Intelligent Energy Storage Management System for Smart Grid integration

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Abstract—**This paper presents an intelligent energy storage system for NZEB buildings integrated in a smart grid context. The proposed methodology is suitable for NZEB buildings that include integrated renewable generation and storage capabilities, aiming at high load matching and low grid interaction, acting as a prosumer. The considered energy storage system is electrochemical storage (batteries) and the renewable production is based on PV panels. The energy storage management is based on a genetic algorithm approach that aims to increase the energy storage system return of investment by, at the same time, minimizing the grid energy consumption, on higher DSO tariff periods, and reducing the number of battery operating cycles. In this way the management system will increase the life time of the energy storage system and reduce the amount of money that the prosumer has to pay to the DSO operator.**

Keywords—NZEB, prosumer, storage, genetic algorithm

I. INTRODUCTION

By 2050, the European Union (EU) aims to reduce by 88-91% its amount of CO2-equivalent emissions, considering as background its 1990 values [1]. In the EU, 40% of energy consumption comes form Building consumption and they are responsible for 36% of CO2 emissions [2][3]. The EU Energy Performance in Buildings Directive (EPBD) mandates that all new buildings, built from 2021 onwards, should be at least Nearly Zero Energy Buildings NZEB [4]. A "nearly zero-energy building means a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" [4]. It is expected that this directive will enlarge the number of energy efficient buildings across the EU. In the EU, the majority of the buildings are more then 30 years old and about 35% are more than 60 years old. As an example, in Portugal about 50% of the building stock is more than 30 years old [5].

A NZEB is a building presenting a nearly zero annual balance between energy demand and on-site energy production. The easiest way to achieve a NZEB condition is to install PV-based on-site generation. With this PV panel installations, NZEBs will present a seasonal grid interaction behaviour. The overall annual import/export energy balance will be nearly zero, but there will be a significate monthly and daily mismatch producing a net export in the summer or mid-day time and a net import in the winter or off sun day time.

Fig. 1 presents a typical daily load and generation on the NZEB building. The blue line denotes the PV production and the red line denotes the load consumption. As it can be seen the majority of the PV generation is not used on-site being exported into the grid. The loads are mainly located outside the generation time period, contributing for a low load matching and a high grid interaction. In a NZEB context load matching can be defined as a way to increase self-consumption and self-sufficiency. High self-consumption implies that most of the amount of the NZEB's on-site generation is instantaneously matched by local load. High self-sufficiency, being the dual concept, implies that most of the building's electricity demand is instantaneously matched by on-site generation.

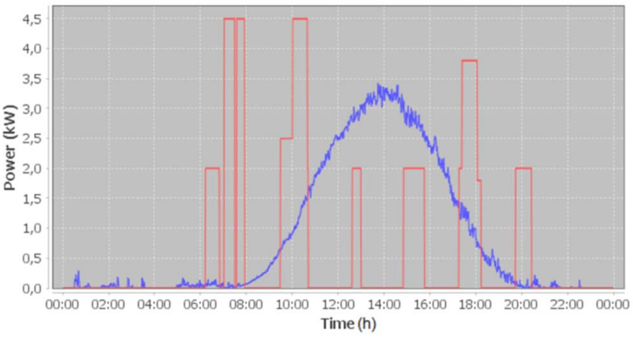

Fig. 1. NZEB daily load and generation profiles.

If load shifting is performed one can achieve higher load matching, meaning that the NZEB will use on-site most of the energy that is producing. If the washing machine and the dishwasher working times are shifted into a time period in which the renewable energy provided by the solar panel is sufficient to cover up its energy consumption one can better use the on-site renewable generation, as presented in Fig. 2. However, several home loads are not shiftable, thus making difficult to achieve higher load matching and lower grid integration.

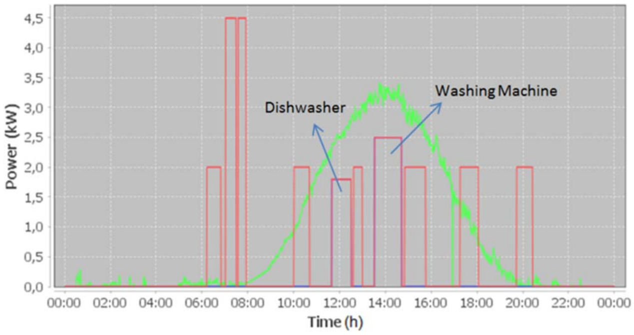

Fig. 2. NZEB daily load and generation profiles after load shifting.

This load/production mismatch can lead to overloading distribution feeders, increasing power losses in the low voltage grid [6] and overvoltage effects can occur along the distribution feeders [7]. Also the existence of this distributed power injection (in case of several NZEBs) will cause controllability problems on the low voltage grid. Being NZEB usually single homes (single-phase feed) their generation will cause phase unbalance on the three-phase low voltage grid. Although some advanced PV inverters can automatically balance the load they are only suitable for three-phase PV systems [8], which is not the case of most households. A major negative impact of this load mismatch, and in particular with the foreseen increasing number of NZEB buildings as low voltage grid loads, is the excessive aging of Distribution Transformers due the existence of reverse power flow higher than their rated power, particularly during day-time periods.

So, in order to mitigate the problems of load mismatch in single NZEBs (thus avoiding problems for the low voltage grid) it is necessary to consider energy storage devices that are able to store the excess of locally produced energy and later use it on-site, reducing the grid interaction as most as possible.

This paper proposes a methodology for optimal energy storage system (battery based) sizing and daily operation in order to extend its life time and, at the same time, increase the monetary revenue for building tenants. This monetary revenue will be achieved by considering load estimation and the existence of distinct tariff periods along the day. The proposed energy management methodology is based on genetic algorithms.

The remaining of this paper is structured as follows: Section 2 addresses Energy Storage Systems, Section 3 details the proposed management solution, Section 4 presents a case study and Section 5 presents conclusions and remarks.

II. ENERGY STORAGE SYSTEMS

As explained before the main goal is to increase the load matching in NZEB, thus avoiding complicated issues for the low voltage grid and more expensive energy usage for the NZB tenants. As presented in Fig. 3, one can consider three possible strategies that can be followed to improve load matching. Strategies A and B refer to demand surplus shifting, as they consist in delaying and anticipating the operation of controllable devices. Strategy C, which will be followed in this work, concerns generation surplus shifting using energy storage devices.

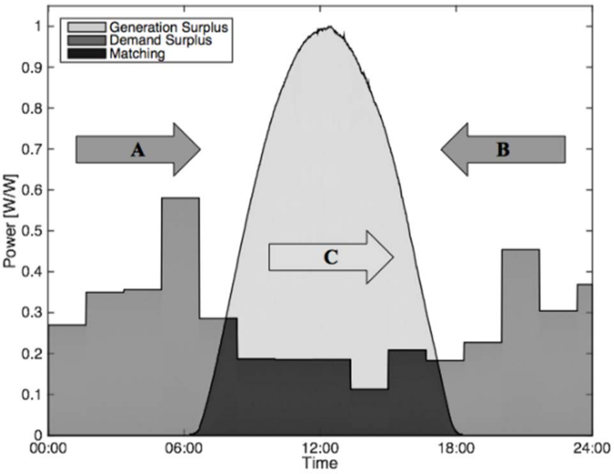

Fig. 3. Strategies for Load Matching improvement at NZEB level.

There are several types of energy storage systems that differ according to the way they are used. These can be classified into mechanical, electrical, electrochemical, thermal or electric vehicle storage systems [11]. The choice of storage system is intrinsically related to the applicability and characteristics that the user is looking for, namely whether they are energy devices and/or power devices, weight, volume and response time. It is important to consider the possibility of energy management and integration with other systems, for example renewable sources. These two characteristics are essential to implement the aforementioned strategy C (Fig. 3).

Many authors have studied Load Matching improvement using electrochemical and chemical (Hydrogen) storage systems [12][13][14][15][16]. From these studies, it can be concluded that Electrochemical and Chemical (Hydrogen) storage are an effective mean to improve residential Load Matching in NZEB.

Traditionally, energy storage systems are integrated through a power electronics converter [17]. In this work an energy router in considered. The energy router is a power electronics based equipment comprising the traditional two AC buses (grid and home loads), three DC buses that directly interconnect to the PV system, DC Home loads and the battery-based energy storage system, as presented in Fig. 4. The Energy Router, derived from the power electronics solid state transformer concept, acts as a power gateway between the local renewable PV production, the local energy storage through the battery pack and the prosumer's power network.

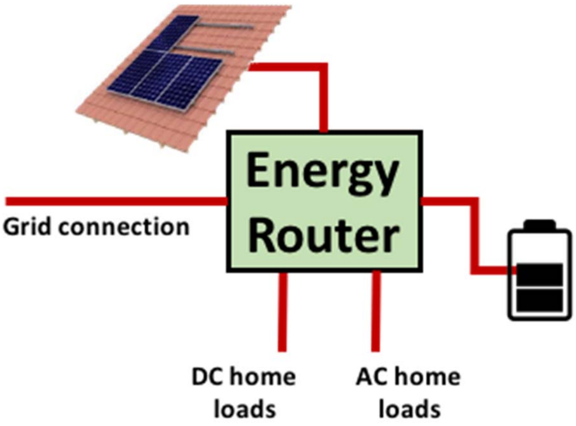

Fig. 4. Energy Router.

III. GENETIC ALGORITHM BASED ENERGY STORAGE MANAGEMENT SYSTEM

The previous setup (fully connected energy router) will allow the management of the energy storage system, exploit cheap energy available from the DSO network, increasing the self-consumption possibilities, perform complex demand response requests only employing storage and without shaving non-controllable loads.

The optimal energy storage management strategy will be implemented using a genetic algorithm based approach. Genetic Algorithms (GA) provide a method to solve optimization problems based on Darwin's theory of evolution, where individuals with better (more fit) abilities survive and generate offspring. In this way, GAs perform operations that simulate genetic modifications similar to those of the evolutionary process, such as crossing and mutation. In an algorithmic perspective (Fig. 5), the chromosomes are represented by a vector of values (real or integers) that are part of a possible solution to a problem.

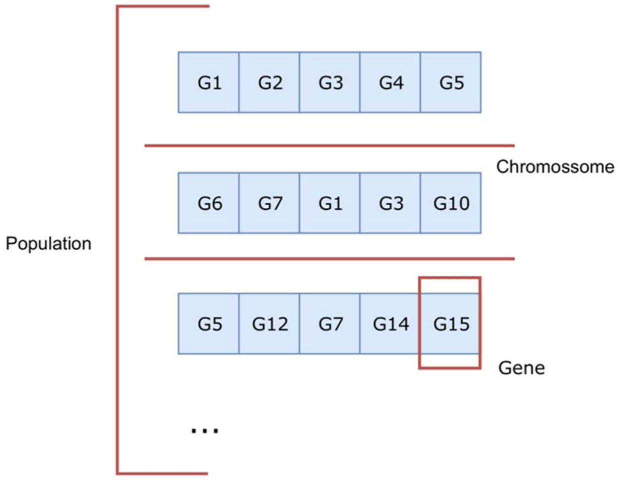

Fig. 5. Genetic algorithm population.

Chromosomes are composed of genes, which are responsible for their characteristics and can be exchanged or transmitted during the reproduction process. In each generation, individuals are evaluated according to their aptitude, that is, the fittest are selected for reproduction while the less fit are eliminated according to the survival principle of the fittest. It is necessary to take into account that different chromosomes can have equal genes in their constitution [18].

In electrical energy systems the use of GA is usually made in order to minimize an objective function through a desired profile, as presented in Fig. 6.

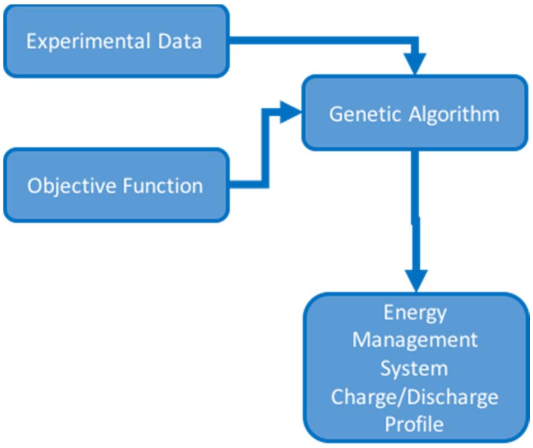

Fig. 6. Genetic algorithm for objective function minimization.

The proposed GA Energy Storage Management System intends to maximize the monetary revenue (considering the different tariff periods and the load matching indicator) and, at the same time, increase the storage system lifetime (by reducing the charge/discharge number of cycles). For this a cost function (objective function) was defined taking into consideration the monetary revenue and the storage system aging (1).

$$\mathrm{Ct}(t) = \mathrm{E}(t)\sum_{t=1}^{T}\left(\frac{\mathrm{Pc}(t)-\mathrm{Pss}(t)}{\Delta t}\right) + \mathrm{Dss}(t) \qquad (1)$$

In eq. (1), Ct denotes the total cost for the user (considering the monetary revenue and the storage system usage), E denotes the energy grid exchange price, Pc denotes the instantaneous load and Pss the instantaneous power exchange with the energy storage system. Dss is an economical cost denoting the energy storage system usage and is defined by (2).

$$Dss(t) = \frac{Css}{Cyc_{max}} Cyc(t) \qquad (2)$$

In eq. (2), Css denotes the acquisition cost of the energy storage system, $\mathrm{Cyc}_{\mathrm{max}}$ denotes the maximum charge/discharge number of cycles and Cyc the number of charge/discharge cycles effectively used.

IV. CASE STUDY

As a case study a single family home was considered. This house has a contract with the local DSO to supply up to 3.45kVA and a three-period tariff is considered. This tariff (Fig. 7) considers three distinct periods. In the “empty” period (denoted as green in Fig. 7 – from 0h to 8h and from 22h to 24h) the energy tariff is 0.0942 €/kWh, in the “full” period (denoted as orange in Fig. 7 – from 8h to 11h and from 13h to 20h and from 21h to 22h) the energy tariff is 0.1715 €/kWh and in the “peak” period (denoted as red in Fig. 7 – from 11h to 13h and from 20h to 21h) the energy tariff is 0.2942 €/kWh. In line with Portuguese self consumption law the energy supplied to the grid (by the small prosumer) is not paid.

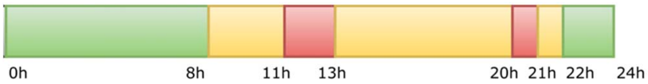

Fig. 7. Three-period tariff.

Considering the daily load diagram of the considered NZEB, the proposed genetic algorithm will establish the charging and discharging periods of the energy storage system in order to minimize the considered cost function (1). In this way it assures a minimal cost for the user, minimizing the battery operation cycles (thus increasing its lifetime) and reducing the grid consumption in the “peak” tariff periods.

Fig. 8 presents the results for a day on the month of May. All simulations were made using Matlab software. The three-period energy tariff is depicted in continuous red, the home consumption (from grid) is depicted in dashed black, the battery power (charge/discharge) is depicted in continuous green and its SoC (State of Charge) is depicted in dash-dot black. In dotted blue is depicted the home consumption (from grid) if the energy storage system was not considered, for comparison purposes.

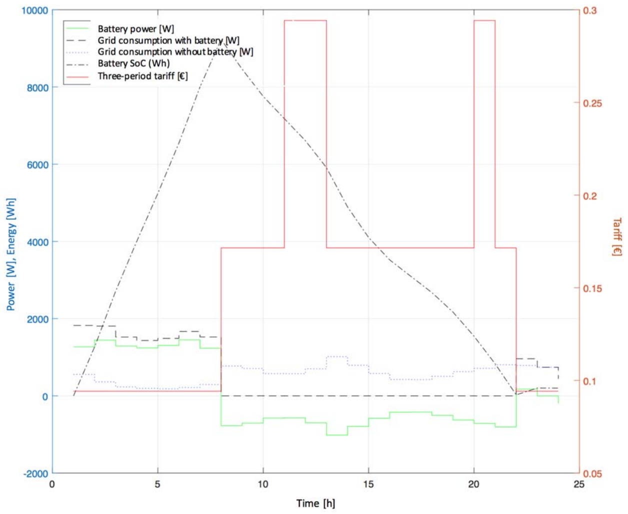

Fig. 8. Load profiles for a typical day in May.

From Fig. 8 it is possible to see the performance of the genetic algorithm. The battery charging/discharging cycles are reduced to a minimum value, in this case only one cycle is achieved. The charging/discharging procedure ensures that no consumption comes from the grid on the most expensive tariff periods, being the load supplied by the energy storage system. Fig. 9 presents the results for a typical day in December. In this case there is a higher load profile mainly because of the heating devices. One can see that, even so the charging/discharging cycles are minimized, there is some consumption from the grid on the “full” tariff period, however there is no consumption from the grid on the “peak” tariff period, thus minimizing the overall cost function.

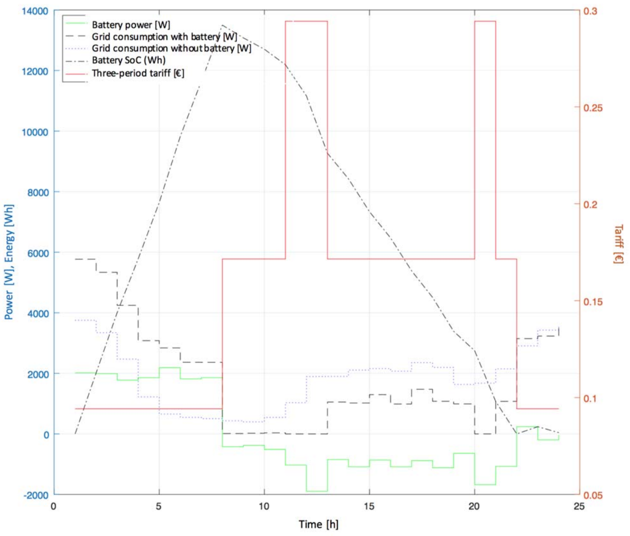

Fig. 9. Load profiles for a typical day in December.

The same genetic algorithm based methodology was applied in order to choose the best economical investment when choosing the appropriate energy storage system (battery capacity) for the considered home. Taking into consideration the annual load diagram and the three tariff periods, Fig. 10 presents the annual operational costs for several battery capacities. From this approach it is possible to select the best capacity, which in this case study corresponds to 13kWh.

V. CONCLUSIONS AND REMARKS

This paper presented an optimal charging and discharging profile for a NZEB building equipped with an energy storage system. This storage system will be responsible to increase the building load matching by storing the non used PV energy. This stored energy will be used to minimize the grid consumption in more expensive tariff periods.

A genetic algorithm based methodology to schedule the charging and discharging cycles of the battery was used. This methodology not only reduces the grid consumption in more expensive tariff periods, thus saving money for the tenants, but also minimizes the number of charging/discharging battery cycles, thus increasing its life time and maximizing the user investment.

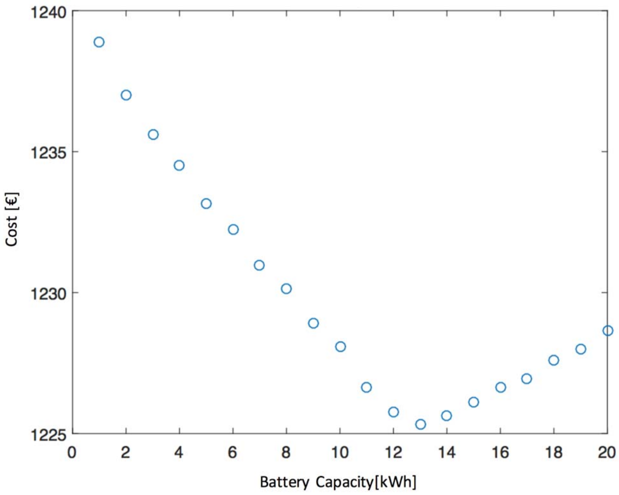

Fig. 10. Relation between operational costs and battery capacity.

The same methodology was also used in order to choose the battery capacity that better fits the home load diagram, in order to minimize the user investment costs.

Simulation results with real load and irradiance data were presented to confirm the algorithms' performance.

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