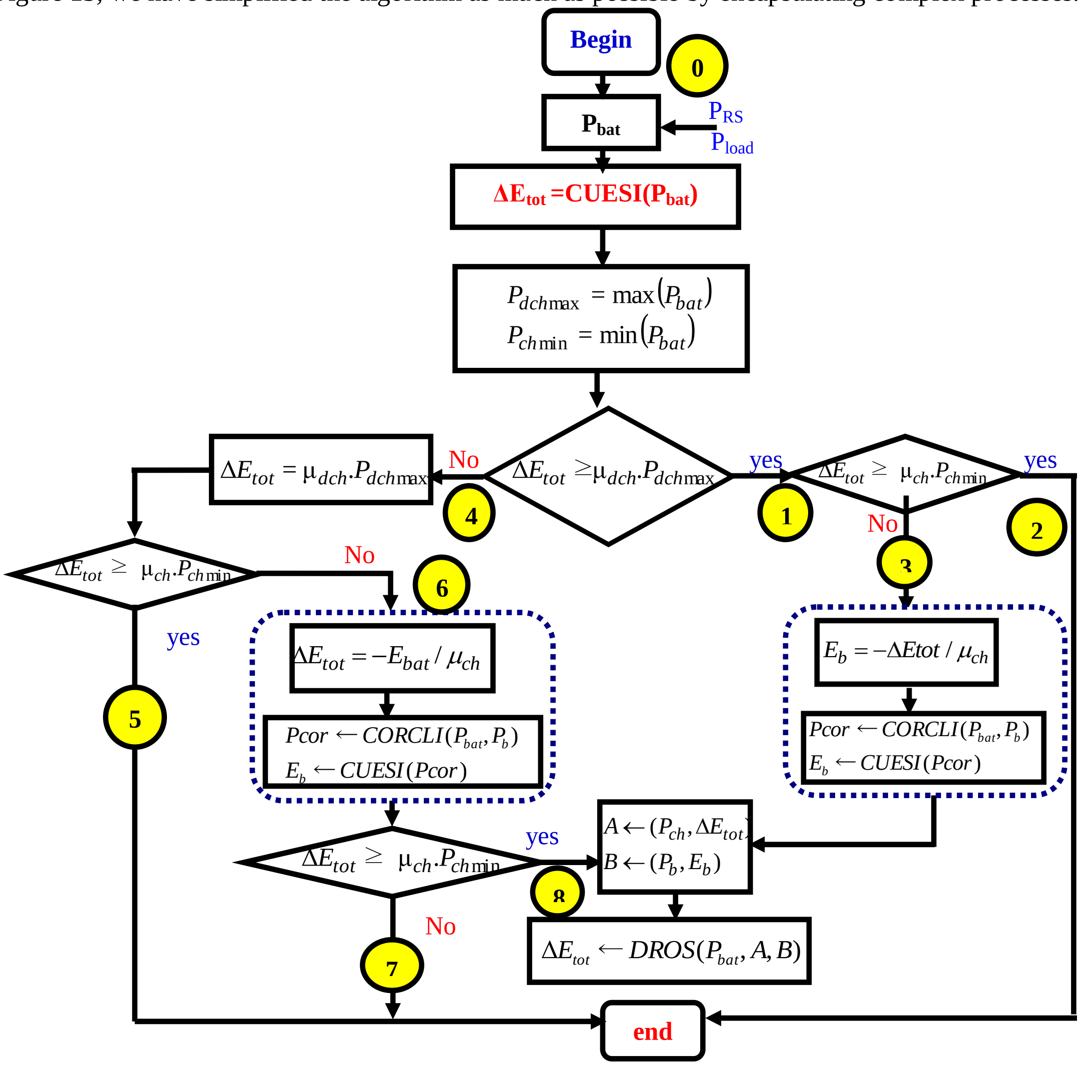


Fig. 9 Dimensioning battery bank algorithm.

- **CUESI** : Calculates the Useful Energy by Saturated Integration. This process returns the required minimum storage capacity which is proportional, to the discharge depth near, to the useful energy.
- **CORCLI** : Performs CORrection by CLIpping the charge power to a given value.
- **DROS** : Dichotomous Research of Optimal Sizing. This algorithm solves the problem of the interdependence between the charge power limitation and the storage capacity of the battery bank.

Globally, we distinguish three main branches, in accordance with the three studied cases. Markings in "numbered circles" allow us to describe the different "paths" of the algorithm. The input data are the useful power supplied by the renewable source and the load power. In the common part (0) to all "paths", we synthesize the battery power. Then, we calculate the storage capacity with the CUESI algorithm and the maximum charge and discharge powers.

- Case 1 corresponds to the "path" $0 \rightarrow 1 \rightarrow 2$. The calculated storage capacity is sufficient to cover the discharge and charge capacities requirements.

$$\begin{aligned} &\Delta E_{tot} \geq \mu_{dch} P_{dch\max} \\ &\Delta E_{tot} \geq \mu_{ch} P_{ch\min} \end{aligned} \qquad (14)$$

The process then ends and ΔE_{tot} is retained as the sizing of the battery bank (dimensioning constrained by the useful energy).

- Case 2 corresponds to "path" 0 → 4 → 5. The calculated storage capacity is not sufficient to cover the discharge power imposed by the battery power.

$$\Delta E_{tot} < \mu_{dch} P_{dch\max} \quad (15)$$

In this case, the storage capacity is increased to cover the discharge constraints. The new value of the storage capacity is sufficient to cover the charge capacity requirements.

$$\begin{aligned} \Delta E_{tot} &= \mu_{dch} P_{dch\max} \\ \Delta E_{tot} &\geq \mu_{ch} P_{ch\min} \end{aligned} \quad (16)$$

Le processus prend alors fin et E_{bat} est retenue comme étant le dimensionnement du pack. C'est le cas de dimensionnement contraint par la puissance de décharge.

- Case 3 corresponds to "path" 0 → 1 → 3. The calculated storage capacity is sufficient to cover the discharge power imposed by the power profile but does not allow to retain the available charge power.

$$\begin{aligned} \Delta E_{tot} &\geq \mu_{dch} P_{dch\max} \\ \Delta E_{tot} &< \mu_{ch} P_{ch\min} \end{aligned} \quad (17)$$

In this case, the algorithm searches, by dichotomous iterations, the limitation of the charge power which minimizes the storage capacity.

There is a connection between cases 2 and 3 which can occur when the increase in capacity due to the discharge constraints in case 2 does not solve the power power problem.

The total number of battery elements N_{bt} is given by the following equation:

$$N_{bt} \leq \frac{\Delta E_{tot}}{E^0_{bat}} < N_{bt} + 1 \quad (18)$$

The of battery elements number connected in series N_{bts}, making it possible to obtain the desired nominal voltage of the DC bus is:

$$N_{bts} = \frac{V_{DCBUS}}{V_0} \quad (19)$$

The total number of battery elements N_{bt} and the number of branches connected in parallel N_{btp} (each branch consists of N_{bt} elements connected in series) are then congruent modulo N_{bts}:

$$N_{bt} \equiv N_{btp}\, mod(4) \quad (20)$$

V. CONCLUSION

In this paper, an optimal battery bank dimensioning algorithm devoted to a standalone renewable source system have been developed and analysed. The algorithm requires only information on the power exchanged from the battery with the rest of the system which is deduced from the produced renewables power and the load power. Therefore, several battery power scenarios were investigated. These scenarios enclose different constraints in which the battery bank can be supposed in order to optimally sizing the battery bank. The developed algorithm can be extended to other electricity generation systems such as hybrid systems, electric vehicles …

ACKNOWLEDGMENT

This work was supported by the Tunisian Ministry of High Education, Research and Technology.

REFERENCES

[1] NIA Aziz, SI Sulaiman, S Shaari, I Musirin, K Sopian, " Optimal sizing of stand-alone photovoltaic system by minimizing the loss of power supply probability". Solar Energy, 2017.

[2] HC Hesse, R Martins, P Musilek, M Naumann, C.N. Truong, A.Jossen, "Economic Optimization of Component Sizing for Residential Battery Storage Systems". Energies, 2017.

[3] S.Bahramara, M. Parsa Moghaddam, M.R.Haghifam, "Optimal planning of hybrid renewable energy systems using HOMER: A review". Renewable and Sustainable Energy Reviews Volume 62, September 2016, Pages 609-620.

[4] Ramin Hosseinalizadeha, Hamed Shakouri, Mohsen Sadegh Amalnick PeymanTaghipourc," Economic sizing of a hybrid (PV–WT–FC) renewable energy system (HRES) for stand-alone usages by an optimization-simulation model: Case study of Iran". Renewable and Sustainable Energy Reviews Volume 54, February 2016, Pages 139-150.

[5] G.N. Tiwari, "Solar energy : Fundamentals, Design, Modeling and Applications", CRC Press, 2002.

[6] D.J. Spiers and A.D. Rasinkoski, "Predicting the service lifetime of lead/acid batteries in photovoltaic systems". Journal of Power Sources, 1995. (Cited on page 123.)

[7] D.J. Spiers and A.D. "Rasinkoski. Limits to battery lifetime in photovoltaic applications". Journal of Power Sources, 1997. (Cited on page 123.)

[8] S. Drouilhet and B.L Johnson. "A battery life prediction method for hybrid power applications" 35th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Etats-Unis, janvier 1997.

[9] A.J. Ruddella, A.G. Duttona, H. Wenzlb, C. Ropeterb, D.U. Sauerc, J. Mertend, C. Orfanogiannise, J.W. Twidellf, and P. Vezing. "Analysis of battery current microcycles in autonomous renewable energy systems". Journal of Power Sources, 2002. (Cited on pages 123, 124, and 136.)

[10] William Henson. "Optimal battery/ultracapacitor storage combination". ASME Wind Energy Symposium Technical, 2008. (Cited on page 124.)

[11] W.D. Kellog, M.H. Nehir, G. Venkataramanan, and V. Gerez, "Generation unit sizing and cost analysis for standalone wind, photovoltaic, and hybrid wind/pv systems", IEEE Transactions on Energy Conversion, 13(1):70-75, 1998.

[12] R. Chedid, H. Akiki, and S. Rahman, "A decision support technique for the design of hybrid solar – wind power systems", IEEE Transactions on Energy Conversion, 13(1):76-83, 1998.

[13] C.R. Akli, X. Roboam, B. Sareni, and A. Jeunesse. "Energy management and sizing of a hybrid locomotive" 12th European Conference on Power Electronics and Applications, 2007. (Cited on pages 6 and 49.).

[14] J. Lagorse, S. Giurgea, D. Paire, M. Cirrincione, M.G. Simoes, and A. Miraoui "Optimal design analysis of a standalone photovoltaic hybrid system", Edmonton, AB, Canada, October 2008.

[15] A. Jaafar, C.R. Akli, B. Sareni, X.Roboam, A.Jeunesse, "Sizing and Energy Management of a Hybrid Locomotive Based on Flywheel and Accumulators", IEEE Transactions on Vehicular Technology, vol 58, n° 8, october 2009.

[16] D. Abbes, A. Martinez, G. Champenois,"Life cycle cost, embodied energy and loss of power supply probability for the optimal design of hybrid power systems", Mathematics and Computers in Simulation (Matcom), 2015, pp. 46 – 62.

[17] X Hu, SJ Moura, N Murgovski, B. Egardt, D. Cao, "Integrated optimization of battery sizing, charging, and power management in plug-in hybrid electric vehicles". IEEE Transactions on Control Systems Technology Volume 24 Issue 3, 2016.

[18] N Murgovski, LM Johannesson, "Optimal battery dimensioning and control of a CVT PHEV powertrain". IEEE Transactions on Vehicular Technology Volume 63 Issue 5, 2014.

[19] http://www.houseofbatteries.com/pdf/NP38-12

