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Abstract

One of the biggest problem regarding the distributed production of renewable energy is the effective employment of the produced energy. Usually, this energy is reintroduced in the grid with a disadvantage for the producer. In this scenario, we propose an approach that aims at exploiting the entire energy production reintroducing into the grid only the part in excess. The proposed solution is based on a device, called *energy switch*, that enables a change of the electric energy source of a system such as one linked to both photovoltaic and classical energy grid. This operation needs many considerations for warranting a correct energy management and avoiding energy lacks potentially dangerous for the appliances. In particular the system has to be able to recognize the situations in which it is possible to use the cheaper source without causing an energy lack to the system. In the proposed solution, the input data for the system are given by the OMeter stations developed by Over Technologies, a spin-off of Sapienza University. A working prototype of the energy switch has been built for future empirical test about its efficiency. The system reduces the problem of choosing which lines to connect to which energy source to the knapsack problem. The performance of the system are evaluated, checking at anytime whether there is a sufficient power supply or, on the contrary, a power fault happened.

1 Introduction

The global scenario of energy production and distribution is continuously changing and evolving. Nowadays, there is a growing attention to the energy production process due to mainly two reasons: the environmental problem and the need for an energy sources, alternative to the classical ones, for facing the growing requirements coming from a demanding technological advancement.

Classical hydrocarbon-based techniques still represent the principal source of energy in the world, due to several political, economical, historical and technological motivations. Coal and oil have been, and still are, the main raw material for obtaining large quantities of energy, and decades of technological advancement in producing electrical power this way allowed the birth of powerful economical superstructures that hinder the development of alternatives solutions for the energy production. Here, we are mostly talking of electricity, that can be considered the most important kind of energy of our times.

The renewable energies, and photovoltaic (PV) one in particular, have been indicated as the best solution for a major independence from the hydrocarbons. The possibility of producing independently energy for covering the consumptions of the private producers resulted in a strong growth of the private PV plants number. However the introduction of this produced energy into the public grid can represent a problem in terms of sustainability that strongly compromises the PV advantages. In this sense, "self consumption" [9], intended as the capability of using the energy before it is reintroduced into the grid, can bring real benefits from the employment of PV, even for little private plants. This work illustrates the design and a first development of a tool, called Energy Switch, that aims at maximizing the quantity of produced power self consumed in a domestic environment.

2 Background

2.1 Renewable Energies Employment

The most common structure for an energy production and distribution network is conceptually similar to the "client-server" paradigm: a big central source as a "server" and many consumptions points as "clients". A single server solution could be inefficient in case of wind power or photovoltaic plants [3] as their availability is not constant during the time, and high production periods are followed by low production ones (or not at all). So, they are often used for integrating the classical energetic sources. A centralized approach requires an high capacity grid for the distribution, which is often not economically convenient.

A very attractive alternative approach is represented by the distributed one. Small PV plants are installed in decentralized places and domestic environments. However, also this solution has some issues that include the complex interaction between the plants and the classic grid: this represents a problem in terms of both technical limits and bureaucratic procedures. The major problem in this integration is represented by the design of the grid, which is originally intended for providing energy, and not for getting it back [7]. A solution that tries to maximize the self-consumption [5] directly reduces or avoids the grid-plant interactions.

At the actual stage, the power produced by private PV is sold to the provider, completely or partially. This technique is called “Net metering”. Its problem is mainly one: for the customer the selling price is much lower than the buying one, so this mechanism is not convenient for the producer and the saving is low. Modern systems should try to use directly the energy sending just the exceeding one, thus the preferable approach is to maximize the immediate consumption of the energy produced by the plant. This technique is named “Self-consumption”.

Clearly, the self-consumption approach is more convenient for the customer/produces with respect to the net-metering one. However, at the state of the art, it is necessary to dimension the plant for providing a peak energy higher than the real need due to the impossibility of dividing the loads. The aim of this work is to design and realize a tool that can split the total loads into two sets $S1$ and $S2$ such that $S1$ contains the elements that maximize the quantity of energy self-consumed by the system, while $S2$ is provided by the grid.

2.2 Electrical Energy Switches

Energy switching is usually operated using electrical components called relays. A relay is an electrically operated switch, used to control a circuit by means of a low power signal. A classical relay (electromagnetic) consists of a coil of wire wrapped around a soft iron core, an iron yoke which provides a low reluctance path for magnetic flux, a movable iron armature, and one or more sets of contacts. The armature is hinged to the yoke and mechanically linked to one or more sets of moving contacts. It is held in place by a spring so that when the relay is not energized there is an air gap in the magnetic circuit. In this condition, if for example there are two sets of contacts, one of the two in the relay is closed, and the other is open.

However, this kind of relay is afflicted by some problems: the heat generated, the corrosion due to the mechanical switching and the risk of sparks if the switch generates a consistent voltage gap. Additionally, if the two sources are not synchronized or the switching procedure is not so fast, the relay will operate in two different situations at the same time, since it operates under alternating current and not direct one. So it is necessary to grant a synchronization between the grid and the inverter and manage the switching at software or hardware level. The solution adopted in this work causes a short energy interruption due to security reasons, but some improvements will be discussed.

2.3 Monitoring Subsystem: OPlatform

The entire system depends by the electrical appliances consumptions monitoring, that allows the creation of $S1$ and $S2$. The subsystem chosen is the *OPlatform* [6]: it is able to micro-account energy consumption of devices, at the level of single power line, which allows at the same time the actuation of devices, thus being also an energy-aware domotic solution.

The *OPlatform* consists of two main devices: the *Ometer* and the *OBox*, which are responsible, respectively, for controlling electrical appliances and for accessing the whole automation system through web based technologies. In our system the functionalities of the *OBox* are extended for serving the energy switching needs. The typical deployment of the *OPlatform* consists of a single *OBox* and several *OMeters*, the number of which depends on the number of electrical devices to be controlled/monitored.

The role of an OMeter is to actuate electrical loads and to wait fo binary input commands. Each OMeter can handle up to 8 independent electrical circuits providing for their actuation by means of relays which bear a maximum current of 16 amperes. Each of these circuits can be, depending on the granularity that user wants to control, a power line to which many loads are connected to, or an individual electrical load. The OMeter, in addition, handles up to 16 dry contact inputs such as toggle switches, PIR (Passive InfraRed) sensors, magnetic contact sensors, etc. As well as switching on/off an electrical load, the OMeter is able to monitor its power consumption in terms of voltage, current, power factor, apparent, active and reactive power.

As far as the electrical consumption monitoring, an OMeter is able to read the power drained by any load (up to 16A) in a 230V, 50Hz electric network. For this, the OMeter is equipped with a microprocessor(other than the one that takes care of the communication) that samples, at very high frequency, instantaneous power data of each output, thus allowing to calculate TRMS (True Root Mean Square) values of the alternate current.

3 Hardware Design and Realization

Since the Energy Switch is a home automation tool, the scenario considered is the domestic one. In particular, the system operates in an environment in which the house is connected to the electric grid and an off-grid photovoltaic little private plant is available. The plant dimensions depend case by case. If the consumption is high, the plant's production can be until 1 kW. On the other hand, if the domestic consumption is lower, the total renewable production can be lower. However the range considered is between 400 and 1000 Watts. Indeed for plants under 1 kW the fixed costs are lower and a production under the minimum indicated above is hardly directly usable.

Since we are taking into account an off-grid PW private plant, the energy in surplus cannot be properly exploited. The optimization of the self-consumption aims at eliminating the problems related to power intake into the grid. Surplus energy management could be done using little batteries. If the system is properly designed, the quantity of surplus energy is very low and little batteries will not afflict the system so much.

The Energy Switch works at outlet granularity. It means that each single outlet can be fed using or the renewable energy produced or the classical provider one. This implies an higher capability of optimization (cfr. Section 4). When the energy consumption of the appliances exceeds the production due to few watts, this approach allows to turn off the minimum energy quantity that makes the total need satisfiable by the PV. The cons of this approach are related to the hardware complexity and cost.

A working prototype implementing the energy switch has been built. More in details, a little real hybrid PV system has been set. The inverter is an Opti-Solar SP Efecto 1000, that provides until 800 Watts of energy. The inverter gives the priority usage to the solar power. Then if it is not sufficient, it takes energy from the battery. As last, if the battery is discharged, it uses the grid's power. So it can work in UPS mode [15]. Moreover it is equipped with a serial communication board based on RS-232 protocol. The first characteristic provides a "free" protection system in case of wrong configuration, the second one provides an easy way for an informations exchange between the inverter and the micro-controller. However the precision is highly improvable, and the communication protocol is not public and open, but this system is used for providing real-time informations about the energy production. The PV subsystem is completed by two panels, for a total maximum production of 220 Watts. This value is the DC power production, the effective AC outgoing from the inverter is lower, depending on the weather and the conversion lost. Since the inverter has a maximum applicable load and the environment is not fixed, a fuse should protect it from an excessive overload, in case of error.

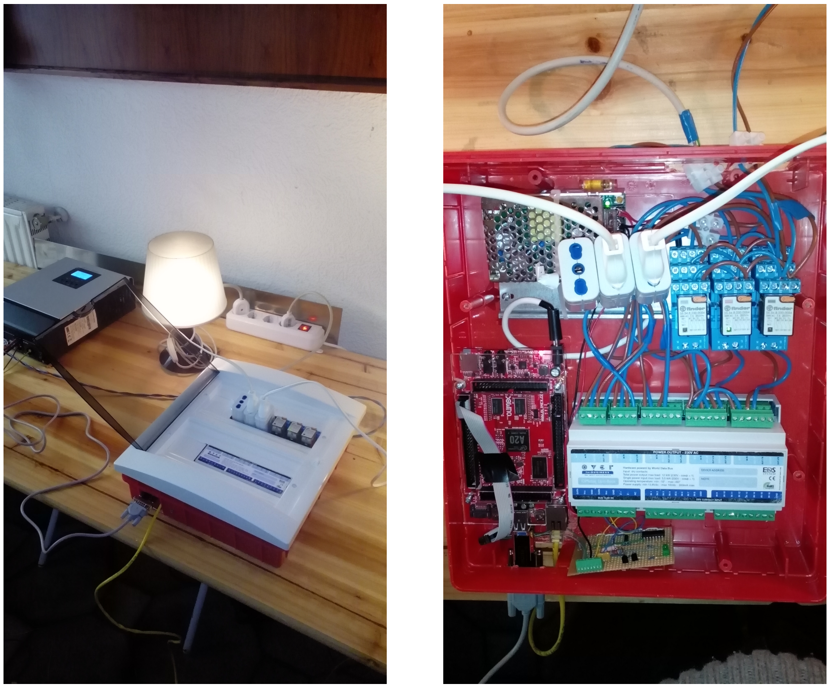
The physical switching is implemented using relays. For the prototype we used 4 contact, 7 ampere, industrial relays. They are controlled through alternate current, so, if the prototype is composed by 3 relays, they are controlled by three O-Meter outs. The other three outs are used for feeding the loads. Practically, half of the gates of the O-Meter are delegated to loads feed, while the other half controls the relays, redirecting them to a source rather than another one. For security reasons now there is a little energy interruption during the switch, for avoiding double feed or sparks. But if the sources are synchronized and the switching operation is fast enough, than the risk is minimum. However, now, sensible appliances can be seriously compromised by this energy little lack. The micro-controller is an Olimex A-20 OLinuXino Micro, a dual core Cortex A7 1GHz frequency board with 1 GB RAM. The prototype developed is a little system composed by three outlets connected both to the inverter and to the grid.

4 Switching Strategy

The system computes the best outlet configuration and connect a subset of the total outlets to the domestic plant and lets the other to be fed by the grid energy. The fine granularity energy monitoring capability offered by the Over platform allows a precise control on the outlets configuration. In particular, combining the information about the produced energy from the inverter and the data about the monitoring activity of the outlets, the system computes the solution of a knapsack [23] problem for maximizing the direct consumption of the energy produced. The knapsack problem is modeled as follows:

$$OP(i,w) = \begin{cases} 0 & \text{if } i = 0 \\ OP(i-1,w) & \text{if } (w_i > w_k) \\ max\,\{OP(i-1,w), v_i + OP(i-1,w-w_i)\} & \text{otherwise} \end{cases}$$

where $OP(i,w)$ is the maximum value subset of outlets $1,\ldots,i$ with consumption limit w (that is the capacity of the Knapsack), i is the i-th item, w_i is its weight (apparent power absorbed) and v_i is its value. So the limit is



(a) Complete prototipe, external view

(b) Energy Switch core, internal view

Figure 1: Two views of the prototype: Figure (a) represents the external view, with the inverter on the left and the core on the right. Figure (b) shows the different internal components: the Olimex, the OMeter and the relays block.

represented by the PV instantaneous production, and the power absorption constitutes the value and the weight of each outlet. The naive solution of the knapsack problem has an exponential computational cost.

The implementation is based on a dynamic programming algorithm that can resolve the knapsack in a pseudo polynomial time. More in details each value is rounded to the nearest integer value: the incoming energy is rounded down, while each single consumption is rounded up. So for the total energy amount we have that $W_c = \lfloor W \rfloor$ and $wa_i = \lceil w_i \rceil$ where W is the instantaneous total panels energy amount and w_i is the instantaneous consumption of the i-th outlet. However this approach works fine if the values are read without any late. In a real application there is the need of considering the total information late. From the inverter side, the late can be considered negligible. Indeed the production changes are quite slow, and in a second the change is not substantial. Otherwise the late for the monitoring system is quite significant. Indeed let's call this late $L_{monitor}$. We have that $L_{monitor} = L_r + L_p + L_e$ where L_r is the late related to the maximum reading frequency of the monitoring system, L_p the propagation delay of the information from the station to the computing unit and L_e is the elaboration time required by the computing unit. From an analysis of these elements, it appears that L_p is very small. Also L_e is quite short, since the hypothesis of low producing plant. L_r instead is around one second. A second is a quite high value in the electrical context, so the effective energy situation at the time of the actuation of the computed configuration can be different and an energy lack can happen. In order to avoid that, the approach proposed is based on the study of the previous behavior of each outlet and on the history of the consumptions. In particular, time is divided in time slots and for each time slot the mean and the variance of the consumptions are computed and considered for taking a decision. For choosing the best approach both the time slots size and the different logics for the system have been tested: so the methodology considered is empirical.

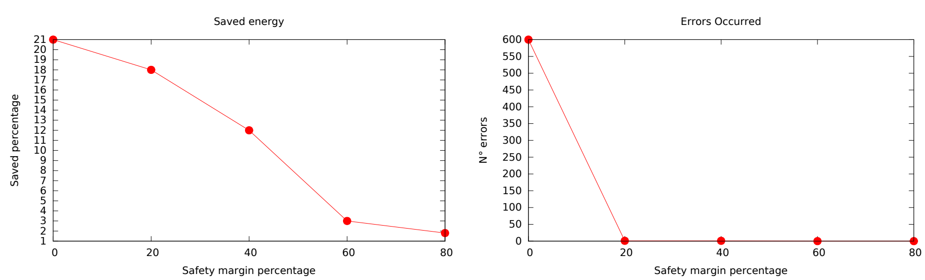
4.1 Fine-Tuning

As previously said, in order to choose the best approach some alternatives have been empirically tested and their performances compared. This methodology has been considered both for tuning the time slot length and for detecting the best switching logic.

We took into account the following switching logics: *(i)* naive, *(ii)* threshold on variance, *(iii)* threshold on variance/mean ratio, *(iv)* adaptive on variance, and *(v)* adaptive on variance/mean ratio. All of them take into account a safety margin. A safety margin is a percentage of the incoming energy that is not considered as available for covering hypothetical errors and energy lacks. On the one hand, the bigger is the safety margin, the lower is the saving; on the other hand, the shorter is the margin, the higher is the error probability. The naive approach has been considered just a comparison term. It does not add any information on the read data, so it is the most speculative approach and counts many errors. For the remaining approaches we can detect two groups: the first two approaches are static, while the others are dynamic.

A static approach implements a logic that excludes an outlet from the knapsack computation if the value of the considered metric overcomes a fixed threshold. Moreover, the percentage of the safety margin is fixed a priori. On the contrary, a dynamic (or adaptive) approach implements a logic that excludes an outlet from the knapsack computation if the value of the considered metric overcomes a dynamic threshold. The safety margin is defined dynamically as well: smaller is the value of the considered metric, lower is the percentage of the safety margin.

Starting from the analysis of the Naive approach results, a clear trend has been detected: the bigger the safety margin is, the lower is the number of total errors, but the energy saving slowly decreases. Even the introduction of a little margin causes a big reduction of the errors. However without a supplementary consideration the system appears not feasible in practical terms. On the contrary, if the supplementary metric analysis is introduced, the performance are quite good with a small safety margin of the 20% (see Figure 2). The best results have been obtained with a time slot 30 minutes length: longer time slots give a less precise description of the consumption regularity, for shorter time slots can be difficult to catch the events and put the influence in the right time slot. However testing them in a real context the best performances have been reached with the adaptive approach using the variance. The saved energy has been the 17% of the total, but the number of errors has been just two. This approach is very dynamic since it is not necessary to define the percentage of the safety margin as for the static approaches. Hence, the results obtained suggest that the most important metric for describing the electric consumption is the variance, computed on 48 daily time slots. If the environment is well known and there are few changes in the system settings, the static approach can be adopted. It allows a greater save but it is weak against the changes. Otherwise the solution adaptive is more general and does not require particular tuning. However its saving is a little lower, so it is the right tuning if the system setting is variable or not defined a priori.



(a) Energy Saved (b) Errors Occurred

Figure 2: Threshold on *variance* approach simulation results. The number of time slots considered is 48. The approach tries to minimize the risks when the benefits would be few. The best results are obtained with a 20% safety margin.

5 Conclusions and Future Works

This work introduces a system that proposes a new approach to the renewable energy management for small production plants in a domestic environment. We demonstrated that the improvement of the self-consumption can warranty a saving in terms of energy and money.

Exploiting information technology algorithms and home automation subsystems, this approach moves the focus from producing more energy to improving the self-consumed produced energy changing dynamically the source of each active appliance depending to their consumption and to the instantaneous production. However, a complete exploiting is still infeasible due to the too quick changes on the production quantity and in the consumption of the appliances, so some methodologies have been presented, evaluated and tested through software simulation for studying the best approach. The tests showed that in the best case the saving obtained is nearly the 20% and this can be considered a promising starting result.

However, a validation phase for confirming these results is still necessary: for doing it, a controlled ecosystem will be implemented where the prototype is monitored in order to measure the effective saving and the hypothetical energy lacks.

This work represents a first step in the proposed direction based on self-consumption. There are many aspects that can be improved and many possible solutions can be applied to this aim. For instance, a better individuation of the users' habits can help in preventing energy lacks and in improving the performance of the system. Moreover, a more complete inverter communication facility would allow a more accurate switching: with the current model, it is easy to measure the instantaneous produced current, but it is not trivial to compute the maximum potential instantaneous current of the panels. This information would be very useful for computing the effective maximum load applicable to the PV plant.

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