Simulative Study of a Smart Node for Domestic Applications, Equipped with PV Panel, Energy Storage and Home Automation

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Abstract— **The increase of renewable energy exploitation is a current topic in the energetic field. One of the main obstacles to the use of renewable energy in the global energetic mix is represented by the fluctuating nature of renewable power sources, since power fluctuations are cause of stress for the electric grid. A possibility to widely exploit renewable sources is the implementation of a "smart grid", consisting in an interconnection of several smart-nodes. To reduce the stochastic effect of the renewable energy source it is possible to equip the nodes an energy storage managed in order to smooth the power peaks. In this regard, a dynamic analysis was carried out in order to integrate the renewable sources with the electric grid.**

This work presents a simulation model of a smart node consisting in a user power profile, a photovoltaic panel and a battery. Tests were worked out in different node configurations, in order to evaluate the incidence on the energy flows and on the grid distortion factor.

Simulations were repeated by implementing the system with an algorithm for home automation in order to exploit intelligently the energy from the renewable source. This algorithm allows to synchronize the operation of certain loads to the sun irradiation power.

Index Terms—**Smart grid; simulation modeling; home automation; energy storage.**

I. INTRODUCTION

GLOBAL energy requirements have increased during the last decades, promoting the intensification of studies regarding energy production through the employ of renewable energy sources. According to an European law regarding buildings energy efficiency, the residential sector is responsible for about 40% of the total primary energy consumption [1].

One of the hardest obstacles to renewable energy wide exploitation is represented by the stochastic nature of energy sources, which is cause of power fluctuations and disturbances in the electric grid.

The installation of distributed renewable energy plants contributes to satisfy the users energy requirements and is very likely to an implementation turned to an intelligent management of energy flows. In fact, the possibility of designing smart-grid systems equipped with energy storage and the application of modern home automation technologies to some of the domestic loads allows to better exploit the energy coming from renewable sources and reduce the power disturbances in the electric grid.

In this paper, several dynamic simulations [2-9] were carried out in order to evaluate efficiency, benefits and drawbacks of employing a smart-node for domestic applications equipped with photovoltaic panel local energy production. In particular, this paper aims to study, through Matlab-Simulink dynamic simulations, the impact of home automation on a house equipped with photovoltaic plant, connected to the electric grid by a smart-node, controlled with two different logics: the first one turned to obtain a smoothing of the electric load diagram; the second one turned to obtain the maximum self-consumption of the renewable power produced.

An accurate modeling work allowed to simulate the monthly consumption of a typical house, taking into account the power fluctuation due to sun irradiation in the different hours of the day and the presence of a battery energy storage. The model employed in this study can simulate a home automation system, linking the operation of some domestic loads (e.g. washing machine and dishwasher) to a minimum power threshold of the photovoltaic plant. In this way, it is possible to employ said loads in a time period which limits the energy requirements from the electric grid, increasing the self-consumed energy.

The final goal of the work was to evaluate the incidence of home automation for a house equipped with different sizes of photovoltaic panel (in a range between 1 and 4 kW) integrated with the electric grid by means of a smart node, by comparing this scenario with one not equipped with home automation, and analyzing the energy saving and the sustainability in terms of grid distortion factor.

II. THE SMART NODE SIMULATION MODEL

Figure 1 represents the scheme of the plant comprising all its sub-systems [10]: the user, the photovoltaic plant, the battery and the electric vehicle. The components are joined together by an intelligent inverter, which converts the electric powers of all the sub-systems into the desired signal typology (AC or DC with the proper voltage), while deciding the amount of power to be delivered to the storage or that to be taken from the electric grid.

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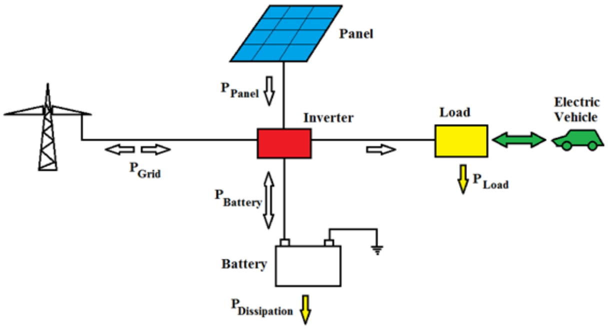

Fig. 1. Scheme of the node physical connections.

The smart node model was implemented in the Matlab Simulink environment. The model sample time was set to 1 minute [11], in order to correctly simulate the dynamic behavior of the system while keeping an acceptable runtime of the simulation (runtime is rather long owing to the long simulated time period, one month).

The model, named TRAMSE, consists of three sections:

- pre-processing, in which the important data of the system are loaded (e.g. panel area, battery size, electric vehicle characteristics, algorithms for system control …);
- processing, consisting in the calculations carried out by the simulation model.
- post-processing, in which the results are provided as output. The system outputs are all the power flows and energy amounts interesting the different system modules, together with performance indicators of which a more detailed description will be given in the next sections.

In the following are described the sub-systems composing the smart-node model.

A. *Load*

The electric load for the domestic user was simulated by a series of Simulink "pulse generators", representing the power of the different electric loads present in a typical house. The loads power value, duration and phase were opportunely set in order to obtain a signal as much as possible similar to reality, with power peaks not exceeding 3 kW and a total energy consumption of about 430 kWh in one month.

B. *Panel*

The panel model was built according to the modality described in [3]. To reduce the computational load for the simulator, the solar panel model above mentioned was employed to derive maps of voltage and current per panel square meter in function of sun irradiation and environmental temperature. Such maps were embedded in the TRAMSE simulator. Of course, the TRAMSE software can receive more precise mapped values, for example coming from experimental tests on a real panel.

Irradiation was calculated through a mathematical model of the solar radiation on the ground [5]; the model takes into account the geographical position of the photovoltaic plant so as its orientation with respect to the sun. The radiation model also accounts for the presence of clouds, which reduce solar radiation to the ground. To simulate the cloudy sky, an algorithm was studied in order to produce the incidence of clouds; the algorithm is based on random numbers generators reproducing the presence, the intensity and the duration of cloudy weather in function of the season.

C. *Electrochemical stationary storage*

To calculate instant by instant the value of the state of charge, the storage was modeled as an integrator Simulink block, whose input is the chemical power to/from the battery.

The chemical power comes from the instantaneous value of the gross power, which is calculated by the control algorithms. To determine the chemical power on the basis of the gross power, the battery efficiency needs to be known. The simulation model allows to set the efficiency curves of the battery in charging and discharging modes, in function of the parameter Power/Energetic Capacity [kW/kWh]; if said curves are not known, a constant efficiency value can be set for charging and discharging.

In this work the curves of battery efficiency were determined by Simulink models [12-17].

III. ALGORITHMS FOR SYSTEM POWER AND BATTERY MANAGEMENT

The system requires a control algorithm to determine the input and output battery power and the amount of power absorbed from the grid and that delivered to the grid. Such algorithm must be structured in order to maintain the battery state of charge within an acceptable range (e.g. between 35% and 95%).

The TRAMSE model was employed to evaluate different possible control logics of the system equipped with energy storage. Among the several possible control algorithms, two were chosen, of which the results are presented: one turned to the grid-smoothing and one to the self-consumption of the energy produced by the photovoltaic panel. The algorithm input parameters are:

- The algebraic sum of panel power and power required by the user (Delta = P_{Panel} + P_{Load}); P_{Load} is a quantity lower than zero according to the convention for which powers entering the system are positive, while powers exiting from the system (included the dissipations) are negative. Instead, P_{Panel} is always positive or zero.
- The battery state of charge (SOC).

The algorithm output parameters are

- P_{Grid}, the power taken from the grid if positive or delivered to the grid if negative.
- $P_{Battery}$, the battery input (positive) or output (negative) power.

A. *Algorithm for grid smoothing mode*

If Delta is negative (i.e. the system behaves as a consumer, requiring power from the grid), the system operates according to the following equations:

$$P_{Grid} = P^{*} - P^{*}(SOC/SOC^{*}) \qquad (1)$$

$$P_{Battery} = P_{Grid} - |Delta| \qquad (2)$$

Equation (1) being a descending straight line, saturated to an upper value P_{Lim} opportunely chosen.

The equation values are set in order to provide a grid power equal to P_{Lim} for the medium/low SOC values and a grid power function of the battery state of charge for the high SOC values. In this way, when the SOC is high the power required for the load satisfaction is taken from the battery, which is discharged, according to Equation (2).

According to Equation (2), the battery is charged when P_{Grid} > Delta, which occurs when the algebraic sum between user power and panel power is lower than the power taken from the grid. The battery is discharged when P_{Grid} < Delta.

If Delta is positive (i.e. the system has a surplus of power produced by the panel and behaves as a producer) the system responds to the following equations:

$$P_{Grid} = Delta \tag{3}$$
$$P_{Battery} = 0 \tag{4}$$

Thus, all the surplus of power not exploited by the user is delivered to the grid, while no power enters or exits the storage.

B. *Algorithm for self consumption mode*

If Delta is positive, the following equations are implemented:

$$P_{Grid} = 0 \tag{5}$$
$$P_{Battery} = Delta \tag{6}$$

Thus, when a power surplus exists, the difference between power produced by the panel and power required by the user is sent to the battery; no power, instead, is delivered to the grid.

If Delta is negative, the system operates according to Equations (7) and (8):

$$P_{Grid} = -Delta + P_{Battery} \tag{7}$$
$$P_{Battery} = P^{*} - k\,SOC \tag{8}$$

Equation (8) being saturated with an upper saturation limit equal to 0. When a power deficit exists (the panel produces less power than that required by the load), the load is fed by the storage power, which is function of the SOC. The remaining power is taken from the grid according to Equation (7).

C. *Home automation simulation*

In this work, the authors decided to apply a form of home automation which allows the control of startup and shutdown of two appliances: a washing machine and a dish washer, synchronizing their operation with the power signals coming from the photovoltaic panel. It is thus possible to exploit the two appliances during the daily hours, in sun presence, during which the photovoltaic plant produces energy, reducing the requirements from the electric grid.

In the case in exam, the pulse generators by which the electric loads are represented in the model (see paragraph II.A) were set so that, for every simulated day, are present two dishwasher cycles and at least one washing machine cycle. Through a series of Simulink switch blocks system equipped with feedback, the startup of the two appliances is carried out only in case the power coming from the panels overcomes a threshold of 0.5 kW.

IV. RESULTS

A. *Monitored parameters*

In order to verify the smart-node energy balance and to examine the interaction between the node and the grid, the monitoring of some parameters is required:

- Energy employed by the user in the monitored period.
- Energy entering in the node from the grid in the monitored period.
- Energy exiting from the node and entering in the grid during the monitored period.
- Energy coming from the photovoltaic panel in the monitored period.
- Energy lost in the electro-chemical storage during the monitored period.
- Gross energy entering in the storage during the monitored period.
- Gross energy leaving the electrochemical storage during the monitored period.
- Battery efficiency, defined as the ratio between battery gross energy output and input.
- Battery to user energy ratio, defined as the ratio between gross energy output from the battery and gross energy required by the user; it allows to have an idea of how much energy flows in the battery during the monitored period related to the user's consumption.
- Grid power distortion factor, defined as:

$$D = \frac{(P_{Grid})_{max} - (P_{Grid})_{min}}{(P_{Grid})_{mean}} \tag{9}$$

being $(P_{Grid})_{max}$ the maximum positive grid power peak and $(P_{Grid})_{min}$ the minimum power peak. This factor provides information on how much the node disturbs the grid with its presence.

- Battery frequency of intervention (F), defined as the ratio between maximum battery chemical power and battery energetic capacity. This index, expressed in kW/kWh, is important as it indicates how much the battery is stressed, giving an idea of how many cycles the battery must bear per each hour of operation.

The tests performed with the model envisaged 24 runs in total; in particular:

tests without storage: panel power of 1, 2, 3 and 4 kW;

tests with storage in grid smoothing mode: panel power of 1, 2, 3 and 4 kW;

tests with storage in self consumption mode: panel power of 1, 2, 3 and 4 kW;

These tests were repeated for a smart node without and with the home automation system.

The storage capacity was set in all cases equal to 12 kWh.

In the following, are reported only the most significant results of the simulations.

B Results for a user with a 1 kW panel

In Figure 2 is reported the diagram of grid power input and output and photovoltaic panel power in a three days period. In the image, can be noticed the influence of clouds presence. Grid power ranges between – 1 kW and + 3 kW, being positive (entering in the system) during the night and negative (exiting the system) during the day.

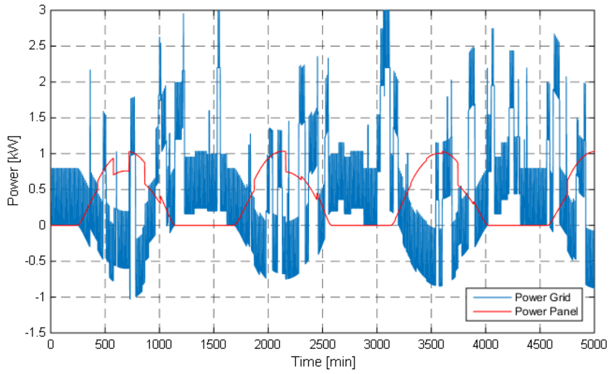

Fig. 2. Grid and panel power without storage.

The system equipped with 1 kW panel and storage controlled by the grid-smoothing mode algorithm is characterized by the diagram with time of grid and panel power visible in Figure 3. In this case the power range is between – 1 kW and + 1 kW.

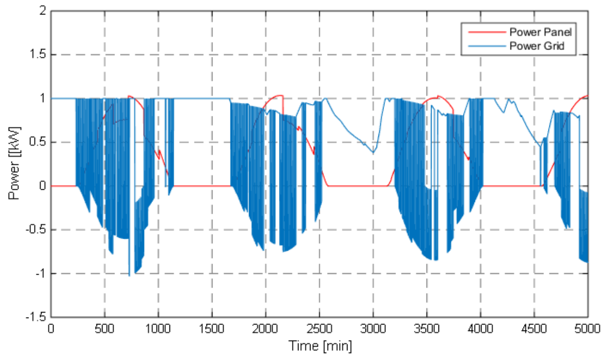

Fig. 3. Grid and panel power with storage in grid smoothing mode.

From Figure 4, reporting the battery state of charge, it is possible to notice that the battery tends to operate with a rather elevated frequency of intervention.

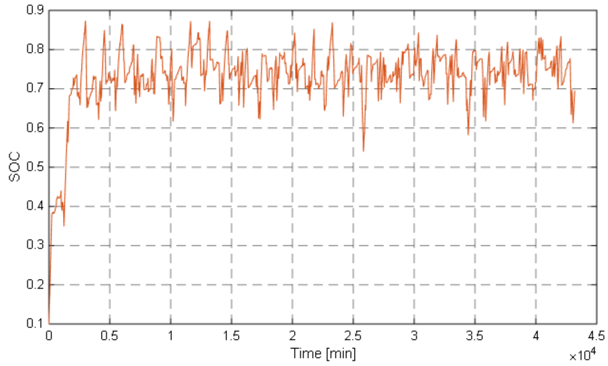

Fig. 4. Battery state of charge for the system with grid smoothing algorithm.

The system equipped with 1 kW panel and storage controlled by the self consumption mode algorithm is characterized by the diagram with time of grid and panel power visible in Figure 5. In this case the power range is between – 1 kW and + 3 kW.

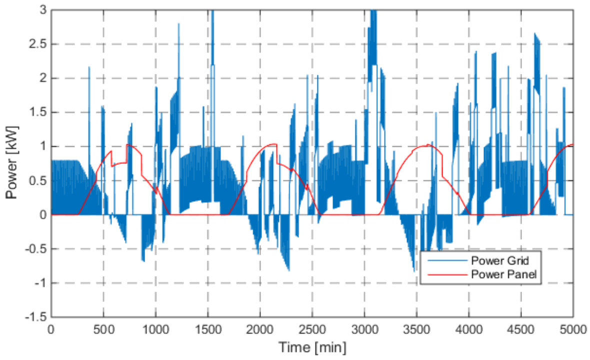

Fig. 5. Grid and panel power with storage in self consumption mode.

In Figure 6, it is possible to observe the battery state of charge variation with time for the system with battery managed in self-consumption mode. From the picture can be observed that employing the self consumption algorithm the battery tends to operate with a daily frequency.

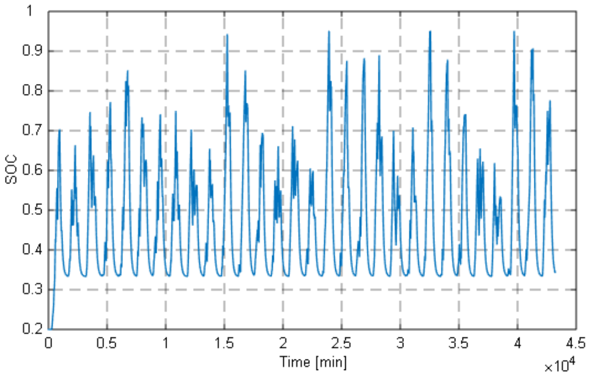

Fig. 6. Battery state of charge for the system with self consumption algorithm.

In Table 1 are reported the most significant simulation parameters. To be noticed in particular the grid distortion factor D equal to 16.61 for the system without battery; the presence of the battery managed in grid smoothing mode allows the reduction of D to less than a half; instead, the self-consumption algorithm results in an increase in the D factor.

TABLE I
SIGNIFICANT PARAMETERS FOR THE SYSTEM WITH 1 KW PANEL WITHOUT HOME AUTOMATION

		Basic + PV panel	**Basic+PV panel +Battery (grid smoothing)**	**Basic+PV panel +Battery (self consumption)**
User Energy	[kWh]	434,33	434,33	434,33
Energy from Grid	[kWh]	308,08	334,47	228,00
Energy to Grid	[kWh]	133,44	133,44	37.04
PV panel Energy	[kWh]	259,70	259,70	259,70
Energy Lost	[kWh]	0,00	19,25	15,45
Gross Energy battery input	[kWh]	0,00	143,19	132,79
Gross Energy battery output	[kWh]	0,00	116,81	116,47
Battery Efficiency	[-]	NC	0,82	0,88
E (Battery to user energy ratio)	[-]	NC	0,27	0,27
D (Grid Distortion Factor)	[-]	16,61	7,27	18,12
F (Battery Engagement Factor)	[kW/kWh]	NC	0,22	0,17

TABLE II
SIGNIFICANT PARAMETERS FOR THE SYSTEM WITH 1 KW PANEL WITH HOME AUTOMATION

		Basic + PV panel	**Basic+PV panel +Battery (spinamento)**	**Basic+PV panel +Battery (autoconsumo)**
User Energy	[kWh]	434,33	434,33	434,33
Energy from Grid	[kWh]	303,11	329,03	224,58
Energy to Grid	[kWh]	128,91	128,91	34,55
PV panel Energy	[kWh]	259,70	259,70	259,70
Energy Lost	[kWh]	0,00	18,90	14,96
Gross Energy battery input	[kWh]	0,00	137,36	128,32
Gross Energy battery output	[kWh]	0,00	111,43	112,49
Battery Efficiency	[-]	NC	0,81	0,88
E (Battery to user energy ratio)	[-]	NC	0,26	0,26
D (Grid Distortion Factor)	[-]	16,60	7,29	17,94
F (Battery Engagement Factor)	[kW/kWh]	NC	0,22	0,17

For comparison, in Table 2 are reported the results of the system with 1 kW panel in presence of the home automation algorithm applied to the washing machine and to the dishwasher.

The configuration equipped with the only panel requires from the grid an energy amount of 303.1 kWh, versus 308.1 kWh of the system without home automation and provides to the grid an energy equal to 128.9 kWh (versus 133.4 kWh).

As visible, the value of the grid distortion factor does not vary significantly in the case of presence of the home automation algorithm.

C Global results

In this section, synoptic tables are provided to indicate the global performances calculated in all the simulations. In particular, tables are provided for the energy amounts exchanged with the grid (input and output) and for the grid distortion factor for all the configurations tested.

TABLE III
SYNOPTIC TABLE FOR ENERGY TAKEN FROM THE GRID, EXPRESSED IN KWH.

Panel power	**1 kW**		**2 kW**		**3 kW**		**4 kW**	
Home automation	No	Yes	No	Yes	No	Yes	No	Yes
No battery	308.08	303.11	245.86	234.39	218.86	202.25	206.62	186.63
Grid smoothing	334.47	329.03	269.54	257.09	240.91	223.06	228.27	206.93
Self consumption	228.0	224.58	164.14	153.09	147.05	132.45	140.66	123.56

TABLE IV
SYNOPTIC TABLE FOR ENERGY PROVIDED TO THE GRID, EXPRESSED IN KWH.

Panel power	**1 kW**		**2 kW**		**3 kW**		**4 kW**	
Home automation	No	Yes	No	Yes	No	Yes	No	Yes
No battery	133.44	128.91	330.92	319.89	563.61	547.44	811.06	791.56
Grid smoothing	133.44	128.91	330.92	319.89	563.61	547.44	811.06	791.56
Self consumption	37.04	34.55	229.42	218.90	474.97	460.86	729.14	712.42

TABLE V
SYNOPTIC TABLE FOR GRID DISTORTION FACTOR.

Panel power	**1 kW**		**2 kW**		**3 kW**		**4 kW**	
Home automation	No	Yes	No	Yes	No	Yes	No	Yes
No battery	16.61	16.60	-42.85	-42.62	-12.72	-12.69	-8.48	-8.47
Grid smoothing	7.27	7.29	-35.97	-35.24	-9.13	-9.08	-6.33	-6.31
Self consumption	18.12	17.94	-56.37	-55.11	-13.40	-13.21	-8.71	-8.61

IV CONCLUSION

Simulations carried out in the course of this work allowed to draw important conclusions about the operation and management of a smart node for domestic use equipped with photovoltaic panel and electrochemical energy storage.

It resulted evident that the storage can be exploited to better manage the power exchanges with the grid; the battery presence carries advantages for the single user (through self-consumption algorithm) or for the grid (through the grid smoothing algorithm).

The sizing of the photovoltaic panel is important in relation with the user's consumption: under-sizing results in a system which behaves predominantly as a "consumer" towards the electric grid, whereas the over-sizing results in a system behaving as a "prosumer", discharging into the grid all of its dynamic oscillations. In relation to this topic, simulations highlighted the existence of a critical sizing for the photovoltaic panel, corresponding to a peak power of 2 kW. In this configuration, the user is characterized by very low average power exchanged with the grid, resulting in a remarkable increase of the grid distortion factor D, which assumed values in the range – 35 - – 56.

To assure a sustainable distortion factor for the grid, it is necessary to install a photovoltaic panel under or over sized, to be far from the critical condition. This rends necessary an analysis of the average user consumption before the installation of the photovoltaic energy source.

The implementation of the system equipped with home automation algorithm carried advantages only in terms of consumptions required by the grid, while did not solve the problems connected to the grid distortion factor.

For what about the distributed generation through smart nodes interconnected to the grid, it is possible to conclude that this solution is convenient only in the case in which the saved energy with this system is higher than the losses due to the installation of an electrochemical storage.

The grid operates today in saturation conditions owing to the presence of the stochastic energy sources. The smoothing of the load diagram generated by the storage systems managed in grid smoothing mode, would contribute to improve this situation, allowing the installation of new renewable energy sources.

Simulations allowed to individuate the optimal configuration for the node, which envisages the user equipped with photovoltaic panel far from the critical power of 2 kW, home automation to ensure a better self consumption of the produced energy and a battery opportunely sized and managed with grid smoothing logics.

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