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Energy homeostasis management strategy for building rooftop nanogrids, considering the thermal model and a HVAC unit installed

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Abstract

This paper presents a case study on power control and energy management for a 60 apartments' residential building with solar generation and energy storage tied to the grid in Santiago, Chile. A new energy management algorithm based on energy homeostasis is designed for a small electro thermal generation system (nanogrid), with smart metering. The test bed employs supervisory control with energy management that regulates the temperature inside a large room by the action of an HVAC (Heating/Ventilating/Air Conditioning) unit. The main objective of supervisory control is to allow temperature comfort for residents while evaluating the decrease in energy cost. The study considers a room with rooftop grid-tie nanogrid with a photovoltaic and wind turbine generation plant, working in parallel. It also has an external weather station that allows predictive analysis and control of the temperature inside the abode. The electrical system can be disconnected from the local network, working independently (islanding) and with voltage regulation executed by the photovoltaic generation system. Additionally, the system has a battery bank that allows the energy management by means of the supervisory control system. Under this scenario, a set of coordination and supervisory control strategies, adapted for the needs defined in the energy management program and considering the infrastructure conditions of the network and the abode, are applied with the aim of efficiently managing the supply and consumption of energy, considering Electricity Distribution Net Billing Laws 20.571 and 21.118 in Chile (https://www.bcn.cl/historiadelaley/historia-de-la-ley/vista-expandida/7596/), the electricity tariffs established by the distribution company and the option of incorporating an energy storage system and temperature control inside the room. The results show the advantage of the proposed tariffs and the overall energy homeostasis management strategy for the integration of distributed power generation and distribution within the smart grid transformation agenda in Chile.

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1. INTRODUCTION

In today's electrical distribution systems, small and medium size distributed generation systems (DGS) such as nanogrids and microgrids can be beneficial for consumers, especially in residential/commercial buildings, as well as for electric utilities for a number of reasons, chief amongst them are: energy cost reduction, green energy generation and distribution quota compliance. Moreover, these alternatives allow for a more flexible, versatile and robust low carbon energy market [1]. This is especially true in those places where electricity supply from centralized power generation plants is impracticable/unfeasible due to technical and/or economic reasons or when, as in Chile's case for the most part, the electricity distribution infrastructure is frail and vulnerable when facing harsh weather or natural disasters like earthquakes. This is so due to the lack of the appropriate backup systems should some unwarranted or unforeseen event occur. The best known example of DGS is the microgrid, or its smaller counterpart the nanogrid, which ─ for the most part ─ operate employing renewable and non-renewable albeit clean energy sources like natural gas. These types of DGS can be supplied in two levels: local level (specific location) and end point level, installed by individual energy consumers, seeking to benefit from existing laws and regulations present in the country, state or province.

An important concept to consider with regards to DGS is energy homeostaticity, a technology derived from energy homeostasis [2-8]. From a systems engineering standpoint, energy homeostaticity is that property of sustainable energy systems (SES) which allows both, the capability and the capacity to anticipate or foresee as well as to react and respond to environmental challenges, threats and/or operational disturbances very rapidly and effectively (in fractions of a second), so as to attain optimal equilibrium between the amount of power supplied by the system and the demand for energy from the loads [3]. This property is engineered in the system itself and is essential in order to manage perturbations and to preserve systems stability as well as continuity of operations in electric power systems [3-8]. For this purpose, two key mechanisms are engineered in the supervisory control and energy management system of the DGS, to operate continuously and recursively to achieve the intended result. Reactive homeostasis—as the name suggests—is a feedback-enabled mechanism that alerts and prompts the energy system to act upon an imbalance between energy supply and demand, in order to attain energy homeostasis (e.g. efficient equilibrium between supply and demand). Predictive homeostasis, on the other hand, is also a feedback-enabled as well as a 'forward-thinking' mechanism that, as a result of big data processing capabilities and intelligent algorithms, allows the system to continuously process data from the environment, including the loads, main grid and weather conditions, as well as from systems operating as part of the smart grid infrastructure to which the nanogrid is connected. Based on this information DGS can foresee and anticipate incoming events and prepare themselves to safeguard and maintain continuity of operations in tandem with the grid. As an example of the important benefits that a building rooftop nanogrid can deliver, with the case study used here to illustrate the underlying concepts, a set of coordination and supervisory control strategies adapted for the needs defined in the energy management program are applied taking into account the infrastructure conditions of the network, and the parameters of the abode (number of residents, energy consumption habits, etc). The chief aim behind this is to efficiently manage the supply and consumption of electrical and thermal energy, considering both, Law 20.571 and Law 21.118 in Chile (https://www.bcn.cl/historiadelaley/historia-de-la-ley/vista-expandida/7596/) [9] and the electricity tariffs established by the electric distribution company. There is also the option of incorporating an energy storage system and temperature control inside the testbed room which was done for this example. Now, consider the case where loads are classified according to their type of consumption (fixed, variable), and according to the time of day they operate (transferable or non-transferable). Knowing that customer satisfaction is a measurable system performance parameter in electric power distribution services anywhere, and that it can also be modeled, an example may be drawn to illustrate the modeled scenario. Satisfaction increases if, for example, in residential buildings with contract-based electricity tariffs, changing per hourly block of day and per day of the week, the energy-consuming processes can finish before the agreed time interval with the electric company or keeping electricity consumption below a certain threshold, during a particular hourly block. This is essential in order to facilitate and make feasible green energy intensive, lower consumption timeslot, in order to save money while favoring green energy use from the nanogrid. Such an arrangement can render benefits for both parties, the consumers and the electric company, fully complying with local laws and regulations while advancing the country's green energy agenda. In addition, the photovoltaic solar power plant is modeled so that its excess energy can be sold to the grid with the benefits stipulated in the Chilean laws 20571 and 21118 that regulate self-generation [9]. A variable electricity tariff time-of-use (TOU) is considered here and the model's objective function aims to minimize the net cost (purchase of energy), taking into account the customer's satisfaction rate, for which the start operating time of appliances such as HVAC, washing machines or electric dryer can be deferred [10,11]. As a result, economic savings for customers using appliances and HVAC, and also for the electric utility are realized and a better use of the installed capacity of renewable or green energy in the nanogrid is reached [10,11]. To further improve this situation, a hybrid tariff has been proposed here which mixes an hourly rate (TOU) with a rate based on the deviation of the system frequency—something which may affect voltage levels—and whose value represents the imbalance between generation and consumption. This hybrid rate, which can be calculated per minute, can provide secondary frequency regulation and it also becomes an incentive for better solar photovoltaic resource management and for a judicious use of energy storage systems. Hence, the case used in the example emulates a hybrid tariff system applied to residential customers in a hypothetical large residential building in Santiago de Chile being serviced by ENEL. The nanogrid is analyzed under various operating conditions. The model simulation shows that for residential customers, the hybrid rate is cheaper than both the hourly rate and the flat rate; something which clearly encourages and incentivizes the consumers' energy consumption to be aligned with the TOU hourly blocks tariff arrangements established by the electric company, while at the same time, encouraging the use of green energy and energy storage, both key aspects of the model. In this case, frequency control can be offered as an ancillary service by the prosumer [12]. Other studies, aimed at achieving some cooperation amongst customers of a residential community being serviced by a local electric utility have proposed a distributed management system of electricity demand, based on game theory, for a group of residential customers [13] which is found less practical and appealing. Other authors focus on the increasing impact of weather on electricity supply and demand [14]. The present energy homeostasis model, which was presented to ENEL for the purpose of its assessment and possible future implementation in the electricity distribution sector in Chile, is not only aimed at enhancing and supporting smart grid's electricity distribution services through distributed generation systems (DGS) tied to the grid for residential and commercial applications. It is also a means to create a new market, with new incentives for those customers who have quite different consumption patterns and who value green energy, decarbonization and want to move towards a new energy matrix for the country altogether. Thus the energy homeostasis model proposed makes it possible to provide a choice on how to consume electricity more wisely which is convenient for the utility and for other energy consumers who have different needs and habits. Moreover, it makes it possible for the utility grid to operate much more securely, assisted by the nanogrid that is running in parallel, and with a control and energy management system that allows the DGS to be both highly efficient and also watchful, ready to support the distribution network, providing ancillary services and back up if necessary. These modular DGS are relatively affordable with current technology and can be installed and managed by electric companies in the near future as part of the plan to diversify and decarbonize, in line with the industry's smart grid transformation and the world's energy outlook [15,16]. After the Introduction, Section II presents briefly the case study and its characteristics. In Section III the case of clustered clients is analyzed following two possible criteria for sharing renewable production: equal sharing and merit-based sharing. Section IV presents the case of separate customers and its implications, plus the simulation results. Finally, Section V contains the conclusions of the study.

2. CASE STUDY

The current challenge consists of regulating and adequately managing the new generation systems, with the ability to adapt to hourly load changes (demand response) and to keep the electrical system stable at all times. For this endeavor, smart metering, high speed big data processing, artificial intelligence resources and the ability to manage energy by combining several energy sources and systems while controlling supply vs demand are essential. All these characteristics make DGS stable during their operation while allowing for independence from the local network (On/Off Grid). This gives rise to a much more sophisticated communication system, which is based on an extensive network of participation amongst subsystems, thus creating an extensive information network, key to the smart grid concept now that internet of things (IOT) and 5-G are coming on board. A nanogrid is a single domain for voltage, quality, reliability, price and management. It must have at least one load or power sink, and at least one outlet to the outside. All power flows are accompanied by communications, either by cable or wireless. The algorithm designed for the internal management of energy will be executed by the supervisory control based on the energy homeostasis concept [5]. Similarly, the control algorithm built will allow the different loads to be coordinated, operating efficiently and thus moving towards a truly sustainable energy system. The nanogrid will be in charge of regulating the power consumption of a variable thermal load (HVAC) and a fixed load inside a room. The thermal load will be modeled in such a way that during a work period during office hours (10:00 to 20:00 hours a day) a comfortable temperature is maintained inside the enclosure. According to the regulations issued by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the thermal comfort temperatures for winter are between 21 - 23 ◦C, while in summer they range between 23.5-25.5 ° C [17]. The nanogrid is especially designed to meet the needs of the community in a significant percentage of its total electricity consumption requirements. As a whole, the DG plant will seek to offer the optimal rate that is possible for the electric utility to provide to its customers, subject to the energy system’s conditions and constraints. The arrangement should result in economic benefits (incentives) for the residential consumers of the community in exchange for maintaining a scheme of efficient, sustainable electricity consumption, aligned with the needs of the entire community (aggregate demand).

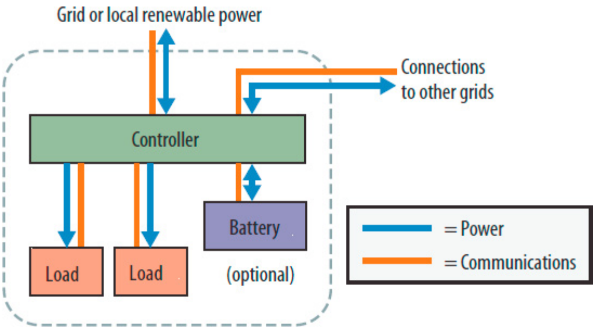


Fig. 1. Conceptual diagram of the building rooftop nanogrid with Energy homeostasis management and supervisory control.

Figure 1 shows the general structure of the control system, with the EMS (energy management system) and the PMS (power management system) are to be designed following a particular energy homeostasis control strategy. The EMS/PMS, receives as input the electric power generation predictions (based one predictive homeostasis data carried out by the control system’s assessment of internal and external variables) [18]. This is done taking into account the photovoltaic generation plant and the electricity consumption ranges in terms of demand side projection in order to decide on the magnitude and the energy flow. In addition, the storage status of the batteries must be permanently monitored. Thus, pursuing the objective of minimizing operating costs, the controller will have the following attributions:

A. Battery management

Defines when and how much energy to charge/discharge. The control system will charge the batteries when the demand is low and will draw energy form the batteries when the tariff of electricity is more expensive, depending on the electric tariff that is being implemented.

B. Active control of the energy demand

It is determined by how much energy is consumed by each client of the nanogrid as recorded by the smart meters. Those customers who are not "solidary" with the green energy community policy in their energy use, namely those who choose to keep up with their electricity consumption habits, opting not to align with the needs of the rest of the community, will be notified through an interface and/or alarm and their loads which exhibit constantly high electric power consumption (e.g. washing machine, charger or heating/AC) will be disconnected by smart switches (smart plug), leaving them with the grid-only option.

C. Payment management

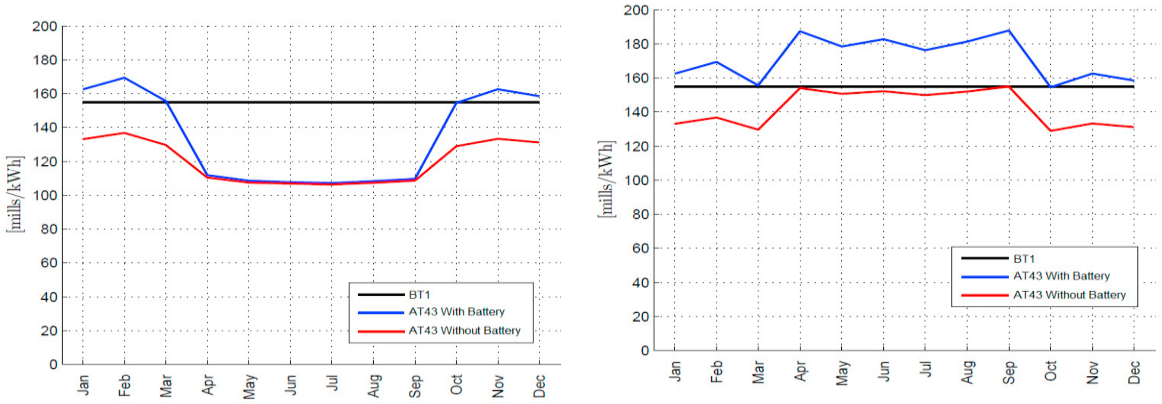
This unit is responsible for prorating payments amongst users and the electric company. Customers who have low or moderate consumption of electricity (those that exhibit a thrifty consumption behavior, favoring to do most power consumption during valley hourly blocks) have the right to receive economic compensation (reward). Such reward is made possible by those who have a higher consumption of electrical energy, particularly those that require higher power consumption more often. This arrangement is being considered for electric utilities like ENEL, as a means to entice and foster a sustainable and more manageable energy consumption in light of the electric supply constraints imposed by DGS which generate mostly renewable energies. Electric companies hope that this will, in turn, reinforce a more frugal or thrifty electricity consumption behavior that can allow for a greater green energy penetration in the distribution sector and an easier stabilization of the system if it were needed.

3. TARIFFS ASSIGNATION FOR CLUSTERED AND SEPARATE CUSTOMERS

Customers are free to choose between different electric rates in the corresponding voltage level. Among the rates offered by the local electricity company, described in a previous section, only BT-1 tariffs and THR are competitive for levels and consumption characteristics of individual customers. In this scenario the option of incorporating a photovoltaic plant in the common roof of the building and an energy storage system is evaluated. Since the energy meter of each customers is operated by the electricity utility, the only option is to deliver the renewable energy to the common services of the building and / or to the main grid. As illustrated in Figure 2, the meter of the customer will effectively record its electricity consumption but will not discriminate if it is supplied by the main network or the micro-grid, generating a conflict between the Electricity Company and customers of the building. Therefore, in agreement with current regulations specified in the net billing laws already mentioned, the convenient strategy is to inject renewable energy into the Common services of the building and then to the main network. The most common tariff used BT-3 and in addition, it is assumed that all the renewable energy is self-consumed. The project income should be calculated as the savings on the electricity common services bill paid by customers on a monthly basis.

4. SIMULATION RESULTS

Results obtained by simulations are presented and analyzed. These results validate the control strategy used to manage the energy of the customers, taking into consideration the benefits that they would receive under different alternatives. A common practice to reduce the maximum demand during peak hours, is to charge the batteries from the main grid during the low demand hours based on weather forecasts and algorithms to predict the photovoltaic generation, the aim is to get into peak hours with the batteries fully charged. In this way, the benefits of the electric tariff to be used (BT4.3 or BT4.3) are maximized. Whether the nanogrid has or not a storage device, the control system shall be provided with a set of controllable loads which can be remotely disconnected, so the maximum demand can be maintained bellow a specified limit. In addition, customers will be notified automatically that their behaviour is not complying with the needs of the community, and they will be penalized. Internal electric tariff for nanogrid customers is shown in Figure 3. This tariff, based on the monomic energy cost is employed with the aim to achieve an efficient energy consumption and to transfer the energy cost directly to customers. It can be observed that the energy cost at peak time is considerably higher than that of non-peak hours, so customers are expected to adapt and move part of their consumption to low demand hours, where the energy cost is lower. If, however, there is a shortage of supply from the nanogrid for whatever reason, the grid supply will automatically take over and supply for the deficit.



(a) Off-peak hours' electric consumption.

(b) Peak hours' electric consumption.

Fig. 2. Energy monomic cost for peak and non-peak hours.

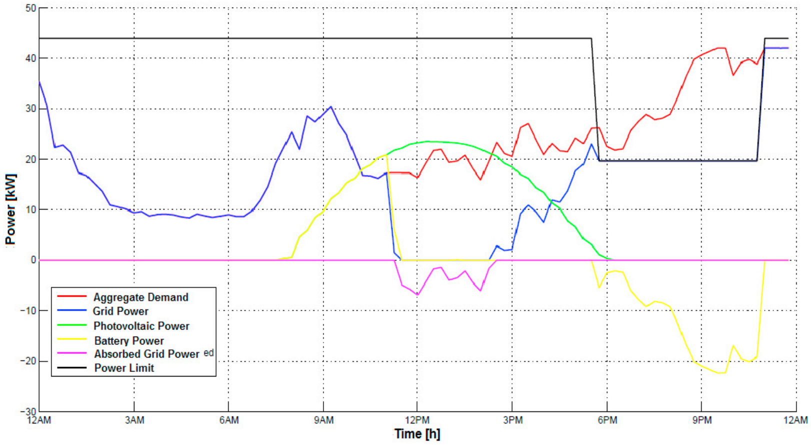


Fig. 3. SB Power flow with battery and hourly tariff.

Figure 2 a) and Figure 2 b) represent energy monomic cost. Figure 4 shows criterion A for allocating renewable energy, which responds to a logic in which customers own the N-th share of renewable energy available, regardless of their consumption patterns, and being able to sell their surplus to other customers or to the network. Figure 5, defined as criterion B, corresponds to the allocation of renewable energy under a scheme based on merit, meaning that the customer achieves a level of thriftiness commensurate with the goals of the community and is able to reschedule power consumption to off peak hours. Customers who have a low consumption in peak hours, are entitled to obtain the renewable energy share proportionally to their consumption. Choosing between one criterion and another, will depend on the degree of commitment that customers may have and their tendency to save energy in order to use more green energy rather than drawing more from the grid. Criterion A seems more suitable in case there is renewable generation and energy storage in accordance with the consumption of the sustainable block™. On the other hand, criterion B might be more suitable in cases where you have a nanogrid with a generation well below the needs of customers as a whole, so their allocation should be based on merit.

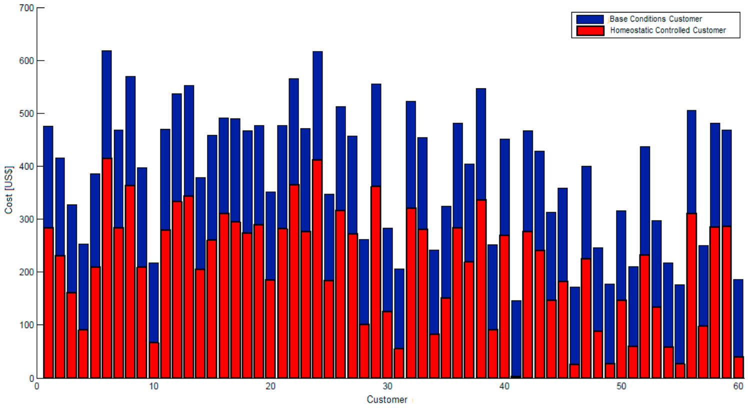


Fig. 4. Annual energy cost per client under criterion A.

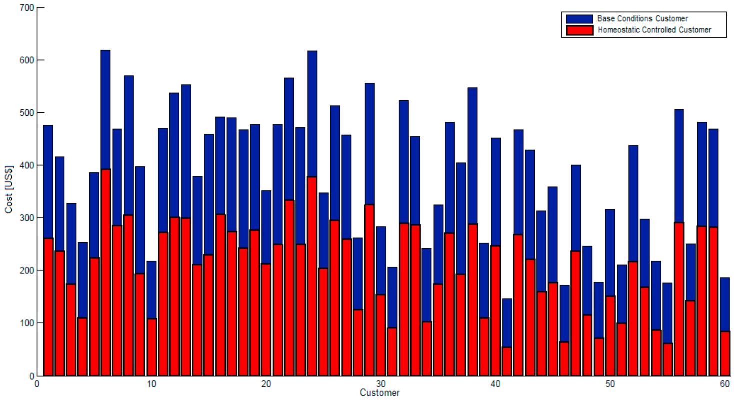


Fig. 5. Annual energy cost per client under criterion B.

5. CONCLUSIONS

The results show that whether using criterion A or B, a high reduction in annual energy cost for the customers is achieved. Using the described techniques for enabling and fostering renewable energy penetration and sharing, it is easier to stablish and to understand how every customer will receive his/her part of the generated green energy, avoiding discordances and problems between them. Moreover, the case of separated (also called nonclustered) customers is also considered, and it is also possible to set them apart from the common billing and energy sharing system. By using these criteria, some problems regarding renewable resources sharing can be solved, encouraging customers to agree with electric utilities to install these DG systems on their blocks.

Finally, it is important to realize both, the diversity of the population's energy consumption habits and the fragility of today's electric power distribution infrastructure, a fundamental issue that cannot be overstated nor can it be ignored or overlooked. Particularly so in a country like Chile, where seismic activity is recurrent and weather patterns have been changing drastically over the last decades, causing much concern over harsh weather events. Thus it is crucial that government authorities, industry regulators and main industry players like ENEL Distribucion in Chile plan ahead and work on a Smart Grid Transformation Roadmap as Chile is doing, in order to advance and pave the way for utilities to embrace grid integrated distributed generators investments. There is much new technology and novel, promising techniques and resources in the market today to go that route safely.

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