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Grid-tied distributed generation with energy storage to advance renewables in the residential sector: tariff analysis with energy sharing innovations; Part I.

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Abstract

This paper analyzes a case study on electrical power control and energy management of a 60 apartments' residential building with solar generation and energy storage in Santiago, Chile. This constitutes both, a challenge and an opportunity, which have not yet been fully addressed by the Chilean regulatory framework, under the perspective of renewable energy sources' integration with the local electric utility, ENEL. Under this scenario, a set of strategies for the coordination and control of the electricity supply versus demand is tested and adapted for the specific needs of the customers and the infrastructure of the network. The microgrid operates in full coordination with the grid to maximize green energy supply vs demand and systems capacity, whereby the different energy consumers and their consumption profiles play a crucial role as "active loads", as they are able to respond and adapt to the needs of the grid-tie microgrid while enjoying economic benefits. Simulations results are presented under different tariff options, systems capacity and energy storage alternatives, so as to compare the proposed strategies with the actual case. Results show the advantage of the proposed electric tariffs and energy management strategies for the integration of distributed generation systems in the context of the smart grid transformation by ENEL in Chile.

Keywords: Demand-side management; grid-tied distributed generation systems; electric utilities; energy sharing; tariffs; energy homeostasis
Introduction

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1. Introduction

In electrical distribution systems, distributed generation (DG) can be highly beneficial for consumers, as well as for electric utilities for a number of reasons. This is especially true in places where the electric supply from centralized power generation plants is way far off, impracticable/unfeasible due to technical and/or economic reasons, or when, as in Chile's case, the electricity distribution networks' infrastructure is both vulnerable to a certain degree, and susceptible of breaking down when faced with environmental and/or natural issues [1]. Such infrastructure is vulnerable especially because it lacks the appropriate backup systems, should there be natural disasters or environmental threats that could strike all of a sudden [1,2]. The epitome of distributed generation systems (DGS) are the minigrid and the microgrid, both employing renewable and non-renewable energy sources and sometimes energy storage units when necessary [2]. Microgrids are a concept of smart city electric supply services' planning in many of today's modern urban centers including Santiago de Chile where ENEL is leading the way[3,4].The main generation resources that comprise a microgrid are small gas turbines, microturbines, fuel cells, wind and solar energy, as well as biomass, small hydroelectric power plants, and all of these types of energy can be supplied at two levels: at the local level (specific location) and at the end point level (installed by individual energy consumers or by the electric utility with the consent and participation of consumers) [3,4,5]. Energy homeostasis is that property of sustainable energy systems (SES) by which the energy system has both the capability and the capacity to respond to environmental or natural challenges and perturbations very rapidly and effectively (in fractions of a second), so as to attain optimal equilibrium between the amount of power supplied by the energy system and the demand for energy from the loads [6,7]. This is essential in order to preserve systems stability and continuity of operations in electric power systems, particularly when these are integrated to other distribution systems such as the grid. 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 homeostaticity [8,9]. As an example and in order to illustrate the above concepts, 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). Customer satisfaction is a measurable system performance parameter in electric power distribution services, and it can also be modeled; something which increases if the energy-consuming processes finish their work before the agreed time interval, rendering benefits for both parties, the consumers and the electric utility. In addition, the photovoltaic solar power plant is modeled in such a manner so that its excess energy can be sold to the grid with the benefits stipulated in the Chilean law enacted in 2014, which regulates self-generation [10]. Moreover, the more energy that is available in the energy system to share amongst the consumers and to inject to the grid, the higher the exergy content of the system itself [11]. A variable electricity tariff time-of-use (TOU) is considered here and the model's objective function is to minimize the net cost (purchase of energy), taking into account the customer's satisfaction, for which the start operating time of appliances such as washing machines or electric dryer can be deferred [12]. As a result, economic savings for customers and for the electric utility are realized and a better use of the installed capacity of photovoltaic panels in the microgrid is reached [12]. To improve this situation, a hybrid tariff has been proposed which mixes an hourly rate or time-of-use (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 every minute, can provide secondary frequency regulation [13,14] and it may act as an incentive to energy consumers for better solar management and use of energy storage systems. Hence, the case of a hybrid tariff system (HTS) applied to a group of residential customers in a large building located in the upper east side of Santiago de Chile is considered. The building is being serviced by ENEL and is analyzed in this example. The microgrid is to be installed in the building by ENEL and has photovoltaic generation and energy storage unit, both of which are analyzed under various operation 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 encourages the behavior of prosumers [8,9] to be aligned with the efficient functioning and usage of the hybrid electric power system (the grid-tie microgrid and the grid supply), while actively encouraging the use of energy storage. In this situation, frequency control can be offered as an ancillary service by the prosumer]15,16].

Other studies, aimed at achieving some cooperation amongst customers of a residential community being serviced by a local electric utility like ENEL have proposed a distributed management system of electricity demand, based on game theory, for a group of residential customers [13]. The model proposes a dynamic pricing strategy (DPS) in which the electricity rate to be charged is a function of the global power demand of the pool of customers. Under this scheme, multiple customers choose time periods within the day as a window of opportunity where the electric rate is cheaper, thus obtaining certain economic benefits being offered by the electric utility, while meeting their daily needs [13]. Thus, the system arrives at a Nash equilibrium point without intervention of the central operator. Simulations results using real energy consumption data, show that peak system reduction is near 20%, thus decreasing the CAPEX necessary to supply the growth of energy consumption [13]. 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, and in other parts of the world, is not only aimed at enhancing, complementing and supporting a variety of electricity distribution services through smart distributed generation systems 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 very different consumption patterns and who value green energy and want to move towards a new energy matrix for the country altogether [17]. Energy homeostasis can also make this possible by providing a choice on how to consume more wisely and in a way that is convenient for the electric utility and for other energy consumers who have different habits [18]. Moreover, this makes it possible for the utility grid to operate much more securely and to be assisted by a minigrid or microgrid that is running parallel with a control and energy management system that allows the DG system to be both highly efficient and also watchful, ready to support with ancillary services and back up if needed. These modular DG plants are already being installed and managed by ENEL Distribucion, the largest electric company in Chile, and a many more are to come in the near future, as part of the plan to diversify in the electricity distribution sector in line with ENEL's Smart Grid transformation [3,4].

In this paper, there is a brief introduction followed by the analysis of the most convenient tariff and cost sharing model between the customers of an apartment building termed a sustainable block™. Section 2 presents the case study and its implications, with the clustered clients' case which is analyzed following two possible criteria for sharing renewable energy production: equal sharing and merit-based sharing and simulation results are presented next. Section 3 has the conclusions of the study. The study consists of grouping 60 residential households which, along with the PV energy plant, comprise a sustainable block™ (SB) to be serviced by the electric distribution company [18]. This community of clients will be connected to the electrical grid installed and managed by ENEL Distribucion. The solar PV plant—the microgrid—is especially designed to meet the needs of the community in a percentage of its total electricity consumption needs with renewable energy. 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 sustainable block™ (SB) in exchange for maintaining a sustainable electricity consumption scheme, aligned with the needs of the entire community (aggregate demand).

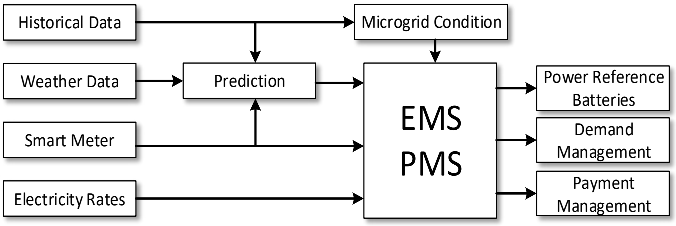


Fig. 1. Supervisory control scheme for the sustainable block™ (SB) with energy management and power management systems.

Figure 1 shows the model diagram of the homeostatic control (HC) system, wherein the EMS (energy management system) and the PMS (power management system) will be designed following homeostatic control strategy. The EMS/PMS module receives as input the electric power generation predictions (based on predictive homeostasis data carried out by the HC system's assessment of internal and external variables) [6,7]. This is done taking into account the photovoltaic generation plant and the electricity consumption ranges recorded in terms of demand side projection, in order to decide on the magnitude and the energy flow rate. In addition, the storage status of the batteries must be monitored. Thus, in pursuing the objective of minimizing grid-tied DG system's operating costs, the homeostatic controller will have the following attributions:

1.1. 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 [19].

1.2. Active control of the energy demand

It is determined by how much energy is consumed by each client of the microgrid as recorded by the smart meters. Those customers who are not "solidary" or choose not to align their electricity consumption 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) will be disconnected by smart switches (Smart plug), leaving them with the grid-only option.

1.3. Payment management

This unit is responsible for prorating payments between users and the electric company. Customers who have low consumption of the microgrid supply (those that exhibit a thrifty consumption behavior) 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 use power consumption more often. This arrangement is being considered by ENEL Distribucion as a means to entice a sustainable and more manageable energy consumption in light of constraints imposed by DG plants generating mostly renewable energies. This, ENEL hopes, will in turn reinforce a frugal or thrifty electricity consumption behavior and an easier stabilization of the system if it were needed [20.21].

2. Tariff calculation and assignation for clustered customers

This scenario evaluates a homeostatic control strategy that permits an efficient energy management in a residential building connected to the main grid, with a photovoltaic generation plant installed on it, plus energy storage and an energy management HC system. For the local electric company ENEL Distribucion, the customers of the building are considered a sustainable block™. Customers ought to reach consensus in order to choose from tariffs that were previously exclusively reserved for the commercial and/or industrial sector. Based on this scenario, supervisory control strategies, adapted for the specific requirements of the clients, are applied in order to reach an efficient and equitable energy management equilibrium. Such strategy should encourage a particular behaviour of consumers in order to achieve and maintain a more flexible, adaptable and sustainable state of equilibrium. In this way, both supply and demand respond to each other in a cooperative way with mutual benefit. The electricity tariffs that should be implemented for the SB will be BT4.3 or AT4.3, depending on the voltage level. These tariffs are common in the industrial sector, having the lowest price for the electric energy consumed, in addition to a charge for the maximum demand for power in peak hours. For this reason, the control strategy to be implemented should limit demand charges in order to maximize the benefits that can be granted to customers, and at the same time, the main network will operate at a higher efficiency point. The transaction module (Figure 2) is in charge for assigning the energy quote for each client and calculate the energy flow among clients and the grid. In order to accomplish the above mention procedure, criteria A and B could be chosen. In 2.1. Criteria A: Customers share the Nth part of generated renewable energy. Figure 2 below highlights the strategy to be used, where each client has access to one Nth part of the renewable energy produced and, for simplicity, all clients contribute to charging and discharging of the battery equally. The module begins by discriminating between clients with energy excess or deficit. The client that has excess of energy, expressed can sell it to clients with energy deficit or to the network, as it may be deemed more convenient. The sum of all the excess energy corresponds to the total energy available for selling. A fraction of this energy will feed the requirements of the customers with deficit P_{Pool_t} and the rest will be injected into the network P_{inGrid_t}. The energy contribution of each client will be identified as a factor of the energy available in the system. Both, the energy supplied to customers with energy deficit and the energy being injected into the grid by the customers with excess will be recorded and processed by the HC system thus assigning economic benefits thereafter according to the energy efficiency and energy sharing criteria. If there are clients with energy deficit, these customers must use energy from the grid P_{grid_t} and/or from the excess of other customers with renewable energy P_{Pool_t}. *2.2.* Criterion B: Substantial renewable energy supply according to customer merit. Following this criterion, customers will be entitled to use renewable energy as a reward by having an efficient and low consumption that enables to bound the maximum demand. The algorithm begins by checking if there is enough power from the microgrid to satisfy the demand of the SB. In case all customers take energy from the microgrid achieving 100% of their energy consumption, the Grid_frac is virtually zero [14,15]. The excess of energy is injected into the main grid and clients will receive an equal income for that contribution. If this condition is not met, it is understood that the energy available in the microgrid is not enough to satisfy the demand. Therefore, this energy must be administered and delivered, as a reward for clients that have a low consumption during peak hours. The module algorithm designed for peak hours is in charge of organizing the customers according to their energy consumption from lowest to highest. The first m customers will have the right to receive energy from the microgrid in proportion to their consumption. Customers who are allowed to receive energy from the microgrid at peak hours will increase an index termed the homeostatic index (H_i)[14,15] which is a measure of efficiency and sustainability of the energy system. Due to the high cost of the peak hour demand, the control system must encourage customers to consume during off-peak hours. To meet this goal, the cost of the electricity supply is transferred to consumers through an internal tariff, which differentiates between low and high demands. Fig. 2 illustrates the applied internal tariff, this will be based on the monomic energy price which consists of a single equivalent price per kWh that considers both, the energy and the power charge.

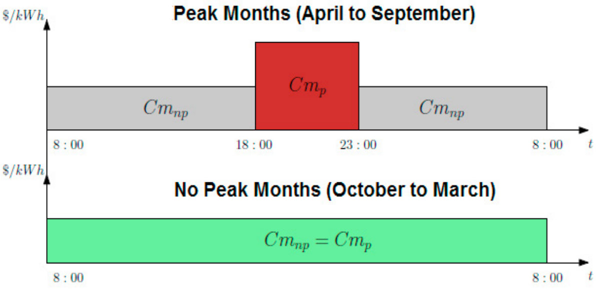


Fig. 2. Internal tariff for Sustainable Block™ customers.

The monomic price for peak hours (C_{Mp}) is calculated on the basis of energy consumed and the maximum read demand, both in peak hours. On the other hand, the other monomic price is calculated in a similar way, but considering off peak hours. Monomic prices are calculated monthly together with the billing cycle. During the months that do not contain peak hours (October to March). After one year of evaluation ($t = 35040, \Delta t = 15min$), the monthly and annual costs are calculated for each clients and for the whole SB. The algorithm utilized is repeated up to 20 years (PV lifetime), each year a loss of efficiency in photovoltaic panels equal to 0.6% is added and a linear reduction of battery capacity is also considered, so that the final battery capacity is 80%. The depth of discharge of the battery is adjusted so that no intermediate replacements occur. 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 5, 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 [20,21], 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.

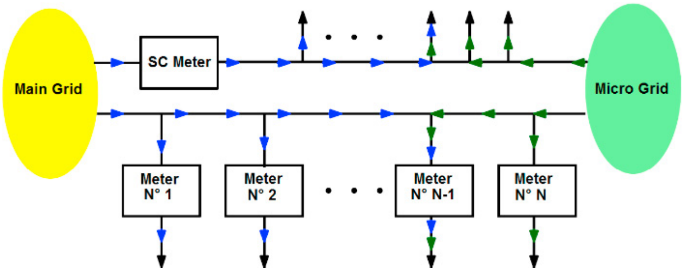


Fig. 3. Energy flux and metering for separate customers

2.1. Simulation Results

The results obtained by simulations are presented and analyzed next. These results validate the homeostatic control strategies used to manage the energy demand of and the energy sharing amongst 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 energy storage unit (batteries) with electricity from the grid during the low demand hours, based on weather forecasts and algorithms to predict the photovoltaic generation. The aim is to reach peak hours with the batteries fully charged. This way, the benefits of the electric tariff to be used (BT4.3 or BT4.3) are maximized. As an example, the Fig. 6 shows the power flows between the different elements during one day considering the existence of a battery and applying hourly tariff.

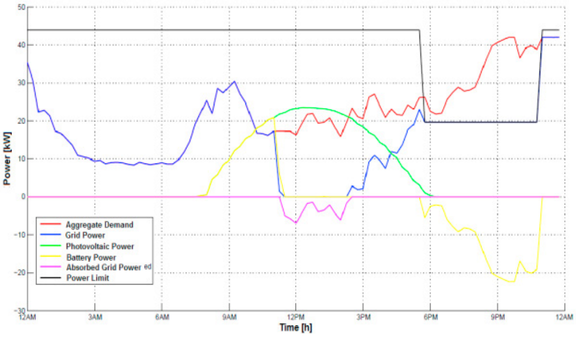
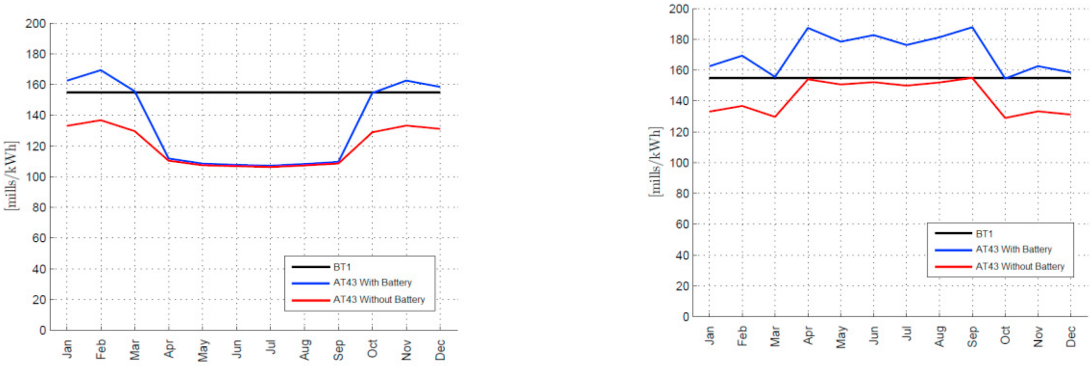


Fig. 4. SB Power flow with battery and hourly tariff.

Whether the microgrid has or does not have a storage unit in operation, the control system is always aware of the available supply and systems capacity and it has, at all times, a set of controllable loads which can be remotely disconnected by the controller, so that the maximum demand can always be maintained bellow a specified limit. In addition, customers will be notified automatically that their behavior is not being solidary with the needs of the community, and they will be penalized. Thus, the microgrid can be seen as a socio-technical complex system, in which energy users play a crucial role as active loads. Internal electric tariff for microgrid customers is shown in Fig. 5. This tariff, based on the monomic energy cost is employed with the aim to achieve an efficient energy consumption and to transfer the energy directly the cost 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 microgrid for whatever reason, the grid supply will automatically take over and supply for the deficit.



(a) Off-peak hours

(b) Peak hours

Fig. 5. Energy monomic cost.

3. Conclusions

The results show that whether using the criterion A or B, a very high reduction in annual cost for the customers is achieved. Using the described techniques for renewable energy sharing it is easier to stablish and understand how every customer will receive their part of the generated energy, avoiding discordances and problems between them. Moreover, the case of separated (also called non-clustered) customers is considered, being possible to put them apart from the common billing and energy sharing system. Using these criteria, some problems regarding renewable resources sharing can be solved, encouraging customers to install these systems on their blocks. Finally, it is important to realize the fragility of today's electric power distribution infrastructure, particularly in Chile where seismic activity is recurrent. 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 techniques in the market today to go that route safely [22]. It is also expected that within the next ten years, consumer households will be increasingly equipped with smart metering, advanced energy efficiency systems and more intelligent appliances with the incorporation of AI. These technologies are the basis for households to better monitor electricity consumption and to actively control loads in residential dwellings. Thus household load profiles under different tariffs and simulation of changes for these profiles when consumers face time-based electricity prices are important.

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