Incorporation of Productive Solar Solutions for Communities into Microgrid Energy Management Systems

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Abstract

The introduction of renewable energy resources into electrical systems and productive processes is a unique opportunity for the sustainable development of communities. Productive processes that use solar energy or PSPs have been conceived to improve the quality of life of rural communities in the Arica & Parinacota region in northern Chile. In this context, this work presents a novel approach for the incorporation of productive solar solutions into Microgrid Energy Management Systems (MG-EMS). EMS minimizes overall operational costs by means of coordinating MGs and PSPs. Therefore, there is a great opportunity in the inclusion of PSPs in EMS and taking advantage of its benefits. The proposal incorporates the field experience of the research team regarding solar energy solutions for rural communities in the north of Chile. In this study, multi-zone time-variant PSPs load models are developed based on the ZIP load model approach. The multi-zone ZIP load model performance is analyzed and compared with a persistence method. The results show the benefits of using more accurate models to capture the particular behavior of productive solar processes compared with a conventional approach. The mean absolute percentage error for multi-zone ZIP (9.99 %) is lower than that of the persistence method (20.41 %) compared with the active power load measured, resulting in the prevalence of the multi-zone ZIP load model. The improvement of MG-EMS performance will also benefit the power system operation and planning.

Keywords - Microgrid, Energy Management System, Productive Solar Processes, Communities

Acronyms List

MG	: Microgrid
DER	: Distributed Energy Resources
EMS	: Energy Management System
GHG	: Greenhouse Gases
PSPs	: Productive Solar Processes
RES	: Renewable Energy Sources
MAPE	: Mean Absolute Percentage Error
RMSE	: Root Mean Square Error
Std	: Standard Deviation

Nomenclature

Parameters:

V_0	: Nominal voltage
P_0	: Nominal active power
$P_{ZIP,RES}$	: Active power of the electric heating resistances
$P_{ZIP,FAN}$	: Active power of the electric fan
Z_{PRES}	: Constant impedance coefficient of the electric heating resistances

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I_{PRES} : Constant current coefficient of the electric heating resistances

P_{PRES} : Constant power coefficient of the electric heating resistances

Z_{PFAN} : Constant impedance coefficient of the electric fan

I_{PFAN} : Constant current coefficient of the electric fan

P_{PFAN} : Constant power coefficient of the electric fan

Variables:

$V(t)$: Current voltage at time *t*

$P_{ZIP}(t)$: ZIP active power consumption at time *t*

$Z_P(t)$: Constant impedance coefficient at time *t*

$I_P(t)$: Constant current coefficient at time *t*

$P_P(t)$: Constant power coefficient at time *t*

$\hat{P}(t)$: Estimated active power consumption at time *t*

$\hat{V}(t)$: Ratio between current voltage and nominal voltage at time *t*

$P_{ZIP,0}(t)$: Active power consumption of the ancillary services of the PSP at time *t*

$\delta_i(t)$: Contribution of the ancillary services in entire estimated power consumption at time *t*

$(1-\delta_i(t))$: Contribution of the PSP in entire estimated power consumption at time *t*

$\beta_i(t)$: Contribution of the electric resistances in the total PSP power consumption at time *t*

$(1-\beta_i(t))$: Contribution of the electric fan in the total PSP power consumption at time *t*

$\Xi_{1i}(t), \Xi_{2i}(t), \Xi_{3i}(t), \Gamma_i(t)$: Estimated parameters of the total power consumption at time *t*

1. Introduction

A microgrid (MG) is a quite appealing alternative for dealing with the challenges of integrating distributed energy resources (DER) units -including renewable energy sources into power systems (Olivares et al., 2014). On the other hand, due to decarbonization, the adoption of renewable energies by production processes has grown in importance in recent years. Nowadays, productive processes are modeled as exogenous loads in MGs and mainly through conventional models (e.g. estimates with time series) (Derakhshandeh et al. 2015). However, productive processes are influenced by several variables (e.g. climate, temperature, etc.) and rational decisions from the operators. Thus, there is still a challenge of capturing their behavior in the models is still a challenge. The objective is MGs and productive processes to become coordinated by the Energy Management System (EMS) to achieve an economical and safe operation.

In the specialized literature, there are several investigations regarding the introduction of MGs, particularly in industrial productive processes. Li et al. (2016) conducted a research on the life cycle of energy use and greenhouse gases emissions (GHG) of a conventional energy supply system and microgrids over an ammonia plant located in central Inner Mongolia, China. The life cycle of energy use and GHG emissions of MGs are assessed and compared to the existing fossil fuel-based energy system. Fang et al. (2018) presented a fuzzy decision-based approach and a controller design method to address the dispatch of energy in offshore industrial microgrids consisting of various forms of distributed generators (renewable sources and onsite diesel generators) and a seawater desalination system.

Previous references mainly focus on industrial processes, however, there is no much evidence on researches involving small-scale production processes for communities.

Most of the investigations published in the literature have utilized a constant power load model to represent electric load behavior. Constant power load models are considered to be independent of either voltage variations or other exogenous variables.

The conventional constant power model might not be enough to represent the behavior of productive solar processes (PSPs) on an accurate basis. Such conventional models do not consider the transition between different operating zones during the running of PSPs, as each zone has its unique characteristics and active elements.

Nowadays, the widely method used for load modeling is to consider as time-invariant combination of constant impedance, constant current and constant power, known as ZIP load model (Bokhari et al., 2014; Hatipoglu et al., 2012; Milanović et al., 2014). However, as load consumption varies with time due to the changes in consumption behavior, the ZIP coefficients also should also change with time. In this work, multi-zone time-variant PSPs load models have been developed based on the ZIP load model approach. Additionally, PSPs load models are incorporated into the EMS approach. The contribution of this proposal is tested by using recent field experiences in Chile. The rest of the paper is structured as follows. In Section 2, a description of the considered productive solar solutions is presented. The proposed methodology for PSPs integration into MG-EMS is outlined in Section 3. Section 4 describes the proposed multi-zone ZIP load model for productive solar processes. Section 5 presents the simulations and results, and finally, Section 6 provides some conclusions based on this work.

2. Description of the Considered Productive Solar Solutions for Communities

Productive processes that use solar energy or PSPs have been conceived to improve the quality of life of the communities in the Arica & Parinacota region in northern Chile. Each of these productive processes are described in more detail in the following subsections.

2.1. River shrimp farming through intensive use of solar energy for sustainable development of the town of Camarones

The purpose is to encourage the farming of river shrimp and trout through intensive use of solar resources throughout the execution of this project (see Fig. 1). For this, it is necessary to have water of adequate quality for its use in aquaculture, based on a low energy consumption technology that enables the use of the abundant local solar radiation both for energetic support and photochemical elimination of arsenic. Additionally, a profitable, scalable and replicable business model will be developed, enabling the production of river shrimp and trout in a sustainable manner, therefore boosting the socio-economic development of the towns of Camarones, Taltape, and Maquita by improving the quality of life of their inhabitants (Ayllu-Solar, 2018a).

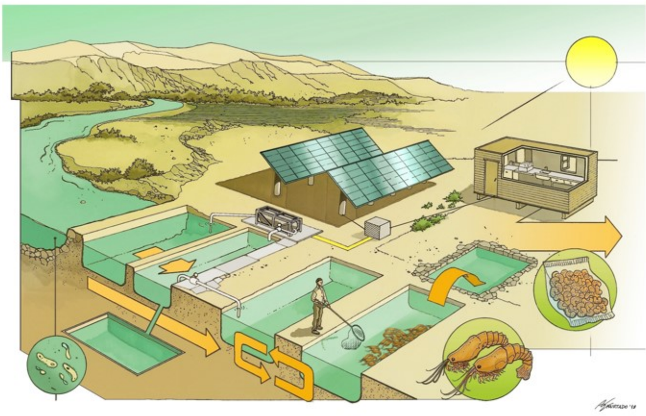

Fig. 1: River Shrimp Farming through an Intensive Solar Energy

2.2. Solar Energy for a Camelid Fiber Collection and Processing Centre

This project seeks to open up an opportunity for the inhabitants of the commune of General Lagos to a sustainable development and adding value to local livestock activity based on their traditional knowledge through the intensive use of solar energy (see Fig. 2), also supporting them in the improvement of productive processes and the enhancement of the livestock traditions and their cultural value (Ayllu-Solar, 2018a).

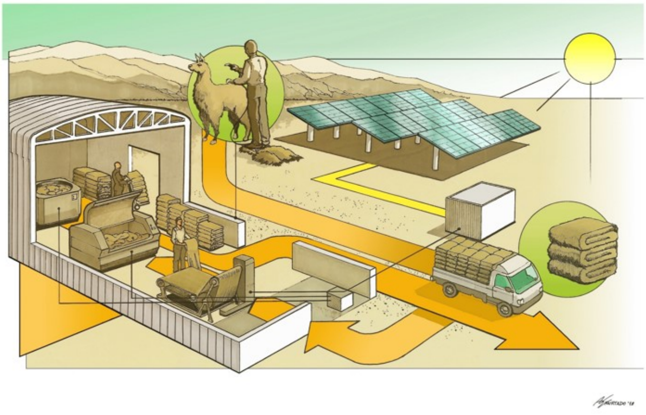

Fig. 2: Solar Energy for a Camelid Fiber Collection

2.3. Solar Energy Processing of Agricultural Products in Vítor and Chaca Valley

This project seeks to add value to the fruit and vegetable production on the valleys of Vítor and Chaca through the implementation of a drying processing system that operates with solar energy (see Fig. 3). With this infrastructure, it is expected that farmers can see their incomes increased and therefore improve their quality of life (Ayllu-Solar, 2018b).

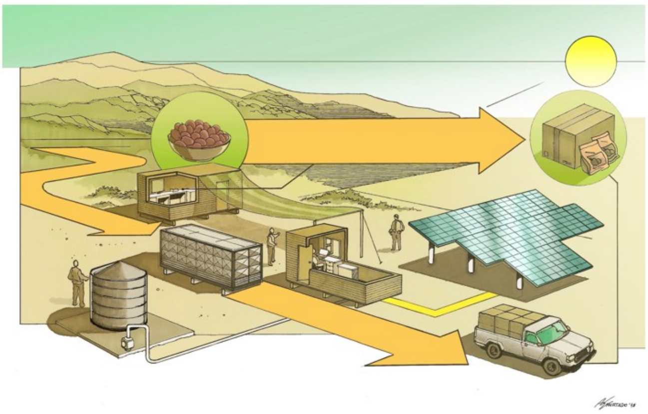

Fig. 3: Solar Energy Processing of Agricultural Products

It is expected that future microgrids will incorporate several PSPs like the ones described in this section. Thus, the definition of a Microgrids as an electricity distribution system containing loads and distributed energy resources that can be operated in a controlled, coordinated way, should consider increasingly the integration of PSPs in a proper manner.

3. Proposed Methodology for PSPs Integration into MG-EMS

The authors (Palma-Behnke et al., 2013) presented an EMS that supplies conventional loads to the MG. On the other hand, new solar solutions are a great benefit for communities. Therefore, there is a great opportunity in the inclusion of PSPs in the EMS and taking advantage of its benefits. The EMS minimizes overall operational costs while coordinating the MG and PSPs. Since the PSPs described in section 2 are susceptible to exogenous variables, accurate models for capturing their behavior are required. There are two possible operation scenarios for the PSP. The first is that the PSP operates autonomously without the need for obtaining/delivering information to the EMS. The second scenario is that the PSP is subject to EMS coordination to operate as a whole system. Fig. 4 summarizes the proposed scheme of PSP integration to the

EMS. This integration allows both MG and PSPs to obtain economic benefits as the overall system is supplied by the energy coming from the main grid when in low-priced electricity. Otherwise, the demand of the MG and the PSPs is supplied by local sources (photovoltaic, storage, diesel generator).

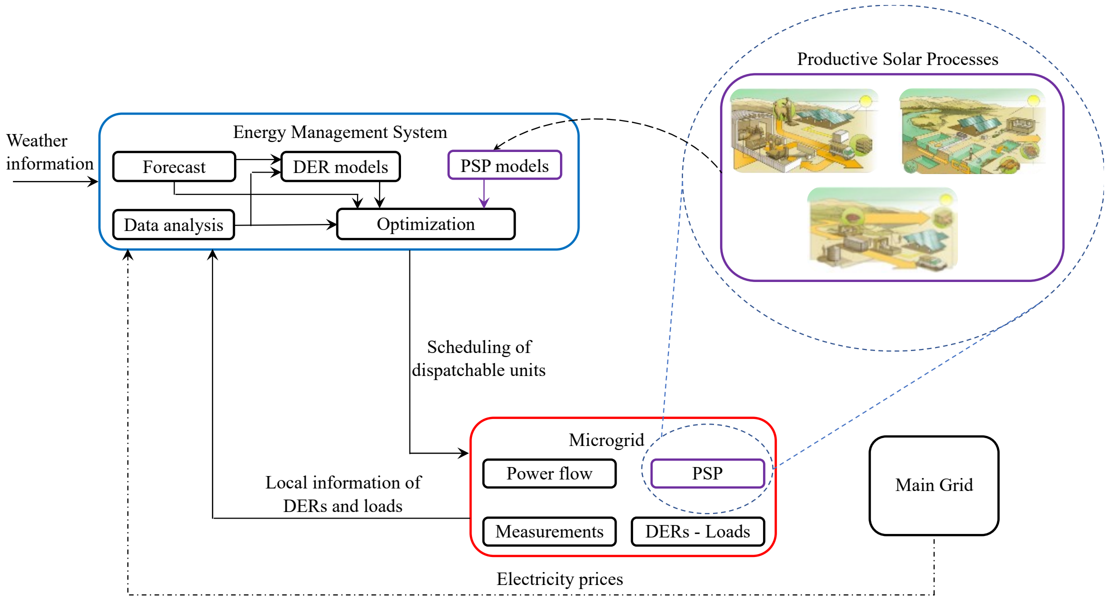

Fig. 4: Proposed Scheme for Productive Solar Processes Integration into the MG-EMS

In the following sections, the proposed scheme for the process described in section 2.3 is explained in detail.

4. Proposed Multi-Zone ZIP Load Model for Vítor and Chaca Valley

4.1. Time-variant ZIP load model

As load consumption varies with time due to the changes in consumption behavior, the ZIP coefficients also should also change with time. For example, a set of loads which are turned on at time t might not remain on at time $t + n$, or a different set of loads should have to be turned on (Hossan et al., 2017). Thus, the time-variant ZIP load model (Hossan et al., 2017; Wang and Wang, 2014) is expressed as follows:

$$P_{ZIP}(t) = P_0\left[Z_P(t)\left(\frac{V(t)}{V_0}\right)^2 + I_P(t)\left(\frac{V(t)}{V_0}\right) + P_P(t)\right] \quad \text{(eq. 1)}$$

$$Z_P(t) + I_P(t) + P_P(t) = 1 \quad \text{(eq. 2)}$$

where P_0 is the nominal power, at nominal voltage V_0, $V(t)$ is the actual voltage , the time-dependent parameters Z_P, I_P and P_P represent the constant impedance, constant current and constant power, respectively.

4.2. Multi-zone PSPs load models

The characteristics of PSPs can be changed throughout the day, as they use solar energy to perform the processes operation. Hence, three zones have been determined depending on the hour of the day and the solar radiation. Fig. 5 shows the three zones considered for the PSPs.

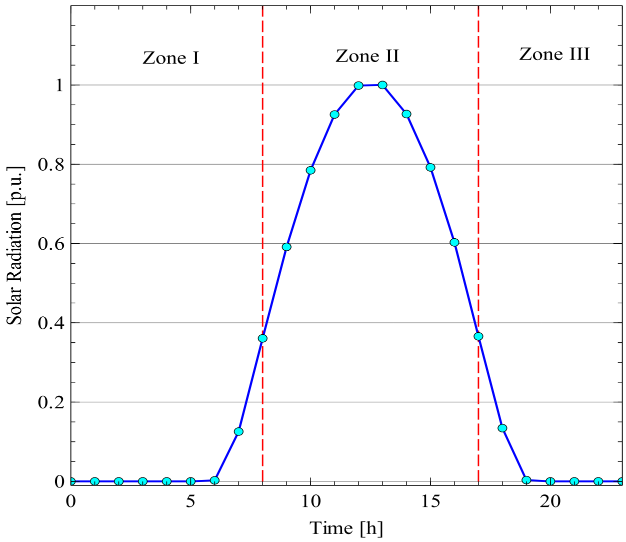

Fig. 5: PSPs Operating Zones Depending on Solar Radiation

Each of the three operating zones has different load model that determine the power consumption. In Zones I and III, a set of electric resistances for heating plus an electric fan are active. In Zone II, there is a electric fan to maintain the temperature of the productive process. Due to the solar radiation contribution, the electric resistances are not required for the productive process in Zone II. The constants for the heater and the fan are found in (Bokhari et al., 2014). The load models of the three zones in Fig. 5 are given by eq. 3 – eq. 5.

- *Zone I*

$$\hat{P}(t) = P_{ZIP,0}(t) + P_{ZIP,RES} + P_{ZIP,FAN} \tag{eq. 3}$$

- *Zone II*

$$\hat{P}(t) = P_{ZIP,0}(t) + P_{ZIP,FAN} \tag{eq. 4}$$

- *Zone III*

$$\hat{P}(t) = P_{ZIP,0}(t) + P_{ZIP,RES} + P_{ZIP,FAN} \tag{eq. 5}$$

where,

$P_{ZIP,0}(t)$	active power of the ancillary services of the PSPs [kW]
$P_{ZIP,RES}$	active power of the electric heating resistances [kW]
$P_{ZIP,FAN}$	active power of electric fan [kW]

4.3. Tuning up of multi-zone PSP model parameters

Once defined the three operating zones of the productive process, the parameters of the corresponding models shall be identified. Since operating conditions change from one zone to another, and from one time to another, a set of tuples of parameters (one per hour) was identified for each model of each zone. For instance, Zone II that goes from 10:00 to 17:00 hours, has a set of nine tuples of parameters. According to equations (3)-(5), the models for Zones I and III have the same structure whereas the model for Zone II does not have the contribution of the electric resistance. Then it can be defined $\hat{V}(t) = \left(\frac{V(t)}{V_0}\right)$. Hence, from equation (1), any ZIP model can be expressed as:

$$P_{ZIP}(t) = P_0\left[Z_P(t)\hat{V}^2(t) + I_P(t)\hat{V}(t) + P_P(t)\right] \tag{eq. 6}$$

Let $\lambda_0(t) = \{Z_{P0}(t), I_{P0}(t), P_{P0}(t)\}$, $\lambda_{RES}(t) = \{Z_{PRES}(t), I_{PRES}(t), P_{PRES}(t)\}$, and $\lambda_{FAN}(t) = \{Z_{PFAN}(t), I_{PFAN}(t), P_{PFAN}(t)\}$ denote the set of parameters of the corresponding models $P_{ZIP,0}\left(\hat{V}(t), t; \lambda_0(t)\right)$, $P_{ZIP,RES}\left(\hat{V}(t), t; \lambda_{RES}(t)\right)$, and $P_{ZIP,FAN}\left(\hat{V}(t), t; \lambda_{FAN}(t)\right)$, where the notation $f(x; y)$ indicates that the function $f()$ depends on x with a set of parameters y. Let $\hat{P}(t)$ be the estimated power at time t. n_i denotes the number of hours of zone i, $i = I, II, III$. Then, the set of tuples of parameters of each zone is determined through the solution of the minimization problem (eq. 7), where Z_i is the i-th zone.

$$\min_{\lambda_{0i}(t), \delta_i(t), \beta_i(t)} \sum_{t=1}^{n_i} \left(P_i(t) - \hat{P}_i(t)\right)^2 \quad \text{(eq. 7)}$$

Subject to:

$$\hat{P}_i(t) = \delta_i(t) P_{ZIP,0i}\left(\hat{V}(t), t; \lambda_{0i}(t)\right)$$
$$+(1 - \delta_i(t))\left[\beta_i(t) P_{ZIP,RESi}\left(\hat{V}(t), t; \lambda_{RESi}(t)\right) + (1 - \beta_i(t)) P_{ZIP,FANi}\left(\hat{V}(t), t; \lambda_{FANi}(t)\right)\right]$$
$$0 \le \delta_i(t) \le 1$$
$$0 \le \beta_i(t) \le 1$$
$$Z_{P0i}(t) + I_{P0i}(t) + P_{P0i}(t) = 1$$

Note that in (eq. 7) the parameters $P_{ZIP,RES}\left(\hat{V}(t), t; \lambda_{RES}(t)\right)$ and $P_{ZIP,FAN}\left(\hat{V}(t), t; \lambda_{FAN}(t)\right)$ were not included as decision variables into the minimization problem. This ought to the fact that these parameters are known, and only their contribution $\beta_i(t)$ to the total power demanded was considered. Furthermore, estimated power was divided into two components, namely, ancillary services and power demand of the productive process itself. In (eq. 7), the contribution $\delta_i(t)$ of each type of demand was also included as a decision variable in order to determine which part of the estimated power corresponds to which type of power demand.
In order to solve the minimization problem (eq. 7), the expression for $\hat{P}_i(t)$ shall be expanded. By performing the corresponding computations, the estimated power at each time t for a zone i can be written in a matrix form (eq. 8), with $\Xi_{1i}(t) = \Lambda_i(t) Z_{P0i}(t)$, $\Xi_{2i}(t) = \Lambda_i(t) I_{P0i}(t)$, $\Xi_{3i}(t) = \Lambda_i(t) P_{P0i}(t)$, $\Gamma_i(t) = \delta_i(t)\beta_i(t)$, and $\Lambda_i(t) = \delta_i(t) P_{0i}(t)$. The parameters $a_i(t)$, $b_i(t)$, $f_i(t)$, and $\Theta_i(t)$ involve products of parameters $P_{ZIP,RES}\left(\hat{V}(t), t; \lambda_{RES}(t)\right)$ and $P_{ZIP,FAN}\left(\hat{V}(t), t; \lambda_{FAN}(t)\right)$, with the voltage variable $\hat{V}(t)$. Since all these parameters and variables are known, and as these products do not involve the decision variables of the minimization problem (eq. 7), they can be computed based on historical data and/or on the current measurement of $\hat{V}(t)$. Therefore, they are constant for the minimization problem although these terms are time-dependent.

$$\hat{P}_i(t) = \underbrace{\begin{bmatrix} \hat{V}_i^2(t) & \hat{V}_i(t) & 1 \end{bmatrix} \underbrace{\begin{bmatrix} 1 & 0 & 0 & a_i(t) & -a_i(t) & 0 \\ 0 & 1 & 0 & b_i(t) & -b_i(t) & 0 \\ 0 & 0 & 1 & 0 & 0 & f_i(t) \end{bmatrix}}_{\bar{A}_i(t)}}_{A_i(t)} \underbrace{\begin{bmatrix} \Xi_{1i}(t) \\ \Xi_{2i}(t) \\ \Xi_{3i}(t) \\ \beta_i(t) \\ \Gamma_i(t) \\ \delta_i(t) \end{bmatrix}}_{\hat{x}_i(t)} + \Theta_i(t) \quad \text{(eq. 8)}$$

Consequently, the minimization problem becomes:

$$\min_{\hat{x}_i} \left\| \vec{P}_i - A_i \hat{x}_i - \Theta_i \right\|_{Q_i}^2 \quad \text{(eq. 9)}$$

Subject to:

$$\Xi_{1i}, \Xi_{2i}, \Xi_{3i} \ge 0$$
$$0 \le \delta_i \le 1$$
$$0 \le \beta_i \le 1$$
$$0 \le \Gamma_i \le 1$$

where, with abuse of notation, $\vec{P}_i = [P_i(1), \dots, P_i(n_i)]^T$, $\hat{x}_i = [\hat{x}_i(1), \dots, \hat{x}_i(n_i)]^T$, $\Theta_i = [\Theta_i(1), \dots, \Theta_i(n_i)]^T$, $A_i = diag\left(A_i(1), \dots, A_i(n_i)\right)$, and $Q_i > 0$ a positive definite matrix, often a diagonal matrix where all its elements are greater than zero. The minimization problem (eq. 9) is a quadratic programming problem that can be solved with any commercial tool available. However, it must be checked whether the Hessian is positive-or negative-definite to verify the convexity of the optimization problem. Due to matrix structure $\bar{A}_i(t)$ in (eq. 8), the resulting Hessian matrix may have both positive and negative eigenvalues. Therefore, a saddle-point is the optimal solution and thus, adequate algorithms shall be used to obtain a numerical solution of (eq. 9). Nevertheless, there are several available tools that are capable of dealing with this issue and allow an efficient finding of saddle points in a finite number of steps (i.e., they have ensured convergence towards the optimal solution). The application of the proposed method to an actual case study is explained below.

5. Simulation and Results

In this section, actual measurements data from a Huatacondo MG are used for assessing the proposed method. Simulations are run using the MatLab simulation software (MathWorks, 2016). In order to assess the performance of the proposed multi-zone ZIP load model, it is compared with the results of a persistence method considering the data measured a week ago (Coimbra and Pedro, 2013).

We assume that the total consumption of the Huatacondo MG consists of a residential load (ancillary services) and an industrial load (PSP). According to section 4.2, three operating zones were determined to perform the parameter estimation and proposal validation.

After solving the optimization problem in (eq. 9), the following results considering a 24-hour period were obtained with actual active power consumption data. Fig. 6 shows an actual active power load profile (Pmeas), the resulting load profile by using a multi-zone ZIP load model (Pest), and the load profile by using the persistence method (Ppers). In addition, we can see that the point-to-point squared error and the absolute error of the Pest are lower than Ppers errors, except from hour 15 where Ppers errors are lower than Pest. This can be explained as shown in Fig. 7, where it can be observed that in hour 15, the voltage used for parameter estimation is lower than the voltage measured. Thus, this variation produces the error to increase in hour 15. Despite this, Fig. 6 shows that proposed multi-zone ZIP load model can be used for other input data.

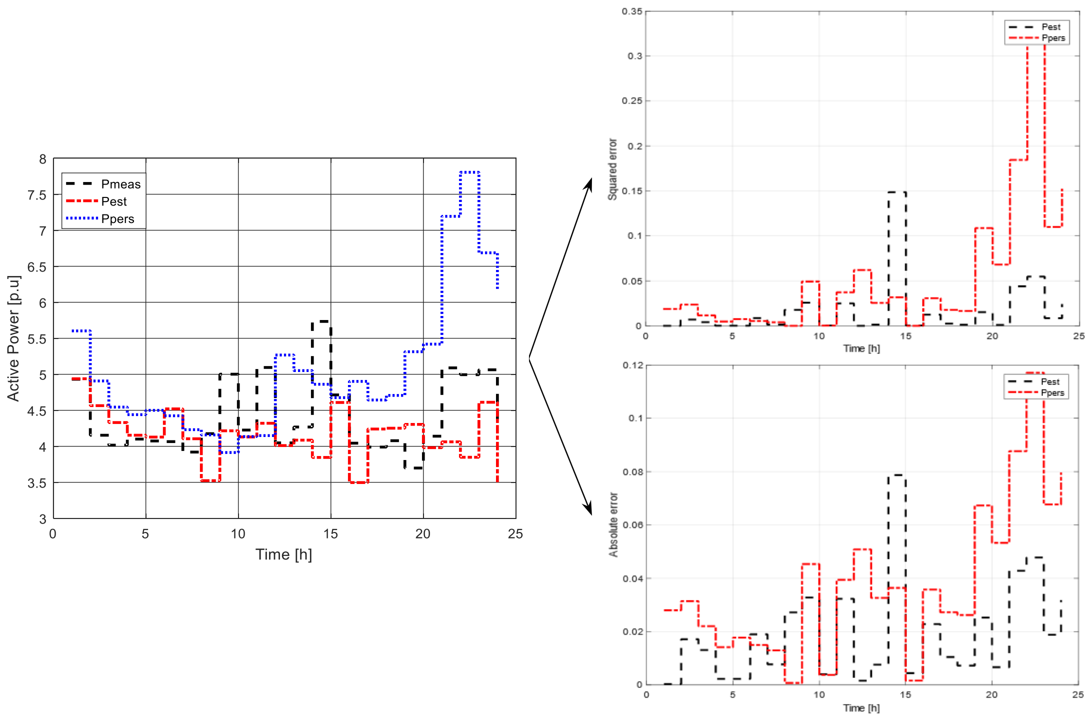

Fig. 6: Comparison of Measured Active Power (Pmeas), Estimated Active Power (Pest) and Persistence Method (Ppers), Squared Error and Absolute Error

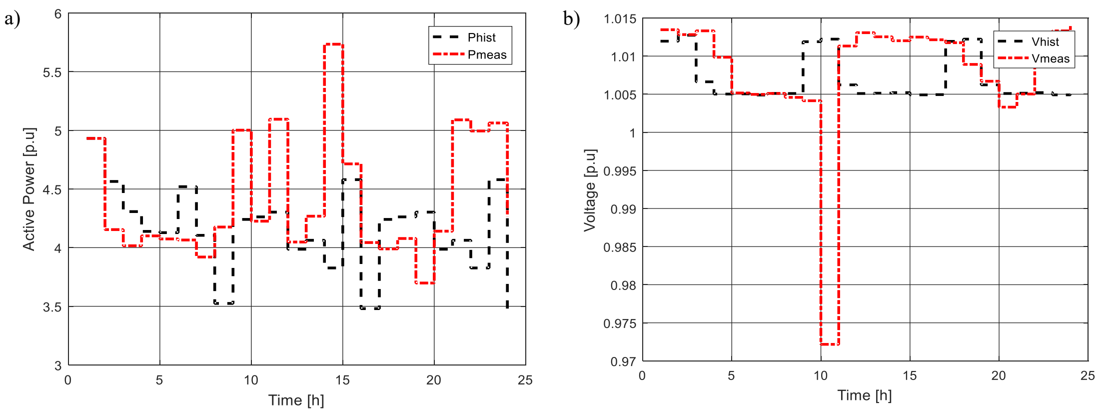

Fig. 7: a) Historic Active Power (Phist) and Measured Active Power (Pmeas), b) Historic Voltage (Vhist) and Measured Voltage (Vmeas)

Tab. 1 shows prediction errors of the multi-zone ZIP load model and the persistence method, considering the following performance indexes: mean absolute percentage error (MAPE), root mean square error (RMSE) and standard deviation (Std). Performance indexes depict that the performance of the multi-zone ZIP load model is better than the persistence method. For instance, the mean absolute percentage error for multi-zone ZIP (9.99 %) is lower than that of the persistence method (20.41 %) compared with the measured active power load. In addition, the RMSE for multi-zone ZIP load model (0.63) is much less than that related to the persistence method (1.14) which results in the prevalence of the multi-zone ZIP load model.

Tab. 1: Prediction Errors

	Multi-zone ZIP model	**Persistence model**
MAPE [%]	9.99	20.41
RMSE	0.63	1.14
Std	0.36	0.99

Finally, Fig. 8 shows the load demand composition found by the estimator. It can be observed that approximately 56% of total measured consumption corresponds to ancillary services (Anc), while approximately 44% corresponds to industrial consumption (Ind). It can be noted that around 60% corresponds to heating (Res) and 40% to ventilation (Fan). These results are according to such productive process considered where a electric fan was expected to be active in the three zones, while heating resistances were active only in Zone II.

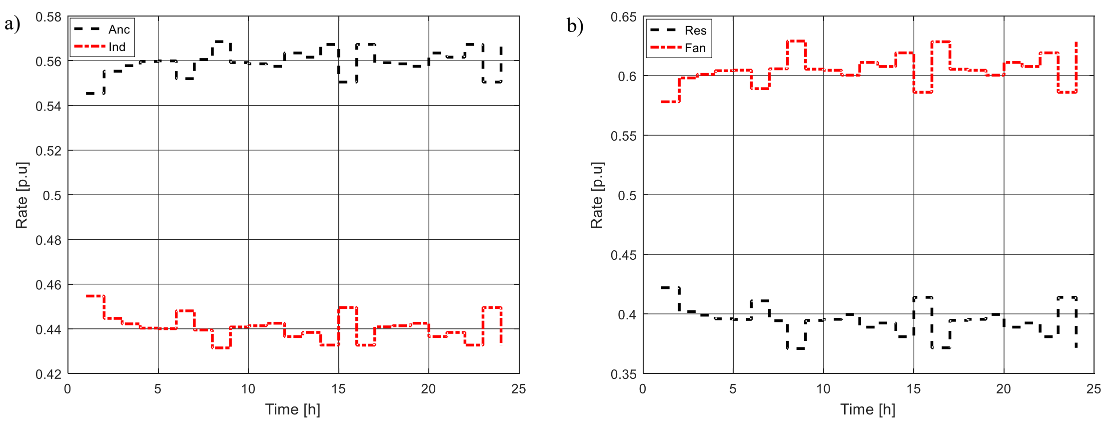

Fig. 8: a) Total Load Consumption Composition (Ancillary (Anc) plus Industrial (Ind)) and Industrial Load Composition (Heating (Res) plus Ventilation (Fan))

6. Conclusions

In this paper, a multi-zone load modeling technique has been developed for PSPs incorporated in an extended ZIP load model. Due to dynamic behavior of the load consumption, the time-dependent ZIP load model has been used to develop the PSP load models. The multi-zone ZIP time variant load model has allowed us to capture and to represent the PSP's electric load consumption profile. This improvement can impact the performance of the MG-EMS based on a better forecasting of the load behavior. To show the prevalence of the proposed method, the multi-zone ZIP load model performance has been analyzed and then compared with a persistence method. Simulations were performed by using the actual data from a PSP located in the north of Chile. The results have shown that the proposed load modeling approach can provide accurate results compared with the conventional models. The mean absolute percentage error for multi-zone ZIP (9.99 %) is lower than that of the persistence method (20.41 %) compared with the measured active power load which shows the prevalence of the proposed approach. The improvement of MG-EMS performance will also benefit the power system operation and planning. Future research work will consider the generalization of the methodology for several feasible PSPs in the form of a repository of models and propose an online update of estimated parameters.

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